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Current Trends in Friction Stir Welding (FSW) and Friction Stir Spot Welding (FSSW)

An Overview and Case Studies

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Foreword

In the coming years, the increase usage of lightweight alloys to replace traditional steel components is part of the aims in the transportation industry. Welding similar and dissimilar materials is an important element in the manufacturing industry. The joining of lightweight metals such as aluminium requires high heat input in the weld region due to its high thermal and electrical conductivity. This results in higher energy consumption and consequently in higher costs and may lead to large heat distortion as well as poor joint strength. On the other hand, friction stir welding (FSW) and friction stir spot welding (FSSW) between aluminium and copper could be useful in the fabrication of electrical connections and components.

The development of solid-state welding of similar and dissimilar materials has provided several benefits over the past years. FSW and FSSW are solid-state welding techniques that are environmentally friendly and are attractive areas of research and development. These joining techniques provide more advantages when compared with some of the more traditional techniques. These advantages include the elimination of solidification cracking, porosity and liquation cracking. This book presents the current trends on FSW and FSSW of similar and dissimilar materials with a focus on the joining of aluminium and copper.

This book provides a number of benefits for researchers and professionals in this field, as well as for experts. The information in the book provides a good platform for future research in the field of FSW and FSSW, and this would lead to the optimization of processes. The authors of this book have worked and have numerous publications in the field of FSW and FSSW and are accomplished researchers in these fields. Thus, the authors are well positioned to write this book. The book comprises six chapters; Chap. 1 gives an overview of different welding techniques with the focus on FSW and FSSW. The different process parameters, joint configurations and the applications of FSW and FSSW are also outlined in Chap. 1. Chapter 2 presents the current state of FSW and FSSW of aluminium and copper. Studies conducted in FSW and FSSW of aluminium and copper are summarized regarding the microstructure evolution and the mechanical properties. This could provide a good comprehension of the current state of the two processes and lead to the optimization of the two welding methods. The current state of FSW and

FSSW of similar aluminium and similar copper is presented in Chap. 3. Selected studies are summarized in terms of the tool geometries, process parameters and the resulting microstructure and mechanical properties. Furthermore, Chap. 3 also provides information which will enable researchers conduct further studies in order to expand the use of the two techniques in various industries. From Chap. 4 to 6, the authors present a case study on the joining of AA1060 to C11000 using FSSW. The case study focused on the microstructure evolution, mechanical properties such as microhardness, shear tensile strength and residual stresses. Furthermore, an investigation on the presence of intermetallics and electrical properties of the produced spot welds is presented. Interestingly, a statistical analysis was conducted and presented.

By presenting an original research on the successful joining of aluminium to copper using FSSW, the authors provide confidence to designers and engineers to consider FSSW for a wider usage in different sectors. Furthermore, the overview on the current state of FSW and FSSW of similar and dissimilar materials will give a substantial background on the current state of these two techniques. The book will also serve as a resource for researchers dealing with various challenges in joining of similar and dissimilar materials.

Therefore, I strongly recommend this book to the readers because of the benefits the book will provide, and I believe that this book will assist new researchers in the field of FSW and FSSW to have a required understanding to succeed in these research fields.

Furthermore, I encourage the readers to take full advantage of this interesting book since it is among the few if not the only book which provides an overview on FSSW between aluminium and copper through many chapters.

The joining of aluminium and copper is particularly interesting, as it can help in the field of electromobility to realize significant weight and cost savings.

Prof. Stefan Böhm

Preface

There are numerous new applications in many industries, including the following: power generation, chemical, petrochemical, nuclear, aerospace and manufacturing. The evolving application required the development of new ways of joining similar and dissimilar materials; and this led to the development of friction stir welding (FSW) and friction stir spot welding (FSSW) for similar and dissimilar materials. There are many books on friction stir welding of similar and dissimilar materials; but the friction stir spot welding process has not yet been given similar attention as an emerging technology. Therefore, this book focuses on reporting the current trends on friction stir welding and friction stir spot welding—with the emphasis on friction stir spot welding between aluminium and copper.

Chapter 1 introduces the theories on different welding techniques. Furthermore, the current state of friction stir welding and friction stir spot welding between aluminium and copper is presented. Chapter 2 presents an overview on friction stir welding and friction stir spot welding between aluminium and copper, with the focus on the microstructural evolution, chemical properties and mechanical properties. The current state of friction stir spot welding and friction stir welding of similar aluminium and similar copper materials is presented in Chap. 3.

Joining dissimilar materials is essential for the manufacturing of various structures and parts in the industrial sector. Materials, such as aluminium and copper, are commonly used in engineering structures and parts. This is due to their unique performance, including higher electrical conductivity, heat conductivity, corrosion resistance and mechanical properties. But the two materials have different melting points, namely 660.3 °C for aluminium and 1085 °C for copper. Consequently, Chaps. 4–6 presents case studies on the joining of aluminium and copper in terms

of the microstructural evolution, the mechanical and electrical properties, and the residual stresses. This book is intended to present the current trends on FSW and FSSW, to enable both engineers and researchers to explore the further development of these two techniques.

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Chapter 1

General Introduction



Abstract The joining technology of similar and dissimilar materials plays a crucial role in various areas, include manufacturing. Many conventional welding techniques have been used over the years to successfully join various materials. Friction stir welding (FSW) and friction stir spot welding (FSSW) are solid state welding processes. This introduction gives a brief overview of the two processes, with the focus on FSW and FSSW between copper and aluminium, which are sometimes difficult to join by using conventional joining methods because of their different melting temperatures and their high chemical affinity. Furthermore, the applications of FSW and FSSW in various industrial sectors include robotics, aerospace and automotive areas. An overview of the experimental studies conducted in joining aluminium and copper was conducted. It was observed that FSW and FSSW of aluminium to copper has not yet been fully researched; but more studies are needed for FSSW, in order to optimize the process, which could lead to its expansion.

Keywords Aluminium • Copper • Friction stir welding (FSW)
Friction stir spot welding (FSSW) • Solid state

1.1 Welding Process Overview

Welding can be defined as a fabrication process used to join materials, including metals and thermoplastics. During welding, the workpieces to be joined are melted at the joining interface; and usually a filler material is added to form a pool of molten material that solidifies to become a strong joint. There are many different types of welding processes, including friction stir welding and friction stir spot welding (FSW/FSSW); and the number of different welding processes has grown in recent years.

1.1.1 Gas Welding

In this welding process, a high temperature flame generated by gas combustion is used to melt the work pieces (and filler) together. The most common type of gas welding is Oxy-fuel welding; where acetylene is burnt in oxygen [1]. The gas-welding process presents many advantages and limitations. Some of these advantages and limitations are depicted in Table 1.1.

1.1.2 Resistance Welding

This welding technique involves the generation of heat by passing a high current through the resistance caused by the contact between two or more metal surfaces that cause pools of molten metal to be formed in the welding area [1]. The most common types of resistance welding are resistance spot welding, resistance projection welding and resistance seam welding [3]. Table 1.2 presents the advantages and the limitations of the resistance welding process.

1.1.3 High Energy Density Welding

The welding of very small areas can be achieved by using high energy density welding methods, by focusing the needed energy on that area. Negligible basemetal degradation, residual stress and distortion can be achieved because the process allows for very low overall heat input to the workpieces. Furthermore, the joining speed can be very fast. Laser beam welding and electron beam welding are the two main procedures known for extreme energy densities [3]. Tables 1.3 and 1.4

Table 1.1 Advantages and limitations of the gas welding joining process [2]

Advantages	Limitations
One of the most versatile welding techniques	Workpieces with higher thicknesses cannot be joined efficiently
The generation of heat is far less than that of the arc welding process	Not all types of metals can be joined
The heat affected zone is very thin	More safety is recommended
Maintenance cost of the equipment is low	An adequate storage of acetylene cylinders is essential
No need for an electric current supply	Refractory metals including tungsten and ceramics cannot be joined
The cost of the equipment is low	Continued heating of the joint results in a large heat affected zone

Table 1.2 Advantages and limitations of the resistance welding joining process

Advantages	Limitations
Can join most metals, but it works better with steel	Equipment cost is much more than arc welding equipment.
Possibility of obtaining extremely fast welding speed	Visual inspection of the joints is not possible except for resistance flash and upset welds
The self-clamping aspect of the electrodes makes it very good for automation and production	Extremely high currents are required, resulting in high power line demands
Filler materials is not needed	Equipment is not portable
Thin sheets can be perfectly joined by resistance spot welding and seam welding	Processes, such as spot welding produce poor mechanical properties (i.e. tensile and fatigue) due to the sharp geometrical features at the edge of the weld
	Electrode wear

Table 1.3 Shows the advantages and limitations of the laser beam welding process [3]

Advantages	Limitations
The process permits low overall heat input	Very expensive equipment
Fast welding speeds	Usually equipment cannot be easily moved
No filler metal required	High reflective metals are difficult to weld with some laser beam welding processes
Heat source concentration allows for the creation of extremely small joint sizes needed for small and intricate components	
Capable of welding joints with difficult accessibility	Laser plume may be a problem
	Lasers have a poor energy efficiency
	Brittle microstructure occurred when welding certain steels due to high weld cooling rate

Table 1.4 Depicts the advantages and limitations of the electron beam welding process [3]

Advantages	Limitations
Low overall heat input is allowed	Need for a vacuum the limits production speed and part size
Weld the greatest single pass thicknesses of any fusion process	Very expensive equipment
No shielding gas or metal filler is needed	Machines are not portable
High reflective metals can be joined without problem	Joint require very precise fit-up
Greater depth of focus than laser beam welding	Fast cooling rates may create brittle microstructures with some steels
Weld “aesthetics” are very high	Dangerous beam welding methods produce dangerous X-rays resulting in the usage of radiation shielding on the machines

present some advantages and limitations of laser beam welding and electron beam energy welding, respectively. Further reading on laser beam welding and electron beam welding processes can be found in a book published by Phillips [3].

1.1.4 Solid-State Welding

In this joining method, pressure and deformation provides a considerable portion of the bonding; and usually no melting of the workpiece is required and no filler material is usually needed. Additionally, the diffusion bonding utilizes a pressure that is great enough to deform the hills and valleys on the abutting surfaces locally. The workpiece doesn't experience gross deformation. Then, at a high temperature below the melting temperature of the workpiece, atoms are allowed to diffuse across the interface to fill in any remaining voids and to complete the joining process [1].

There are many types of solid state welding including forge welding, cold welding, friction welding, explosive welding, diffusion welding, ultrasonic welding, friction stir welding and friction stir spot welding.

1.1.4.1 Friction Stir Welding (FSW)

Friction stir welding (FSW) is one of the solid state welding techniques invented and patented in 1991 by The Welding Institute (TWI) for butt and lap joining of ferrous, non-ferrous metals and plastics. The process consists of plunging a specially shaped rotating tool between the butting faces of the workpieces. The rotating tool and the workpieces' relative motion generates frictional heat; and this results in creating a plasticized region around the plunged portion of the tool [4].

It has been reported that the friction stir welding of aluminium alloys has advantages when compared with fusion welding processes. Problems, such as solidification cracking, porosity and liquation cracking are eliminated when using FSW due to its solid-state nature [5]. Figure 1.1 shows a schematic illustration of the friction stir welding method.

The FSW process provides many benefits compared to the conventional welding processes, Table 1.5 presents a list of the benefits expected from the usage of friction stir welding as a joining process.

Furthermore, FSW provides numerous energy benefits including the usage of only 2.5% of the energy needed for a laser weld; and the reduction in fuel consumption in lightweight aircraft, automobiles and ship production [6].

1.1.4.2 Friction Stir Spot Welding (FSSW)

Friction stir spot welding (FSSW) is a spot welding process and an alternative joining method of friction stir welding (FSW) technique. A non-consumable

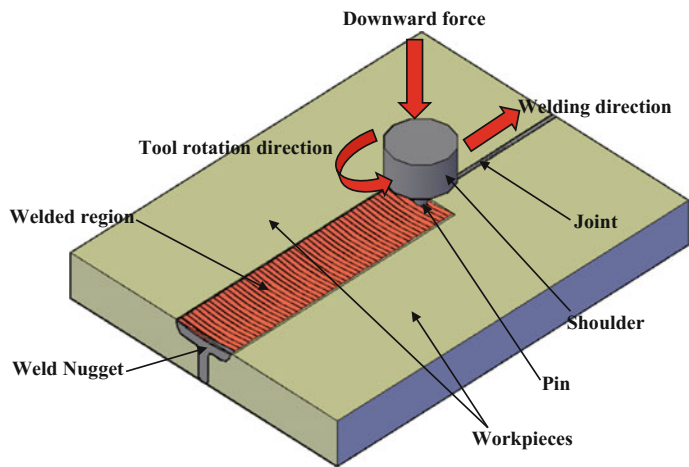


Fig. 1.1 A schematic illustration of FSW technique

Table 1.5 Advantages of the friction stir welding joining process [6]

Metallurgical benefits	Environmental benefits
Solid-phase welding process	Shielding gas not required
Acceptable distortion	Requires minimal surface cleaning
Good dimensional stability and repeatability	Eliminates grinding wastes
No loss of alloying elements	Eliminates solvents required for degreasing
Improved mechanical properties in the joint	Consumable materials saving include rugs, wire, or any other gases
Area	
Fine recrystallized microstructure	No harmful emissions
Solidification cracking is non-existent	
Replaces multiple parts joined by fasteners	

rotating tool is plunged into the materials to be joined. After reaching the selected plunge depth, the rotating tool is held in that position for a pre-determined time. This is sometimes referred to as the hold time; it is also called the dwell time. Then, the rotating tool is retracted from the welded joint leaving behind a friction stir spot weld. Basically, during the process, tool penetration and the dwell time determine the heat generation, material plasticization around the pin, weld geometry and the resulting mechanical properties of the completed welds [7]. A schematic illustration of the FSSW process is shown in Fig. 1.2.

It has been reported that the tool shoulder generates the bulk of the frictional or deformational heat. However; the pin assists in creating a material flow between the

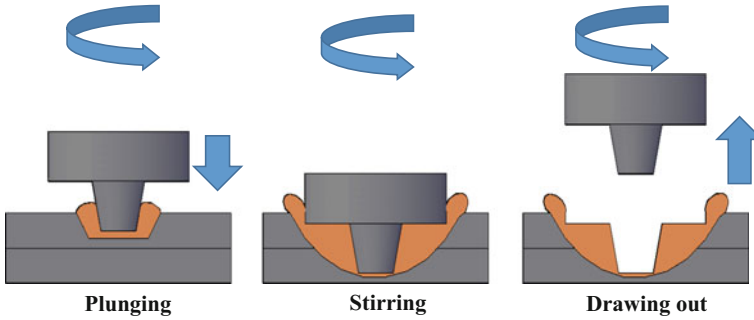


Fig. 1.2 Schematic illustration of the friction stir spot welding process

work pieces [7]. In addition to the tool geometry, the tool rotation speed; the tool plunge depth and the dwell time are the other parameters involved in FSSW. The above-mentioned parameters determine the strength and the surface finish of the welded joints [7]. There is a nomenclature to describe the different microstructural regions present after joining workpieces by using FSSW. The cross-sectioned FFS Weld shows the five characteristics, which include the parent material (PM), the heat affected zone (HAZ), the thermomechanically affected zone (TMAZ), the stir zone (SZ) and the Hook, which is also called the copper ring (for FSSW Al/Cu). The different microstructural regions of the FSS Weld are shown in Fig. 1.3.

As can be seen, the parent material (PM) is the material that is far from the welded region and that has not been affected; although that area may have experienced thermal cycling from the weld. The microstructure or other properties of the PM are not affected by the heat generated during the FSSW process. The heat affected zone (HAZ) is the area which is closest to the centre of the weld; and it has been thermally affected during welding. Consequently, the microstructure and/or the mechanical properties of the HAZ are modified compared to the PM; but there is no plastic deformation in this region.

The thermomechanically affected zone (TMAZ) is located in the region where the materials are plastically deformed by the tool. In some materials, it is possible to

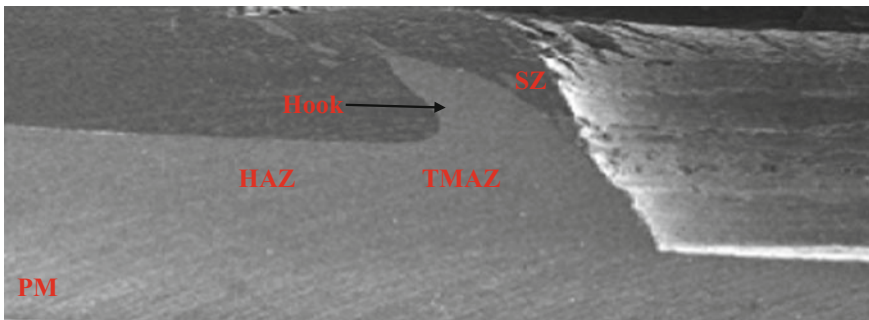


Fig. 1.3 Cross-sectional appearance of a typical friction stir spot weld

obtain substantial plastic strain without recrystallization in this weld region. Furthermore, there is a distinct boundary between the recrystallized zone and the TMAZ. In the immediate vicinity of the keyhole, there is a zone called the stir zone (SZ); and this zone is the fully recrystallized region of the spot weld. The grains found in the stir zone are roughly equiaxed and often smaller than the grains in the parent material.

While, the Hook which is also called the copper ring in friction stir spot welding between aluminium and copper is a characteristic feature of friction stir spot welds in lap configuration; where there is the formation of a geometrical defect originating at the interface of the two welded sheets [8–10].

1.1.4.3 FSW and FSSW Joint Configurations

Friction stir welding can be used to join different material shapes by the usage of various types of joint configurations, including: butt, lap, T-butt, and fillet shapes. The most-used joint configurations for friction stir welding are butt and lap joints. Different weld configurations are shown in Fig. 1.4. On the other hand, the joint configuration of friction stir spot welding is usually a butt configuration.

1.1.4.4 FSW and FSSW Tools

A basic and conventional geometry of a FSW tool is shown in Fig. 1.5. FSW tools follow the same basic trends in terms of their shapes and geometries. They are generally comprised of three generic features, including a shoulder, a probe also

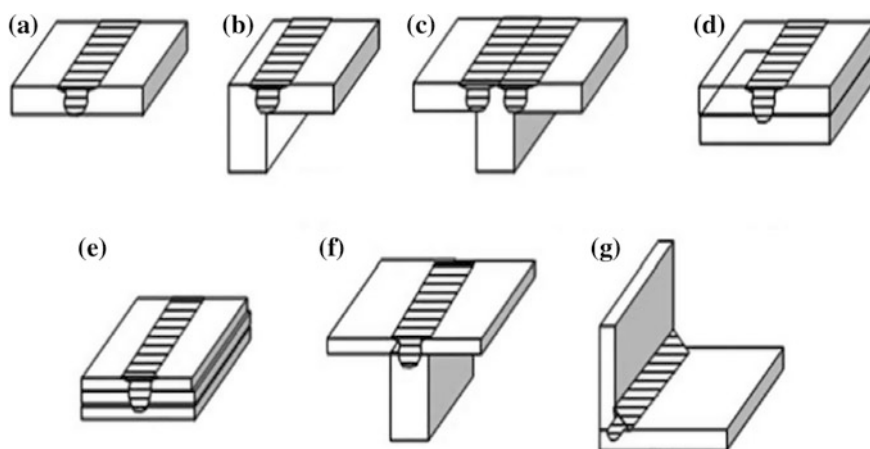
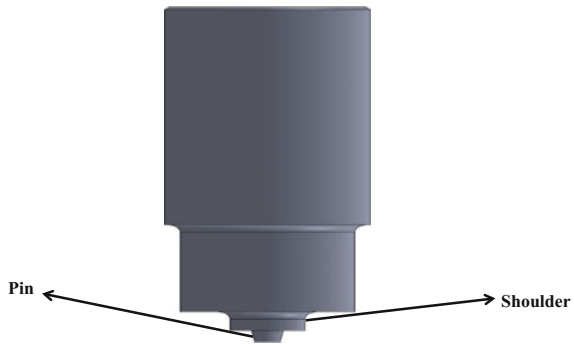


Fig. 1.4 Joint configurations for friction stir welding: **a** Square butt, **b** Edge butt, **c** T-Butt joint, **d** Lap joint, **e** Multiple lap joint, **f** T-Lap joint, and **g** Fillet joint [11] Reprinted with permission from Elsevier

Fig. 1.5 A Schematic illustration of the tool geometry used in friction stir welding and friction stir spot welding processes



known as a pin; and any external features. The heat input, forging action, and stirring action of the tool induces a plastic flow in the material, forming a solid state weld. It was early realized in the development of the friction stir welding method that the tool's design is critical in producing sound welds [12]. Friction stir welding, friction stir spot welding and friction stir processing (FPS) processes all use similar tools; and these tools have various shapes; and they are manufactured by using different materials.

Numerous tools, with different geometries have been used to produce sound welds by using FSW and FSSW. Mubiayi and Akinlabi [9] used a H13 tool steel hardened to 50-52 HRC. Two tool geometries were used, namely a flat pin/ flat shoulder and conical pin/concave shoulder tools to successfully friction stir spot weld AA1060 to C11000 workpieces. On the other hand and most recently, Mehta and Badheka [13] used a M 2 grade tool steel with a threaded cylindrical pin to friction stir weld Electrolytic Touch Pitch (ETP) Cu and AA6061-T651. The details of the various tools used to join similar and dissimilar materials, using FSW and FSSW are presented in Chaps. 2 and 3.

1.1.4.5 Tool Material

There are many characteristics that have to be considered when choosing the tool material for friction stir welding, friction stir spot welding and friction stir processing [14]. These characteristics include:

- Resistance to wear;
- No detrimental reactions with the parent materials;
- Good strength, dimensional stability and creep resistance at ambient and elevated temperatures;
- Good thermal fatigue strength to resist repeated thermal cycles;
- Good fracture toughness to withstand the damage during plunging and holding;
- Low coefficient of thermal expansion;
- Good machinability to enable the manufacturing of complex features on the shoulder and the pin

Tool material characteristics can be critical for FSW, FSSW and FSP. The candidate tool material depends on the base material to be used and the desired tool life; and it further depends on the experience of the users and their preferences [6].

The commonly used tool materials include: tool steel, polycrystalline cubic boron nitride (pcBN) tools and Tungsten-based tools [15]. Additionally, other tools materials, such as silicon nitride (Si_3N_4) and Molybdenum-based alloys are also used as welding tools.

The selection of tool material is very important. Rai et al. [15] reported that the weld quality and tool wear are two important considerations in the selection of tool material, the properties of which may affect the weld quality by influencing heat generation and dissipation. The interaction between the base materials and an eroded tool material may also affect the microstructure of the produced weld. Besides the potentially detrimental effects on the weld's microstructure, the processing cost of friction stir welding is increased by the occurrence of significant tool wear.

Owing to the severe heating of the tool during friction stir welding, substantial wear may result if the tool material has low yield strength at high temperatures. Furthermore, the stresses experienced by the tool depend on the strength of the base metal at elevated temperatures common under the FSW conditions. Also, the temperatures generated in the base material depend on the tool material properties included, the thermal conductivity for a given base material and the process parameters [15].

A tool typically comprises a pin also called a probe and a shoulder. The two principal parts of the tool have different purposes; therefore, it is essential to choose their geometries properly, in order to produce sound welds. Furthermore, the tool geometry affects the generation of the heat rate, the traverse force, the torque and the thermomechanical environment experienced by the tool. The flow of plasticized material in the base material is affected by the geometry of the tool, as well as the linear and rotational motion of the tool.

The important factors of the tool are: the shoulder diameter, shoulder surface angle, pin geometry, including its shape and size; and also the nature of the tool surfaces [15].

1.1.4.6 Areas of Applications of FSW and FSSW

Many emerging applications in power generation and the chemical, petrochemical, nuclear, aerospace, industries, as well as manufacturing led to the development of FSW for similar and dissimilar materials. FSW and FSSW that are used in various industries include: aerospace [16], automotive [17] and robotics [18]. This shows that the two welding processes are used in many industries; hence their optimization could lead to the increase of their usage in new sectors to avoid many of the disadvantages of conventional welding techniques; since FSW and FSSW are solid state joining techniques.

1.1.4.7 Current State of FSW and FSSW Between Aluminium and Copper

Over the years researchers have conducted much research work on friction stir welding and friction stir spot welding using similar and dissimilar base materials. This section focuses on the current state of research conducted so far on the joining of aluminium and copper using FSW [10, 13, 19–61] and FSSW [9, 60, 62–79]. The data were extracted from major research journals, conferences and from the web of science, in order to investigate the current state of FSW and FSSW Al/Cu (number (a) and percentage per year (b)), as depicted in Fig. 1.6a, b and Fig. 1.7a, b, respectively. This was done from the year 2010 to date, excluding various review papers.

It can be clearly seen that FSSW between aluminium and copper process is still an under-researched area; and more scientific studies need to be conducted, in order to fully understand the process. This should enable the process to be optimized and

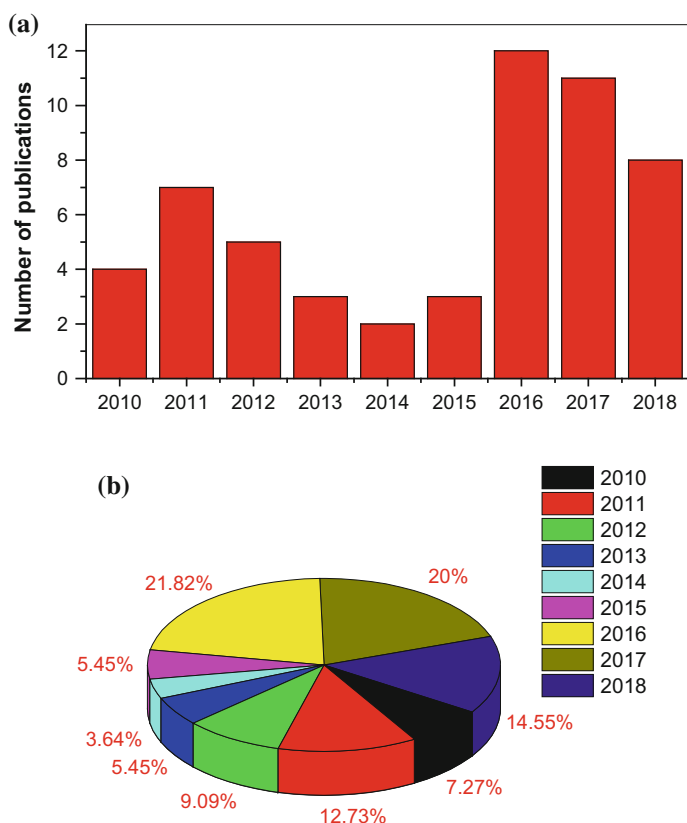


Fig. 1.6 Shows **a** number of publications on FSW Cu/Al from the year 2010, **b** percentage per year from 2010 (number of publications)

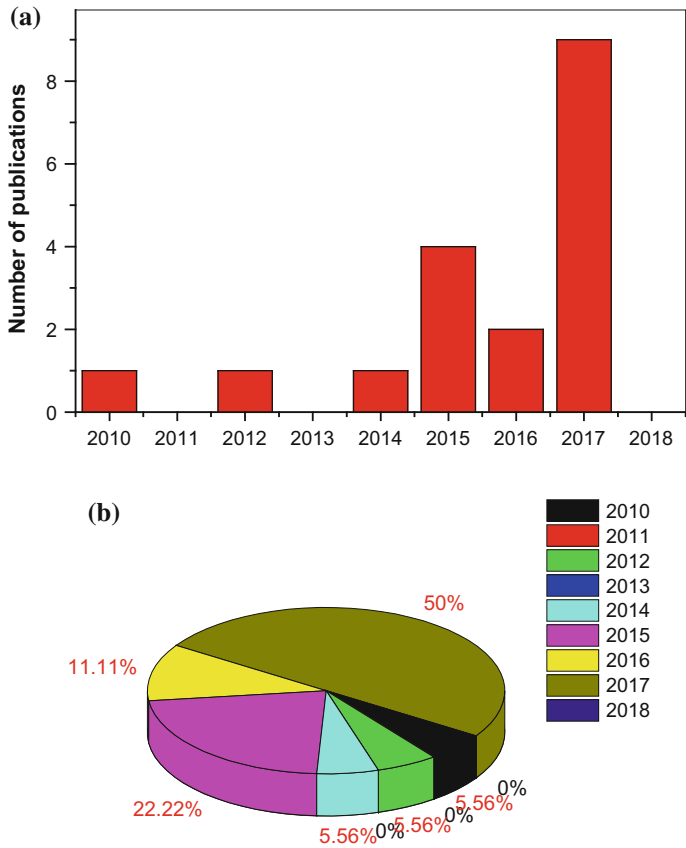


Fig. 1.7 Shows **a** number of publications on FSSW Cu/Al from the year 2010, **b** percentage per year from 2010 (number of publications)

to be used industrially. Furthermore, friction stir spot welding can be an alternative joining process to resistance welding. As depicted in Fig. 1.7a, b, it can be seen that there is an improvement in the number of published outputs since the year 2017, which shows that an interest is being shown by researchers to conduct more studies on FSSW Al/Cu. This could lead to the optimization of the technique and consequently enable the technique to be fully used in various industries.

However, most of the research conducted on friction stir spot welding between Al/Cu focus on the joining of pure aluminium to pure copper. Research studies on other aluminium and copper alloys are needed to expand and attract interest on the usage of this joining technique; and this should result in its application in more industries.

1.2 Conclusions

This chapter has focused on a brief introduction to friction stir welding (FSW) and friction stir spot welding (FSSW) joining techniques, with an emphasis on the joining between aluminium and copper. The background and the current state of research conducted on FSW and FSSW have been presented. More studies are needed – especially for FSSW Cu/Al, in order to expand its application; and such a process could be an alternative to resistance welding. Furthermore, industrial applications of FSW and FSSW has been outlined in this chapter. It may thus be concluded that the industrial applications of the two joining processes can be expanded to other sectors if the processes are to be fully optimized.

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Chapter 2

Friction Stir Welding and Friction Stir Spot Welding of Aluminium/Copper Alloys



Abstract The development of laboratory work on friction stir welding (FSW) and friction stir spot welding (FSSW) FSW of dissimilar materials should provide a good insight into their possible industrial applications; and therefore, enhance their industrial development. Many applications in various industries, especially in the manufacturing sector, have led to the development of processes, such as FSW and FSSW for similar and dissimilar materials. Aluminium and copper have different properties including melting temperatures, which make the two materials difficult to join. Choosing suitable parameters, such as rotation speed, welding speed, and tool plunge depth and dwell time is important when fabricating sound FSWelds and FSSWelds. This chapter presents the current state of FSW and FSSW of aluminium and copper. An overview of the research conducted in the field of FSW and FSSW between aluminium and copper is summarized in terms of the microstructural evolution and the mechanical properties. The quality of the fabricated welds, spot welds and explanations of various properties of the welds by various researchers is presented and summarized. This could provide an insight into the current state of the two processes; and it could also lead to the optimization of the techniques by conducting more research in the field of FSW and FSSW Al/Cu. Furthermore, future scope on the usage of the two techniques is addressed.

Keywords Aluminium • Copper • Hardness • Intermetallics • Microstructure
Tensile strength

2.1 Introduction

This chapter focuses on the literature related to friction stir welding (FSW) and friction stir spot welding (FSSW) between aluminium and copper. The factors affecting the friction stir spot welding process will be outlined.

2.2 Solid State Welding

Solid-state welding occurs where joining is produced at temperatures below the melting point of the base materials without the usage of any filler metal. There are many solid-state joining processes including friction welding, friction stir welding (FSW), spot welding, and resistance welding. In the solid-state joining processes, there are fewer defects; because the metals do not reach their melting temperatures [1].

2.3 Metallurgy of the Aluminium-Copper System

The high metallurgical reactivity and affinity between aluminium and copper leads to the formation of hard and brittle intermetallic compounds in two zones, viz. the joint interface and the stir zone [2]. Copper and aluminium are the equilibrium solid phases of the Al-Cu system, and the terminal Face-Centred Cubic (FCC) solid solutions; copper (Cu) is typically designated α ; henceforth, the low-temperature ordered phase based on the FCC structure is designated α_2 ; where β represents the disordered Body-Centred Cubic (BCC) solid solution; β_1 , the ordered BCC phase, which occurs in its metastable form; and β_0 , a high-temperature phase; (iii) ε_1 and ε_2 comprise those phases of indefinite structure; (iv) phases with structures based on γ brass, γ_0 , γ_1 and δ ; and (v) the equiatomic phases, η_1 and η_2 , and the near-equi-atomic phases, ζ_1 and ζ_2 , with structures related to the η structures; and (vi) θ , and metastable transition phases θ' and θ'' , formed from supersaturated (Al) before the $\{\theta + (\text{Al})\}$ equilibrium is reached.

The solubility of aluminium in copper is 19.7 atomic percentage of aluminium; and the solubility decreases below the peritectoid temperature [3]. The Al/Cu phase diagram is depicted in Fig. 2.1.

Furthermore, Table 2.1 shows a list of the characteristics of common inter-metallics including their atomic percentages and weight composition, as cited by Akinlabi [3].

In the open literature, there are many research projects on friction stir welding (FSW) between aluminium and copper [2, 4–46]. On the other hand, friction stir spot welding (FSSW) between aluminium and copper has not yet received the same exposure as FSW [47–66].

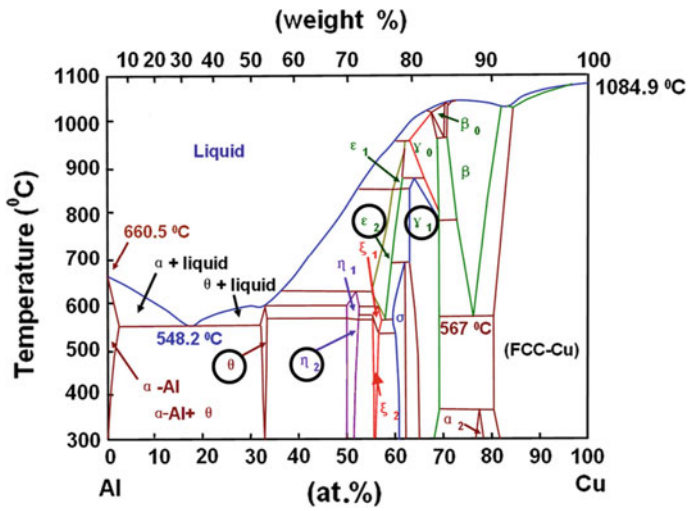


Fig. 2.1 Binary diagram of Al/Cu [67]. Reprinted with permission from Elsevier

Table 2.1 Shows the characteristics of common intermetallic compounds (adapted from [3])

Phase	Composition, atomic % Cu	Composition weight % Cu	Chemical formula	Formation temperature (°C)
Al	0–2.48	0	Al	0
θ	31.9–33.0	54	Al ₂ Cu	550
η_1	49.8–52.4	70	AlCu	591
η_2	49.8–52.3	70	AlCu	591
ζ_1	55.2–59.8	76	Al ₃ Cu ₄	624
ζ_2	55.2–56.3	76	Al ₃ Cu ₄	624
δ	59.3–61.9	78	Al ₂ Cu ₃	700
γ_0	59.8–69	84	Al ₄ Cu ₉	950
γ_1	62.5–69	84	Al ₄ Cu ₉	950
β_0	67.6–70.2	88	AlCu ₃	1048
β	70.6–82.0	88	AlCu ₃	1048
Cu	83.3–100	89–100	Cu	1083

2.4 Friction Stir Welding

Friction stir welding (FSW) is a solid state joining technique invented and patented by TWI (The Welding Institute) in 1991 for butt and lap welding of ferrous and non-ferrous metals and plastics. FSW is a continuous process that involves plunging a portion of a specially shaped rotating tool between the butting faces of the joint. The relative motion between the tool and the substrate generates frictional

heat that creates a plasticized region around the immersed portion of the tool [1]. Over the years, the FSW technique has been successfully used to join similar and dissimilar materials.

2.5 Friction Stir Welding Between Aluminium and Copper

During friction stir welding, the tool material, geometry and features (i.e. the shoulder pin), the welding speed and the rotation speed are considered to be the main process parameters. The importance of the different process parameters was presented in Chap. 1. Based on the importance of the above mentioned process parameters, it is advisable to carefully select these parameters, in order to produce sound welds. Friction stir welding between aluminium and copper has successfully been achieved by many researchers using different process parameters. Table 2.2 presents the base materials, the tool material and the shape and process parameters utilized by researchers to join aluminium to copper using the FSW technique. Furthermore, Table 2.2 shows the type of obtained intermetallics and remarks made in various research studies. It can be seen in Table 2.2 that steel is the most used FSW between aluminium and copper tool material—even if some researchers have used other tool materials. Other tool materials include tungsten carbide [17] and chromium alloy steel [23] that are used to join aluminium to copper. It may be concluded that tools made with steel can successfully be used to join aluminum and copper by using the friction stir welding technique.

2.5.1 *Microstructure Evolution and Chemical Properties*

The microstructural evolution provided valuable information regarding the metallurgy of the welds. The visualization of different regions of the welds, including the SZ, TMAZ and HAZ will provide valuable information to better understand the effect of process parameters on the weld texture, grain size and some resulting mechanical properties.

Friction stir welding of similar and dissimilar materials comprises four zones, namely, the base material, the heat affected zone (HAZ), the thermomechanically affected zone (TMAZ) and the stir zone (SZ).

Figure 2.2 shows the microstructure of friction stir welding of AA5754 to C11000 welds produced at 600 rpm rotation speed and at welding speeds of 50 and 150 mm/min. These microstructures were seen in the stir zone; and they were produced by using 15 and 25 mm tool shoulder diameters.

The joining of aluminium and copper using FSW has been produced and studied by various researchers. In this chapter, an overview of the different conducted

Table 2.2 Presents the parent material, the tool material and the shapes and process parameters used for friction stir welding between aluminium and copper

Parent materials and material thickness	Tool material and shape	Process parameters	Intermetallics/Remark	References
AA1060 and commercial pure copper (5 mm)	Not provided by the authors	Rotation speed: 600 rpm. Welding speed: 100 mm/min	Intermetallic compounds: Al_2Cu , Al_4Cu_9 , AlCu	[4]
AA1060 (4 mm) and commercially pure copper (3 mm)	Quenched and tempered steel. Shoulder diameter: 15 mm. Left-hand threaded pin (diameter: 5 mm)	Rotation speed: 1180 rpm. Welding speed: 30, 60, 95, 118, 190, 300, and 375 mm/min	Maximum tensile shear strength of joint was obtained at welding speed of 95 mm/min No cavity defects, and few microcracks were observed at this welding speed	[6]
AA 6061 T6 and commercially pure copper (2 mm).	H13 tool steel. Shoulder diameter: 12 mm. Top pin diameter: 4 mm. Bottom pin diameter: 2 mm. Pin length: 1.85 mm	Rotation speed: 1000 rpm. Welding Speed: 20 mm/min	Intermetallic compounds: CuAl_2 , CuAl and Cu_9Al_4 in the stir zone	[7]
AA 5083-H111 and Cu-DHP, R240 (1 mm)	Conical (diameter: 14 mm) and Cylindrical pin diameter: 3 mm Scrolled shoulder diameter: 14 mm) and Cylindrical pin diameter: 3 mm	Rotation speed: 750 and 1000 rpm. Welding speed: 160 and 250 mm/min	Large amounts of Cu_9Al_4 were found on the conical shoulder/cylindrical pin. CuAl_2 was detected for the scrolled shoulder/cylindrical pin	[8]
AA 1060 and commercially pure copper (5 mm)	Heat-treated tool steel. Shoulder diameter: 20 mm. Pin diameter: 6 mm. Pin length: 4.8 mm	Rotation speed: 400–1000 rpm. Welding speed: 100 mm/min	Sound defect free welds were obtained under the larger pin offsets. Defects formed easily at smaller pin offsets	[9]
AA1050 H16 and brass (CuZn30) (3 mm)	Hot working alloy steel. Shoulder diameter: 15 mm. Tapered slotted pin	Rotation speed: 200, 400, 650, 900 rpm. Welding speed: 8 mm/min	Intermetallic compounds: CuZn , CuAl_2 and Cu_9Al_4 formed at interface	[10]

(continued)

Table 2.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Intermetallics/Remark	References
AA1050-H16 and brass (3 mm)	Hot working alloy steel. Shoulder diameter: 15 mm. Tapered slotted pin	Rotation speed: 200, 400, 650, 900, 1100 rpm. Welding speed: 8 mm/min	At low rotation speeds, no detectable intermetallic compound As rotation speeds increases, the gradual formation of intermetallics is initiated at the interface	[2]
AA1060 and commercially pure copper (3 mm)	Heat treated tool steel. Shoulder diameter: 20 mm. Pin diameter: 8 mm. Pin length: 4 mm	Rotation speed: 600 rpm. Welding speed: 50 mm/min	Thin, continuous and uniform intermetallic layer was found at the interface	[11]
AA 5083-H111 and Cu-DHP, R 240 (1 mm)	H13 steel tool. Conical shoulder diameter: 14 mm Cylindrical pin diameter: 3 mm	Rotation speed: 750 and 1000 rpm. Welding speed: 160 and 250 mm/min	Lower heat input, formation of a thin layer of intermetallics (Al/Cu interface). Increase the heat input promoted material mixing and formation of increasing amounts of intermetallics	[13]
AA5052 aluminium and pure copper (3 mm)	High speed steel. Flat edge concave shoulder (diameter: 12 mm) and a conical pin diameter: 3 mm)	Rotation speed: from 400 to 1200 rpm. Welding speed: from 25 to 200 mm/min	Intermetallic compounds: include CuAl ₂ , CuAl, Cu ₆ Al ₄ and Cu ₃ Al	[14]
AA 1350 and Commercially pure copper (3 mm)	Concave shoulder (diameter: 16 mm) Cone-threaded pin (diameter: 5.2 mm). Pin length: 2.75 mm	Rotation speed: 1000 rpm. Welding speed: 80 mm/min	No intermetallic compound is found according to the XRD results	[15]
AA5754 and C11000 (3.175 mm)	Three different shoulder diameter tools: 15, 18 and 25 mm. Pin diameter: 5 mm	Rotation speed: 600, 950 and 1200 rpm. Welding speed: 50, 150 and 300 mm/min	Higher hardness values were obtained at the joint interfaces due to the strain hardening and the presence of intermetallic compounds	[16]

(continued)

Table 2.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Intermetallics/Remark	References
Aluminium and copper (3 mm)	Tungsten Carbide tool. Shoulder diameter: 20 mm. Pin diameter: 7 mm	Rotation Speed: 125, 710 rpm. Welding Speed: 50, 355 mm/min	Microhardness values in the nugget zone is higher than the parent materials and no significant difference found in other zones of the weld	[17]
AA 6063 and commercially pure copper (4 mm)	AlSiH13 tool steel and High Speed Steel (HSS). Shoulder diameter: 18, 15 mm. Pin diameter: 7 mm. Pin length: 3.7 mm	Rotation speed: 1000–1400 rpm. Welding speed: 40–80 mm/min	At higher rotation speed stacking layered structure developed at the Al–Cu interface, and crack initiated easily resulting in the poor mechanical properties	[18]
AA 6082-T6, 5083-H111 (6 mm) and Copper-DHP (R240) (6 mm)	Conical shoulder diameter: 9.5 mm Conical pin diameter: 3 mm. Pin length: 1 mm	Rotation speed: 600 rpm. Welding speed: 50 mm/min	Hardness testing and X-ray diffraction showed important differences in microstructure evolution for both types of welds	[20]
AA5083 (2.5 mm) and commercially pure copper (3 mm)	H13 quenched and tempered steel tool. Shoulder diameter: 19.1 mm. Pin diameter: 5 mm. Pin length: 3.8 mm	Rotation speed 600, 825, 1115, 1550 rpm. Welding speed: 15, 32 mm/min	Intermetallic compounds were detected mostly at the brittle fracture areas	[21]
AA 1050 and commercially pure copper (3 mm)	H13 tool-steel. Shoulder diameter: 15 mm. Pin diameter: 3 mm	Rotation speed: 600, 800, 900, 1000, 1200, 1400 rpm. Welding speed: 50, 63, 80, 100, 125 mm/min	Intermetallic compounds are found in weld zone of FSWed annealed and CGPed samples (Al ₂ Cu and Al ₄ Cu ₉ mainly)	[22]
AA 5086-H116) and pure copper (6.3 mm)	Chromium alloy steel. Concaved shoulder diameter: 18 mm. Cylindrical tool with a counter threaded pin diameter: 6 mm, pin length: 5.9 mm	Rotation speed: 560, 710 rpm. Welding speed: 69 mm/min	The microstructure revealed some particles of copper inclusion in the nugget zone	[23]

(continued)

Table 2.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Intermetallics/Remark	References
1A99 (2 mm) and industrial pure Cu (2 mm)	H13 tool steel. Pinless tool. Shoulder diameter: 16 mm	Rotation speed: 1200, 1600 and 2000 rpm. Welding speed: 20, 40 mm/min	Mechanical properties showed considerable relations with the interlayer, include the microstructure and the extent of diffusion and extrusion	[24]
AA1100-H14 and commercially pure copper (6 mm)	Hardened super high speed steel. Concave shoulder diameter: 18 mm. Plain taper pin diameter: 5.5, 7.2 mm. Pin length: 5.8 mm.	Rotation speed: 1070 rpm. Welding speed: 50, 90, 70,80, 90 mm/min	High tensile properties are attributed to many factors include, the formation of defect free stir zone and formation of nano scale thin intermetallic layer at the Al/Cu interface	[25]
AA6061-T651 and electrolytic-tough-pitch (ETP) Cu (6.3 mm)	Tool steel of M2 grade material. Two different tool designs. Tool 1: Taper threaded pin: diameter: 6 mm (root), 3 mm (tip) Tool 2: cylindrical threaded pin: diameter: 8 mm. Shoulder diameter: 26.64 mm	Tool 1: Rotational speed: 1500 rpm. Welding speed: 30 mm. Tool 2: Rotation speed: 1500 rpm. Welding speed: 40, 55, 70 and 95 mm/min	Intermetallics in the stir zone made the joint area brittle and hardness increased	[26]
AA6351 and pure copper (3 mm)	High speed steel. Shoulder diameter: 18 mm. Pin diameter: 2.5 mm. Pin length: 2.7 mm	Rotation speed: 150—900 rpm in step of 150 rpm. Welding speed: 60 mm/min	Intermetallic compounds: Al_4Cu_9 , $AlCu$, Al_2Cu and Al_2Cu_3 were found at the interface and the stir zone	[28]
6063-O and pure copper (6 mm)	AlSi H13 tool steel. Shoulder diameter: 25 mm. Pin diameter: 6 mm. Pin length: 5.6 mm	Rotation Speed: 560, 710, 900 rpm. Welding speed: 16, 20, 25 mm/min	The tool rotation speed played a major role in the influence of microhardness than the tool tilt angle	[29]

(continued)

Table 2.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Intermetallics/Remark	References
AA 7075 and pure copper (5 mm)	Tool with frustum threaded pin. Shoulder diameter: 18 mm. Pin diameter: 6 mm. Pin length: 4.8 mm	Rotation speed: 1400, 1300, 1200 rpm. Welding speed: 50-75-100 mm/min	The preheating of aluminium/copper dissimilar joints improved the mechanical properties of the produced welds	[30]
1050-H16 and pure copper (3 mm)	Cylinder shoulder diameter: 14.5 mm and thickness: 12 mm. Cylindrical pin diameter: 4.5 mm and thickness: 2.25 mm	Rotation speed: 1000 rpm. Welding speed: 40 mm/min	Welding speed and penetration volume are reduced by further distancing from the surface of workpiece. Due to the reduction in the torque caused by the tool shoulder	[31]
AA6061-T651 and electrolytic tough pitch copper (6.3 mm)	Tool steel of M2 grade. Cylindrical threaded pin diameter: 8 mm. Shoulder diameter: 26.64 mm	Rotation speed: 1300 rpm. Welding speed: 40 mm/min	Formation intermetallics increases as the tilt angle increases. Al_2Cu , Al_3Cu_4 and Al_4Cu_9 , $AlCu_3$ were found in the stir zone for a tilt angle of 0 and 2 respectively	[32]
Al-Cu laminated composites (Al: 1 mm, Cu: 1.8 mm)		Rotation speed: 1200 rpm. Welding speed: 50 mm/min	Welding from aluminium side, finer grain structure is developed (no intermetallics). Welding from Cu side, intermetallics formed in some locations in nugget zone	[34]
AA1050 Al and pure copper (2 mm)	H13 tool steel. Shoulder diameter: 17 mm. Threaded pin diameter: 5 mm. Pin length: 1.8 mm	Rotation speeds: 1000, 1200 and 1400 rpm. Welding speed: 20, 50 mm/min	Intermetallic compounds phases increased with increasing rotation speeds. Hardness values in the stir zones was high due to the presence of intermetallics	[35]

(continued)

Table 2.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Intermetallics/Remark	References
AA1050 and pure copper (4 mm)	H13 tool steel. Shoulder diameter: 25 mm. Cylindrical pin diameter: 6 mm. Pin length: 3.5 mm	Rotation speed: 600, 1200, 1800 rpm. Welding speed: 20, 30, 40 mm/min	Macrostructure showed the flow of the mixed materials at the nugget zone, the formation of the intermetallics and differentiation between the nugget zone and thermomechanically affected zone	[36]
AA 6061 and pure copper (5 mm)	Tool with frustum threaded pin. Shoulder diameter: 18 mm. Pin diameter: 6 mm. Pin length: 4.8 mm	Rotation speed: 1400, 1300, 1200 rpm. Welding speed: 50, 75, 100 mm/min	Intermetallic compounds include AlCu, Al ₂ Cu ₃ and Al ₄ Cu ₉ were observed in the lower part of the weld	[37]
AA6061-T651 and Electrolytic Touch Pitch (ETP) copper (6.5 mm)	Tool steel (M2 grade). Shoulder diameter: 26.64 mm. Threaded cylindrical pin diameter: 8 mm. Pin length: 6.3 mm	Rotation speed: 1500 rpm. Welding speed: 50 mm/min	Intermetallic compounds: CuAl ₂ and Cu ₉ Al ₄ were present in the stir zone along with solid solutions of copper and aluminium	[4]
AA6061-T651 and electrolytic touch pitch (ETP) copper (6.3 mm)	Tool steel M2 grade. Nine different tool designs. Shoulder diameter: 26.63 mm. Three different pin diameters: as 6, 8 and 10 mm (first experiments). Second and third, Polygonal tool pin profiles such as triangular, square and hexagonal designs were used	Rotation speed: 1500 rpm. Welding speed: 50 mm/min	Intermetallic compounds: CuAl, CuAl ₂ , Cu ₃ Al and Cu ₉ Al ₄ were found in the stir zone	[38]
AA 1050 and pure copper (4 mm)	H13 tool steel. Shoulder diameter: 25 mm. Cylindrical pin diameter: 6 mm. Pin length: 3.5 mm	Rotation speed: 600, 1200, 1800, 2400 rpm. Welding speed: 30 mm/min	Intermetallics played an important role in achieving successful dissimilar joint, nonetheless the increased thickness of intermetallics reduced the tensile strength	[40]

(continued)

Table 2.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Intermetallics/Remark	References
AA 6063 and commercially pure copper (6 mm)	SKD61 tool steel. Shoulder diameter: 20 mm. Conical right hand threaded pin length: 5 mm and 0.8 mm pitch	Rotation speed: 1100, 1400, 1800 rpm. Welding speed: 20, 40 mm/min	Energy dispersive spectroscopy and X-ray diffraction analysis detected the presence of intermetallics include AlCu, Al ₂ Cu and Al ₄ Cu ₉ in the stir zone	[41]
AA6060 and C11000 (3 mm)			Intermetallic compounds were formed at the aluminum alloy/copper interfaces	[42]
AA6061 (outer diameter: 54 mm, thickness: 3 mm) and annealed pure copper tubes (outer diameter: 58 mm, thickness: 2 mm)	H13 steel tool. Concave shoulder diameter: 16 mm. right-hand-threaded cylindrical pin diameter: 5 mm. Pin length: 3 mm	Rotation speed: 710, 1000 rpm. Welding speed: 30, 45, 60 mm/min	Copper and aluminum tubes were successfully joined in lap joints	[43]
AA 16061-T6 and pure commercial copper (4 mm)	H13 RC 50–55 tool. Scrolled shoulder diameter: 11.52 mm. Threaded pin diameter: 5 mm. Pin length: 3.8 mm	Rotation speed: 900 rpm. Welding speed: 20, 40, 150 mm/min	Twice the hardness of the parent materials was observed in the stir zone and surrounding areas due to the presence of intermetallics and grain size refinement	[33]
AA6060-T5 (6 mm) and commercially pure copper (3 mm)	Heat treated tool steel (H13). Normal concave tools and tool with scroll shoulder. Shoulder diameter: 25 mm. Pin diameter: 8 mm	Preliminary experiments, rotation speed: 1400 rpm. Welding speed: 40 mm/min. Second experiments, rotation speed: 500, 710, 1000, 1400 rpm. Welding speed: 56 mm/min	Temperature above eutectic promoted extensive intermetallic growth, particularly Al ₂ Cu	[44]

(continued)

Table 2.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Intermetallics/Remark	References
AA 6061-T4 and T2 commercially pure copper (5 mm)	Shoulder diameter: 16 mm. Pin length: 5 mm	Rotation speed: 1100 rpm. Welding speed: 30 mm/min	Tensile test results indicated that the joint fractured along the Al/Cu interface and microdefects were found on the fracture	[45]
AA6063 (3 mm) and Cu-DHP (3 mm)	Tool steel SKD61. Shoulder diameter (20 mm). Conical pin diameter: 6 mm with 1.26 mm pitch and spiral threading	Rotation speed: 800, 1000 rpm. Welding speed: 20, 40 mm/min	Intermetallics (Al_4Cu_9 and $AlCu_4$) were favoured while using 1000 rpm and 20 mm/min than 800 rpm and 40 mm/min	[46]
AA6061-T4 (4.2 mm) and T2 commercially pure copper (2.3 mm)	Shoulder diameter: 12 mm. Pin diameter: 4.3 mm on the bottom, 3.2 mm on the top. Pin length: 4 mm	Rotation speed: 900, 1100, 1300 rpm. Welding speed: 150 mm/min	Rich particles zones made of copper particles dispersed in an aluminium matrix, and Flow tracks were observed	[64]

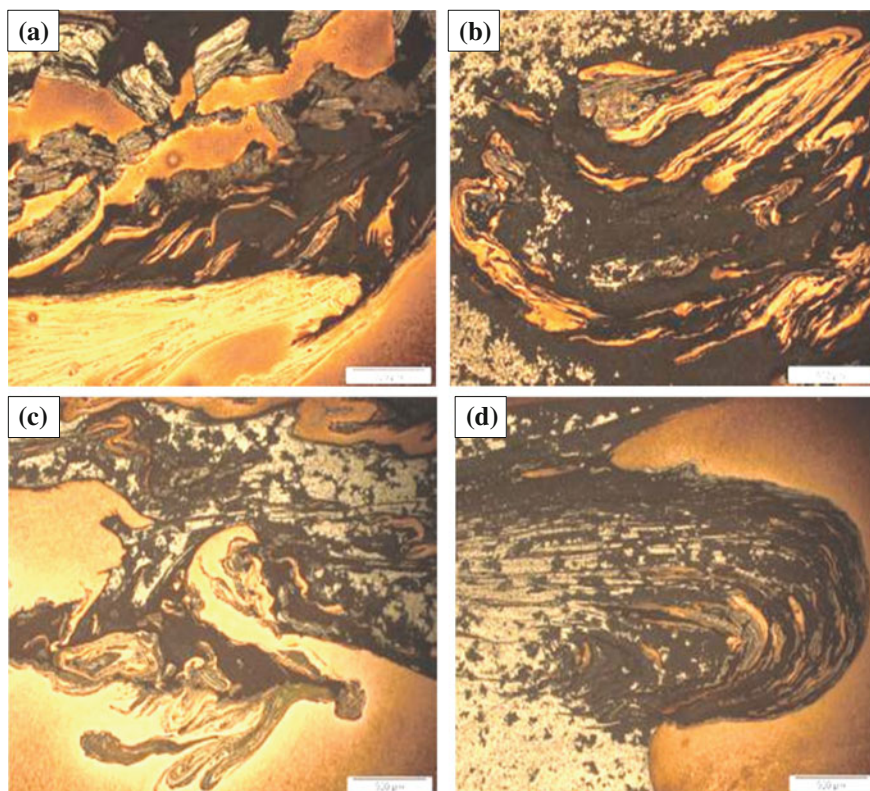


Fig. 2.2 Shows the microstructure of FS Welds produced **a** at 600 rpm and 50 mm/min, **b** 600 rpm and 150 mm/min in the stir zone using a 15 mm shoulder diameter tool, **c** at 600 rpm and 50 mm/min, **d** 600 rpm and 150 mm/min in the stir zone using a 25 mm shoulder diameter tool [3]

studies is presented to show the current state of FSW between aluminium and copper.

Figure 2.3 depicts the microstructure of aluminium/copper joint produced at a welding speed of 20 mm/min [67]. The microstructures show different morphologies in the different regions of the weld. For example, Fig. 2.3b shows the dispersion of fine copper fragments and particles in the nugget region close to the aluminium matrix. It can also be seen in Fig. 2.3e that a large number of finer and denser particles were dispersed in the aluminium matrix [67]. Furthermore, the energy dispersive spectroscopy analyses were carried out (represented by the crosses). The results showed the presence of intermetallics (Al_4Cu_9 and Al_2Cu in Fig. 2.3c).

AA1060 aluminum alloy and commercial pure copper were successfully friction stir welded by offsetting the tool into the aluminum side [4]. An excellent metallurgical bonding on the Al/Cu interface with the formation of a thin, continuous and

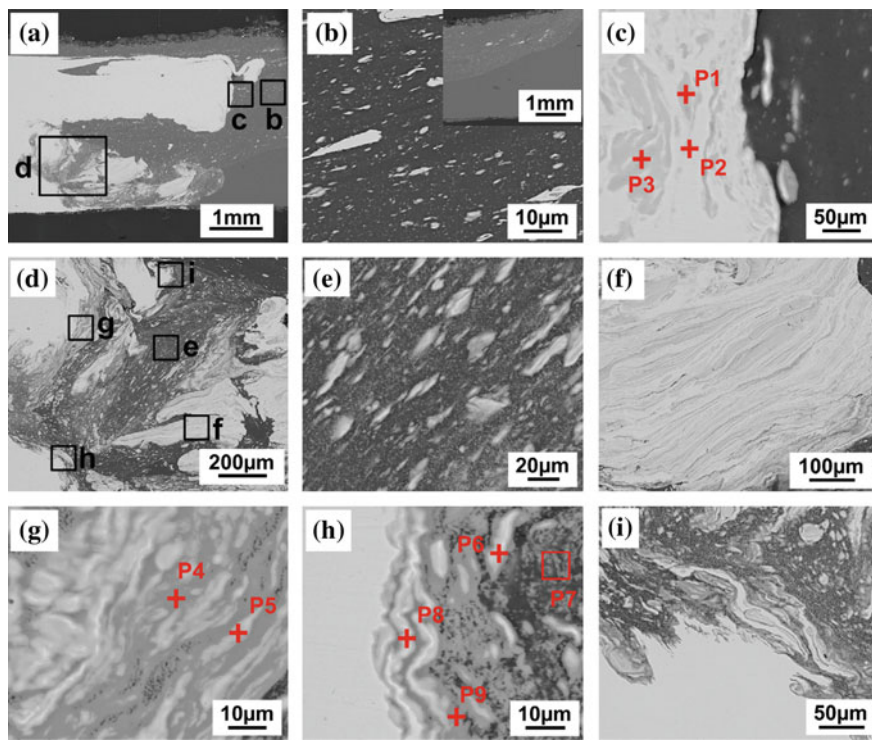


Fig. 2.3 Shows the interfacial microstructure of Al/Cu welds produced at a welding speed of 20 mm/min, broad view of the cross section (a), b–d magnified views of regions b–d marked in (a), and (e–i) magnified views of regions e–i marked in (d) [67]. Reprinted with permission from Elsevier

uniform Al/Cu intermetallic compound layer was achieved. Additionally, several intermetallic particles were generated in the nugget zone, forming a composite structure [4].

Xue et al. [5], joined 1060 aluminum and commercial pure copper and correlated the presence of intermetallics to the strength of the joints. Figure 2.4 presents the microstructures of the Al/Cu joint. The nugget region comprises a mixture of the Al matrix and copper particles (Fig. 2.4a); while Fig. 2.4b depicts the presence of a large number of fine particles with various sizes disseminated in the aluminium matrix, and also the presence of some large particles [5].

In another conducted study, the aluminium close to the aluminium/copper interface, a dark area, was formed in a study on friction stir welding of AA1060 to commercially pure copper [6]. The presence of intermetallic compounds of Al_4Cu_9 and Al_2Cu , and some microcracks were also identified in the joints. When the welding speed was increased, the frequency of the microcracks decreased. Furthermore, the formation of cavity defects inside the welds produced at higher

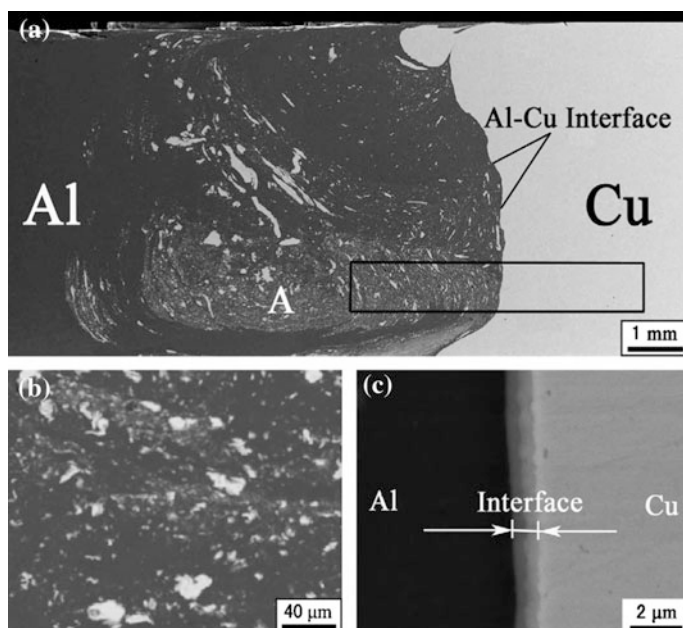


Fig. 2.4 Backscattered electron images (SEM) of the FSW Al/Cu weld: **a** cross section, **b** magnified view of region A as marked in **(a)**, and **c** microstructure of the Al/Cu interface [5]. Reprinted with permission from Elsevier

welding speeds (118 and 190 mm/min) was observed; and this was due to insufficient heat input [6].

AA 6061 T6 alloy and commercially pure copper sheet were friction stir welded by Ratnesh et al. [7]. They stated that sound welds with high plasticity can be produced by shifting the centre line of the tool towards copper sheet to create proportional heating and plasticization of copper and aluminium. When the tool centerline was shifted toward the copper side, sound welds were obtained. When the aluminium was on the advancing side, imperfect welds were produced; and when copper was put on the advancing side, sound welds were produced [7].

AA 5083-H111 and deoxidized high phosphorus copper sheets were joined by using FSW [8] and using different tool geometries and process parameters. They found that the tool geometry and position of the sheets intensely influenced the morphology of the aluminium and copper flow interaction zones. Furthermore, the tool geometry and the position of the sheets influenced the distribution of both materials in the joint and also the formation of intermetallics. Additionally, the material accumulated under the tool during welding was found as another important aspect determining the weld morphology [8].

The study further investigated the position of the sheets during the joining. The welds produced with Al placed at the advancing side exhibited a very irregular morphology, being significantly thinner and exhibiting flashes; and this is attributed

to the expulsion of the Al from the weld area. Whereas, when the copper alloy is located at the retreating side of the tool, the copper materials were transported into the aluminium matrix (advancing side) by the shoulder [8].

1060 aluminum alloy and commercially pure copper were joined by friction stir welding and the effect of welding parameters on surface morphology, the interface microstructure and mechanical properties were investigated [9]. The results revealed that good quality defect-free joints could be obtained under larger pin offsets of no less than 2 mm; when the hard copper sheet was put on the advancing side. On the other hand, a lot of weld defects were then formed in the nugget region at the lower rotation speed of 400 rpm; while at higher rotation speed, good metallurgical bonding between the copper fragments and the aluminium matrix was achieved. The Al/Cu butted interface was thin, uniform and continuous at the lower rotation speed of 400, 600 rpm; although, thick stacking layered structures developed on the interface at higher rotation speeds of 800, 1000 rpm [9].

They further reported that, a thin, uniform and continuous intermetallics layer at the aluminium/copper butted interface was essential for producing sound friction stir welding Al/Cu joints. The stacking layered structure developed at the Al/Cu interface under higher rotation speeds, resulting in an easy initiation of cracks, consequently resulting in the poor mechanical properties. As the rotational speed increases the porosity of the joint surface also increases [9].

AA 1050 and brass were used as parent materials; and they were friction stir welded [10]. The weld defects can be eliminated when the optimum process parameters are used; while when the optimum parameters are not used the defects in the joints are intensified. In the nugget region of the aluminium, the distribution, shape and size of the particles are non-homogeneous and irregular; and the brass particles are not uniform and of different sizes [10].

The structure in the nugget zone of aluminum is comprised of a composite structure, containing intermetallics and brass particles, particularly at the upper zone of the weld cross section. Moreover, at rotation speeds higher than 450 rpm a multilayer intermetallic compound formed at the joint interface [10]. In that formed layer, CuZn, CuAl₂ and Cu₉Al₄ intermetallics were present. On the other hand, the optimum process parameters would produce a defect-free joint, due to the a suitable material flow and a thin multilayer intermetallic compound at the joint interface—in addition to a composite structure in the SZ; and this resulted in a strong joint [10].

Esmaeili et al. [2], investigated the effect of the intermetallics formation on the mechanical behavior of friction stir welded aluminium 1050 to brass. They found that CuAl₂ is the dominant intermetallic in the composite structure of the SZ; while four intermetallics bands were detected at the interface. They further reported that at low rotation speeds, intermetallic compounds were not detected; and this was attributed to the low levels of heat input. On the other hand, when the rotation speed is increased, the formation of intermetallic compounds gradually formed at the interface. When the rotation speed is further increased, the thickening and development of interfacial intermetallics occurred [2].

Friction stir welding was used to join aluminium and copper plates [11]. A good metallurgical bonding on the aluminium/copper interface was realized due to the

formation of a thin, continuous and uniform Al/Cu intermetallics layer. Additionally, they observed many copper particles consisting of pure copper and intermetallics layers at the lower part of the nugget zone, forming a composite structure. Moreover, a good bonding was achieved between the aluminium matrix and the copper particles in the composite structure due to the formation of a small number of intermetallics [11].

Cu-DHP, R240 and 5083-H111 sheets were friction stir welded using different weld conditions, in order to analyze the mechanisms intermetallic compounds formation and their relation to the welding process parameters [13].

A thin intermetallic layer distributed along the Al/Cu interface was seen inside the nugget under lower heat input; but increasing the heat input promoted material mixing and the formation of high amounts of intermetallic rich structures. Furthermore, the formation of intermetallics and the morphology of the mixing regions are strongly affected by the welding process parameters [13].

On the other hand, increasing the rotational speed/welding speed ratio, the weld nuggets exhibited heterogeneous phase composition with significant amounts of both base materials, as well as some intermetallic phases (CuAl_2 , Cu_9Al_4); Furthermore, the welds obtained under the higher rotational speed/welding speed ratio, only Cu, Cu (Al) solid solution and Cu_9Al_4 were obtained. One of the reasons for its occurrence is due to the structural evolution of the CuAl_2 under mechanical conditions developed inside the shear layer surrounding the tool pin under high heat input conditions [13].

AA 5052 aluminium alloy and pure copper were joined by using FSW [14]. Several intermetallics were found, including CuAl_2 , CuAl, Cu_9Al_4 , and Cu_3Al , together with Al and Cu (Al) solid solution. Additionally, at the interface, the intercalations, with flat or bended characteristics, are made of $\text{CuAl} + \text{Cu}_9\text{Al}_4$ laminae combined with $\text{Al} + \text{CuAl}_2 + \text{Cu(Al)}$ laminae and spaced by Cu(Al) laminae. The formation reason for these structures is due to the intense stirring action of the tool pin similar to the principle of mechanical alloying, and the formation reason for intermetallics is due to the short-circuit diffusion caused by extreme deformation [14].

The dissimilar friction stir welding of pure copper/1350 aluminum alloy sheet was successfully joined with a pin offset technique under a tool rotation rate of 1000 rpm and a welding speed of 80 mm/min [15].

A complex microstructure was formed in the nugget region, in which a vortex-like pattern and lamella structure could be found (Fig. 2.5). In their study, intermetallic compounds were not found in the nugget region [15].

In another study, a microstructural evaluation of the joint interfaces showed good mixing of both materials due to the adequate heat input into the welds during the welding process. A 92% reduction in grain sizes was observed in the stir zone compared to the base materials [16]. Akinlabi et al. [19] further established that better metallurgical bonding and good mixing of both materials joined were achieved in welds produced at lower feed rates of 50 and 150 mm/min; while defects, such as worm-hole defect were found to be common in the welds produced

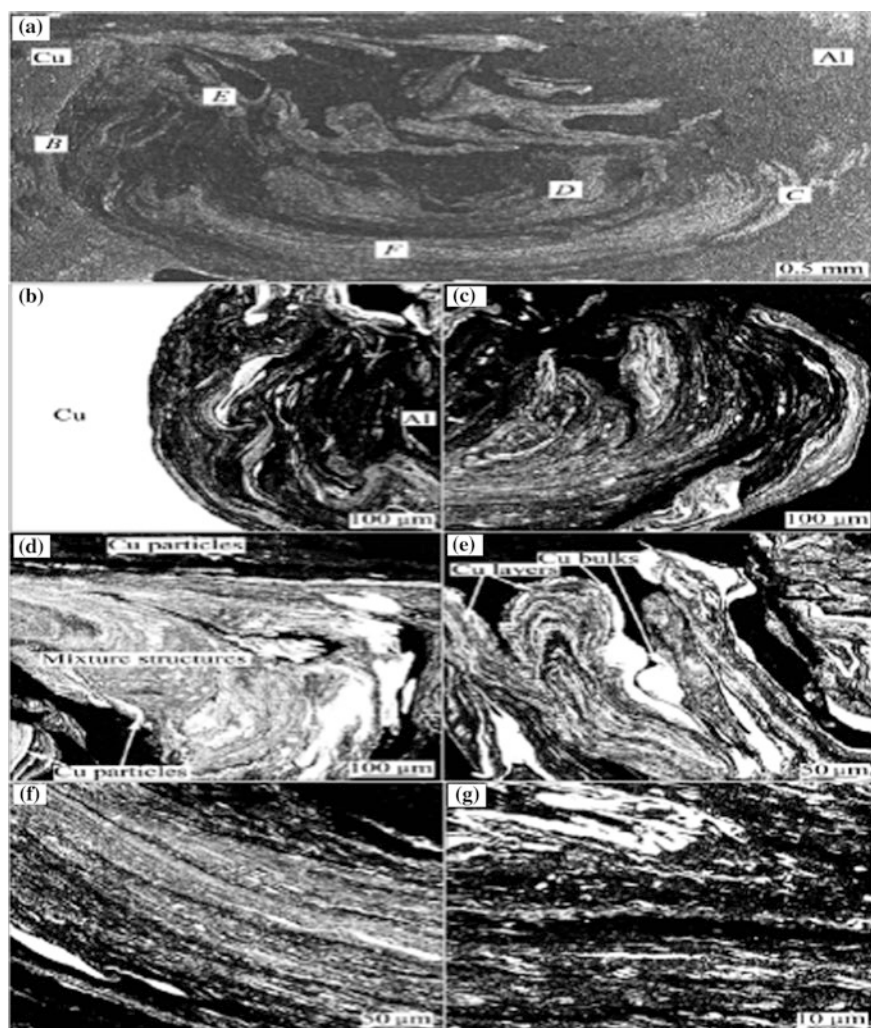


Fig. 2.5 Microstructure (SEM) of Al/Cu weld: **a** Macrostructure of joint; **b–f** BEI images of different regions marked *B–F* in **(a)**; **g** magnified view of layer structure, as shown in **(f)** [15]. Reprinted with permission from Elsevier

at a high feed rate of 300 mm/min. This shows that the welding speed affects the quality of the produced joints [19].

AA 6101 and pure copper were welded; and the influence of the microstructures and the mechanical properties were analyzed [17].

AA 6063 aluminium alloy and commercially pure copper sheets were joined, using FSW and the effect of welding parameters on surface morphology, interface microstructure and mechanical properties were investigated [18].

Under higher rotation speeds, a stacking layered structure developed at the aluminium/copper interface; and crack initiated easily, resulting in poor mechanical properties [18].

AA 6082 and AA 5083 aluminium alloys were friction stir welded to copper, using the same welding parameters [20]. The usage of the two aluminium alloys joined with copper showed differences in the obtained results [20]. At high temperatures and strain rates, the different plastic properties of the AA 5083 and AA 6082 aluminium alloys, have an important effect on the metallurgical and material flow phenomena taking place during Al/Cu joining and, subsequently, on the resulting properties of the welds [20].

Galvao et al. [20] maintained that the usage of a very small tool played a decisive role in the microstructural evolution of the AA 5083-H111 aluminium alloy during welding.

Significant internal defects were detected for the AA5083/copper welds; and this was the result of ineffective material mixing; while for the AA6082/copper welds, a relatively uniform material mixing was observed [20].

Furthermore, the formation of submicron-sized microstructures in the SZ (aluminium) was observed in the AA5083/copper welds; where atypically high hardness values were measured [20].

Although, the AA5083/copper welds exhibited an excellent surface finish, nonetheless they showed highly defective Al/Cu interfaces. On the other hand, the AA 6082/copper welds exhibited poor surface properties; but they showed strong parent materials mixing in the SZ [20]. Figure 2.6 presents the surface appearance of the weld produced between copper and AA6082 (Fig. 2.6a), cross sections (Fig. 2.6b, c); where the Al/Cu interaction can be seen, as well as the presence of a well-defined shoulder influence region. Figure 2.6d shows an enhanced image of a part of the weld where deformed copper particles are seen across the entire plate thickness [20].

Two dissimilar sheets, namely, AA5083 aluminum alloy and commercially pure copper were friction stir welded to investigate the effect of process parameters on the microstructure, the mechanical properties and the defects [21]. Bisadi et al. [21], observed that very low or high welding temperatures lead to many joint defects. This could be seen, at very low welding temperature. Defects, like channels, showed up at a region near the sheets interface, especially in the copper sheet. Similarly, at extremely high temperature some cavities appeared at the interface of the defused aluminum particles and the copper sheet material [21]. Figure 2.7 shows the microstructure of the weld produced at 1550 rpm and 15 mm/min.

In Fig. 2.7, a region can be seen in which some cavity defects are present. These cavity defects were formed when the aluminium particles were forced into the copper sheet and after quenching. AA 1050 aluminum alloy and commercially pure copper sheets were used and friction stir welded [22]. They used a technique for imposing a severe strain on the sheets. This is called the constrained groove pressing (CGP) method. The aluminium and the copper sheets were annealed at 350 and 650 °C, constrained groove pressed; and then friction stir welded [22]. Several forms of intermetallics were found in the weld zone of FSWed annealed and CGPed

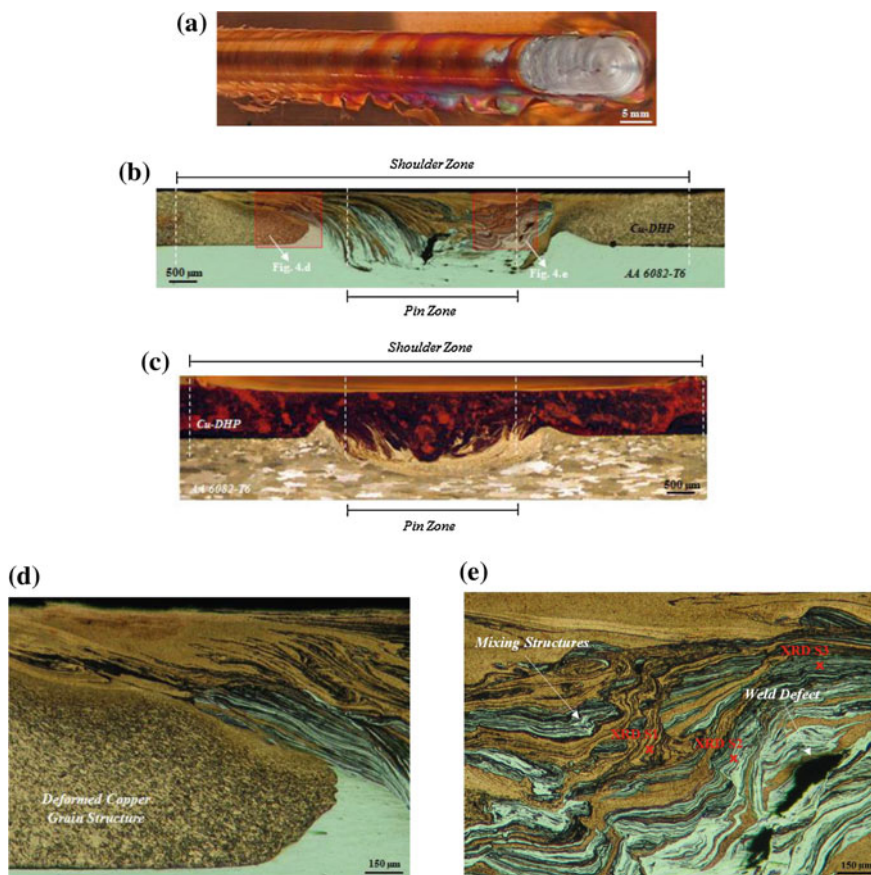


Fig. 2.6 Surface image (a); copper (b) and aluminium (c) etched cross section images and images of the under shoulder copper structure (d) and of the mixing structures (e) of the copper/AA6082 weld [20]. Reprinted with permission from Elsevier

samples, comprising mainly Al_2Cu and Al_4Cu_9 [22]. AA 5083-H116 aluminium alloy and pure copper were successfully FSWelded by offsetting the pin to the aluminium side and controlling the parameters [23].

It was identified that it is difficult to produce a good quality Al/Cu direct weld without offsetting the pin in the softer material, which is aluminium. Furthermore, it was found that the heat dissipation in the copper side was higher than in the aluminium side [23].

The aluminium/copper weld comprised many copper particles of different shapes and non-uniform distribution, which were disseminated in the nugget zone; which led to the reinforcement of the weld nugget region by the presence of copper particles. Defects, such as voids and cracks were seen in the aluminium side [23]. Additionally, when a zero or negative pin offset is used, the samples failed and this

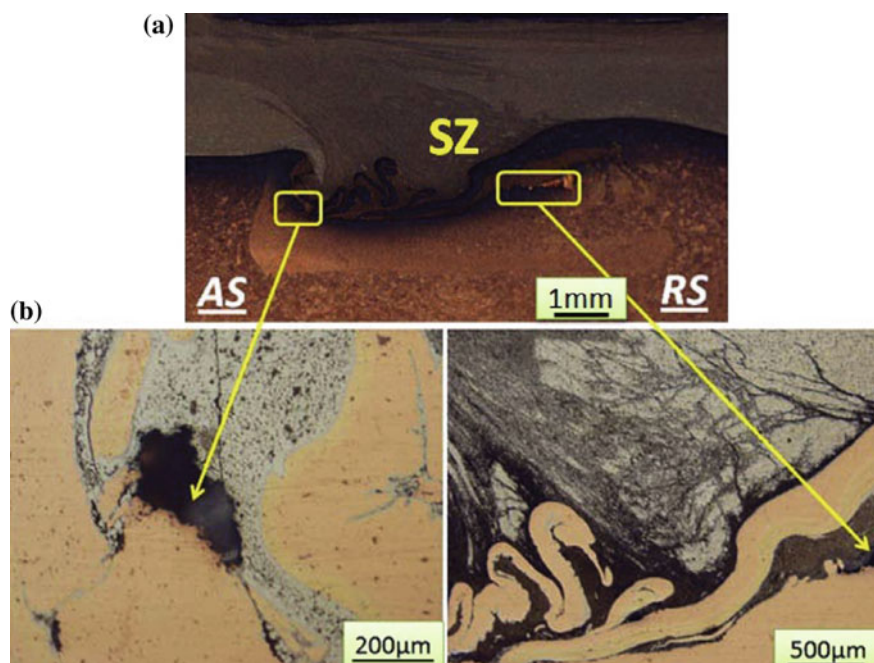


Fig. 2.7 Macrostructure and **b** voids caused by high welding temperature in the weld produced at 1550 rpm and 15 mm/min [21]. Reprinted with permission from Elsevier

was due to cracks during the preparatory machining. Apparently, this occurred because of an inadequate stirring action on the copper side of the weld, which led to the shifting of the weld nugget onto the aluminium side. There was no copper content in the nugget region of the broken samples [23].

AA1A99 aluminium and pure copper sheet, using a zinc foil as filler metal were friction stir welded [24]. The interlayer thickness decreases with the increase of the weld heat input (the increase of the rotating speed and the decrease of the traverse speed). The rotating speed played a more important role in the thickness of the interlayer; and the microstructure showed the tendency to diffuse [24]. With the assistance of zinc foil and the mechanical actions of the tool shoulder, consequently, a great inter-diffusion of aluminium and molten zinc, and the extrusion of Zn/Al liquid phase with not much copper occurred. Furthermore, the excessive liquid phase is primarily extruded toward the retreating side and the edge of the stir zone [24].

AA1100-H14 aluminum alloy and commercially pure copper were joined by using the friction stir welding technique [25].

Intermetallic compounds layers were observed and Al_2Cu , AlCu , Al_4Cu_9 were identified. At the tool welding speed of 80 mm/min, the optimum heat input plasticized the materials and enabled them to flow; and this resulted in producing defect-free welds. It can be said that the optimum heat input was low enough to

reduce the diffusion between aluminium/copper interfaces, which resulted in the formation of a thin intermetallic thickness of 1.9 μm [25].

AA 6061-T651 and copper friction stir welding joints were fabricated by using different tool geometries [26]. The Taper tool pin profile was not found to be suitable for dissimilar materials; where uniform mixing of the parent materials was not achieved; whereas, with a cylindrical tool pin profile defect-free joints were produced [26]. Furthermore, by increasing the shoulder diameter and tilt angle, an increment of the plunge load was observed [26]. Consequently, defect-free copper to AA6061-T651 joints were obtained under the plunge load, ranging from 600 to 700 kgf [26].

Sheets of aluminum alloy 7075 and copper were warm friction stir welded (WFSW) [30]. The effect of the preheating heat treatment on the microstructure and the mechanical properties of Al/Cu dissimilar friction stir welded joints was investigated. Due to the presence of aluminum particles in copper on the advancing side, the flow of materials is upward on the bottom of the welded sheet; although it is downward on the retreating side [30].

Pure copper and AA1050-H16 alloy plates were joined to investigate the maximum penetration of the parent materials [31]. The tool-offset parameter is the main factor for determining the penetrating metal in a dissimilar weld, so that by placing the tool offsets on each side of the workpiece, the metal placed in that level would be the penetrating metal [31]. It was found that, velocity and penetration volume are reduced by further distancing from the surface of the workpiece due to the reduction in the torque caused by the tool shoulder [31].

Dissimilar materials AA6061-T651 and electrolytic tough-pitch copper were welded by the friction stir welding process [32]. Defect-free aluminium/copper joints were produced at tool tilt angles of 2°, 3°, and 4°; while defects were observed on the welds produced when using tool-tilt angles of 0° and 1° [32]. The production of flashes increased, as the tool tilt angle increases. Additionally, Al_2Cu and Al_3Cu_4 intermetallics were found in the SZ region for a tilt angle of 0°; while Al_4Cu_9 and AlCu_3 were found in the SZ for a tilt angle of 2° [32].

Al-Cu bilayer laminated composites was friction stir welded [34]. They observed that during friction stir welding of Al-Cu bilayers, forces and torques are remarkably influenced by the material type of the layer that is in contact with the shoulder: either aluminium or copper.

Furthermore, due to lower flow stress, the softer layer (aluminium) is more likely to develop sticking boundary conditions; whereas, the harder layer (copper) is more likely to develop a slipping boundary condition. Consequently, higher tool plunge depth is needed during welding from copper side to cause sticking boundary condition, which would result in making sufficient material flow during welding and produce defect-free joints [34].

A finer grain structure is developed in the copper layer; and no intermetallics are formed in NZ; when joining from the aluminium side. But when welding from the copper side, intermetallics are formed in some regions of the nugget zone [34].

The effects of the intermetallic compounds on the mechanical properties of Al/Cu dissimilar joints was investigated [35]. Rotation speed greatly affected the

microstructures in the stir zone and intermetallic compound phases including CuAl_2 , Al_4Cu_9 were formed in the stir zone [35].

Khodir et al. [35], observed in the stir zone, a composite-like structure of aluminium matrix strengthened with copper particles. An increase of tool rotation speeds resulted in the formation of intermetallics, which increased the hardness values in the stir zones. On the other hand, they reported that the formation of intermetallics at the joints (Al/Cu) interfaces had little or no significant effect on the tensile strength of the welds [35].

AA1050 Al alloy and commercially pure copper sheets were FSWelded to investigate the effect of the used process parameters on the mechanical properties [36].

It was reported that defect-free welds can be obtained; when the hard sheet (copper) is placed on the advancing side; whereas defects are generated when the softer sheet (aluminium) is placed on the advancing side [36]. Furthermore, a pin offset of not less than 1.5 mm towards the softer sheet (aluminium) leads to defect-free welds; and therefore a good metallurgical bonding between the aluminium and copper was achieved [36]. In contrast, when a smaller pin offset is used, the defects in the welds increase. This was apparently due to the high percentage of copper in the welded zone [36].

Friction stir welding was used to join electrolytic tough pitch copper and AA6061-T651 [4]. When using a heating assisted friction stir welding; the surface oxide formation was observed. Intermetallics, such as CuAl_2 and Cu_9Al_4 were found in the stir zone alongside with solid solutions of copper and aluminium. The amount of intermetallic compounds formed in the stir zone was increased, as the preheating current increased; whereas, the cooling assisted the friction stir welding; it significantly inhibited the formation of intermetallics [4].

Workpiece materials are AA1050 and pure copper sheets; and these were joined using FSW [40]. Intermetallics play an important role in achieving successful dissimilar joints; but the increased thickness of the intermetallics reduces the tensile strength. They further reported that the use of Ni, Ti, and Zn as interlayer prevented the formation of severe brittle intermetallics compared to direct FSW of Al/Cu [40]. Figure 2.8 depicts the macro- and micro-zones of the weld cross-section of the welds produced at 1200 rpm, 30 mm/min, 1.5 tool offset and 0.10 tool plunge depth. It can be seen in Fig. 2.8b that the joint interface is distinct and free of any defect. Furthermore, intermetallics were observed in the entire weldment, as depicted in Fig. 2.8c.

Rojanapanya et al. [41] studied the effect of tool rotational and welding speeds on surface morphology, microstructure and the mechanical properties of friction stir welded AA6063/copper joints.

Defect-free Al6063/copper welds were obtained when fabricated under the following welding conditions: 1100 rpm and 20 mm/min, 1400 rpm and 20 mm/min, and 1800 rpm and 20 mm/min. High tool-rotation speed and low welding speed could be used to successfully produce dissimilar FSW Al6063/copper welds [41]. Kalashnikova et al. [42], joined AA6060 and C11000 metals. Intermetallics copper/aluminum were formed at the aluminum alloy/copper

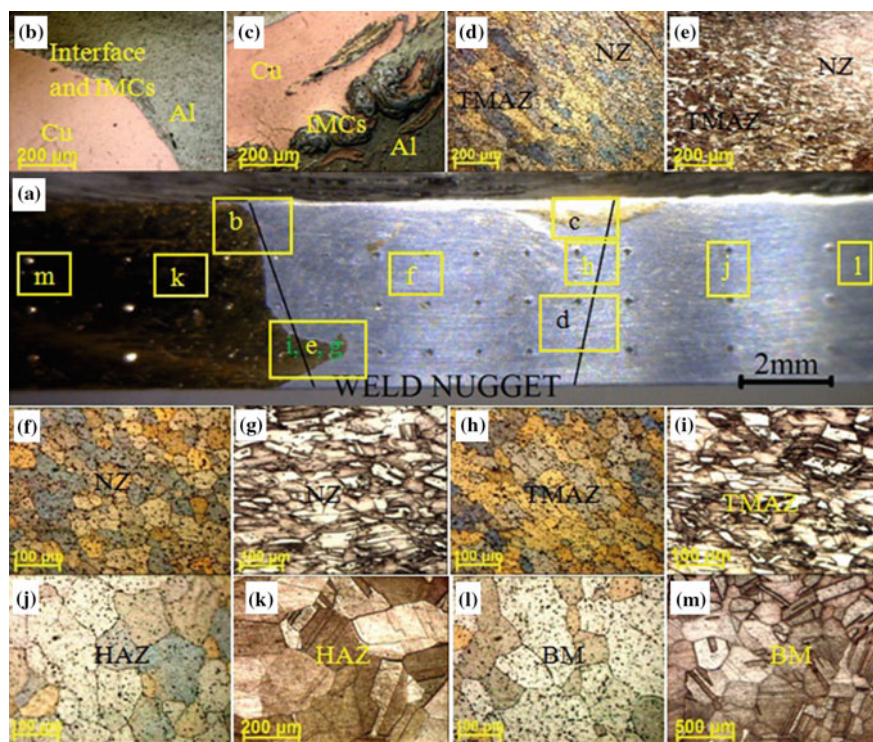


Fig. 2.8 Shows **a** weld beads of the welds produced at 1200 rpm, 30 mm/min with macro/micro view at different regions, **b** joint interface and material flow, **c** intermetallic formation and flow, **d** interface of the nugget region and TMAZ on the aluminium side, **e** interface of NZ and TMAZ on the copper side, **f** NZ microstructure on the aluminium side, **g** NZ microstructure on the Cu side, **h** TMAZ microstructure on the Al side, **i** TMAZ microstructure on the Cu side, **j** HAZ microstructure on the Al side, **k** HAZ microstructure on the Cu side, **l** microstructure of parent material on the Al side, and **m** microstructure of parent material on the Cu side [40]. Reprinted with permission from Springer

interfaces. They stated that the hardness and brittleness of the intermetallics was not as high as that of the intermetallics formed by fusion welding [42]. Figure 2.9 presents the microstructure of the two weld samples; and the welds were produced from AA6061 and annealed pure copper tubes [43].

Figure 2.9a shows the penetration of copper lamellas into aluminum, thereby indicating that the pressure applied by the tool shoulder has effectively driven copper flow down into the aluminum sheet, therefore creating a good mixture of Cu/Al particles. In Fig. 2.9b, the joint structure incorporated dark regions, which are an indication of the presence of voids [43].

The friction stir welding of aluminum grade Al6061-T6 to pure copper was investigated using experimental and numerical approaches and the conditions that resulted in sound weld quality were identified [33]. The aluminum/copper weld was

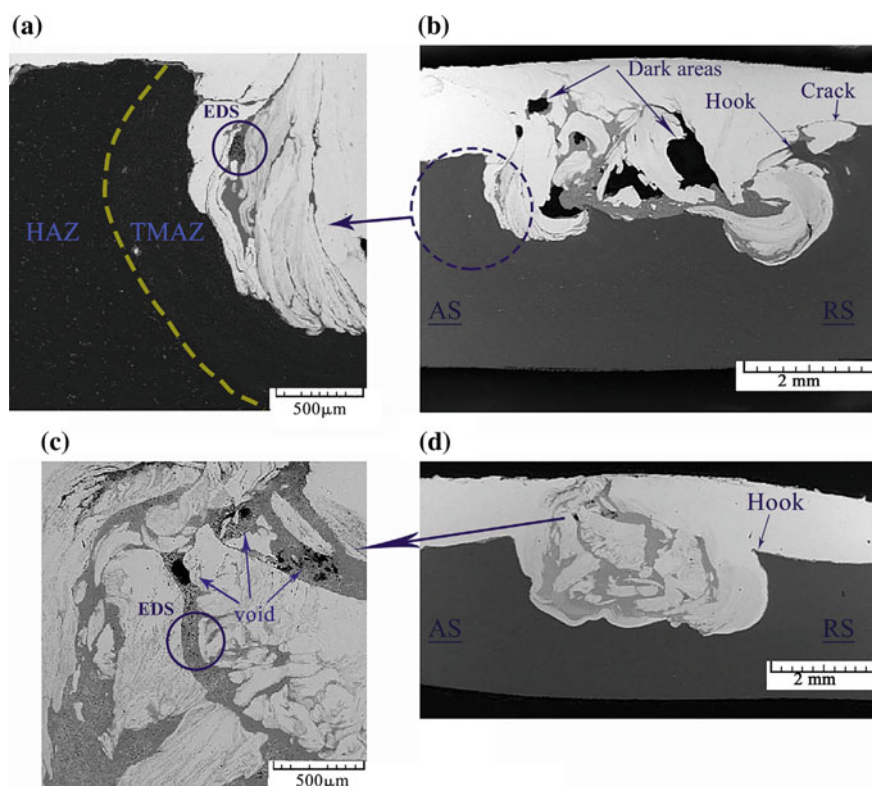


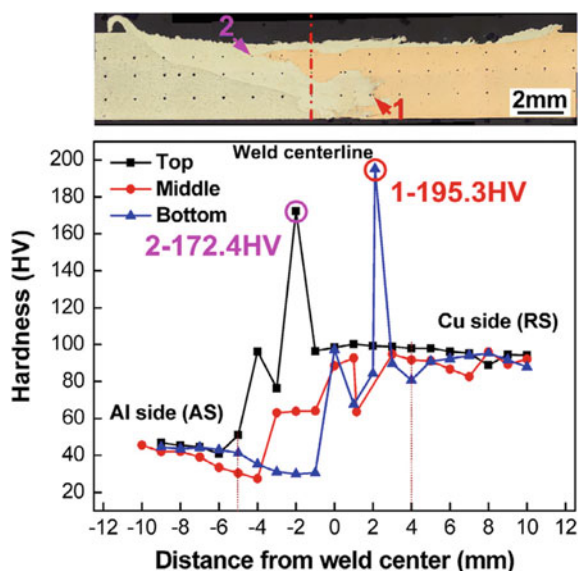
Fig. 2.9 Shows the microstructure **a** magnified images of TMAZ and HAZ and **b** nugget zone of Lrs1 (710 rpm, 30 mm/min), **c** a closer look at the hole created on the surface of Hrs3 weld (1000 rpm, 60 mm/min) and **d** Hrs3 nugget zone [43]. Reprinted with permission from Elsevier

found to consist of several single and two-phase intermetallic compounds including Al_2Cu , Al_4Cu_9 , $\text{Al} + \text{Al}_2\text{Cu}$ [33].

2.5.2 Mechanical and Electrical Properties

Producing sound welds and good mechanical properties is the aim of many researchers working on joining aluminium and copper using FSW. Mechanical properties, such as tensile strength and microhardness of the friction stir welding of aluminium to copper are different from the properties of similar materials. The obtained properties—after joining the dissimilar materials (Al/Cu) exhibit different patterns. And various researchers have presented their results. This section presents a summary of the numerous results obtained; and these are explained by different researchers. Figure 2.10 depicts the microhardness profile of the welds produced at a welding speed of 20 mm/min [67].

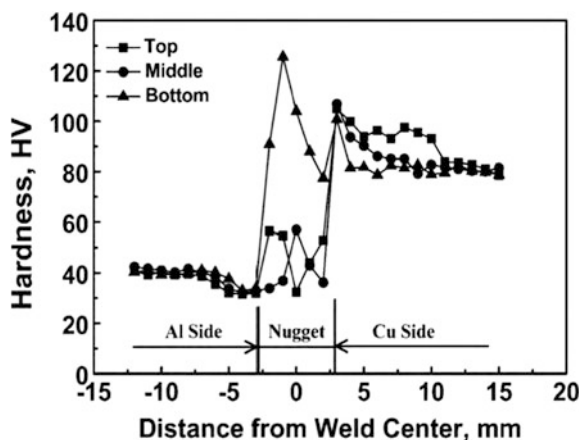
Fig. 2.10 Shows the hardness values measured at the top, middle and bottom of the transverse cross section of the weld [67]. Reprinted with permission from Elsevier



The microhardness value obtained in the HAZ in aluminium side was lower than that of the base metal. This was due to the softening of the HAZ; and it could probably be attributed to the grain coarsening and the dissolution of the strengthening precipitates, prompted by the thermal cycle of the FSW technique [67]. On the other hand, a non-homogeneous distribution of microhardness values was observed in the weld nugget zone. The obtained higher microhardness value in the WNZ, compared with that of the aluminium parent material was probably attributable to the formation of very fine recrystallized grains and the copper-rich disseminated particles. Furthermore, the sudden drop in microhardness values occurred adjacent to the interface. However, the distinct rise in microhardness at the interface was attributed to the presence of nano-scaled intermetallic compounds [67].

The ultimate tensile strength of the composite structure was as high as 210 MPa; and the hardness increased substantially, due to the strengthening effect of the Al/Cu intermetallic particles. The reinforcing particles were mainly composed of Al_2Cu , Al_4Cu_9 , with a few AlCu particles [4]. An excellent metallurgical bonding with a bond strength of more than 210 MPa, and 180° bending without fracture, was generated at the Al/Cu interface. This is due to the formation of a continuous and uniform intermetallic layer with a proper thickness of $\sim 1 \mu\text{m}$; while the intermetallic layer consisted of Al_2Cu and Al_4Cu_9 sub-layers [4]. Furthermore, tensile tests indicated that the FSW joint failed in the heat-affected zone on the aluminum side with the Al/Cu interface bond strength being higher than 210 MPa [4]. Figure 2.11 shows the hardness profile at the different locations of the weld, namely the top, middle and bottom [5].

Fig. 2.11 Hardness profiles along top, middle and bottom lines of transverse cross section [5]. Reprinted with permission from Elsevier



It can be observed that the hardness values in the particle-rich zone (PRZ) are much higher than those in the region those without any, or only a few strengthening particles. In the no or few strengthening particles region, the hardness is similar to that of the aluminium parent material in the upper nugget zone. Consequently, the strengthening by the dispersed intermetallics particles apparently played the main role in the strengthening mechanism of the present composite structure [5].

In another study, the maximum shear tensile strength was achieved where there were no cavity defects; and fewer microcracks were observed; and this was achieved by using 95 mm/min as the welding speed [6].

Moreover, at higher welding speeds (118 and 190 mm/min), the welds were produced with incomplete welded interfaces; and this was due to the formation of cavities. Additionally, this also resulted in the decreasing behavior of the tensile shear strength [6].

The presence of intermetallics in the stir zone favored the high hardness; and these intermetallics were CuAl_2 , CuAl and Cu_9Al_4 . An increase of the amount of intermetallics at the aluminium/copper interface was observed, when the rotational speed was increased [7]. Ratnesh et al. [7] further maintained that the comparison of the fracture location and the microstructure revealed that intermetallics formed in the interfacial region were responsible for the low tensile strength [7].

The intermetallic compounds formed in the region under the shoulder prevented the material mixing through the entire thickness of the sheet; and hence, the formation of the typical onion ring structure. Nonetheless, the formation of a large volume of material with very brittle intermetallic compounds has a very negative effect on the final strength of the joint, particularly for very thin sheets in the welding [8].

It has been reported that good tensile strength properties were obtained at higher rotation speed and with a proper pin offsets of 2 and 2.5 mm. Additionally, the weld fabricated at 600 rpm with a pin offset of 2 mm could be bended to 180° without fracture; while, poor tensile properties were obtained at the very large pin offsets

and/or low rotation speed, due to the insufficient reaction between the copper bulk/fragments and the aluminium matrix. On the other hand, an adequate reaction was attained in the friction stir welding of the Al/Cu welds fabricated at higher rotation speeds and suitable pin offsets of 2 and 2.5 mm; and consequently good tensile properties were obtained [9].

Furthermore, the joints produced at 600 rpm with a pin offset of 2 mm exhibited sound bending properties. Although, poor bending properties were achieved when a higher rotation speed of more than 600 rpm is used, which was linked closely to the stacking layered structures at the interface [9].

In another study, AA 1050 and brass were used as the parent materials; and they were friction stir welded [10]. The maximum tensile strength obtained of the weld was 80% of the parent material (aluminium). Moreover, by leaving the optimized condition, large brass fragments and weld defects developed, resulting in the attaining of a lower weld strength, as well as shifting the fracture path from the interface to the SZ [10]. Additionally, severe mechanical twinning was observed in the TMAZ of brass, which resulted in high values of hardness in this zone. The results showed that the optimum ultimate strength of the sound weld is obtained from a proper material flow and metallurgical bonding through a narrow inter-metallic layer at the interface, in addition to crack deflection (onion rings) by the occurrence of a lamellar composite structure in the SZ [10].

A rotation speed increment affected the mechanical properties of the friction stir welded aluminium 1050 to brass [2]. The increase was accompanied by thickening and development of interfacial intermetallics. A rotation speed of 450 rpm (optimum) produced a thin interfacial intermetallic compound and a lamellar composite structure in the SZ, which improved the tensile strength of the joint [2]. On the other hand, when the rotation speed is further increased, a lower tensile strength is obtained, which is accompanied by the disappearance of the lamellar composite structure, the increase in the weld defects, and the thickening of the interfacial intermetallic layer [2].

Joints produced by using AA 1060 and commercially pure copper were characterized [11]. The friction stir welding lap aluminium/copper joints failed in the heat affected zone of the aluminium side; and the tensile shear load reached up to 2680 N, when the aluminium sheet is put on the advancing side. On the other hand, the hardness increased clearly in the layered structure due to the strengthening effect of the aluminium/copper intermetallic compounds, which were mainly composed of Al_4Cu_9 phases [11].

AA 5754 and C11000 copper were friction stir welded by using different tool shoulder diameters (15, 18, 25 mm), varying the rotational speed (between 600 and 1200 rpm) and with a welding speed between 50 and 300 mm/min. A good metallurgical bond between the two dissimilar materials was achieved at the joint interfaces [12].

The electrical resistivity of the joint increased, as the heat input to the welds increased. Furthermore, 9.8% was found as the maximum percentage increase in resistivity compared to the average joint resistivity of the base materials [12]. Additionally, Akinlabi and Akinlabi [16] stated that, higher microhardness values

were also measured at the joint interfaces, as the consequence of the heat input into the welds [16].

Higher microhardness values were recorded at the joint interfaces, resulting from strain hardening and the presence of intermetallic compounds [16].

The ultimate tensile strength of the good appearance and defect-free joint is limited to the value of 127 MPa; and intermetallics were found on the fractured surface, which should be the cause of the low tensile strength obtained [14]. On the other hand, the hardness profiles are consistent with the variation in the structures within the weld nugget; and higher peak hardness was obtained at a lower tool rotational speed [14].

The hardness profile indicated that the hardness on the copper side of the nugget is higher than that on the aluminum alloy side; and the hardness at the bottom of the nugget is generally higher than that in other regions. The ultimate tensile strength and the elongation of the dissimilar welds were 152 MPa and 6.3%, respectively; and the joints failed in a ductile-brittle mixed fracture mode [15].

Figure 2.12 presents the microhardness measurements (top, middle and bottom) on the transverse cross-section of the friction stir welds [15]. It can be seen that the microhardness value at the bottom of the nugget is usually higher than that at the top or in the middle region; and this was attributed to the increased presence of intermetallics at the bottom [17].

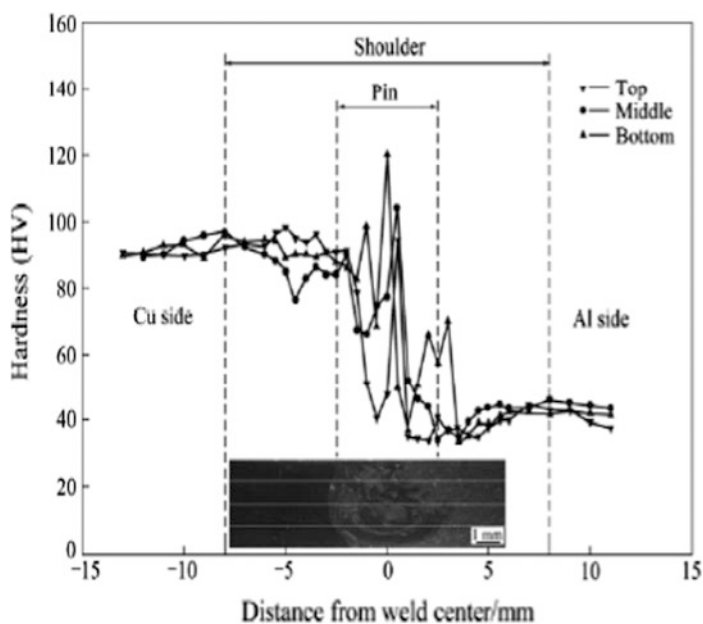


Fig. 2.12 Presents the microhardness values of the cross section of Al/Cu dissimilar weld [15]. Reprinted with permission from Elsevier

Microhardness in the weld nugget region is higher than in the parent material; and no substantial difference was found in other regions of the weld. On the other hand, the tensile strength of the weld is very poor compared to the tensile strength of both parent materials; and all the joints fractured from NZ [17].

Copper-DHP/AA 5083 FS Weld, exhibited an impressive hardness increase in the aluminium part of the weld; and this was due to the formation of an ultra-refined microstructure, as shown in Fig. 2.13a [20]. While for the copper/AA6082-T6, the hardness increase was limited to the upper copper layer.

Bisadi et al. [21], observed that for all the tested shear tensile samples, the fracture occurred on the advancing side of the joint beside the stir zone.

The thinning of the aluminium sheet, caused by the shoulder depth, the hooking defect, and also the brittle Al/Cu compositions are the main reasons for this. Also intermetallic compounds were detected mostly at the brittle fractured regions [21].

On the other hand, the maximum microhardness of the copper side of the joint was observed at the weld stir zone, because of its fine grain size; although the grain size reductions, together with the hardness values of the joint aluminium side stir zone, were considerably lower than that of the aluminum parent material. This could be due to the presence of micro voids in that region. The hardness values of different weld regions are affected by the welding temperature, in addition to the amounts of the strain and the material flow [21]. Figure 2.13 presents the macrostructure of the joint sample 4, together with the microhardness tested lines (a), as well as the microhardness profiles measured on both sides of the welds, namely at the copper side (b) and the aluminium side (c) [21].

Barekatin et al. [22] observed that for the FSWed CGPed samples, the welding heat input caused the grain growth and a decrease in the hardness value at aluminium side of the stir zone.

There was a relative reduction in the hardness in the stir zone of CGPed; whereas for the annealed sample, an increment compared to the parent material was observed; and this was due to grain refinement. On the other hand, Barekatin et al. [22] further found that, generally the weakest parts of the produced joints of the annealed and CGPed samples were respectively the aluminium parent material and the stir zone [22].

The maximum tensile strength for AA 5083-H116 aluminium alloy and pure copper joint was 206.7 MPa for the weld—produced at a rotation speed of 710 rpm, welding speed of 69 mm/min and 0.2 mm pin offset [23].

The mechanical properties have shown significant relations with the interlayer, including the microstructure and the extent of diffusion and extrusion [24].

An increase in microhardness values occurred in the copper side, this is due to the interdiffusion; while on the aluminium side, this is due to the interdiffusion and the extrusion. Kuang et al. [24] further said that at a rotation speed of 1600 rpm and a welding speed of 20 mm/min, successful welds can be produced; and these weld

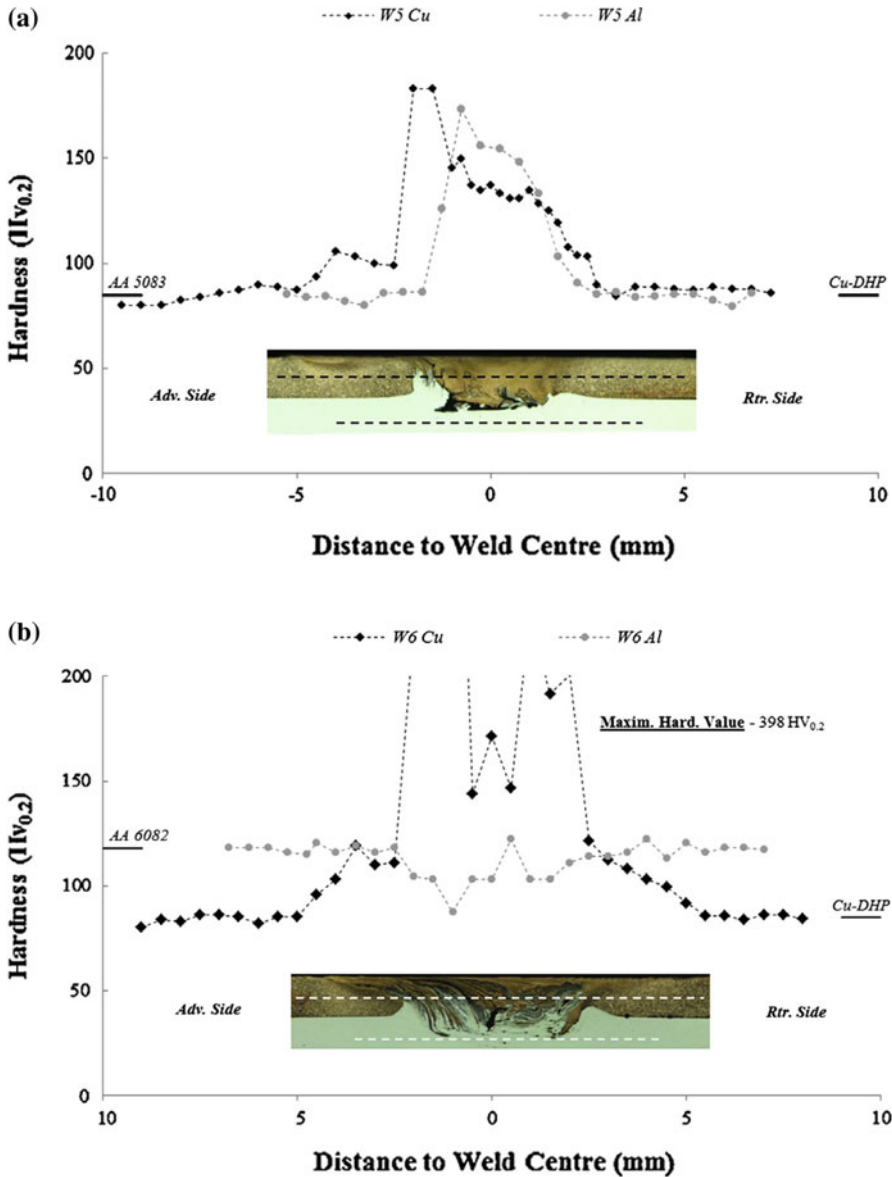


Fig. 2.13 Depicts the hardness profiles measured across the transverse cross-section of the copper/AA5083-H111 (a) and copper/AA6082-T6 (b) welds [20]. Reprinted with permission from Elsevier

exhibits the highest joint strengths without any weld keyhole [24]. The microhardness values of the different aluminium side weld regions are generally much lower than those of the parent material (aluminum) [24]. The microhardness distribution profile of the joints produced at 1200, 1600, 2000 rpm and 40 mm/min welding speed is shown in Fig. 2.14a, b (Fig. 2.15).

The weld produced at the tool welding speed of 80 mm/min resulted in a higher tensile strength and joint efficiency of 113 MPa and 70.62%, respectively [25].

The higher tensile properties are attributed to the formation of defect-free SZ, the formation of nano-scale thin intermetallic layer at the aluminium/copper interface, the distribution of fine copper particles in the aluminium SZ area, and the grain boundary strengthening [25].

On the other hand, the maximum hardness of 188 HV was reported for the defect-free dissimilar FSW welds. The presence of intermetallic compounds in the SZ made the weld area brittle; and it increased the hardness [26].

Furthermore, the maximum tensile strength of 133 MPa and the hardness of 181 HV (in the nugget zone) were obtained when the welds were produced at 1500 rpm, 40 mm/min, 2°, 2 mm and cylindrical profile (rotation speed, welding speed, tilt angle, tool pin offset and tool pin profile) [26].

On the other hand, the low joint efficiency of the tensile specimen was attributed to the dominant brittle fracture mechanism in comparison with the ductile fracture [26].

Christon and Balachandar [29] welded aluminium alloy 6063-O and pure copper using the FSW technique.

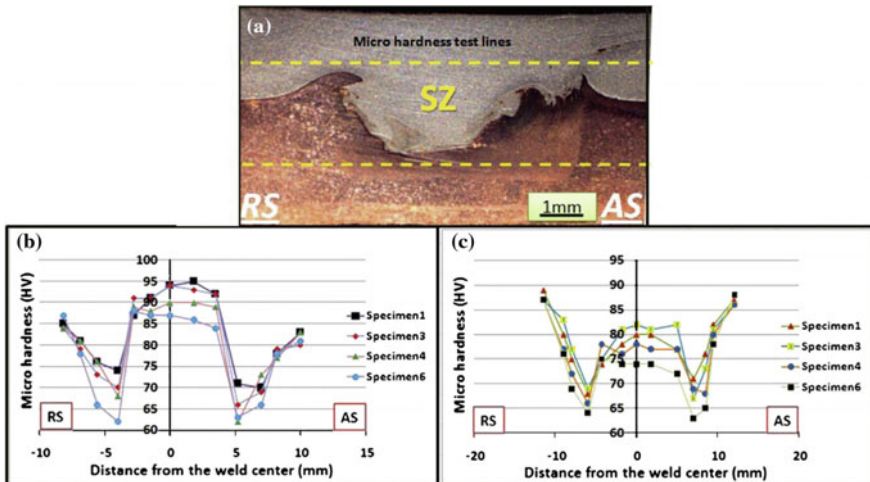
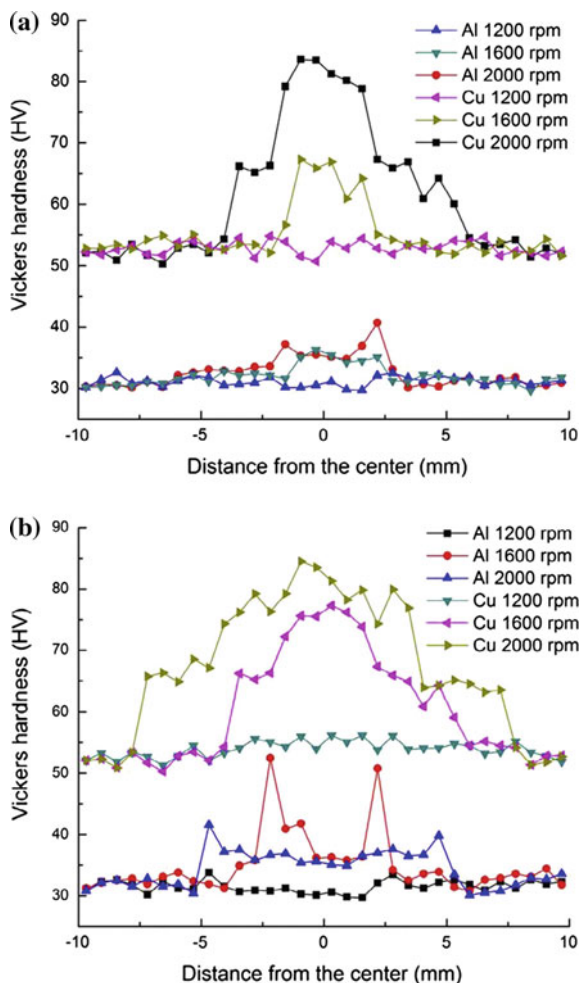


Fig. 2.14 The macrostructure and the microhardness measured tested lines of sample 4 **a** the microhardness profiles; **b** the copper side; and **c** the aluminium side of the joints produced at the welding speed of 32 mm/min [21]. Reprinted with permission from Elsevier

Fig. 2.15 Microhardness profiles measured 0.2 mm near the middle-layers using different process parameters [24]. Reprinted with permission from Elsevier



The maximum microhardness value was recorded for the joint produced at 900 rpm tool rotational speed and 25 mm/min welding speed. The microhardness profile was largely affected by the tool rotational speed, rather than the tool tilt angle. Whereas, the tilt angle had more influence on the microhardness when compared with the influence of the welding speed [29].

Safi et al. [30] stated that the preheating of aluminium/copper joints improved the resulting mechanical properties of the welds. The maximum strength was obtained for the weld with the preheating of 75 °C, using a rotation speed of 1300 rpm, and a welding speed of 75 mm/min [30].

Fig. 2.16 Microhardness profile of welds produced at 1500 rpm, 50 mm/min and different tool pin offset (1, 2, 3 mm) [38]. Reprinted with permission from Elsevier

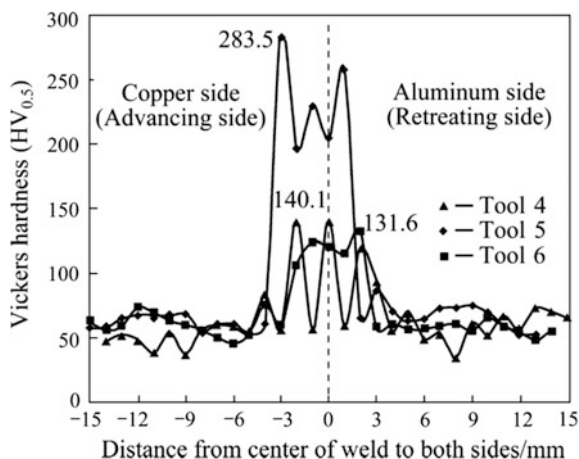


Figure 2.16 presents the microhardness profiles of the friction stir welded Cu (ETP) and the AA6061-T651, when using a set of process parameters and different tools [38]. Maximum microhardness values were measured in the stir zone for all the welds used; and these values were attributed to the presence of hard and brittle intermetallic compounds.

The maximum ultimate tensile strength values of the specimens with Ti and Zn interlayers were 139.01 and 142.29 MPa, which were 105 and 107% of the aluminium parent materials [40].

This is because of the controlled formation of intermetallics at the nugget zone; since the Ti interlayer acts as a diffusion layer; and the finer grain in the nugget zone with the Zn interlayer behaves as an alloying element at the weld zone [40].

The average elongation percentage in the case of Ti and Zn interlayers is lower than that in the joints without the interlayer and the aluminium parent material. This was because Ti acts as a diffusion layer; consequently, the joint starts to fracture at the joint of the layer with less elongation; while the Zn particles become hard—with less ductility in the nugget zone [40].

The maximum microhardness was measured on the bottom layer on the advancing side of the nugget zone; and hence, the average nugget zone microhardness value is higher than that in other zones. Furthermore, the average microhardness and maximum microhardness at different zones varied with different interlayers (Fig. 2.17); and these values depended only on the intermetallic compounds present at the indentation point, the intermetallics flow, and the specific interlayer microhardness [40].

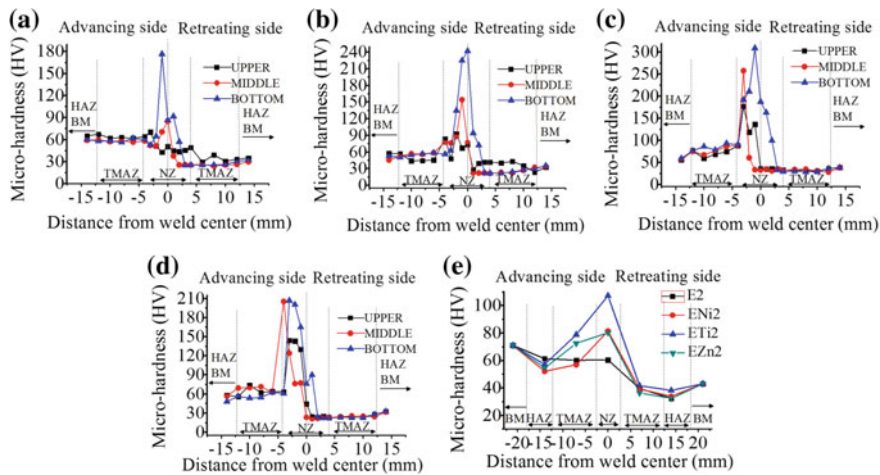


Fig. 2.17 Shows the microhardness variation at different regions: **a** without the interlayer; **b** with the Ni interlayer; **c** with the Ti interlayer; **d** with the Zn interlayer; and **e** the average microhardness values [40]. Reprinted with the permission from Springer

In Fig. 2.18, the microhardness profile of the welded samples (AA6061 and the annealed pure copper) at 710 and 1000 rpm are presented [43]. The hardness is higher at the center of the joint compared to other regions. The highest hardness (copper tube) was found at the center 165.4 HV for samples joined at rotation speed of 710 rpm and welding speed of 30 mm/min, and 142.6 HV for the joints produced at 1000 rpm and 30 mm/min. Similarly, for the aluminium tubes, the hardness value was 120.1 HV for the joints when using 710 rpm and 30 mm/min and 109.4 HV for the joints produced at 1000 rpm and 60 mm/min. The lowest hardness value for the Cu and Al tubes was found in the heat affected zone on the advancing side [43].

In another research study, the presence of intermetallics and grain size refinement in the joint nugget caused the measured hardness values in the SZ and surrounding regions to reach more than twice the hardness values of the parent materials [33].

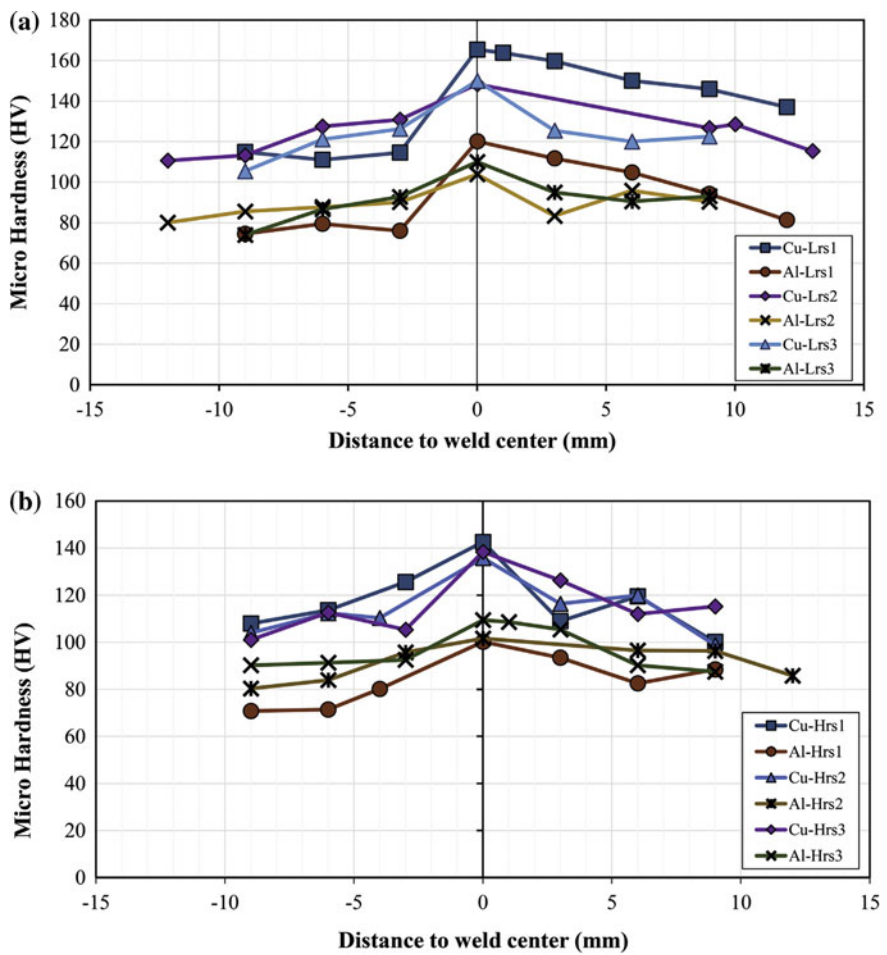


Fig. 2.18 Microhardness profile for **a** samples joined at rotational speed of 710 rpm and **b** samples joined at 1000 rpm [43]. Reprinted with permission from Elsevier

2.6 Friction Stir Spot Welding Between Aluminium and Copper

Conventional friction stir spot welding (FSSW), which is a variant of friction stir welding (FSW) was developed as a suitable alternative to riveting and resistance spot welding (RSW). Friction stir spot welding (FSSW) is a variant of friction stir welding (FSW) process for spot welding applications. The process uses a non-consumable rotating tool, which is plunged into the sheets to be joined; which are largely in lap configuration. After reaching the set plunge depth, the tool is held in that position for a specific time—called the dwell period. Afterwards, the rotating

tool is withdrawn from the welded workpieces, leaving behind a friction stir spot weld. The heat generation, material mixing (plastic deformation) around the pin, weld geometry and the resulting mechanical properties of the spot welded joint are basically determined by the tool penetration and the dwell time [68].

Friction stir spot welding and friction stir welding processes use both similar tools to join different materials; and the tools are non-consumable [69]. It has been reported that the shoulder generates the bulk of the frictional or deformational heat; while the tool pin facilitates the material flow between the sheets [68]. The tool rotation speed, the tool plunge depth and the dwell time are the other parameters involved in the FSSW method. The above mentioned parameters play a huge role in determining the strength and the surface finish of the produced spot welded joints [68]. The purpose is to present the current state of FSSW Al/Cu, in order to demonstrate that the process can produce sound spot welds and can be a good alternative to resistance spot welding and riveting.

The microstructural regions in a typical friction stir spot weld are similar to the one found in friction stir welding. There is the presence of a hook also called a copper ring for FSSW of aluminium and copper [47, 66]. There is a nomenclature to describe the different microstructural regions present after joining the workpieces by using FSW. The cross sectioned FS Weld shows the five characteristics. These include the parent material (PM), the heat affected zone (HAZ), the thermomechanically affected zone (TMAZ), the stir zone (SZ) and the Hook.

As can be seen, the parent material (PM) is the material that is far from the welded region and that has not been affected; although that area may have experienced thermal cycling from the weld. The microstructure, or the other properties of the PM are not affected by the heat generated during the FSSW process. The heat affected zone (HAZ) is the area, which is closer to the center of the weld; and it is thermally affected during welding. Consequently, the microstructure and/or the mechanical properties of the HAZ are modified compared to the PM; but there is no plastic deformation in this region.

The thermomechanically affected zone (TMAZ) is located in the region where the materials are plastically deformed by the tool. In some materials, it is possible to obtain substantial plastic strain without recrystallization in this weld region. Furthermore, there is a distinct boundary between the recrystallized zone and the TMAZ. In the immediate vicinity of the keyhole, there is a zone called the stir zone (SZ); and this zone is the fully recrystallized region of the spot weld. The grains found in the stir zone are roughly equiaxed and often smaller than the grains in the parent material. While, the Hook which is also called copper ring in friction stir spot welding between aluminium and copper is a characteristic feature of friction stir spot welds in lap configuration where there is the formation of a geometrical defect originating at the interface of the two welded sheets [47, 66].

Table 2.3 depicts a summary of the different studies conducted in the joining of aluminium and copper when using friction stir spot welding. The base materials, tool geometries, process parameters and the type of intermetallics found in the spot welds are presented in Table 2.2.

Table 2.3 Depicts the base material, the tool material and the shapes and the process parameters used for friction stir spot welding between aluminium and copper

Parent materials and material thickness	Tool material and shape	Process parameters	Intermetallics/ remarks	Reference
6061-T6 Al and oxygen free pure Cu (in the H01 condition) (1.5 mm)	H13 tool steel tool steel (42–46 HRC) with threaded pin. Shoulder diameter: 10 mm, concave shaped. Pin diameter: 4 mm, pin lengths: 1.83 and 2.60 mm. Thread pitch: 0.7 mm	The rotation speed: from 1000 to 2000 rpm; and 3000 rpm. Shoulder plunge depth: 0.0 and 0.13 mm. Dwell time: 3 and 6 s	No intermetallics in the strong weld. Weak weld show a layered intermetallic structure in the stir zone	[47]
AA 1050 and pure copper (3 mm)	Shoulder diameter: 20 mm Pin diameter: 5 mm (with right hand threads)	Rotation speed: 1600 rpm. Dwell time: 10 s. Pin plunge depth: 2.8, 4 and 5 mm	Intermetallic compounds: AlCu, Al ₂ Cu and Al ₄ Cu ₉ formed at the interface	[48]
1050 aluminium foils (500 µm) and pure commercial copper foils (100 µm)	Tool steel (H13) material with the hardness of 53RC	Tool rotation: 560, 710, 900 1120, and 1400 rpm. Dwell time: 4 s	Intermetallic compounds: Al ₂ Cu and AlCu ₃ identified in stir zone	[49]
AA1060 and C11000 (3 mm).	H13 tool steel hardened to HRC 50–52. Pin length: 4 mm. Shoulder diameter: 15 mm. Tool geometry: flat pin/flat shoulder and conical pin/ concave shoulder	Rotation speed: 800 and 1200 rpm. Shoulder plunge depth: 0.5 and 1.0 rpm. Dwell time: 10 s	Intermetallic compounds: AlCu, Al ₂ Cu, AlCu ₃ , Al ₂ Cu, Al ₃ Cu ₄ , Al ₂ Cu ₃ and Al ₄ Cu ₉ in the stir zone and the keyhole	[66]
AA6061-T6 and commercially pure copper (0.5 mm)	H13 hot die steel. Pinless tool. Pin diameter: 3.3, 4.95, 3. Aluminium embedded: 3 and 6 mm diameter). Copper embedded: 6 mm	Rotational speed: 2500 rpm. Feed rate: 0.25 mm/min. Dwell time: 4 s	Intermetallic compounds at the interface of copper/aluminium	[53]
AA 5086 H32 and rolled copper C10100 (1.5 mm)	H13 steel tool. Cylindrical pin and shoulder. Shoulder diameter: 16 mm. Pin diameter: 6 mm. Pin length: 1.5 mm	Rotation speed: 775, 916, 1125, 1333, 1475 rpm. Dwell time: 8, 9.5, 11.5, 13.5, 15 s. Plunge depth: 1.6, 1.8, 2.1, 2.4, 2.6 s	Plunge depth affect the corrosion aspects of the welds to a greater extent than the tool rotational speed and hold time	[62]

(continued)

Table 2.3 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Intermetallics/ remarks	Reference
AA 5052 (1.5 mm) and copper alloy C27200 (1.6 mm thick)	H13 tool steel. Cylindrical straight profile. Shoulder diameter: 16 mm. Pin diameter: 6 mm. Pin length: 1 mm	Rotation speed: 1050, 1130, 1300, 1470, 1550 rpm. Plunge depth: 1.25, 1.35, 1.85, 2.35, 2.5 mm. Dwell time: 11, 12, 14, 16, 17 s	High tensile shear failure load and low interface hardness was observed for joints made under optimum conditions	[59]
AA 5083 and C10100 (3 mm)	H13 tool steel. Cylindrical straight profile. Shoulder. Shoulder diameter: 16 mm. Pin diameter: 6 mm. Pin length: 1.5 mm	Rotation speed: 100 rpm. Plunge depth: 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75 mm. Dwell time: 18 s	Variation of shear tensile and interface hardness values occurred with the increase in plunge depth	[54]
AA 5083 and C 10100 (1.5 mm)	H13 tool steel. Cylindrical shoulder (diameter: 16 mm). Cylindrical pin (diameter: 6 mm, pin length: 1.2 mm)	Rotation speed: 800, 962, 1200, 1437, 1600 rpm. Dwell time: 11, 12, 13, 14, 15 s. Plunge depth: 1.4, 1.6, 1.8, 2, 2.2 mm	Less than 4.5% error was between the predicated and actual values (indicated good predication capability of the model) for the shear tensile and interface hardness	[52]
AA6061 (2.45 mm) and commercial copper (3 mm)	High speed steel. Concave shoulder diameters: 11, 14, 16, 18, 21 mm and 0.8 mm pitch metric. Threaded pin of 4.5 mm diameter	Rotation speed: 1600, 1800, 200, 2200, 2400 rpm. Dwell time: 15, 20, 25, 30, 35 s	Rotational speed have the greatest influence on shear tensile followed by the dwell time, tool diameter ratio and plunge rate	[51]

2.6.1 Process Parameters

Sound spot welds are obtained when the process parameters are well combined. In FSSW, the main process parameters comprise the material of the tool to be used, the tool geometry (pin and shoulder), the rotational speed and the dwell time. The above-mentioned parameters have been studied by various researchers to investigate their effect on the fabricated spot welds and to achieve a defect-free spot weld. Mubiyi and Akinlabi [66] FSSWelded 1060 aluminium alloy (AA) and C11000

copper, by using a H13 tool steel hardened to HRC 50–52. Two different tool features were used to produce the spot welds: a flat pin and a flat shoulder, as well as a conical pin and a concave shoulder. Two rotation speeds, namely 800 and 1200 rpm were employed; while the two shoulder plunge depths of 0.5 and 1 mm were used.

Siddharth and Senthilkumar [54] used a H13 tool steel with a cylindrical straight flat geometry to join aluminium 5083 and C10100 copper. The rotational speed was 1000 rpm; the dwell time was 18 s; and the different plunge depths were: 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, and 2.75 mm.

Al5052 and C27200 sheets were spot welded by using a H13 steel tool and various other parameters [62]. Shiraly et al. [56] joined 1050 aluminium foils and pure commercial copper foils. A H13 steel tool was used and the tool rotational and dwell time were kept constant at 1120 rpm and 4 s, respectively. The spot welds were made by using a threaded cylindrical and a triangular pin. Shiraly et al. [49] further used 1050 aluminium foils and pure commercial copper foils using rotation speeds of 560, 710, 900, 1120, 1400 rpm, 4 s dwell time, and successfully fabricated FFSWelds. Siddharth and Senthilkumar [62], friction stir spot welded Al 5086-H32 and rolled C10100 copper sheets by using a cylindrical shoulder and a cylindrical pin H13 steel tool.

The joints were produced by using various rotational speeds (775, 916, 1125, 1333, 1475 rpm), plunge depths (1.6, 1.8, 2.1, 2.4, 2.6 s) and dwell times (8, 9.5, 11.5, 13.5, 15). Garg and Bhattacharya [53], used a circular pin and a pinless H13 steel tool. They also used embedded assembly tools and aluminium and copper rods were inserted. A tool rotation speed of 2500 rpm and 4 s dwell time were employed. Manickam and Balasubramanian [51], spot welded AA6061 aluminum alloy and commercial copper sheets by using a non-consumable rotating tool made of high speed steel (HSS). The tool shoulder was concave and a threaded pin.

Many tool rotation speeds (1600, 1800, 2000, 2200, 2400 rpm) and dwell times (15, 20, 25, 30, 35) were employed. Abbass et al. [61] joined aluminium alloy AA2024T3 and commercially pure copper workpieces by using a machined tool from high speed tool steel, which has a hardness of 54 HRC. Heideman et al. [47], welded 6061-T6 aluminium and oxygen free pure copper, using the tools used in this study, which comprised a threaded pin design, using a prehardened H13 tool steel (42–46 HRC). A concave shoulder and a threaded pin were used. The rotational speed was varied between 1000 and 200 rpm. Two different plunge depths were used, namely 0.0 and 0.13 mm. Furthermore, two different dwell times were used, namely 3 and 6 s.

Ozdemir et al. [48] produced FSS Welds when using three different plunge depths, namely: 2.8, 4 mm and 5 mm. Additionally, the spot joints were produced by using a 1600 rpm rotation speed with a 10 s dwell time. All the above mentioned process parameters and the intermetallic compound obtained are summarized in Table 2.2.

2.6.2 Microstructural Evolution

Studies have been conducted to attempt to understand the microstructural evolution of friction stir spot welded aluminium/copper. The obtained microstructure demonstrates different textures, grain size and grain morphologies. The microstructures of FSS Welds produced at various process parameters are shown in Fig. 2.19.

Mubiayi and Akinlabi [55], observed the presence of copper rings (also called hooks) in all the spot welds; and it was found that the length of the copper ring increases with the shoulder plunge depth; however, for the spot welds produced at 1200 rpm for the flat pin/flat shoulder, a decrease in length was observed and a slight increment for the conical pin/concave shoulder. Furthermore, a good material mixing, a distribution of copper particles and fragments with irregular shapes and various sizes in the aluminium matrix was observed.

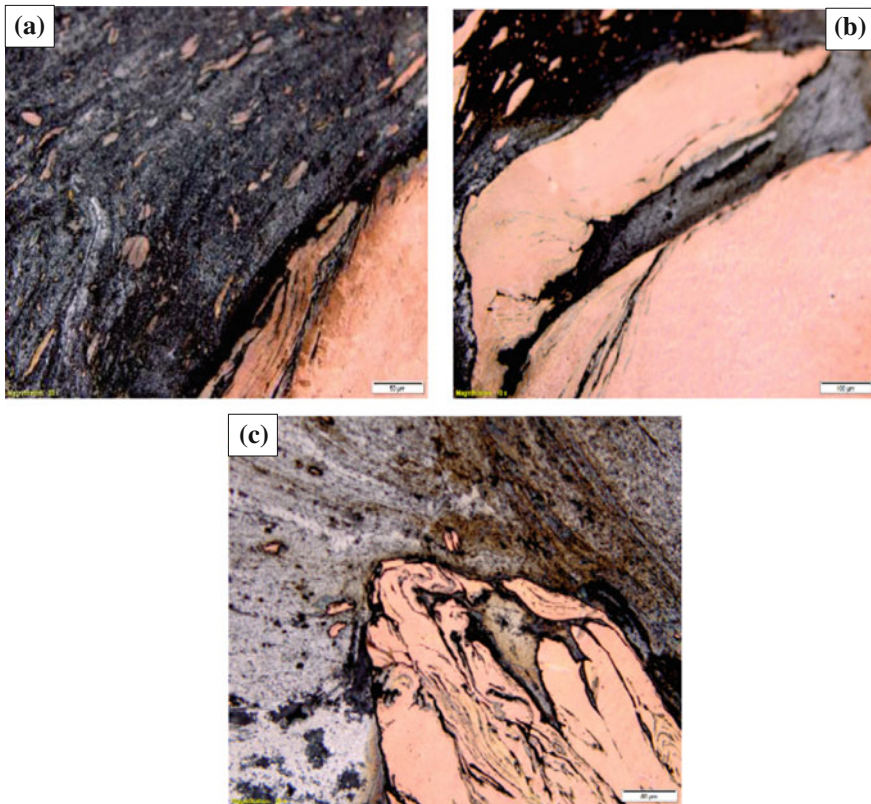


Fig. 2.19 Microstructure of the spot weld fabricated **a** at 800 rpm, 1 mm shoulder plunge depth using a flat pin and flat shoulder tool, **b** at 1200 rpm, 1 mm shoulder plunge depth, using a flat pin and flat shoulder tool, **c** at 1200 rpm, 0.5 mm shoulder plunge depth, using a conical pin and a concave shoulder tool

The X-ray diffraction analyses were conducted in three different locations of the spot welds samples, viz., SZ, TMAZ and HAZ. The most common intermetallic compounds detected in the spot welded samples were found to be Al_4Cu_9 , AlCu_3 , Al_2Cu_3 and Al_2Cu . The presence of intermetallics was confirmed with an energy dispersive spectroscopy (EDS).

Ozdemir et al. [48], obtained friction stir spot welds without any macroscopic defects; and observed that the grains on the copper side in the vicinity of the aluminium/copper interface were finer compared to those of the copper parent material. This was attributed to the effect of the rotating pin, which deformed the grains in the vicinity of aluminium/copper interface, and also the heat input, which favored the recrystallization of the grains in the SZ [48]. They also found hard and brittle intermetallic compounds of Al_4Cu_9 , AlCu and Al_2Cu near the aluminium/copper interface [48].

The presence of a copper ring was also observed by Heideman et al. [47]. The copper ring extruded upwards from the copper workpiece at the bottom into the aluminium workpiece at the top. They observed that the copper ring promoted interlocking and bonding between the two workpieces. They further said that the interface between the copper ring and the nearby aluminium was an area of free intermetallic compounds.

On the other hand, Shiraly et al. [49], observed that the spot weld produced at a lower rotation speed; and it was not bonded; this was attributed to no intermixing between the upper and the lower workpieces. The stir zone comprises the crushed materials and also Al_2Cu and AlCu_3 intermetallics, which favored high micro-hardness values together with the additional stirring of the material.

Siddharth and Senthilkumar [54] observed that a variation in plunge depth affects the material flow within and outside the weld zone. They further observed a change in material expulsion rate, the pattern of material settlement around and beneath the tool shoulder. The same phenomenon was observed at the proximity of shoulder/pin interface and beneath the pin.

Four distinctive microstructural regions were identified regarding the material flow for both tool pins namely, the triangular and the cylindrical regions were observed by Shiraly et al. [56]. First the upward motion of the lower workpiece material in the stir zone extremity; and it was attributed to the pin pressure to its underneath materials. The second region was formed due to the downward motion of the material near the pin. The third was formed due to the rotational motion within the different materials flows; while the last was formed due to the effect of the shoulder; and it was found in the upper part of the SZ.

The microscopic microstructural results showed that with an increase in the tool pin diameter from 3.3 to 4.95 mm, the size of stir zone region increases; and it provides a solid bond [53].

Furthermore, Garg and Bhattacharya [53], observed the presence of a hook at the interface of the mating surface and a weakly joined region in its vicinity, leading to the failure of many of the spot welds produced. The EDS analysis revealed the formation of intermetallics at the joint interface (Al/Cu), which offered some

resistance to the propagation of cracks under the uniaxial tensile load, due to the interlocking of the intermetallic compounds.

Siddharth and Senthilkumar [62], conducted a study on the effect of corrosion on the spot welded joints. The microstructure of the spot welded region of a corroded sample, produced with optimized FSSW process parameters, was also analyzed. The microstructure of the corroded weld region was identified with the difference in the pit density. Furthermore, they observed that voids were affected by corrosion and were found in the form of dark spots. There was also the presence of a less corroded region, in which corrosion was found near the cracked regions. They suggested that, the effective stirring of the tool pin and the higher intermixing of the softened materials minimized the occurrence of cracks.

Abbass et al. [61], successfully performed the friction stir spot welding of dissimilar metals of AA2024 T3 with pure copper sheets. They observed a good mixing and a high degree of interference between the two workpieces; and that was observed in the weld joint interface.

2.6.3 Mechanical and Electrical Properties

Understanding the mechanical and the electrical properties of friction stir spot welding of dissimilar materials, including aluminium and copper, is of importance; since it would enable researchers to produce good quality spot welds. These could enhance the usage of the technique in various industries. The technique is attractive; since it is a solid state welding method, which helps to avoid and eliminate defects found in other joining techniques, such as the fusion welding processes.

High failure loads of 5225 N and 4844 N were obtained, when using a flat pin/flat shoulder at 800 rpm, 1 mm shoulder plunge depth and 1200 rpm and 1 mm shoulder plunge depth, respectively. Strong welds were also obtained by increasing the shoulder plunge depth. Furthermore, the two highest failure loads obtained using a conical pin/concave shoulder were 2991 N and 4606 N; where the parameters used were 800 rpm, 0.5 mm pin plunge depth and 1200 rpm, 1 mm shoulder plunge depth, respectively.

On the other hand, the higher microhardness values were obtained in the stir zone for all the welds; and there was no apparent trend linking the process parameters and the tool geometries to the microhardness results [66]. Additionally, Mubiayi et al. [63], analyzed the probability density function (PDF) histograms of the microhardness. The results revealed that the process parameters and the tool geometries have significant effects on the distribution of the microhardness values in different locations of the produced spot welds.

Heideman et al. [60], found that the rotational speed had the most significant effect on the weld strength, which increases with increasing rotational speed. This was observed when the average weld strength increased by 150%, and when the rotation speed was increased from 1000 to 2000 rpm. But when the rotational speed was increased from 2000 to 3000 rpm, no increase in the weld strength was

observed. Furthermore, the pin length also affected the weld strength. The extrusion of copper upward into the aluminium (copper ring) tended to increase the weld strength.

Ozdemir et al. [48], found the lowest failure load from the tensile shear test was obtained for a 2.8 mm plunge depth; whereas, the 4 mm and 5 mm plunge depths produced closer results that could be considered as being within the acceptable values of the weld strength. On the hand, the microhardness values were high at the bottom region of the keyhole in the copper material; and this was found to be due to the heat input introduced by the stirring pin. Additionally, higher hardness measurements were obtained on the aluminium side, due to more diffuse and selective penetration of copper into aluminium for 4 mm plunge depth compared to the uniform penetration of copper into aluminum observed with a 5 mm plunge depth. While using the 5 mm plunge depth, the higher hardness on the copper side was achieved by the increase of the heat input and the decrease in the grain size.

Shiraly et al. [49], observed that the maximum shear failure load increases with the increase of the rotational speed; and that has a direct correlation with the increasing area and the effective length of the stir zone. Also, the spot weld failed through the stir zone region; and they concluded that shear failure strength is only related to the area and the effective length of the stir zone. On the other hand, they observed that the microhardness values decreased progressively—by taking the distance from the keyhole until it reaches the thermomechanically affected zone to reach the microhardness of the parent material, due to the decrease in the thermal and mechanical effects of the tool.

Abbass et al. [61], obtained the highest tensile shear strength of 1527 N using the optimum friction stir spot welding parameters (1250 rpm, dwell time of 90 s). This was achieved by using a straight cylindrical pin geometry. Furthermore, plunging time parameter more than other welding parameters mostly affected the tensile shear results.

Manickam and Balasubramanian [51], used statistical techniques to predict the tensile lap shear strength of FSS Welded AA6061 aluminium and copper alloys, incorporating significant weld process parameters. They found that a maximum tensile strength of 4.79 kN was obtained at 2000 rpm, 7 mm/min plunge rate, 25 s dwell time and tool diameter ratio of 3.5. Of the four above mentioned process parameters, the tool rotational speed was found to have the highest influence on the shear tensile strength, followed by the dwell time, the tool diameter ratio and the plunge rate.

A maximum shear tensile strength of 2.60 kN, a minimum of 70.45 HV microhardness and the corresponding values of the process parameters were tool rotational speed of 1250 rpm, dwell time of 12.5 s, plunge depth of 1.9 mm. These were found by Siddharth and Senthilkumar [52].

Garg and Bhattacharya [53], found that the maximum shear tensile strengths for both similar and dissimilar FSS Welded joints were achieved by using the pinless tool. When the tools with pins are used, the shear tensile strength decreases with an increase of the tool plunge depth; but it increases with the pin diameter. When the pin diameter is increased from 3.3 to 4.95 mm, the size of the stir zone region

increases; and this resulted in producing stronger bonds; and it improves the tensile shear strength of the produced spot welds. They further maintained that the hook formation at the interface and the weak bonded area in its vicinity led to the failure of most of the produced spot welds.

The effect of FSSW process parameters on the electrical resistivity of spot was reported by Mubiayi et al. [58]; and the electrical resistivity results revealed high values for all the spot welds compared to the parent materials; but the electrical resistivity of the spot welds produced at 800 rpm, 1 mm shoulder plunge depth, when using a conical pin and a concave shoulder exhibited lower values than those of the parent materials.

2.7 Conclusions

Joining similar and dissimilar materials is an important component in the manufacturing industry. The development of solid state welding techniques has provided more benefits, when compared with some of the more traditional joining techniques. The current state of FSW and FSSW processes between aluminium and copper has been carried out. It was observed that the two processes have been successfully used to join aluminium to copper; and good quality welds had been produced. This was accomplished by using different process parameters and tool geometries. In addition, significant progress and development of FSW and FSSW methods has been achieved worldwide and the processes has established themselves as a viable joining alternative to well established joining processes. The presence of defects, including cracks, voids and pores are usually observed in FSW and FSSW between Al/Cu.

Furthermore, when some process parameters are used, the presence of hard and brittle intermetallic compounds in those welds is detrimental; and it clearly affects the mechanical properties of the produced welds. Therefore, the optimization of process parameters and the usage of the right welding tool shapes is of importance when attempting to produce sound welds.

It was noticed that FSW between Al/Cu has been fairly researched whereas the FSSW Al/Cu is not yet well researched. Hence, more studies need to be undertaken to further understand, optimize the process and this could result in using the technology in various industries. It has been reported that FSSW is an alternative to riveting and resistance spot welding hence, FSSW Al/Cu could be useful in making electrical connections and components. Even though, the ability of FSW and FSSW to join lightweight, high strength aluminium alloys to other materials (i.e.: copper) is desirable, extending this process into high melting temperature materials has been proven challenging due to tool cost and tool wear rates. Therefore, more research need to be undertaken to provide efficient and low cost tools. Most of the published researches on FSW and FSSW Al/Cu are on the characterization and properties of

the produced welds but not on the industrial applications of the techniques. Therefore, since the two processes are solid state joining techniques and environmental friendly, more research need to be undertaken to expand the usage of the techniques in various industries.

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Chapter 3

Friction Stir Welding and Friction Stir Spot Welding of Similar Aluminium and Copper Alloys



Abstract Friction stir welding (FSW) and friction stir spot welding are solid state joining processes employed for the joining of similar and dissimilar materials. The processes are used by many researchers; because these processes produce sound welds; and they do not have common welding problems, such as solidification and liquefaction cracking related to the fusion welding methods. FSW and FSSW of similar aluminium and copper gained ground in the development of solid state joining processes. It may be observed that for FSW and FSSW of similar copper, many research studies were carried out using pure copper as the parent material. Whereas, for similar aluminium, almost the entire aluminium alloy series is utilized. Good quality joints with enhanced properties have been produced; and more studies are required, in order to fully optimize these processes. This could be beneficial in curbing global warming; since FSW and FSSW are both labelled as being environmentally friendly joining processes. In this chapter, FSW and FSSW research studies on similar aluminium and copper are briefly summarized in terms of the process parameters, the microstructural evolution and the mechanical properties.

Keywords Aluminium • Copper • Microhardness • Microstructure
Tensile strength

3.1 Introduction

Friction stir welding (FSW) and friction stir spot welding (FSSW) are both solid state welding processes. Nevertheless, over the past years, the processes have advanced as excel-lent fabrication processes for many materials, including magnesium, titanium, and steel. In these two processes, the filler materials and the shielding environment are not used. FSW and FSSW between similar aluminium and copper alloys have been successfully studied by many researchers worldwide.

This chapter focuses on providing an overview of friction stir welding and friction stir spot welding of similar aluminium and copper materials. The most used

similar aluminium alloys are a different series, including, 1xxx [1, 2], 2xxx [3, 4], 3xxx [5], 5xxx [6, 7], 6xxx [8, 9] and 7xxx [10, 11].

It may be observed that most of the copper used as a parent material for FSW and FSSW is pure copper [12–21]. However, copper alloys have also been used; and they have been successfully joined [22].

3.2 Friction Stir Welding of Similar Aluminium Alloys

Many aluminium alloys have been successfully be joined by using friction stir welding. This section will outline the FSW of similar aluminium alloys, focusing on the microstructural evolution, the weld defects and the mechanical properties. Table 3.1 depicts the type of aluminium used, the thickness, the tool shape, as well as the materials and the remarks for the FSW of similar aluminium alloys.

3.2.1 *The Friction Stir Welding of Similar Aluminium 2xxx Series*

Aluminium 2xxx series are heat-treatable alloys with copper as a major alloying element. Various researchers have carried out investigations on microstructural evolution and the mechanical properties of the friction stir welding of series 2xxx alloys by using various welding process parameters. A summary of the welding process parameters used and the tool geometry/shape is presented in Table 3.1.

AA 2219 was friction stir welded; and the research examined the electro-chemical properties and the microstructure of the produced welds, in an attempt to comprehend the link between the properties and the process parameters [3].

Ma et al. [3] indicated that laser surface melting (LSM) is an effective means for protecting friction stir weld surfaces against corrosion via an improved microstructure and the distribution of phase. Furthermore, the laser melting created a homogeneous layer with a fine microstructure at the surface, which was essentially free of precipitates and intermetallics [3]. The depletion and enrichment of metal ions in different areas of the laser treated sample specimen was due to the heat input generated by the laser melting. They further said that the aluminum concentration along the edges of the melt tracks in the vicinity of the thick planar boundary layer was lower; while the copper concentration along the melt track edges was higher. Figure 3.1 displays the micrograph of the laser surface melted FS Weld treated with laser powers. The depth, width, overlapping region, and the intersection angle of the melt tracks are shown. Figure 3.2 shows the microstructure of the weld produced when using 1500 W laser melting power. A visible laser fusion zone between A and B (Fig. 3.2a). As shown in Fig. 3.2b, the fusion zone in the region was heated twice, resulting in coarse grains. In Fig. 3.2c a columnar

Table 3.1 Presents a summary of the tool properties, the process parameters, as well as a remark for similar aluminium friction stir welds

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
AA 2219 (4 mm)	H13 steel tool Concave shoulder diameter: 16 mm. Pin diameter: 5 mm. Pin length: 3.75 mm	Rotation speed: 1000 rpm. Welding speed: 100 mm/min	The laser treatment improved the pitting resistance of the weld	[3]
AA7010-T76516 (3 mm)	Shoulder diameter: 18 mm. Conical pin diameter: (root: 6.2 mm tip: 4 mm). Pin length: 5.9 mm	FSW: Rotation speed: 700 rpm Welding speed: 100, 200, 400 mm/min. SSFSW: Rotation speed: 1300,1500, 1700 rpm Welding speed: 100, 200, 400 mm/min	The welding speed importantly determined the maximum longitudinal residual stress, when compared to the rotation speed	[10]
AA7075-T6 (20 mm)	H13 die steel. Shoulder diameter: 38 mm. Pin diameter: root: 14 mm, head: 8 mm. Pin length: 19.5 mm	Rotation speed: 235 rpm. Welding speed: 37.5 mm/min	In the weld nugget zone, the grain size decreased from the top to the bottom of the weld (nugget zone)	[23]
AA7050-T7451 (12 mm)	Shoulder diameter: 22 mm. Pin diameter: root: 12 mm, top: 2 mm	Rotation speed: 800 rpm. Welding speed: 2.5 mm/s	The location of strain localization and fatigue crack initiation site is load-dependent	[24]
AA2024 (4 mm)	Hardened tool steel. Shoulder diameter: 20 mm. Pin diameter: root: 6 mm. Pin length: 3.8 mm	Rotation speed: 600, 800, 1000 rpm. Welding Speed: 80, 100, 120 mm/min	Rotation speed of 1000 rpm, welding speed of 80 mm/min and tool offset of 0 mm are the optimum process parameters	[25]
AA7449 (7.2, 11.7 and 17.5 mm)	Two tools: Smaller tool: Shoulder diameter: 15.8 mm Pin root diameter 8.8 mm	Rotation speed: 200, 300, 350, 600 rpm. Welding speed: 2, 4, 5, 8 IPM	Natural aging is very effective at improving the strength of the welds	[26]

(continued)

Table 3.1 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
	Pin tip diameter 6.0 mm Pin height 6.2 mm Larger tool: Shoulder diameter: 25 mm Pin root diameter: 13 mm Pin tip diameter: 3.5 mm. Pin height: 11 mm			
AA2014-T651 (6 mm)	H13 tool steel. Shoulder diameter: 18. Pin diameter: top: 6, bottom: 4. Pin length: 5.8 mm	Rotation speed: 931 rpm. Welding speed: 41 mm/min	The water cooled joints corrosion resistance was improved by the discontinuity, small size of precipitates and other factors	[27]
AA7050-T7651 (6.35 mm)	H13 steel shoulder diameter: 17.8 mm. MP-159 treated tri-flat conical pin: Pin diameter: root: 7.9 mm. Pin length: 6.1 mm	FSW, Rotation speed: 640 rpm. Welding speed: 400 mm/min. SSFSW, Rotation speed: 640, 1000 rpm. Welding speed: 400 mm/min	In SSFSW, temperature reduction and narrowing of thermal field correlated with the improvement of hardness and residual stress	[28]
AA2024-T4 (2.88 mm)	Concave shoulder diameter: 12 mm. Threaded pin diameter: root 3.4 mm. Pin length: 2.8 mm	Rotation speed: 600, 800, 1000, 1200 rpm. Welding speed: 50, 100, 150, 200 mm/min	The material flow of weld zone and base material was incompatible for the FSW sheet, resulting in the rapid thickness reduction of weld zone	[29]
AA 6082-T6 (1 mm)	Steel tool. Cylindrical shoulder diameter: 12 mm. Non threaded conical pin diameter: minimum: 4 mm, maximum: 8 mm	Rotation speed: 600 rpm. Welding speed: 250–1600 mm/min	Post-welding heat-treatment decreases the strength of the joints in cyclic loading	[8]

(continued)

Table 3.1 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
AA7449 (13 mm)	Shoulder diameter: 25 mm. Pin diameter: root: 11 mm, tip: 3.5 mm. Pin length: 11 mm	Rotation speed: 150 rpm. Welding speed: 8 IPM	Microstructure with high solid solution strengthening, larger grains/sub-grains, larger precipitates, and average dislocation density at the top of NZ (highest heat input weld)	[30]
AA2050-T3 (20 mm)	H13 steel scroll shoulder diameter: 29 mm. MP159 truncated cone pin with threads and three flats. Pin diameter: root: 13 mm, tip: 8 mm. Pin length: 15 mm	Rotation speed: 200, 280, 420 rpm. Welding speed: 4, 8, 12 IPM	higher heat input resulted in strength recovery in weld nugget after post weld heat treatment	[31]
AA5052-H32 (6 mm)	H13 steel. Tapered pin. Pin length: 5.7 mm	Rotation speed: 400, 500, 600, 700, 800 rpm. Welding speed: 45, 55, 65, 75, 85 mm/min	The tensile results revealed that the tool tilt angle affect significantly affected the tensile strength of the joint	[6]
AA6061 Al alloy (30 mm)	Concave shoulder diameter: 10 mm. Taper threaded pin length: 1.7 mm	Air: Rotation speed: 800 rpm. Water: 400, 800 rpm. Welding speed: 50 mm/min	Samples joined in water displayed high hardness and strength than the joined in air	[32]
AA6005A-T6 (4 mm)	Shoulder diameter: 10 mm. Pin diameter: 7.4 mm. Pin length: 3.8 mm	Rotation speed: 2000 rpm, Welding speed: 2000 mm/min	The increase of axial force, resulted in the microhardness in different regions roughly increase	[33]
AA6061-T6 (4 mm)	D2 tool steel. Shoulder diameter: 15 mm. Straight cylindrical pin diameter: 4 mm. Pin length: 4 mm	Rotating speed: 1200 rpm. Welding speed: 50 mm/min	A remarkable reduction in hardness in the stir zone was observed	[34]

(continued)

Table 3.1 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
AA2060-T8 Al-Li (2 mm)	Tool steel. Shoulder diameter: 10 mm. Threaded conical pin diameter: Top: 2.6 mm, Bottom: 4.2 mm. Pin length: 1.8 mm	Rotation speed: 600, 800, 1000 rpm. Welding speed: 300 mm/min	The microhardness of the weld nugget zone is lower than that of the parent material	[35]
AA2A97 (1.4 mm)	Triple helix shoulder diameter: 10 mm. Cylindrical pin diameter: 3 mm. Pin length: 1.5, 1.7, 2.0 mm	Welding speed: 200 mm/min Rotation speed: from 800 to 1200 rpm	The tool pin length affects the hook defect and size	[36]
AA5083 (5 mm)	Tool diameter: 20 mm. Pin diameter: 6 mm. Pin length: 1.8 mm	Rotation speed: 600, 800, 1000, 1250 rpm. Welding speed: 30, 40, 50, 63 mm/min	The increase in the tensile strength of water-cooled welded samples may be due to the increase of hardness in the SZ caused by the formation of fine grain	[37]
AA5754-H114 (2.5 mm)	H13 tool steel. Shoulder diameter: 15 mm. Truncated cone pin base. Diameter: 3.9 mm. Pin length: 2.3 mm	Rotation speed: 1200 rpm. Welding speed: 100 mm/min	The grain size in the SZ is smaller than those of the TMAZ and the base material	[38]
AA5754 (2 mm)	H13 tool steel. Shoulder diameter: 12 mm. Truncated cone pin diameter: base 3.5 mm. Pin length: 1.8 mm	Rotational speed: 1200, 1500, 2000, 2500 rpm. Welding speed: 30, 60, 100 mm/min	The lowest environmental impact index value can be obtained at 1200 rpm and 100 mm/min	[39]
AA5083 (6 mm)	H13 tool steel. Shoulder diameter: 24 mm. Taper with threaded tool pin. Pin diameter: 8 mm. Pin length: 5.8 mm	Rotation speed: 710, 1120 rpm. Welding speed: 40 mm/min	Microhardness decreased up to 124 HV and is lower than the microhardness of the parent material	[40]

(continued)

Table 3.1 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
AA6082 (6.35 mm)	The tool made of die steel with threaded pin	Rotation speed: 500 rpm., Welding speed: 20 mm/s	The temperature on advancing side is higher than on the retreating side	[41]
AA1050-H4 (3 mm)	Shoulder diameter: 22.32 mm. Pin length: 2.62 mm. Pin diameter: 4.67 mm	Rotation speed: 975, 1500, 2310 rpm	The increase in preheat time resulted in the decrease in resultant force	[1]
AA 2014-T6 (6 mm)	H13 tool steel. Concave shoulder diameter: 24 mm. Pin diameter: 8 mm. Pin length: 5.6 mm	Rotation speed: 1800 rpm. Welding speed: 20, 31.5, 40 mm/min	The concave shoulder radius (2.5 mm) generated a large amount of heat due to the larger contact area resulting in improved mechanical properties	[42]
AA6061	High speed steel. Circular pin is Shoulder diameter: 15 mm. Pin diameter/diagonal (mm) 4,5,6,7,8 mm. Pin Length: 5.3 mm	Rotation speed: 800, 950, 1100, 1250, 1400 rpm. Welding speed: 30, 36.25, 42.5, 48.75 mm/min	Tensile strength is high for lower speeds, minimum diameter and at higher feeds and beyond that it decreased	[43]
AA6061-T6 (6.32 mm)	H13 tool steel. Concave shoulder diameter: 15 mm. Conical threaded pin: with three flats that tapers from 7 mm (diameter) down to 5 mm (diameter) at the tip. Pin length: 5 mm	Set 1: Rotation speed: 637 rpm. Welding speed: 95 mm/min Set 2: Rotation speed: 2500 rpm. Welding speed: 50 mm/min	The initial testing showed promising agreements with the CFD simulations	[44]
AA6063-T4 Lap (3 mm). Butt (3 and 6 mm)	SS 316 tool. Shoulder diameter: 24 mm, Square pin size: 6 mm. Pin length: 2.65, 4.85, 5.65 mm	Rotation speed: 450, 635, welding speed: 18, 38, 64 mm/min	The peak weld zone temperatures are lower for sheets of lower thickness	[45]

(continued)

Table 3.1 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
AA6351 (6 mm)	HCHCr tool steel. Shoulder diameter: 18 mm. Square pin diameter: 6 mm	Rotation speed: 710, 1000, 1400 rpm. welding speed: 14, 21, 29 mm/min	33% improvement in mechanical properties was obtained	[46]
AA5059 (4 mm)	High speed steel. Shoulder diameter: 12 mm. Pin diameter: 4 mm. Pin length: 3.7 mm	Rotation speed: 600, 741.9, 950, 1158, 1300 rpm. Welding speed: 10, 16.1, 25, 33.1, 40 mm/min	The rotation speed mainly influences the tensile strength	[47]
AA5086-H34 (6 mm)	Heat-treated H-13 hot steel tool. Shoulder diameter: 16 mm. Pin diameter: 6 mm. Pin length: 5.7 mm	Rotation speed: 500, 800, 1000, 1250, 1600 rpm. Welding speed: 41.5, 80, 125 mm/min	Increasing the rotation and welding speed led to grain refinement	[48]
AA6063-T4 (6 mm)	Standard molybdenum bearing grade SS 316 tool. Flat shoulder diameter: 24 mm. Square pin size: 6 mm. Pin length: 5.65 mm	Rotation speed: 806 rpm. Welding speed: 18, 48, 78, 110 mm/min	The peak temperature in different weld areas decreases with the increasing welding speeds	[49]
AA5086 (8 mm).	Shoulder diameter: 20 mm. Pin diameter: 8 mm. Pin length: 7.5 mm	Rotation speed: 1000 rpm. Welding speed: 63–100 mm/min	The corrosion-current density in the HAZ and the WNZ increases with the increment of the welding speed	[50]
AA2014-T6 (5 mm)	H-13 tool steel. Shoulder diameter: 24 mm. Conical pin with threads diameter: top: 6 mm, bottom: 3.6 mm. Pin length: 5 mm	Rotation speed: 1000 rpm. Welding speed: 600 mm/min	At a specific rotation speed, the volume of shoulder driven flow reduces with increasing shoulder diameter	[51]

(continued)

Table 3.1 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
AA7075-T6 (5 mm)	Hot die H13 tool steel Flat shoulder diameter: 12, 13.5, 15, 16.5, 18 mm. Threaded cylindrical pin diameter: 4, 4.5, 5, 5.5, 6 mm	Rotation speed: 350, 425, 500, 575, 650 rpm. Welding speed: 35, 50, 65, 80, 95 mm/min	The rotation speed, welding speed and tool size influence the joint efficiency	[52]

crystal area on the right side of the fusion area can be seen; while a fine layer was observed in Fig. 3.2e. And in Fig. 3.2f the microstructure of the unmelted metal is clearly shown.

The microscopic appearances of the samples after 24 h of being immersed are shown in Fig. 3.3. No pitting in the laser melted area (Fig. 3.3a) and severe pitting in the base material was observed. For the corrosion, the pitting resistance of the produced friction weld was improved by the laser treatment [3]. Whereas, large pits were formed and observed in the laser untreated weld during the corrosion. However, no such pits were observed in the laser melted area [3].

Sudhagar et al. [25] used AA 2024 as the parent material and they friction stir welded the samples by using selected process parameters. They attempted to select the optimum process parameters to join AA 2024. They indicated that the quality of the friction stir welded joint is determined by numerous criteria (rotation speed, welding speed, tool offset); therefore it should be necessary to analyze all the criteria. They found that, the optimum process parameter conditions that produce the maximum response are: rotation speed (1000 rpm), welding speed (80 mm/min) and tool offset (0 mm). According to the technique for order preference by similarity to ideal solution (TOPSIS), the maximum value of tool rotational speed, the minimum value of the welding speed and the tool offset at 0 mm yield maximum tensile strength, impact toughness and hardness [25].

The FSW of AA2014 (6 mm thick) sheets was successfully joined by using water cooling. Sinhmar and Dwivedi [27] observed various enhancements in the welds' properties compared to the naturally cooled FSW welds. The microstructure was more refined, with the small precipitates; and that was obtained by using the water cooling during the joining process. The microhardness value in the nugget zone was similar to that of the parent material; but in the heat affected zone, the microhardness was lower. Furthermore, the width of the water cooled HAZ was reduced due to faster heat removal rate [27].

On the other hand, the yield strength and the ultimate tensile strength of the produced joints were lower compared to that of the parent material. But, the water cooled joint exhibited higher strength when compared to the naturally cooled weld; and this is taken to be due to the difference in the cooling rate. Furthermore, the

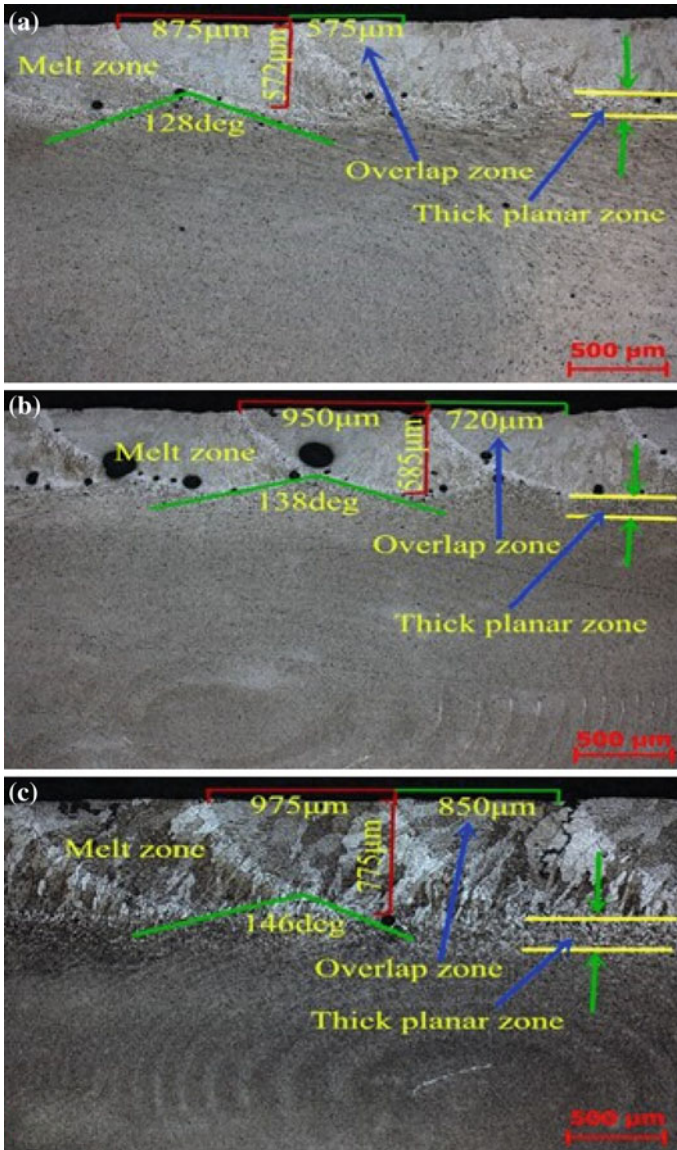


Fig. 3.1 Shows the optical micrographs of the laser surface melted friction stir weld treated by using different laser parameters **a** 1000 W, **b** 1200 W, **c** 1500 W [3]. Reprinted with permission from Elsevier

parent material was susceptible to corrosion, due to the formation of the micro level galvanic coupling by a continuous chain of precipitates at the grain boundaries. And as for the water cooled welds, the corrosion resistance was improved; and this was

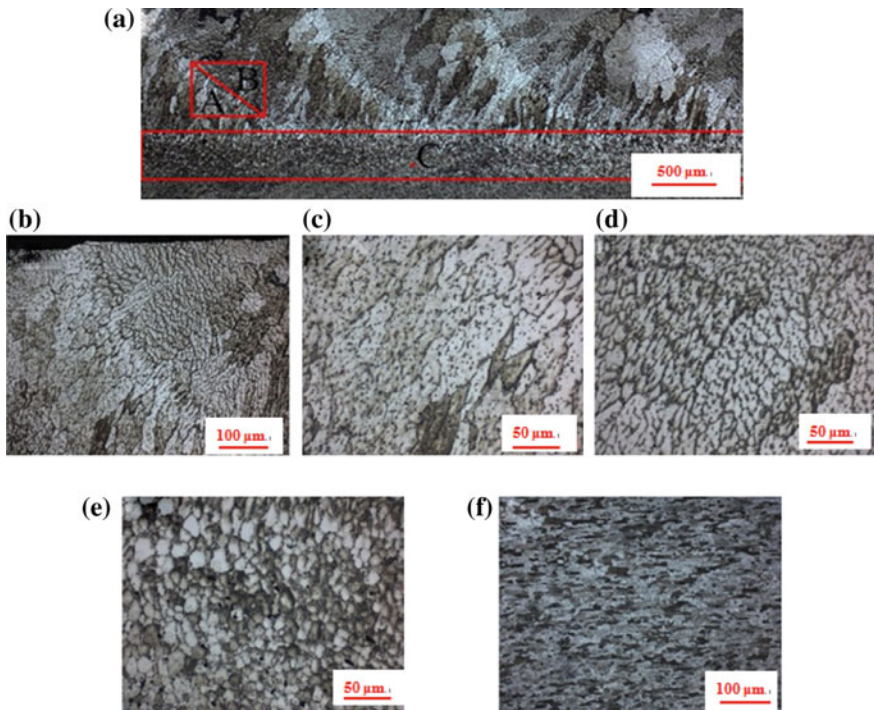


Fig. 3.2 Shows optical micrographs of laser-melted FSW joints [3]. Reprinted with permission from Elsevier

due to the discontinuity and the small size of the precipitates, along with other factors [27].

A study was conducted by Liu et al. [35] on the friction stir welding of AA 2060-T8 when using a rotation speed ranging from 600 to 1000 rpm and a constant welding speed of 300 mm/min. When the rotation speed increases from 600 rpm to 1000 rpm, the thermomechanically affected zone (TMAZ) on the retreating side enlarges; and the distance of the TMAZ penetrating into the weld nugget zone (WNZ) increases [35].

As for the weld produced at 1000 rpm, the TMAZ on the retreating side is closely extended into the center of the WNZ; and that led to a crack propagation along the TMAZ/WNZ boundary; while performing the tensile testing [35].

The microhardness values of the weld nugget zone are lower compared to the parent material and all the joints fractured in the weld's nugget zone [35]. The maximum tensile strengths were 440 MPa; and these were obtained at the rotation speed of 800 rpm.

Nevertheless, the maximum elongation of the weld is only 2.8%; and this was much lower than that of the parent material. This was due to the microstructure of the weld nugget zone, which is non-homogeneous along the depth, resulting in a

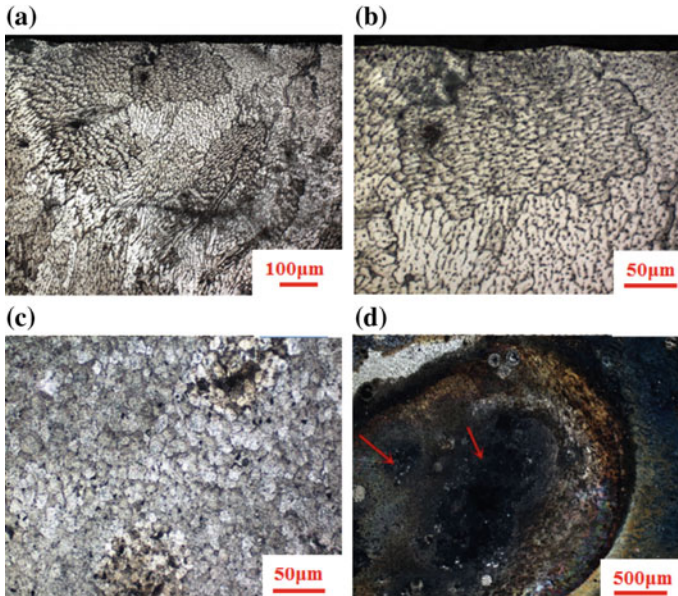


Fig. 3.3 Shows the microstructure after immersion test [3]. Reprinted with permission from Elsevier

concentration of stress during the tensile testing. Because of that, the crack is effortlessly initiated from the bottom [35].

The role of the tool shoulder diameter and the rotation speed was investigated on AA2014 by using the FSW technique [51]. It was found that the joints produced by using tools with different shoulder diameters (from 12 to 15 mm) at 600 mm/min and 1,000 rpm, the joint bead morphology was smoother, and without any defects on the surface.

On the other hand, when the tool diameter was further increased (from 18 to 24 mm), surface defects were observed.

Furthermore, the peak temperatures measured below the shoulder, at the nugget/thermomechanically affected zone interface, increase with an increment of the tool shoulder diameter [51]. Additionally, the temperature gradient becomes less steep with the increment, the tool shoulder diameter, and the temperature reaching a minimum for the 18 mm diameter shoulder.

When the shoulder diameter is increase beyond 18 mm, there is a moderate decrease in the temperature gradient up to 24 mm shoulder diameter.

On the other hand, at a given rotation speed, the volume of the shoulder driven metal flow was reduced, even though only slightly, with the increment of the tool shoulder diameter [51].

3.2.2 Friction Stir Welding of Similar Aluminium 5xxx Series

The 5xxx series comprises magnesium as a major alloying element; but the series is non-heat treatable; and it exhibits good corrosion resistance amongst the non-heat treatable aluminium alloys.

Heirani et al. [37], friction stir welded AA5083 (5 mm thick) using different process parameters. They investigated the effect of the welding environment (water and air) on the microstructure and the mechanical properties of the produced welds. The water environment condition led to a high cooling rate; so that the grains did not have enough time to grow. This resulted in the disappearance of the HAZ; and that was achieved at 600 rpm and 30 mm/min. They also said that, the higher cooling rate in the thermomechanically affected zone and the heat affected zone made the microstructure similar in all the produced samples. Furthermore, peak temperature values in the stir zone made modifications in the microstructure, which permitted the shape, the size of the grains and the distribution of the precipitates to be totally different for each sample [37]. Additionally, in comparison with the air cooled weld samples, the increment in the tensile strength of the water cooled samples could be due to the increment of hardness in the stir zone caused by the presence of an ultrafine grain structure.

This means that the increment of hardness in the stir zone leads to a high resistance to uniform plastic deformation during the joining process; and consequently, the tensile strength improves [37].

AA5059 (4 mm thick) sheets were friction stir welded; and the optimization of the process parameters was investigated to improve the joint strength of the fabricated welds [47]. It was found that, the friction stir welding process and the tool parameters played a major role in defining the joint strength. Babu et al. [47] attempted to establish an empirical relationship between the friction stir welding process parameters and the predicted maximum tensile strength. Higher tensile strength properties were attained for the weld produced at a rotation speed of 950 rpm, a welding speed of 25 mm/s and an axial force of 3.4 kN [47]. They developed an empirical relationship by using a statistical tool, including the design of the experiment (DOE), regression analysis, and the analysis of variance (ANOVA) to predict the tensile strength of the FS welds at a 95% confidence level. Furthermore, they found that the rotation speed played a principal role in influencing the resulting tensile strength.

A study on the effect of the process parameter on the properties of AA5086 friction stir welds was carried out [48]. The welds produced at very low rotation speeds resulted in the formation of tunneling and wormhole defects; and this was a result of insufficient heat generated and insufficient metal transportation [48]. Similarly, when the rotation speeds are very high, tunneling and wormhole defects are generated due to the large turbulence in the plasticized metal. The ultimate tensile strength of the produced welds increased significantly when the rotation speed is increased [48]. They further said that, in order to achieve the maximum

joint strength for each rotation speed, an optimal welding speed should be used. On the other hand, the microhardness values increased with the usage of higher welding speeds; and this can be explained by the reduction in the heat input and more material deformation at higher welding speed [48]. Furthermore, the microhardness of the thermomechanically affected zone exhibited lower values when compared with those of the parent material; and this can be attributed to the dissolution and the growth of the precipitates during the joining process [48].

They concluded that the best friction stir welding conditions are 1250 rpm and 80 mm/min—resulting in a 51% improvement in the elongation and an 8% increment in the microhardness of the produced weld samples. Also, the ultimate tensile strength was recorded when using the best welding condition. This resulted in obtaining a value of 85% of the parent material [48].

Figure 3.4 presents the different microstructure displayed in the stir zone of the welds produced using the various process parameters. The increment of the welding speed resulted in a greater plastic deformation in the weld zone. When Fig. 3.4 a and c are compared, the grain size in the stir zone is reduced when the welding speed is increased; and that was due to the more dynamic recrystallization and also the less annealing effect of the welding heat input at higher welding speed. Similar observations were made by comparing Fig. 3.4d, f.

Figure 3.5 displays the microhardness profiles of the welds produced at 1000 and 1250 rpm rotation speed and at various welding speeds. It can be seen in Fig. 3.5 that the recorded microhardness values in the advancing side are higher than those in the retreating side.

3.2.3 *Friction Stir Welding of Similar Aluminium 6xxx Series*

Aluminium 6xxx series alloys are heat treatable Al/Mg/Si alloys and are used in many structural applications. This section provide an overview on selected studies on the joining of aluminium 6xxx series alloys using friction stir welding.

Costa et al. [8] joined thin sheets of AA6082-T6 using the FSW technique at a constant tool rotation speed of 600 rpm and welding speeds ranging from 250 to 1600 mm/min.

The friction stir lap joints' strength, in both the as-welded and age hardened conditions, decreased with the increments in the welding speed.

The post welding heat treatment enhanced the weld strength in monotonic loading; and this was for the defect-free welds; while in cyclic loading, the post welding heat treatment decreased the welds' strength. Furthermore, the weld geometry is the main factor governing the fatigue strength of the produced lap welds.

Costa et al. [8] maintained that the best joint efficiency was obtained in the retreating side of the welds produced at low welding speeds in both monotonic and

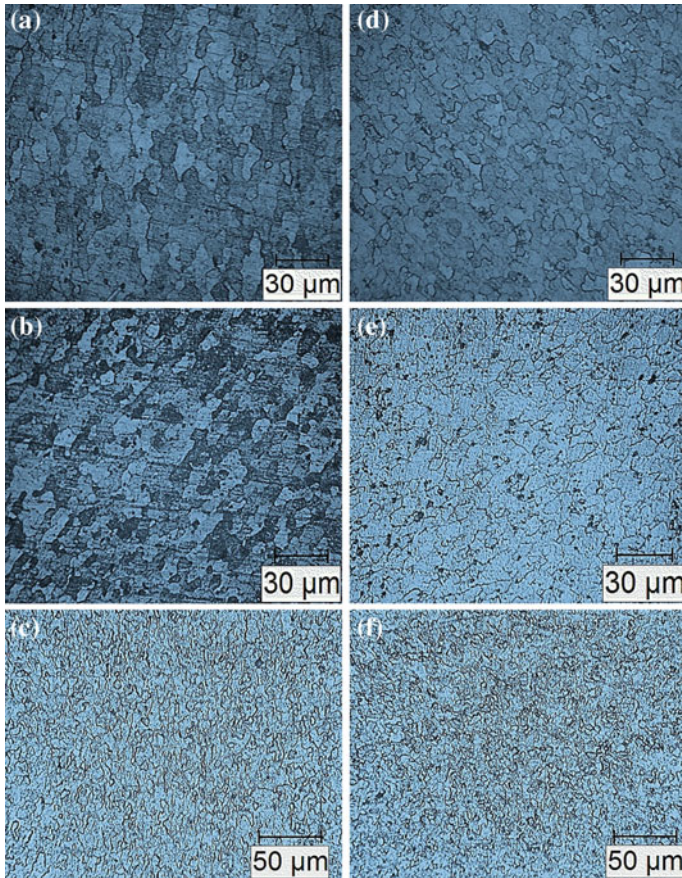


Fig. 3.4 Presents the microstructure obtained in the stir zone for the welds produced at rotation and welding speeds of **a** 1000 rpm/41.5 mm/min, **b** 1000 rpm/80 mm/min, **c** 1000 rpm/125 mm/min, **d** 1250 rpm/41.5 mm/min, **e** 1250 rpm/80 mm/min, and **f** 1250 rpm/125 mm/min [48]. Reprinted with permission from Springer

cyclic loading. Figure 3.6 depicts the strain distribution in the transverse tensile samples at maximum load. In Fig. 3.6, in the strain maps it can be seen that at higher welding speeds, the width of the plastically deformed region is smaller. And these samples failed in the middle of the thermomechanically affected zone, in which very large strain values were obtained. On the other hand, the width of the softened region is larger; and the higher strain values are observed on the advancing side of welds produced at lower welding speeds [8]. Here, the hardness profiles of both welds depicted in Fig. 3.7, showed that lower hardness values were recorded in the heat affected zone and in the middle of the thermomechanically affected zone for the welds produced at welding speeds of 350 mm/min and 1000 mm/min, respectively [8].

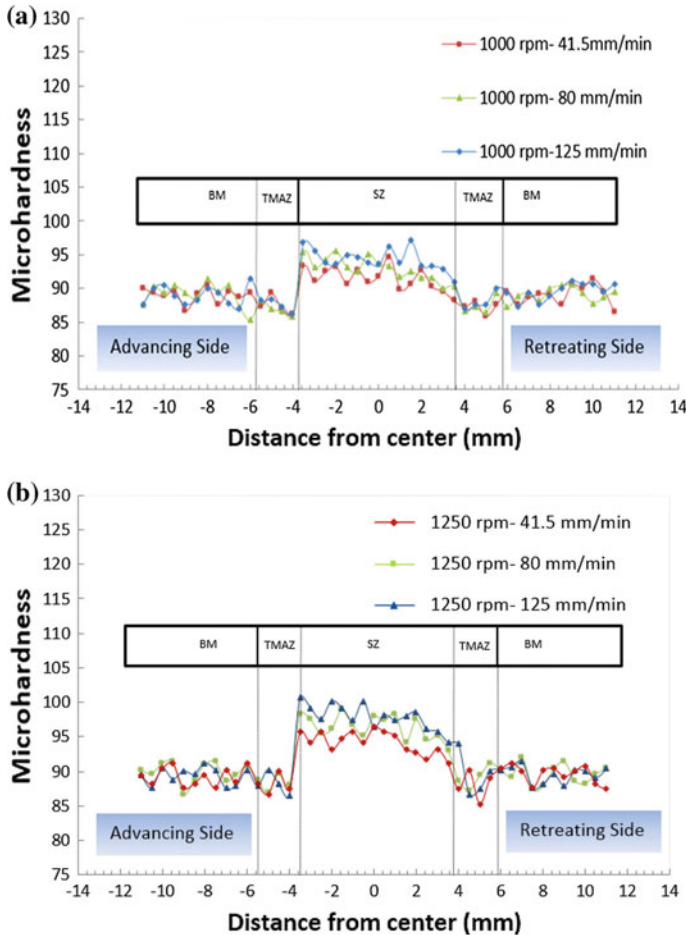


Fig. 3.5 Displays the microhardness profiles of the welds produced when using different welding speeds and at the rotation speeds of **a** 1000 and **b** 1250 rpm [48]. Reprinted with permission from Springer

Furthermore, in Fig. 3.7, it can be seen that the maximum strains were recorded in the lower hardness zones of both welds. Figure 3.8 depicts a comparison of the local stress-strain curves attained in the transverse tensile test between the as welded and the age hardened samples produced at 350 mm/min and 1000 mm/min welding speeds [8]. It can be seen that the strength exhibited by both post welding heat treated samples reached was almost the values of the parent material in the TMAZ [8].

Liu et al. [32] ultrafine grained (UGF) AA6061 sheets fabricated by cold rolling were FS welded at different rotation speeds under two cooling conditions, namely: air cooling and rapid cooling in water. Friction stir welding in water could

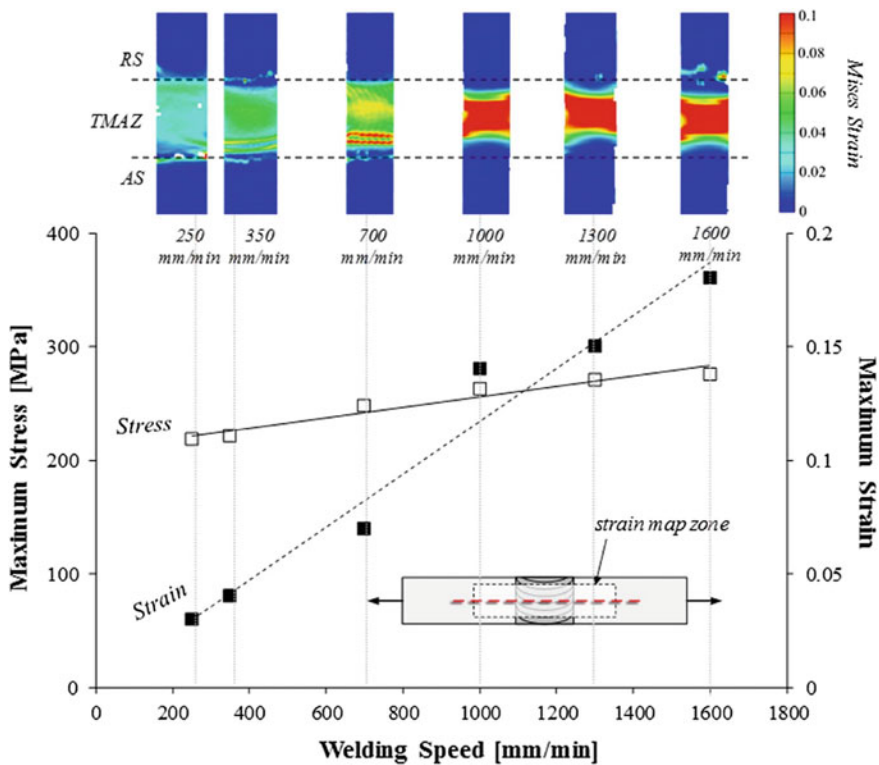


Fig. 3.6 Shows the evolution of the maximum stress and maximum strain in the thermomechanically affected zone with the welding speed. Strain distribution in the transverse tensile samples at maximum load [8]. Reprinted with permission from Elsevier

effectively prevent the grain coarsening in recrystallization, maintain the high dislocation density, and decrease the precipitation rate of the ultrafine grained AA6061 [32]. Consequently, large bulk UFG AA6061 were successfully fabricated by cold rolling with large deformation and low heat input friction stir welding. The specimen joined in water exhibited high hardness and tensile strength when compared with the specimen joined in air. Furthermore, the joint efficiency of 73% was achieved for the specimen welded in water at the rotation speed of 400 rpm.

Dislocation, grain boundaries, solid solution, and precipitation hardening were the strengthening mechanisms of the specimen joined at 400 rpm in water. They concluded that the friction stir welds exhibited higher elongation compared with that of the rolled AA6061 base material [32].

AA6063-T4 (3 and 6 mm thick) aluminum alloy sheets were friction stir butt and lap welded using three different backing plate materials, namely: mild steel, stainless steel, and asbestos [45]. The effects of the backing plate material on the microstructure, the peak mid-section temperature in HAZ and NZ and the resulted mechanical properties were established and attained for the entire case scenario.

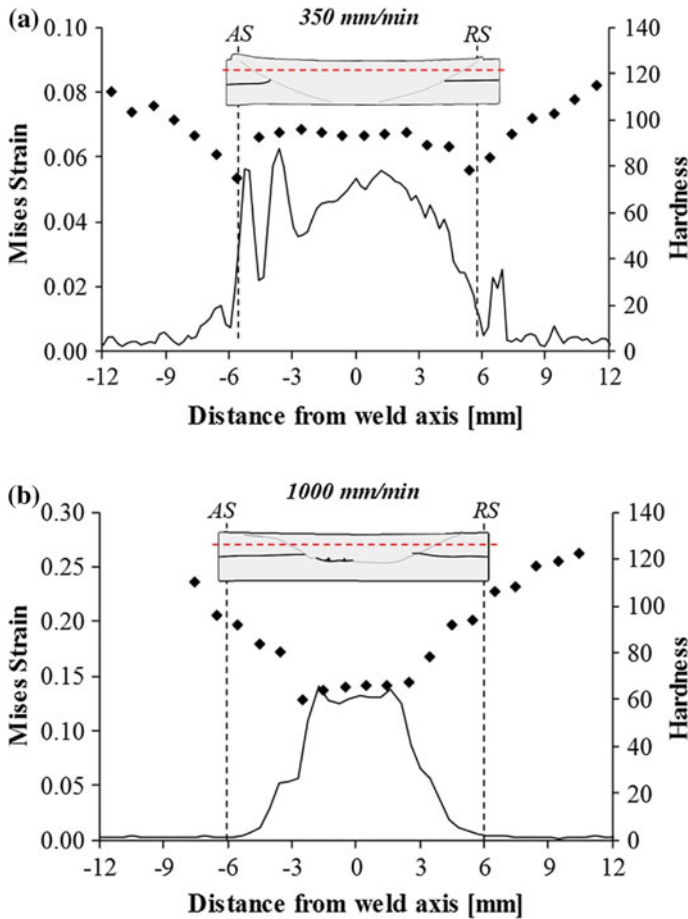
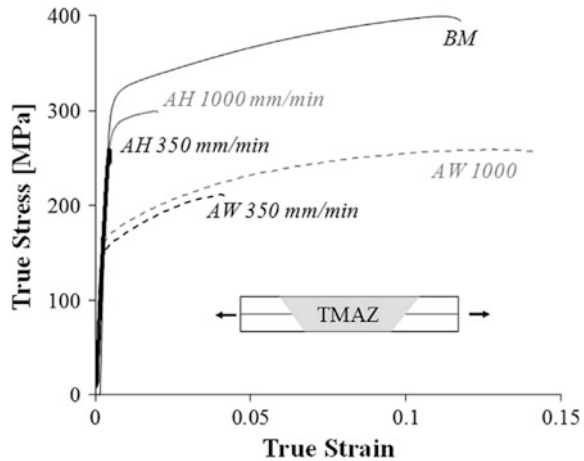


Fig. 3.7 Shows the hardness and the strain profiles, in the top plate, for the welds produced at welding speed 350 mm/min (a) and 1000 mm/min (b) [3]. Reprinted with permission from Elsevier

They observed that the weld zone temperatures were considerably affected by the usage of a specific backing plate material, in particular for the lap weld configuration [45]. Defect-free lap joints were produced when the asbestos backing plate was used; while defects such as tunnel, hook, and cold lap defects were observed when the mild steel and stainless steel backing plates are used. The microhardness in the weld nugget zone (NZ) is mostly controlled by the average grain size in joint NZ; and the grain size controlled by the peak temperature and cooling rates in NZ.

For this research work, the asbestos backing plate provided the largest process window, in which defect free joints could be produced [45]. Furthermore, the peak weld zone temperatures are lower for sheets of lesser thickness; therefore, choosing an appropriate backing plate is more important during the FSW of thinner sheets.

Fig. 3.8 Depicts the stress-strain curves for the thermomechanically affected zone and in the as welded and in the age hardened conditions [8]. Reprinted with permission from Elsevier



Imam et al. [45] stated that the sheet positioning plays a critical role in temperature asymmetry in lap welding configuration. This was seen in obtaining higher peak temperature in the heat affected zone in the sheet placed on the top [45].

3.2.4 Friction Stir Welding of Similar Aluminium 7xxx Series

Aluminium alloys 7xxx series are high strength, age hardenable; and they are extensively used in aerospace structural components. Many researchers have successfully joined 7xxx series by using the friction stir welding technique.

In this study, Mao et al. [23] investigated the consequences of the microscopic heterogeneity of microstructural evolution, precipitate distribution and mechanical properties along the thickness direction in the weld nugget zone. The parent material was joined by using FSW. This was 20 mm thick AA7075-T6. They observed an increment trend of the grain size from the top to the bottom in the weld nugget zone (WNZ). The grain size was estimated by electron backscattering diffraction (EBSD). The results showed that, at 3 mm from the top surface, the smallest grain size was about 2.5 μm ; whereas the grains size reached 11.4 μm at 18 mm; and these are coarse.

However, they noticed a changing trend of high angle grain boundaries (HAGBs) along the thickness direction that was opposite; and this was consistent with the degree of dynamic recrystallization [23].

They further said that the original coarse precipitates were broken up, dissolved and re-precipitated in the weld nugget zone. The re-precipitated particles are finer and more homogeneous at 1 and 3 mm; and they are mostly η (MgZn_2) and η , (MgZn_2) phases; and the content is higher. However, coarser particles were

observed at 13 mm and 18 mm; and those particles contained fewer fine η and undissolved coarse S and T phases [23].

In the mechanical properties, they noticed a decreased trend from the top to the root of the slices along the thickness direction of the weld nugget zone [23]. Furthermore, 415 MPa, 255 MPa and 8.1% were found respectively for the maximum ultimate tensile strength (UTS), yield strength (YS) and elongation of the slice in the top middle of the WNZ. And they attributed that to finer grains, additional high angle grain boundaries (HAGBs) and more dispersive re-precipitated particles. Lastly, they said that, the tensile strengths and the elongation of the slice located in the weld nugget root were the lowest [23].

Sun et al. [28], friction stir welded AA7050 and investigated the effect of tool shoulder coupling on the microstructure, the distribution of the residual stresses and the hardness. And they accomplished that by decreasing the downforce on the tool in the conventional FSW process, and comparing the results to stationary shoulder friction stir welding (SSFSW) welds produced under identical conditions [28].

The obtained results confirmed that when same welding parameters are used, a wider thermal field is found with FSW than that in SSFSW.

The additional heat generated by the shoulder in conventional FSW expanded the welds at the top surface and led to superior temperature variation throughout the thickness of the sheets.

While, a narrower and more uniform through thickness temperature profile was found in SSFSW. And this was beneficial in getting a thinner weld zone (WZ) with a more uniform thickness microstructure and avoiding overheating near the weld crown [28]. The hardness and the residual stress distribution were both significantly affected by the reduction of the tool downforce in FSW using a stationary shoulder.

While using the same rotation speed, the SSFSW procedure was found to lead to overall lower, more consistent weld temperatures; and a considerably reduced heat affected zone width [28]. They further stated that, the tensile residual stresses was decreased of about 20% in width; and there was a 25% reduction in the peak magnitude when the same FSW welding parameters were used for SSFSW [28].

They attributed this improvement to the more concentrated thermal field in SSFSW, and the lower weld temperatures, which reduced the compressive plastic misfit generated during the welding.

Martinez et al. [30], tried to understand the effect of FSW on thick sheets; they conducted a thorough analysis on the top and bottom of the weld nugget of the precipitation strengthened (PS) AA7449 (13 mm thick).

They stated that, with a copper backing plate and the usage of the optimized welding process parameters, a joint with varying microstructure was produced. They observed two different zones in the nugget zone; and this was due to the heat gradient and cooling rates experienced in the nugget zone [30].

High solid solution strengthening, larger grains/sub-grains, larger precipitates, and average dislocation density were observed at the top of the weld nugget with the weld produced at the highest heat input [30]. They further said that this microstructure responded well to natural ageing. Furthermore, the copper backing

plate removed the heat very quickly, resulting in keeping the weld peak temperature low at the bottom region of the weld nugget [30].

On the other hand, with less heat at the bottom of the nugget, finer precipitates, finer grains/sub-grains, and higher dislocation density were formed; and consequently, the microstructure, at the bottom of the nugget displayed high hardness values [30].

The decrease in strength is negative in the heat affected zone; but after natural aging, improvements in hardness are perceived. They concluded that, by choosing the correct FSW process parameters, strong welds of thick precipitation strengthened AA7449 can be achieved and with natural ageing of 12 months, the hardness values were substantially improved [30].

3.3 Friction Stir Spot Welding of Similar Aluminium

Table 3.2 shows a summary of the type of similar aluminium used, the thickness, the tool shape and the materials and remarks made for the FSSW of similar aluminium.

Table 3.2 Presents a summary of the tool properties, the process parameters and a remark for similar aluminium friction stir spot welds

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
2A12-T4 alloy (upper sheet, 3 mm and lower sheets 5 mm)	The tool shoulders are both concentric circles structure. The shoulder diameter: 15 mm. Pin diameter: bottom: 6 mm, tip: 3 mm. Pin length: 6 mm	Rotation speeds: 1000 rpm, 1500 rpm and 2000 rpm Dwell time: 10 s. Shoulder plunge depth: 0.2 mm	Hook and redistributed alclad layer influences the fracture mode	[4]
AA2198-T851 (3 mm)	Shoulder diameter: 15 mm. Shoulder material: nickel–cobalt alloy MP159 Pin diameter: 7 mm, Pin material: molybdenum–vanadium hot work tool steel (X38CrMoV5-1)	Rotation speed: 400 rpm. Welding speed: speed 500 mm/min	Defect free and highly efficient joints are achieved	[53]

(continued)

Table 3.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
AA5052-H32 rolled: 2 mm and HDPE as the core layer: 1 mm	H13 tool steel Flat shoulder diameter: 10 mm. Straight cylindrical pin diameter: 4 mm. Pin length: 3 mm	Rotation speeds: from 1000 rpm to 2000 rpm at an interval of 200 rpm. Tool plunge depth: 3.6 mm. Dwell time: 15 s.	The sandwiched sheets show good mechanical performance	[7]
AA6061-T6 (1 mm)	WC-Co tool. Tool 1: Shoulder diameter: 12 mm. Pin diameter: 4 mm. Pin length: 1 mm. Tool 2: Shoulder diameter: 12 mm. Pinless	Rotation speed: 30, 40 and 50 rpm. Dwell time: 30 s	An ultrafine grain structure with a high density of dislocations was formed in the stir zone	[54]
Alclad 2024-T3 (1.6 mm). AA1230 (0.05 mm) were clad on the surfaces of AA2024-T3	Flat shoulder and M5 threaded triangular pin. Shoulder diameter: 12 mm. Pin diameter: 5 mm. Pin length: 2.8 mm	Rotation speed: 500 rpm. Feed rate: 120 and 180 mm/min	The fatigue life estimations based on this model agree well with the experimental results	[55]
AA6061-T6 (2 mm)	Conventional FSSW, tool Shoulder diameter: 18 mm. Pin diameter: 5 mm	Conventional FSSW: Rotation speed: 900 rpm, Dwell time: 2 s, Shoulder plunge depth: 0.3 mm. FSSW-FFP: Rotation: 1800 rpm, Dwell time: 2 s Shoulder plunge depth: 2.2 mm	Fatigue strength of the FSSW-FFP is higher than that of the conventional FSSW	[56]
AA6060-T5 (2 mm)	Tool steel (X210 CR 12). Shoulder diameter: 14 mm. Pin diameter: 5 mm. Pin length: 3.95 mm	Rotating speed: 1000, 1400, 2000 rpm. Welding feed rate: 16, 20, 25, 31.5 mm/min	The shape of the tool has a great influence on the mechanical resistance of the joints	[57]

(continued)

Table 3.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
AA5052 H112 (1 mm)	Stainless steel (1Cr18NiTi. Concave shoulder, Shoulder diameter: 10 mm. Conical pin, Pin root: 4.5 mm, Pin tip: 3 mm. Pin length: 1.8 mm	Rotation speed: 1541 and 2256 rpm. Dwell time: 5, 10 and 15 s. Welding speed: 50 mm/min	Hardness in the TMAZ and SZ improved due to the recrystallization	[58]
AA7075-T6 (2 mm)	Flat tool Shoulder diameter: 16 mm. Pin diameter: 6 mm Pin length: 2.5 mm	Rotation speed: 2000 rpm. Dwell time: 30 s. Shoulder plunge depth: 1 mm.	Good agreement between fatigue life predictions and experimental data	[59]
AA7075-T6 (2 mm)	Clamping ring diameter: 15 mm. Sleeve diameter: 9 mm. Pin diameter: 5 mm	Rotation speed: 1500, 1750 and 2000 rpm. Dwell time: 3,4 and 5 s	Extending dwell time contributed to the improvement of mechanical properties at higher rotational speed	[11]
AA3003-H12 (3 mm)	H13 hot work tool steel 10° concave shoulder and a threaded cylindrical pin. Shoulder diameter: 12 mm. Pin length: 3 mm	Rotation speed: 1500, 200, 2500 rpm. Dwell time: 1.5, 2, 2.5 s. Plunge depth: 3.2, 4, 4.8 mm	Higher hardness in the SZ of the weak joints than in the strong joints	[5]
AA6061-T6 (1 mm)	Cylindrical shoulder, cone-shaped pin. Shoulder Diameter: 12 mm. Pin diameter: 5 mm. Pin length: 1.5 mm	Rotational speed: 3450 rpm. Dwell time: 40 s	Under cyclic loading conditions, the fatigue crack is initiated near the possible original notch tip in the SZ	[60]
AA6061-T6 (1.6 mm)	Flat shoulder and a M 5 threaded pin. The shoulder Diameter: 10 mm. Pin length: 2.4 mm	Rotation speed: 1000, 2000, 3000 rpm. Dwell time: 0.5 s	Flash removing process in general has little effects on the mechanical properties except under very low indentation rates	[9]

(continued)

Table 3.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
AA2024-T3 (1.6 mm). AA1230 layers (0.05 mm were cladded on AA2024-T3	Triangular threaded pin/flat shoulder. Shoulder diameter: 12 mm. Pin diameter: 5 mm. Pin length: 2.8 mm	Rotation speed: 500 rpm	Nugget pullout failure mode in quasi-static and low-cycle	[61]
AA2198-T8 (1.8 mm)	H13 steel pinless cylindrical tool. Shoulder diameter: 15 mm.	Rotation speed: 600, 750, 950, 1180, 1500 rpm, Dwell time: 3, 6, 9, 12, 15 s. Plunge depth: 0.3 mm	The morphology of the hook defect affected significantly shear tensile strength and the fracture mode	[62]
AA 6061-T6 (2 mm)	FSSW: Shoulder diameter: 18 mm. Pin diameter: 5 mm. FSSW-FFP: two tools: extrusion tool and friction forming. High carbon steel	Rotational speed: 900, 1120, 1400 and 1800 rpm	W-shaped hardness profile was observed and the minimum hardness was measured in the HAZ	[63]
AA5083-O (2 mm)	Sleeve diameter: 9 mm. Pin diameter: 5.2 mm	Rotation speed: 2300, 2500, 2700 rpm, Plunge depth: 2.2, 2.3, 2.4 mm. Dwell time: 1.5, 2.5, 3.5 s	The hook defect affected the fracture modes	[64]
Rolled 6061-T6 (2 mm)	RFSSW clamp diameter: 14 mm. Sleeve diameter: 9 mm Pin diameter: 5.3 mm	Rotation speed: 2100 rpm. Shoulder plunge depth: 1.9, 2.2, 2.5 and 2.8 mm. Dwell time = refill time: 3, 5, 7 and 9 s	The strength of refill friction stir spot joints depended mainly on the size of the hook defect	[65]
AA 2099-T83 (1 mm)	H13 tool steel, Shoulder diameter: 9 mm. Pin diameter: 6.4 mm. Clamping ring diameter: 18 mm	Rotation speed: 2100 rpm. Dwell time: 3 s	The local melting of the secondary phases from the AA2099 affected the failure of the joints	[66]

(continued)

Table 3.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
AA1100 (2 mm)	H13 steel (hardened)	Rotation speed: 1000, 2000 rpm. conventional FSSW tool plunge depth: 3.7, 3.8 mm. Dwell time: 3, 6 s	The rotational speed has the strongest effect on welding strength for both conventional and refilled FSSW	[2]
AA6061 (0.9 mm)	H13 hot die steel material. Shoulder diameter: 16 mm. Pin geometry: circular, square and triangular. Pin diameter: 6.5 mm. Pin length: 1.4 mm	Rotation speed: 1000, 1500, 2000 rpm. Dwell time: 2, 4, 6 s	The optimal shear strength was obtained for tool rotation speed of 1000 rpm and dwell time of 4 using a square tool pin geometry	[67]
Rolled AA6061 (3 mm)	High carbon steel, cylindrical-conical grooved	Rotation speed: 800, 1200, 1600 rpm. Plunge Depth: 5, 5.5, 6 mm. Dwell Time: 4, 6, 8 s.	The association of ultrasonic vibration and FSSW improved the lap shear strength and hardness	[68]
AA7075-T6 (0.8 mm (lower) and 1.6 mm (upper))	Shoulder diameter: 9 mm, pin diameter: 5.2 mm	Rotation speed: 2000, 2200, 2400, 2600, 2800, and 3000 rpm. Tool plunge depth: 1.35, 1.4, 1.45, 1.5, 1.55, 1.6, 1.65, 1.7, and 1.75 mm. Dwell time: 1, 1.05, 1.1, 1.15, 1.2, 1.25, 1.3, 1.35, 1.4, 1.45, and 1.5 s	Increases in both the tool rotational speed and dwell time increased the load capacity of the spot weld and the temperature inside the weld	[69]
AA 6063-T6 (3 mm)	Cylindrical with threaded pin and a flat scrolled shoulder. Shoulder diameter: 10 and 15 mm. Pin diameter: 4 and 5 mm. Pin length: 3.5 to 5.7 mm.	Rotation speed: 1,000, 1,500, 2,000 rpm. Plunge depth: 5.5 mm.	Crack always first starts at the tip of the hook.	[70]

(continued)

Table 3.2 (continued)

Parent materials and material thickness	Tool material and shape	Process parameters	Remark	References
A6061-T6 (2 mm)	Concave shoulder diameter: 12 mm. Circular pin diameter: 4 mm. Pin length: 2.6 mm	Rotation speed: 1,550 rpm. Shoulder plunge depth: 0.5 mm	The hook affects the fracture mode	[71]
AA6061-T6 (2 mm)	Champing ring diameter: 18 mm. Shoulder diameter: 9 mm. Pin diameter: 5.3 mm	Rotation speed: 1100 to 1700 rpm. Shoulder plunge: 2.5 mm	The presence of defects such as partial bonding, bonding ligament and hook are observed at all welds interface	[72]
Al-Mg-Si wrought Alloy (3 mm)	Shoulder diameter: 9 mm. Clamping ring diameter: 17 mm. Pin diameter: 6 mm	Rotation speed: 1800, 2400, 3000 rpm' Plunge depth: 3, 3.4, 3.8 mm.	The hook height and welded area play important roles in the mechanical strength of produced joints.	[73]
AA7074-T6 (1.6 and 0.8 mm)		Rotation speed: 2000–2800 rpm. Dwell time: 1.5–3.5 s. Plunge depth: 1.5–1.9 mm.	The increase of welding time beneficially influencing the shear strength	[74]
AA2024-T3 (1.6 mm)	H13 steel. Shoulder diameter: 14 mm. Pin diameter: 5 mm. Pin length: 2.4 mm	Rotation speed: 630, 1000 and 1600 rpm. Shoulder plunge depth: 0.3, 0.5 and 0.7 mm. Dwell time: 5 s	Maximum failure load increases with increasing tool rotation speed and the shoulder plunge depth	[75]

3.3.1 Friction Stir Spot Welding of Similar Aluminium 2xxx Series

The joining of aluminium 2xxx series has been successfully carried out using FSSW by many researchers. This section present selected study on friction stir spot welding between similar aluminium 2xxx series.

Reimann et al. [53] presented a solution for closing the termination holes or flaw repairs by using refill friction stir spot welding (RFSSW). They used a semi stationary shoulder bobbin tool friction stir welding (SSUBT-FSW) to produce high quality welds in AA2198–T8; and then they sealed the keyholes produced in

SSUBT-FSW by using RFSSW. They stated that RFSSW of AA2198–T851 was successfully used for the first time to close a keyhole produced by the SSUBT-FSSW technique. They obtained defect-free highly efficient welds. They further said that their study proves that the RFSSW technique can be used as a termination hole closure method [53]. A high sleeve force of 12 kN and 11 kN probe force was obtained for the RFSSW keyhole closure during the retracting phase of the process. The torque was principally supplied by the sleeve with a link to the plunge depth and the maximum torque of 11 Nm. The calculated resulting energy input of RFSSW was 7.36 kJ.

Furthermore, their investigation showed that at 9 mm from the center of the spot weld, the thermal cycle during RFSSW keyhole closure welding with heating rates is 75 °C and the maximum temperature was 333 °C. Additionally, the exposure time to high temperatures for RFSSW keyhole closure welds is a bit longer than in the SSUBT-FSW welds [53]. While performing RFSSW keyhole closure, welds in an SSUBT-FSW weld seam, the overall mechanical properties are driven by the higher thermal imprint of RFSSW.

On the other hand, the analysis of the microstructure exhibited flawless welds holding typical microstructural structures for single SSUBT-FSW and RFSSW joints.

However, when the processes are combined to apply a keyhole closure technique, remnants of the SSUBT-FSW stir zone microstructure are perceived surrounding the lower parts of RFSSW joint spots [53]. As for the mechanical properties of the closed keyholes obtained by using RFSSW in SSUBT-FSW joints; they are similar to the performance of RFSSW keyhole closure welds in the parent material. They achieved efficiencies of 67%, 57% and 78% for hardness, yield strength and ultimate tensile strength, respectively [53].

Swept friction stir spot welding of alclad AA2024-T3 (cladded with AA1230) was carried out [55]. Figure 3.9a illustrates a cross section along the symmetry plane of a swept friction stir spot weld before testing. In Fig. 3.9b shows a close view of region I where relatively coarse grains are seen in the parent material. On the other hand, Fig. 3.9c illustrates a close view of region II where fine grains with several AA1230 fragments in the SZ. Figure 3.9d, e displays the magnified view of region III and IV where the joint interfacial surfaces become cracks and then gradually disappear inside the SZ.

Li et al. [62] used a probeless tool to friction stir spot weld 1.8 mm thick AA2198-T8 sheets. They investigated the relationship between the morphology of the stir zone and the mechanical properties of the probeless friction stir spot welded (P-FSSW) AA2198-T8 sheets.

The stir zone and the thermomechanically affected zone are the two distinct zones in the P-FSSWed joint and respectively contained fine recrystallized and highly deformed grains [62].

On the other hand, the hook angle strongly affected the shear tensile strength; and the maximum shear tensile strength was achieved when the hook angle is around 90° [62].

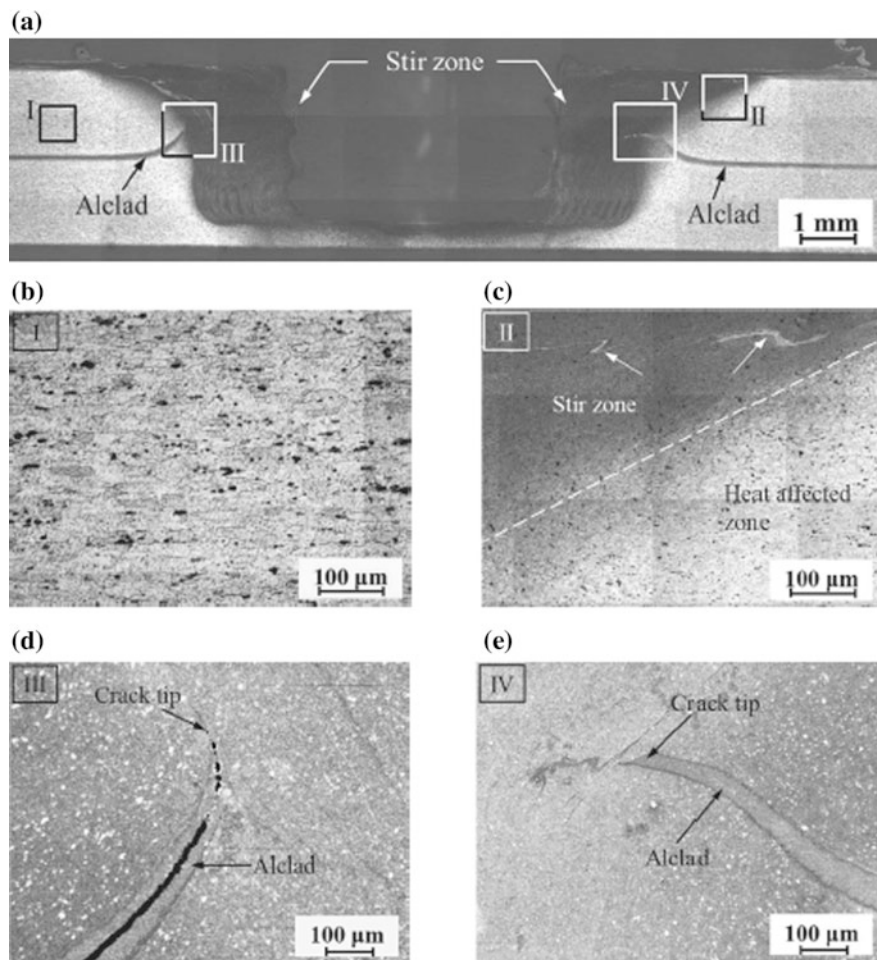


Fig. 3.9 Shows **a** the micrograph of a cross section along the symmetry plane of a swept friction stir spot weld of Alclad AA2024-T3, **b** a close view of region I, **c** a close view of region II, **d** a close view of region III, and **e** a close view of region IV [55]. Reprinted with permission from Elsevier

Furthermore, the hook defect morphology substantially affected the fracture mode, which is determined by the ratios hook/shoulder diameter and the hook height/sheet thickness. They proposed a phenomenological model to describe the morphology of P-FSSWed joints [62]. They further maintained that, according to the model, the actual stir zone (SZ) is within an ellipse, which can be determined by the ratios SZ/shoulder diameter and the triangle height/stir zone depth. Furthermore, the dwell time and the rotation speed significantly affect the SZ/shoulder diameter and the triangle height/stir zone depth, which respectively approached 0.9 and 2.4 mm; whereas the SZ edge angle approached 45° .

This is taken to be due to the material extrusion of SZ in a path along the surrounding “cold” metal, which is to be found around the joint interface [62].

Friction stir spot welding of AA 2024-T3 (1.6 mm thick) was conducted; and the effects of the rotation speed and the tool shoulder penetration depth on surface appearance, macrostructure, temperature profile, maximum failure load and failure modes were investigated [75].

It was found that, the surface appearance of the produced joints was more affected by the shoulder penetration depth more than the tool rotation speed at the bottom surface [75].

On the other hand, the tool rotation speed and the shoulder penetration depth significantly affected the stir zone (SZ) area. Whereas, the maximum failure load increased with the increment of the tool rotation speed and the tool shoulder penetration depth; nonetheless, the shoulder penetration depth had more of an effect than the rotation speed. Furthermore, two different failure modes were observed under tensile shear loadings, namely: the shear fracture mode and the tensile shear fracture mode [75].

3.3.2 Friction Stir Spot Welding of Similar Aluminium 5xxx Series

This section presents selected studies conducted by various researchers on the joining of 5xxx series using friction stir spot welding technique. The microstructure evolution and mechanical properties of selected studies are presented.

Rana et al. [7], performed friction stir spot welding of AA5052-H32/HDPE/AA5052-H32 sandwich sheets, using six different rotation speeds to evaluate the optimum range. They found that the optimum rotation speed is 1800 rpm and beyond; and the sandwich sheets exhibited good mechanical properties. They observed the fully development of two hooks in sandwich sheets; whereas only one hook was seen in the case of the bimetallic sheets after FSSW. The geometries of the hook changed with the rotation speed; and this ultimately affects the weld strength.

The improvement in the mechanical properties was due to the presence of a larger hook width and smaller hook height at higher tool rotation speeds [7]. When compared to the bimetallic sheet, the lesser peak temperature of the sandwiched sheets suggested that a part of the heat generated is consumed for the melting of the polymer layer. On the other hand, the sandwiched sheet displayed finer grains, when compared with the bimetallic sheet; and this was due to lower peak temperatures; while the grain size increases with increases in the rotation speed, due to larger heat generation [7].

They further said that the presence of the polymer has deteriorated the joint's performance; and that was seen from the lap shear, cross-tension and peel tests. Nevertheless, at a higher rotation speed of 1800 rpm, the performance of the

sandwiched sheet was closer to that of the bimetallic sheet. But for uniaxial tensile test, higher strength and extension at the failure for the sandwiched sheet was better than that of the bimetallic sheet [7]. As for the failure modes, a partial nugget failure and nugget pull out were the two failure modes most observed in the FSSW of the sandwiched sheets.

In another study, Zhang et al. [58], used normal FSSW and walking FSSW to join AA 5052-H112 sheets (1 mm thick). They investigated the effect of the rotation speed and the dwell time on the microstructure and the mechanical properties.

The increase of the rotation speed resulted in the growth of coarser microstructural morphology. In addition, no lower sheet material beneath the hook flowed upward into the upper sheet [58].

They observed a softening in the welds and the minimum hardness of 19.2 HV was obtained; and this is equal to 45.7% that of the parent material is recorded in the heat affected zone. While the hardness in the thermomechanically affected zone and the stir zone improved due to the recrystallization, which exhibited a W-shaped hardness distribution appearance.

The joints' strength decreased with the increment of rotation speed and the strength was almost independent of the tool dwell times. The shear tensile strength and the cross tension strength at 1541 rpm reached the maximum of 2847.7 N and 902.1 N, corresponding to the dwell time of 5 s and 15 s. They noticed a slight improvement in the strength for the welds produced by using walking FSSW compared to normal FSSW.

They observed two different fracture modes for both shear tensile and cross-tension loadings. Shear fracture and shear tensile mixed fracture were observed under shear tensile loadings; while nugget debonding and pull out for cross tension loadings was observed.

An in the case of walking FSSW, the fracture mode is only associated with the type of the external loadings rather than the rotation speed and the dwell time [58].

Xu et al. [64], used refill friction stir spot welding (RFSSW) to join AA5083-O (2 mm thick). The effect of welding process parameters on the microstructure and the mechanical properties of the produced welds were investigated. Defects, including void and incomplete refilling, were observed when the sheets were joined without surface indentation. The defects can be eliminated when a 0.3 mm joint surface indentation by the pin and the sleeve is used.

In different areas of the produced joints, the distribution of the phase exhibited many differences; and the main secondary phases for the AA5083-O are Al_3Mg_2 phase and the $\text{Al}_6(\text{MnFe})$ phase. The microhardness in the stir zone was higher than that of the parent material, due to the grain refining. Furthermore, the microhardness of the joint gradually decreased with the increment of the weld heat input.

On the other hand, Xu et al. [64] said that the Box–Behnken experimental design method can be effectively used to predict the link between the welding parameter and the lap shear properties.

While using the rotation speed of 2300 rpm, the plunge depth of 2.4 mm and the refilling time of 3.5 s, the optimum failure load of 7.72 kN was obtained. They also

observed, three fracture modes, namely: the shear fracture mode, the shear-plug fracture mode and the plug fracture mode; and these fracture modes were linked to the hook defect [64].

Figure 3.10 displays the microstructure of RFSSW in different weld regions using 5083-O sheets as base material [64]. Figure 3.10a shows the dissolution of some secondary phases in the HAZ due to the heat cycle during the welding process. This resulted in the reduction of the quantity of secondary phases in the heat affected zone. Furthermore, the size and the quantity of the secondary particles are much smaller than those of the parent material and the heat affected zone and this was due to both heat cycle and mechanical stirring during the welding process [64]. After the completion of dynamic recrystallization, high number of secondary phases are observed in the SZ (Fig. 3.10b) when compared with the sleeve affected zone (SAZ) (Fig. 3.10c). Furthermore, more secondary phases particles are observed in the pin affected zone (PAZ) (Fig. 3.10d).

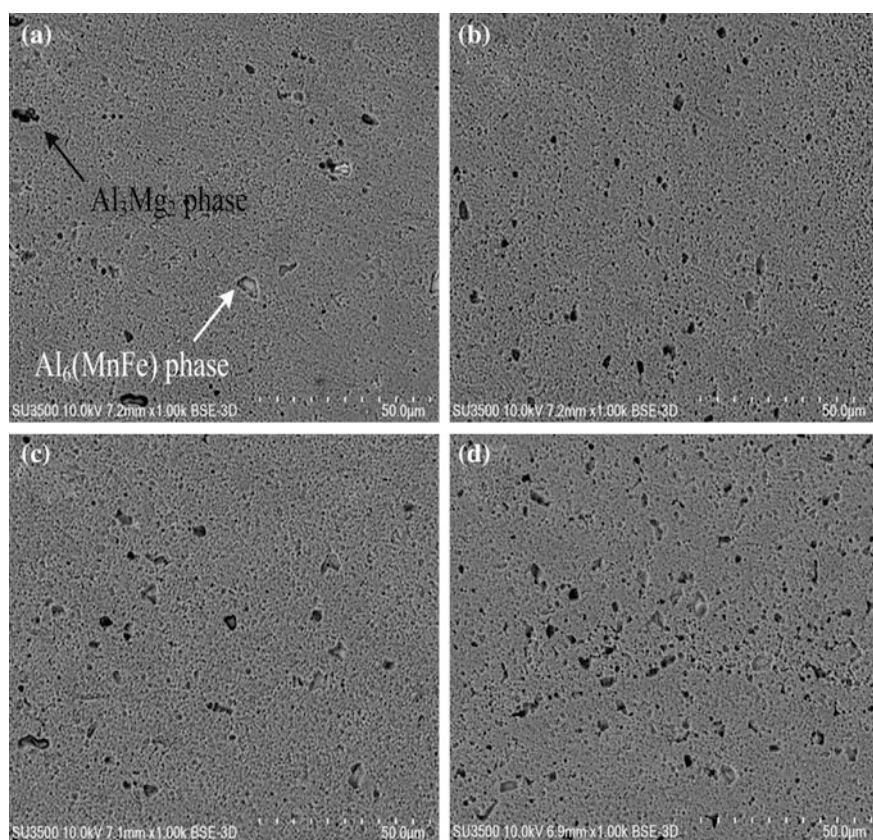


Fig. 3.10 Displays secondary phases in various areas: **a** heat affected zone, **b** thermomechanically affected zone and **c** sleeve affected zone and **d** pin affected zone [64]. Reprinted with permission from Elsevier

In the same study, Fig. 3.11 displays the microhardness profiles of the welds using different welding process parameters. It can be seen in Fig. 3.11a that the microhardness values are not exactly symmetrical with respect the weld center. Figure 3.11b shows that with the increment of the rotation speed, a decrease in the microhardness is observed. While the microhardness variation of the produced welds using various refilling time (Fig. 3.11c, d). It was further said that similar to the joint produced using different rotation speeds, the microhardness profile values are affected by the heat input during the joining process. In Fig. 3.11d, it can be seen that the microhardness in the stir zone is almost equal to the microhardness measured in the parent material [64].

3.3.3 Friction Stir Spot Welding of Similar Aluminium 6xxx Series

This section presents some studies carried out by various researchers on the welding of AA6xxx series using friction stir spot welding technique.

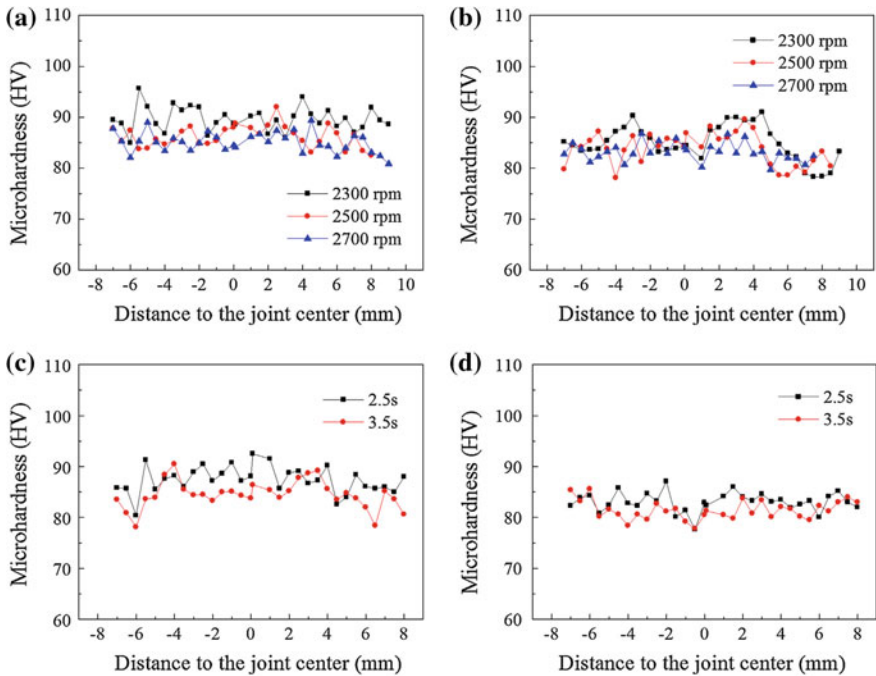


Fig. 3.11 Shows the microhardness profile of the RFSS Weld, **a** top sheet, **b** bottom sheet using different rotation speeds, **c** top sheet, **d** bottom sheet using different refilling time [64]. Reprinted with permission from Elsevier

In this study, friction stir spot welding with refilling by the friction forming process (FSSW-FFP) was successfully modified by using a filler plate. The parent material used in this study is 2 mm thick AA 6061-T6 sheets [63].

The formed keyholes are overcome by adopting the new refilling technique. And that led to the improvement of the mechanical properties of the produced joint.

They observed grain refinement in the stir zone and the thermomechanically affected zone areas; and this is due to dynamic recrystallization.

The hardness profile exhibited a W shape for both processes, namely, conventional FSSW and FSSW-FFP; and a minimum hardness value was identified in the heat affected zone [63].

A better static shear tensile strength was obtained for the FSSW-FFP samples compared to those of the conventional FSSW samples. The absence of the keyhole and the presence of extra material from the filler plate addition in the FSSW-FFP method was responsible for the increase in static shear strength for the joint produced by using a FSSW-FFP technique [63].

At the rotation speed of 1800 rpm, a static shear strength of 9520 N was obtained for the FSSW-FFP, which was 38.5% higher than that of the conventional FSSW process.

In the conventional FSSW procedure, the shear fracture mode was observed for the weld samples at all rotation speeds. Whereas, three different fracture modes were observed in FSSW-FFP samples (circumferential fracture, nugget pull out and base material fracture). And the crack initiation started always in partially bonded region in all the fracture modes.

The microstructural evolution, the texture and the mechanical properties during the refill friction stir spot welding (RFSSW) of the AA6061-T6 alloy was investigated by Cao et al. [65].

It was observed that the microstructural evolution was governed by grain subdivision and geometric dynamic recrystallization during the RFSSW, but also by the static recrystallization involvement.

Shear texture formation was governed by the shear generated by the rotation of the tool shoulder inner wall. At the tool shoulder boundary, the shear texture formation was linked with the material flow when material was discharged from the bottom of the thread on the rotating shoulder [65].

Furthermore, a maximum of 9757 N tensile shear strength was obtained, which was higher than those obtained using FSSW and the shear strength of refill friction stir spot welds principally depended on the size of the hook defect [65].

A6061-T6 sheets (2 mm thick) were used to produce the joints by FSSW [71]. The obtained results revealed that the shoulder plunging speed had an obvious effect on the hook geometry and the tensile shear load; however, the pin's plunging speed had almost no effect on the hook geometry. Song et al. [71] observed that the tensile shear load and the fracture mode were determined by the effective bond width and the effective sheet thickness used to describe the hook geometry [71].

Furthermore, the fracture mode was governed mainly by the hook geometry; and the weld with a small effective sheet thickness failed in a shear tensile mixed

fracture; whereas the joint with a small effective weld width failed in a shear fracture [71].

The largest shear tensile load was obtained when the joint failed in the shear tensile mixed fracture.

3.3.4 Friction Stir Spot Welding of Similar Aluminium 7xxx Series

Aluminium 7xxx series are widely used in many industries include in aerospace and the alloys are high strength age hardenable. Therefore, this section present few selected studies where friction stir spot welding technique was successfully used to join AA7xxx series.

Shen et al. [11] investigated the microstructure and the mechanical properties of AA7075-T6 welds joined by refill friction stir spot welding (RFSSW).

They successfully refilled the keyhole of the weld; and the microstructure exhibited variations in grain sizes, width and the thickness. Furthermore, they observed that weld defects include hooks, voids, the bonding ligament and incomplete refill were linked to the material flow [11]. Figure 3.12 illustrates the microstructures on longitudinal section of RFSS Weld produced at the rotation speed of 1200 rpm and dwell time of 4 s.

The W shaped appearance of the microhardness profile was observed. Additionally, the hardness gradually decreased in the HAZ towards the center of the joint and reached the minimum value in the boundary of the HAZ and TMAZ [11]. Figure 3.13 displays the hardness profiles of the welds measured in the mid thickness of the top sheet.

Thereafter, the hardness of the TMAZ and SZ intensely increased in the direction of the center of the weld and reached the maximum value in the vicinity of the tool pin. The obtained maximum hardness value is almost equivalent to that of the parent material's hardness value [11].

In general, the desirable mechanical properties can be achieved at lower rotation speeds and shorter duration times.

On the other hand, the shear fracture mode is observed under shear tensile loadings; whereas nugget debonding, and plug type fracture modes are observed under cross tension loadings [11]. Additionally, the fracture modes under cross tension loadings are associated with the processing parameters. Figure 3.14 depicts the shear tensile strength and the cross tension strength of the produced joint using different process parameters.

Kubit et al. [69] analyzed the effects of rotation speed, tool plunge depth and welding time on the load capacity of the RFSSW joints. The rotation speed, the tool plunge depth and the welding duration exhibited a significant influence on the welding process and the load capacity of the joint. For the welding duration ranging from 1–1.5 s, the value of the Fisher-Snedecor F statistic was below the critical

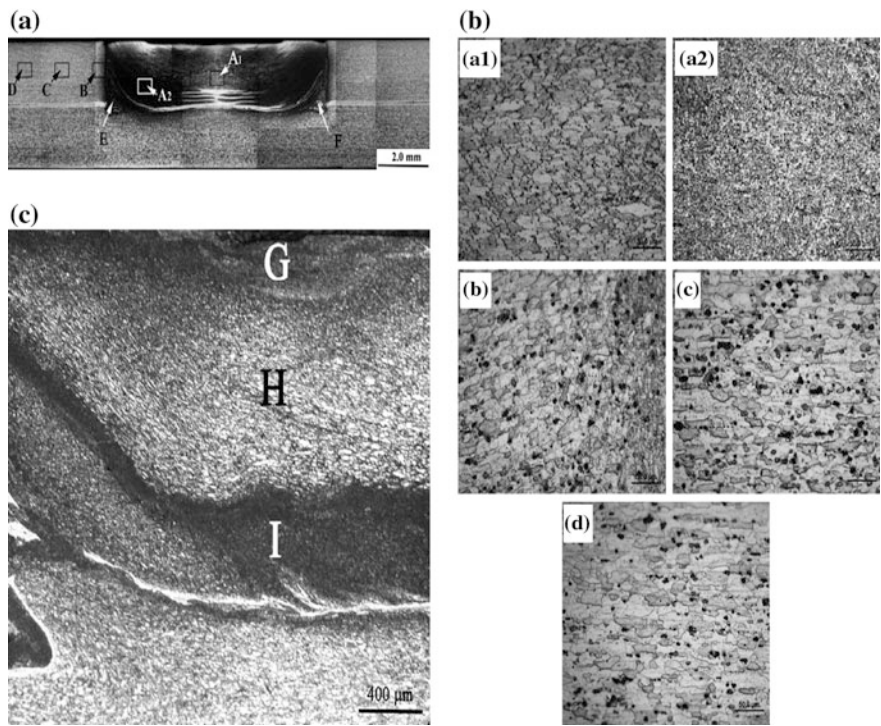


Fig. 3.12 Shows the microstructures on longitudinal section of RFSS Weld produced at the rotation speed of 1200 rpm and dwell time of 4 s, **a** cross section of weld zone, **b** magnified views of the area A1-D marked in (a), respectively and **c** grain sizes variation in the thickness direction [11]. Reprinted with permission from Elsevier

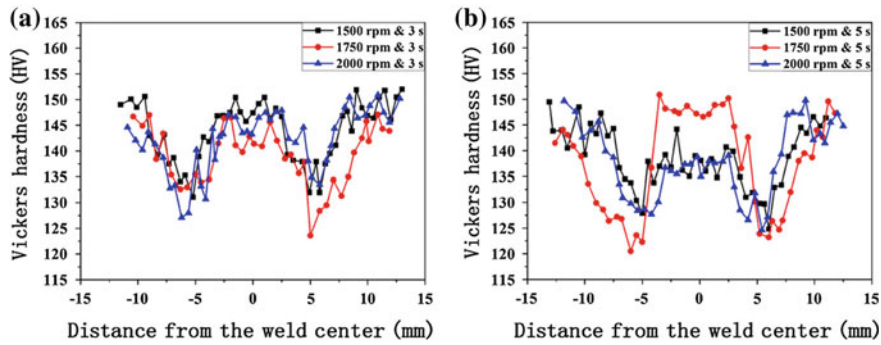


Fig. 3.13 Shows the hardness profiles of the joints in the mid thickness of the top sheet [11]. Reprinted with permission from Elsevier

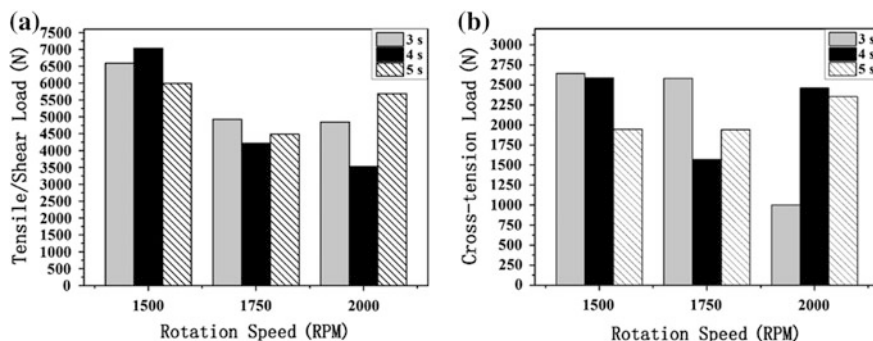


Fig. 3.14 Shows **a** the shear tensile strength and **b** the cross tension strength of the produced welds [11]. Reprinted with permission from Elsevier

value. This showed that the welding duration had no significant effect on the load capacity of the produced joint. Furthermore, the value of the tool plunge depth has an impact, not only on the load capacity, but also on the type of joint fracture in the static shear tensile test, as well. A shear fracture was observed in the case of the shear tensile test of the joints produced when using low values of tool plunge depth ranging from 54 to 57% of the lap joint thickness.

However, the plug shear fracture mode was observed for the joints produced at a tool plunge depth of 57–61.5% of the lap joint thickness. For the tool plunge depth ranging from 61.5 to 67%, the plug type fracture mode was observed. A lower load capacity characterized the welds, which exhibited the plug type fracture compared to those welds produced at lower tool plunge depths [69]. Furthermore, they also found that alclad between the upper and the lower sheets deteriorated the weld quality between the SZ and TMAZ. An intense change in the grain size in the vicinity of the shoulder's vicinity was observed; and this could lead to crack initiation. Furthermore, larger grains were observed in the weld center compared to the ones observed at the periphery of the SZ [69]. A fine grain structure was observed in the nugget zone, which indicated that recrystallization had occurred; and this was caused by both high heat and pressure [69]. They said that increasing the rotation speed and the welding duration time led to an increment of the load capacity and the temperature inside the weld.

3.4 Friction Stir Welding of Similar Copper

A summary of studies conducted on friction stir welding of similar copper materials is presented in this section. Table 3.3 depicts an overview of the process parameters, the tool geometries and some conclusion on FSW of similar copper materials. Various research studies have been carried out to join similar copper as base materials. Most of the studies focused on the effect of the process parameters on the

Table 3.3 Depicts a summary of the tool properties, the process parameters and a remark for similar copper friction stir welds

Parent material and material thickness	Tool material and shape	Process parameters	Remark	References
Commercially pure Cu (2 mm).	WC-based alloy tools. Concave shoulder diameter: 12 mm. Unthreaded pin diameter: 4 mm. Pin length: 2 mm	Rotation speed: from 400 to 1200 rpm. Welding speed: from 200 to 800 mm/min	The increase of applied load has more influence on the microstructure refinement than the decrease of rotation speed	[13]
Copper (4 mm).	T6 grade of tungsten high speed steel (Shoulder). C-2 grade of sintered carbide (pin). Concave shoulder diameter: 17.8 mm. Frustum non-threaded pin length: 3.5 mm. Pin diameter: bottom: 6.5 mm, top: 5.5 mm	Rotation speed: 710 rpm. Welding speed: 40 mm/min	In each rotation of the tool, the four formed different zones are merged and one new layer of weld is formed	[14]
Cold rolled copper (6 mm)	M2 high speed tool steel of 55 HRC. Shoulder diameter: 24 mm. Pin diameter: 18 mm. Pin length: 5.4 mm	Welding speed: 30, 45 mm/min. Rotation speed: 1300, 1400, 1600 rpm	The average hardness of the nugget zone was lower than the parent material	[15]
OFHC copper (2 mm)	H13 tool steel. Pin diameter: 3 mm. Shoulder Diameter: 12 mm. Pin length: 1.75 mm	Rotation speed: 400, 700, 900 rpm. Welding Speed: 100, 200, 300, 400 mm/min	Defect-free welds can be produced using various FSW conditions except for very low heat input conditions	[16]
Commercially pure copper (10 mm)	H13 steel tool. Shoulder diameter: 30 mm. and a Square pin equivalent diameter: 9 mm. Pin length: 9.7 mm	Rotation speed: 700 rpm. Welding speed: 50, 100, 150, 200 mm/min.	Higher welding speeds caused lower heat input and peak temperature and therefore finer grains	[17]
Copper alloy (4 mm)	Tungsten carbide (WC) pin. High-speed steel (HSS-T1) shoulder. Concave shoulder diameter: 17.8 mm.	Set 1: Rotation speed: 500, 630 rpm. Welding speed: 20, 50.4 mm/min. Set 2:	The increase of welding speed or the decrease of rotation speed leads to increase in the weld strength and	[76]

(continued)

Table 3.3 (continued)

Parent material and material thickness	Tool material and shape	Process parameters	Remark	References
	Non threaded pin length: 3.5 mm. Pin diameter: bottom: 6.5 mm, top: 5.5 mm	Rotation speed: 500, 630, 710 rpm. Welding speed: 20, 37.8, 40, 50.4, 56, 63 mm/min	decrease in the elongation	
Commercially pure copper-1/2H (5 mm)	Shoulder diameter: 20 mm. Cylindrical threaded pin diameter: 6 mm. Pin length: 4.7 mm	Set 1 Rotation speed: 400, 600, 800 rpm. Welding speed: 50 mm/min. Set 2 Rotation speed: 800 rpm. Welding speed: 50, 100, 200 mm/min	The ultimate tensile strength was similar to that of the base material under several heat input conditions	[18]
Copper (5 mm)	Shoulder diameter: 20 mm. Pin diameter: 8 mm. Pin length: 4.7 mm	Rotation speed: 500, 710 rpm. Welding speed: 56, 112 mm/min	The properties of the SZ improved with the increment of weld passes	[19]
Commercially Cu (3 mm)	High-speed tool steel (AISI H13). Bohler tool steel (K390). Unthreaded tool	Rotation speed: 1,200 rpm. Welding speed: 50,100 mm/min	Using of cryotreatment increased the wear resistance of the two tools	[20]
Pure copper (5 mm)	Not provided	Welding speed: 20, 28, 40 mm/min. Rotation speed: 355, 500 rpm	SEM micrographs exhibited that friction stir welding process led to reduction of the grain size of parent material	[21]
Cu alloy (2 mm)	H13 hot work steel. Shoulder diameter: 12 mm. Pin diameter: 3 mm. Pin length: 1.75 mm	Rotation speed: 400, 800 rpm. Welding speed: 100, 400 mm/min	The rotation speed and welding speed affect the grains sizes	[22]

resulting microstructure and on the mechanical properties. It is expected that the successful joining of similar copper could enhance the usage of copper/copper alloys structures for numerous applications in various industries.

Researchers have successfully friction stir welded similar copper over the years; and more needs to be done to optimize the process. It was observed in the studies

carried out, that pure copper is the most used parent material. More studies need to be undertaken on copper alloys to further broaden the understanding of how copper alloys behave when they are friction stir welded.

Commercially pure copper sheets of 2 mm were joined by using the friction stir welding technique with different process parameters, including rotation speed, welding speed and the applied load [13].

The microstructure in SZ and across the cross section perpendicular to the joining direction were characterized and the mechanical properties of the produced joints were assessed.

Sun and Fujii [13] stated that at a constant welding speed (650 mm/min), the average grain size in the SZ can be refined to about $9.8\text{ }\mu\text{m}$ by a decrease of the applied load to 1000 kg. While, the grain size can be further refined to about $3.8\text{ }\mu\text{m}$ by increasing the applied load (1500 kg). And they concluded that, increasing the applied load has much more influence than the reduction of rotation speed on the microstructure refinement [13].

Figure 3.15 depicts the TEM images of the microstructure of the SZ observed under different applied loads, as well as the microstructure of the parent material. It can be seen that twin structures can be easily be observed for the sample joined at 1000 kg/800 rpm and 1000 kg/900 rpm; but they are somewhat difficult to be found in the sample joined at 1500 kg/400 rpm, where the joint displays much smaller grains. Furthermore, the twin structure was also found in the parent material, but in smaller quantities and of similar twin layer width [13].

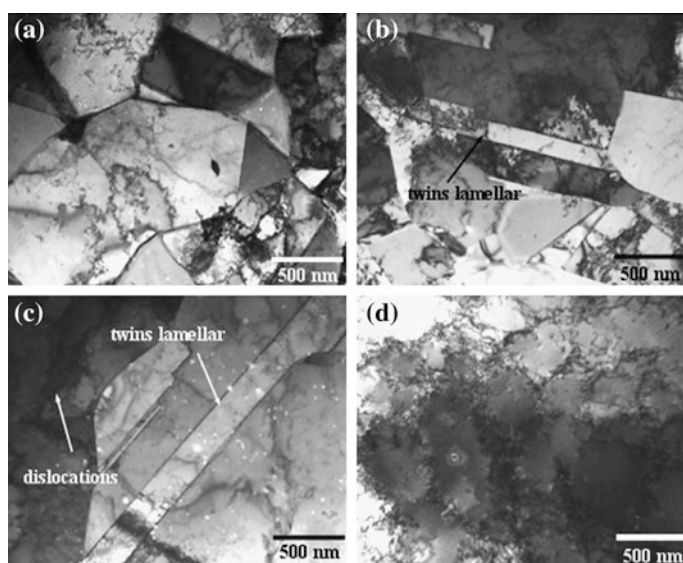


Fig. 3.15 Shows the TEM micrographs of the microstructure in the SZ joined at different conditions: **a** parent material, **b** 1000 kg/800 rpm; **c** 1000 kg/900 rpm; **d** 1500 kg/400 rpm [13]. Reprinted with permission from Elsevier

As for the mechanical properties, the joints produced when using an applied load of 1000 and 1200 kg displayed lower hardness values in the SZ than the one obtained for the parent material (100 HV) and that resulted in the joints fracturing in the SZ during the tensile tests. Nevertheless, the increase of the applied load to 1500 kg resulted in the increment of the hardness to about 105 HV; and this resulted in the joint finally being fractured from the parent material [13].

Figure 3.16 depicts the hardness profile on the centerline of the cross section of the SZ under various welding conditions. It can be seen in Fig. 3.16, that for welds produced under higher applied loads like 1200 and 1500 kg, the TMAZ can be easily distinguished, due to the higher hardness value. Furthermore, the joints produced when using 1000 kg, the HAZ displayed lower hardness values [13].

They further said that the process window was attained and sound welds can be obtained under welding speeds ranging from 200 to 800 mm/min, rotation speeds ranging from 400 to 1150 rpm and applied loads ranging from 1000 to 1500 kg [13].

Teimurnezhad et al. [14] friction stir welded copper alloy in a flat-butt configuration. They said that four distinguishable zones, namely: the surface layer, the surface material, in situ material and TMAZ (retreating side) were developed in the SZ. Furthermore, in each rotation of the tool, all these mentioned zones are merged and one new layer of the weld is formed.

The formed surface layer came from the top surface of the sheets; and it originated from material close to the edge of the tool shoulder. The microstructure

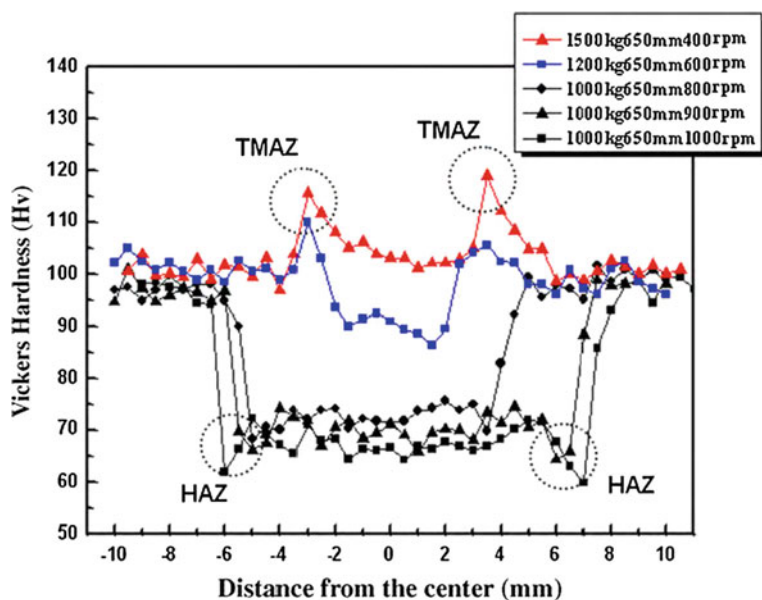


Fig. 3.16 Shows the hardness profile of the friction stir welded samples under various welding conditions [13]. Reprinted with permission from Elsevier

depicts a gradual variation of the grain size from the base material to the stir zone on the retreating side, and abruptly on the advancing side [14].

A 5 mm thick copper alloy sheets were friction stir welded to optimize the friction stir welding parameters [77]. They successfully produced the joints by using four different types of tool, namely: cylindrical, cylindrical threaded, taper and taper threaded tools.

A rotation speed of 900 rpm using cylindrical threaded tool exhibited the maximum yield strength; this is because the higher thermal conductivity of copper and the heat generated by cylindrical tools is enough even though it was less than the heat generated by the taper tools [77].

The microstructure in the NZ exhibited fine equiaxed grains (1–2 μm); whereas elongated grains (20–30 μm) were found in the parent material. The hardness measured in the nugget zone was lower than that of the parent material; and this was because of the annealing effect during the welding process [15]. The obtained hardness of the parent material ranged from 120 and 125 VHN; but values ranging from 85–92 VHN were measured in the nugget zone.

On the other hand, the tensile strength and the maximum joint efficiency obtained were, respectively, 242 MPa and 73%.

Furthermore, the tensile fracture took place in the heat affected zone on the advancing side of the weld; and this was due to the presence of few coarse grains in that region. In a similar way, the variations of the measured hardness showed a relative correspondence to the fracture location [15]. The bending test performed on the joints showed that, the face bend of the welded plate withstood a maximum load of 4.5 kN; and the cracks were seen on the retreating side of the heat affected zone [15].

OFHC copper sheets of 2 mm thick were employed as the parent material; and they were friction stir welded using various welding speeds (100, 200, 300, and 400 mm/min) and rotation speeds (400, 700, 900 rpm). A comparison between the numerical and the experimental results was carried out; and this showed that the model developed was basically accurate [16]. A thermal model was developed to predict the grain size and the resulting mechanical properties of the produced welds.

Heidarzadeh et al. [16] stated that defect-free welds can be produced at different FSW conditions (rotation speed, welding speed) except for very low heat input conditions, including 400 rpm/200 mm/min, 400 rpm/300 mm/min, and 400 rpm/400 mm/min [16].

Higher rotation speeds and lower welding speeds resulted in higher peak temperature, and therefore higher grain size. This showed that the peak temperature was the dominant factor controlling the grain size of the welds.

On the other hand, the hardness distribution in the stir zone follows the Hall-Petch relationship. Finer grain sizes lead to higher hardness of the joints. While, the obtained numerical results are in agreement with experimental results for defect-free joints [16]. And the ultimate tensile strength of the joints increases with decreasing grain size.

Additionally, higher rotation speeds, lower welding speeds, or higher heat input, cause an increase in the tensile elongation of the produced weld. The fractured

surfaces of the welds produced at higher heat input exhibited more dimples and fewer large voids compared to the welds produced at lower heat input conditions [16].

Azizi et al. [17] joined 10 mm thick pure copper sheets using FSW at a constant rotational speed of 700 rpm and different welding speeds, namely: 50, 100, 150, and 200 mm/min. They found that higher welding speeds resulted in lower heat input and peak temperatures and hence finer grains. The peak temperature was the dominant factor controlling the grain size in the stir zone; and higher welding speeds resulted in obtaining finer grain sizes in the stir zone. This is because of lower heat generation and peak temperature, and hence higher values of the Zener-Hollomon parameter [17]. Additionally, higher welding speeds lead to the formation of defects in the joints. They further found that when increasing the welding speed, the ultimate tensile strength increases to a maximum value; and it then decreases. Similarly, the increase in the welding speed resulted in the increase of hardness and a decrease in elongation.

On the other hand, the welds produced at lower welding speeds revealed more ductile fracture mode [17]. 4 mm thick copper sheets were butt welded along the rolling direction in a flat position, using two different welding parameters [76]. They analyzed the formation of an onion ring structure on the transverse cross section and consecutive quasi-circles on the longitudinal cross section. On the transverse cross section of the joint, the edge of the layers appeared like concentric quasi-circles; and these circles are called onion rings. The onion ring structure was produced by a non threaded tool pin. Pashazadeh et al. [76] said that the crumbly stirred materials are pushed and squeezed into the vacant region on the back of the tool pin by rotation and the movement of the welding tool. They further said that, each layer of these materials is formed during one tool rotation. Because of the pressure and heat; the materials penetrate into retreating and advancing edges, and also into each other [76]. The overall structure of the layers are similar to the pin geometry; but because of the variation in pressure and temperature in a number of regions, distortions occur on the surface of the layers; and the materials with more temperature and pressure experience more retreat [76]. As for the mechanical properties, Pashazadeh et al. [76], stated that when the welding speed (translational) increases, or when the rotation speed is decreased, the weld strength increases and the elongation decreases. As for the hardness profile, they said that the core of the onion ring shaped structure at two points close to the joint surface and weld root displayed maximum hardness [76].

In the heat affected zone, the lower hardness values were measured on the retreating side when compared with those obtained on the advancing side.

Xue et al. [18] produced defect free welds of 5 mm thick pure copper sheets under relatively low heat input conditions (rotation speed of 400–800 rpm and welding speed of 50–200 mm/min). They observed that the grain size in the stir zone under various parameters was smaller than that of the base material; and it decreased when the weld heat input settings were decreased. Furthermore, a higher percentage of the high-angle grain boundaries (HAGB) ranging from 90.2 to 94.5% was seen in the stir zone, and the percentage of the HAGB increases with the increment of the weld heat input.

On the other hand, when the heat input is decreased, the fraction of the twins and the number of the twin lamellas were reduced. Furthermore, the variation of heat input affected the grain structure in different regions. For example, in the TMAZ equiaxed recrystallized grain structure was observed under high heat input (600 and 800 rpm for 50 mm/min). But when the heat input is decreased, elongated grains were observed in the TMAZ. In the heat affected zone, the grains were slightly coarsened when compared with the grain structure found in the base material [18]. When the welding conditions were varied, not much change in the grain size was observed in the stir zone.

Figure 3.17 displays the microstructure of the parent material and the stir zone, using various welding parameters [18].

On the other hand, when the welds are joined under higher heat input settings (600 rpm for 50 mm/min and 800 rpm for 50 to 200 mm/min), the measured hardness values of the stir zone were lower than those of the parent material, while

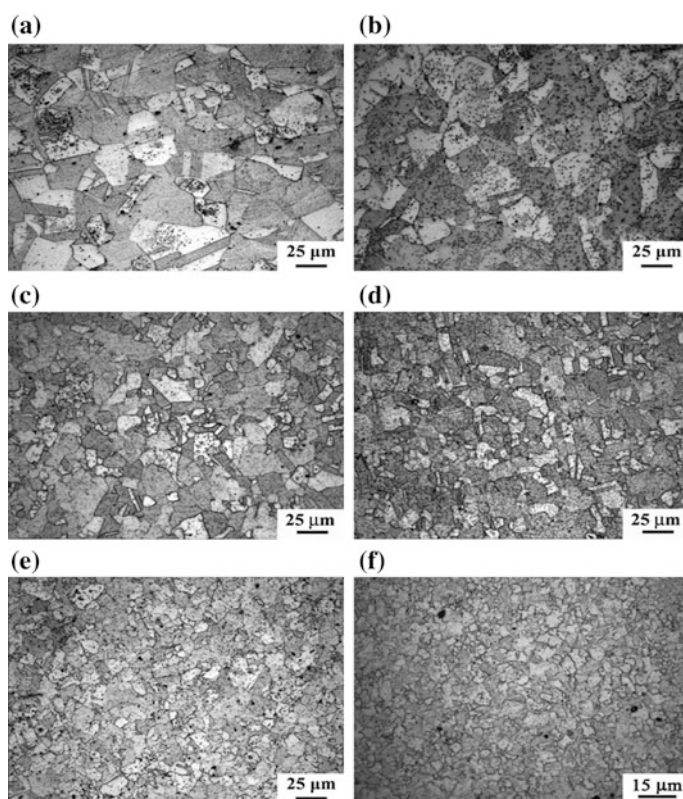


Fig. 3.17 Displays the microstructures of **a** parent material and stir zone at welding speed of **b** 50 mm/min, **c** 100 mm/min, and **d** 200 mm/min (rotation rate: 800 rpm) and rotation speed of **e** 600 rpm and **f** 400 rpm (welding speed: 50 mm/min) [18]. Reprinted with permission from Springer

at a very low heat input setting (400 rpm for 50 mm/min), the measured hardness value of the stir zone was higher than that of the parent material [18]. Furthermore, when the heat input settings were decreased, the hardness in the stir zone increased and the width of the low hardness region narrowed [18].

Figure 3.18 shows the hardness profiles measured along the centerline across the stir zone of the FSW copper joints when using different welding parameters [18].

As for the ultimate tensile strength, the fracture occurred in the heat affected zones for all the produced joints; and the ultimate tensile strength was similar to that of the parent material [18].

Nia and Shirazi [19], investigated the effects of various welding parameters, including the rotation and the welding speeds of the tool on the microstructural and mechanical properties of FS Welded copper sheets (5 mm thick).

The combination of rotation speeds (500 and 700 rpm) and welding speeds (56 and 112 mm/min) were found to be appropriate conditions for producing defect free welds on the copper samples.

Nia and Shirazi [19], said that the rotation speed and welding speed have a large effect on the amount of heat transferred to the samples, which in turn has a direct impact on the mechanical and microstructural properties of the welded samples.

For those produced at 710 rpm and 56 mm/min, the grain size in the HAZ increased by about 35.3% compared to the grain size of the parent material; while when 500 rpm and 112 mm/min were used, the grain size increased by only by 5.8%. This resulted in the reduction of tensile strength (710 rpm and 56 mm/min) by about 29%. Nevertheless, when 500 rpm and 112 mm/min are used, a 1.5% decrease in tensile strength can be observed [19]. For all the welds produced in this study by using different process parameters, the weakest welding region was the HAZ, where the lower hardness values were measured and where fracture occurred for tensile strength tests [19].

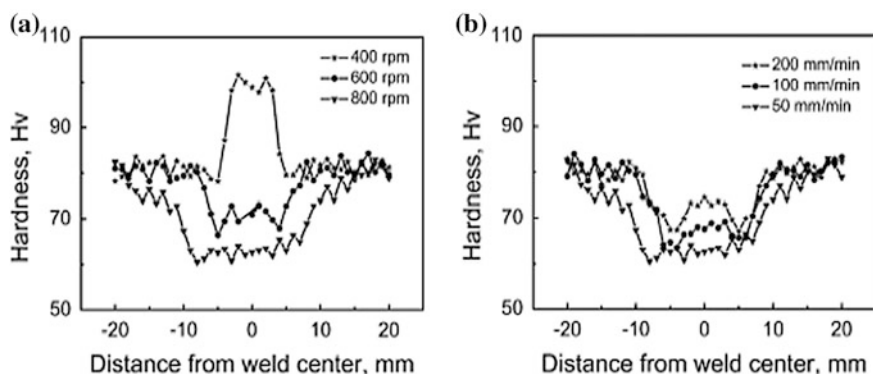


Fig. 3.18 Shows the hardness profiles measured in cross sections of joints produced at **a** different rotation speeds (welding speed: 50 mm/min) and **b** different welding speeds (rotation rate: 800 rpm, the advancing side is on the right side) [18]. Reprinted with permission from Springer

They also said that even if using a higher number of welding passes would improve the properties of the SZ, they would cause more weaknesses in the HAZ; and this would have a negative effect on the mechanical properties of the produced welds. They recommended that instead of increasing the number of passes, the joining process should have been conducted at lower temperatures [19].

Surekha and Els-Botes [20] friction stir welded copper (3 mm thick) at 1200 rpm and 50, 100 mm/min with a tool tilt of 3° using various tools, including AISI H13 tool steels. They also said that Cryotreated AISI H13 steel can be used at higher heat input. They investigated the wear behavior of powder metallurgically (P/M) produced and wrought alloy tools before and after cryotreatment. They indicated that the P/M produced Bohler K390 tool steel with and without cryotreatment was superior in wear resistance compared to the wrought alloy tool; and this is because of the uniform distribution of the alloying elements and the low thermal conductivity. On the other hand, the cryotreatment of both tool steel (wrought and powder metallurgically) exhibited an increase in their wear resistance; and this was due to the conversion of retained austenite into a harder plate martensite and the formation of fine eta carbides.

The effect of friction stir welding on the electrochemical behavior of pure copper in 0.01 M borax solution (pH = 9.1) was investigated by Fattah-Alhosseini et al. [21].

The SEM micrographs presented showed that the friction stir welding technique led to a reduction of the grain size of the parent material. On the other hand, the X-Ray diffraction results showed that after using the FSW procedure, only three peaks of pure copper were observed; and this indicated the absence of unwanted phases, including oxides in the structure. The electrochemical impedance spectroscopy (EIS) demonstrated that the technique (FSW) could improve the corrosion resistance of the parent material. Additionally, the EIS measurements showed that a minimum and a maximum polarization resistance was observed for the parent material and for the joined sample (500 rpm and 28 mm/min), respectively [21].

Emami and Saeid [22] FS Welded a single-phase brass (2 mm thick) at different welding settings. Sound welds were produced except for the weld produced at 400 r/min and 300 mm/min. The microstructure in the stir zone was made of fine equiaxed grains, and their sizes decreased with an increment of the welding speed and/or a reduction of rotation speed [22]. They indicated that the observed microstructural behavior could be due to the production of the weld at a lower heat input and the dynamic recrystallization at lower peak temperatures.

Figure 3.19 displays the microstructure variation in the stir zone obtained under different process parameters [22].

Due to the variations in grain size, the hardness in the stir zone demonstrated a decrease by increasing the rotation speed and the welding speed [22]. Figure 3.20 presents the typical hardness profile along the centerline on the cross section of the joint using 800 rpm and 100 mm/min [22].

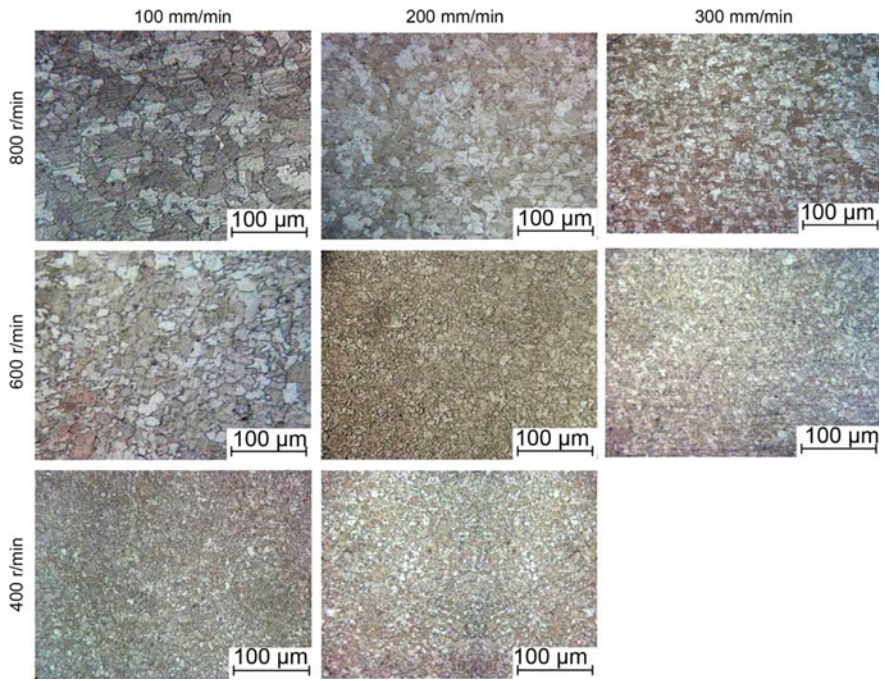
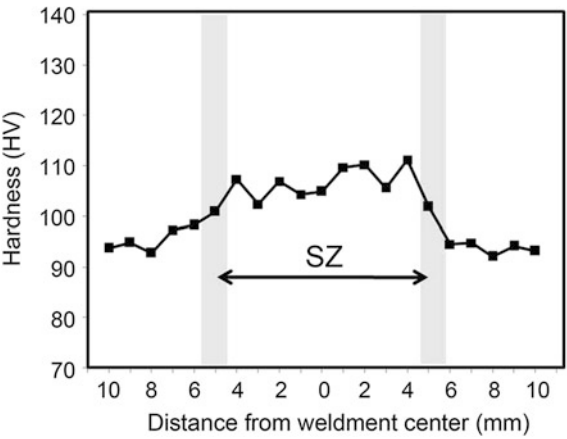


Fig. 3.19 Shows the variation in SZ microstructures at different welding conditions [22]. Reprinted with permission from Springer

Fig. 3.20 Depicts the hardness profiles in cross section of the weld [22]. Reprinted with permission from Springer



3.5 Friction Stir Spot Welding of Similar Copper Alloys

Friction stir spot welding of similar copper alloys has not received a lot of attention in the past few years. Only very few papers are available in the open literature [12, 78]. A 3 mm commercially pure copper sheets were friction stir spot welded by Akinlabi et al. [78] to characterize the produced joints by using different process parameters. In a similar study, Sanusi et al. [12], friction stir spot welded 3 mm commercially pure copper to investigate the effects of corrosion on the fabricated spot welds.

3.5.1 Microstructural Evolution and Weld Defects

In the stir zone, the formation of fine, equiaxed grains that is larger than those of the base metal and uniformly distributed, very fine strengthening precipitates was observed. This can be seen in Fig. 3.21 where the microstructures are presented for the welds produced at rotation speed of 1200 rpm (I), 1600 rpm (II) and 2000 rpm

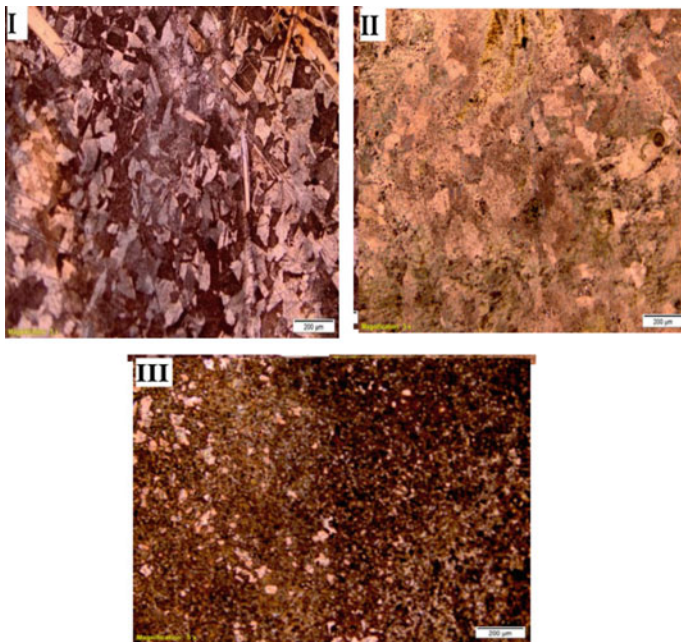


Fig. 3.21 Depicts the OM microstructures of FSSW of copper produced at 1200 rpm (I), 1600 rpm (II) and 2000 rpm (III) [78]. Reprinted with permission from Elsevier

(III) respectively [78]. Furthermore, a fully bonded region was observed in the stir zone of the produced spot welds. The grain sizes in the spot weld produced at 2000 rpm are much finer than the grain sizes observed in the spot weld produced using 1200 and 1600 rpm. This is due to dynamic recrystallization while the joining process was taking place [78]. Consequently, using the right rotation speed could enable the friction stir spot welding as a prospective technique for welding pure copper and its alloys [78].

On the other hand, Akinlabi et al. [78] observed weld defects at the edge of the welded sample and the energy dispersive spectroscopy analysis detected the presence of Ca and Mg in the welded region; and this was suspected to come from the tool wear.

Sanusi et al. [12] also joined commercially pure copper and analyzed the microstructure and then carried out corrosion tests. The different microstructures have a negative effect on the corrosion resistance of the materials. The joints produced at a rotation speed of 1200 rpm had the lowest corrosion potential and behaved worse than the welds produced at 1600 and 2000 rpm. Furthermore, similar polarization curves were observed for the spot welds produced using different rotation speeds, which is an indication that there is no significant difference in the polarization behavior between the produced samples [12].

The lower corrosion potential for the weld produced at the rotation speed of 1200 rpm could be due to the presence of residues from the tools in the joints [12]. The surface corrosion rates of the produced joints at rotation speed of 1200, 1600 and 2000 rpm were 0.0008702 mm/year, 0.0005701 mm/year and 0.0005596 mm/year, respectively. Sanusi et al. [12] concluded that the corrosion resistance of copper friction stir spot welds in 3.5% NaCl was definitely improved.

3.5.2 Mechanical Properties

The average microhardness value measured for the welds produced at 1200, 1600 and 2000 rpm was 64.3 HV, 60.2 HV and 67.2 HV, respectively [78]. And it can be seen that the spot weld produced at 2000 rpm had the highest average microhardness value. Figure 3.22 depicts the microhardness value measured from the nugget zone of the produced spot welds. In Fig. 3.22, a variation of the microhardness values was observed value; and this is attributed to the rotation speeds, the plastic deformation and the high-temperature exposure within the SZ [78]. Furthermore, the parent material exhibited higher microhardness (~ 91 HV) values compared to the

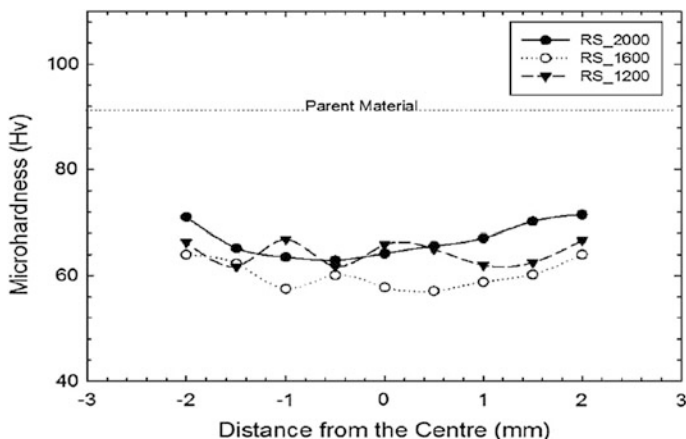


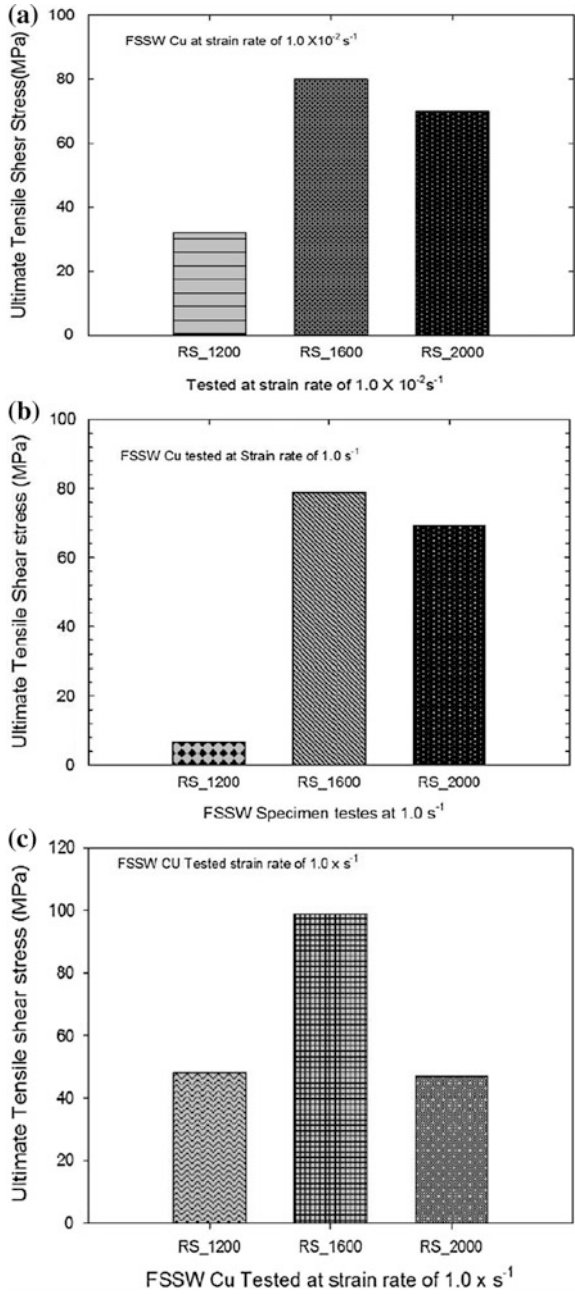
Fig. 3.22 Shows the average microhardness values of the parent material and the produced spot welds of pure copper at different rotation speeds [78]. Reprinted with permission from Elsevier

produced spot welded samples; and this decrease was attributed to the heat distortion during FSSW, which increased the density of the dislocations [78].

The ultimate tensile shear strengths at strain rate of $1.0 \times 10^{-1} \text{ s}^{-1}$ for the spot welds produced at 1200, 1600 and 2000 rpm are, respectively, 48 MPa, 99 MPa, and 47 MPa (Fig. 3.23a). While, the tensile shear strengths at the strain rate of $1.0 \times 10^{-2} \text{ s}^{-1}$ for the spot welds produced at 1200, 1600 and 2000 rpm are 32 MPa, 80.12 MPa, and 70.01 MPa, respectively (Fig. 3.23b). Furthermore, in Fig. 3.23c, the tensile shear tests result at strain rate at 1.0 s^{-1} of the produced samples are displayed. The results indicated that the tensile shear values of 6.75 MPa, 78.9 MPa, and 69.23 MPa were obtained for the spot welds produced at 1200, 1600 and 2000 rpm rotation speeds, respectively [78].

From the obtained results, Akinlabi et al. [78], stated that the tested specimens at 1200 rpm rotation speed (low) were weak and not well bonded; whereas the welds produced at a medium rotation speed (1600 rpm) had the highest strength and can be considered as the optimum rotation speed.

Fig. 3.23 Depicts the ultimate tensile shear strengths at strain rate of **a** $1.0 \times 10^{-2} \text{ s}^{-1}$, **b** $1.0 \times 10^{-1} \text{ s}^{-1}$ and **c** 1.0 s^{-1} for the spot welds produced at 1200, 1600 and 2000 rpm [12]. Reprinted with permission from Elsevier



3.6 Conclusion

Friction stir welding and friction stir spot welding of similar aluminium and copper have been used successfully by various researchers. The numerous advantages of friction stir welding and friction stir spot welding have permitted the processes to have a positive impact in the field of welding. Neither of the processes requires any sample preparation, besides the removal of the oxide layer and the degreasing of the sheets prior the commencement of the joining process. In the studies found in the open literature, the two processes have successfully joined various materials, including similar aluminium and copper; and they have produced sound welds with improved tensile strength, good fatigue properties and corrosion resistance.

FSW and FSSW are solid state welding methods; and they are environmentally friendly, which makes the two processes an attractive area of research and development. The environmental friendliness of the processes (FSW and FSSW) is exhibited in their ability to not produce harmful emissions, to not require shielding gas for low melting materials; and minimal surface cleaning is required. Furthermore, the two processes eliminate the usage of solvents required to clean the surfaces of the samples. Even though FSW and FSSW give good quality welds, the usage of the right process parameters and tools is required, in order to produce sound welds.

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Chapter 4

Microstructure and Chemical Analysis of Friction Stir Spot Welding Between Aluminium and Copper (Case Study)



Abstract The Friction stir spot welding technique was used to produce lap spot welds of AA1060 and C11000. Various process parameters and tool geometries were used to fabricate the welds. The microstructures of the produced spot welds produced were examined by using optical microscopy (OM) and scanning electron microscopy (SEM). The chemical analysis of the cross sections of the welds was investigated by using energy dispersive spectroscopy (EDS) and X-ray diffraction (XRD). A good Al/Cu material mixing was observed in most of the fabricated spot welds. The presence of copper rings on both sides of the keyhole with different lengths was observed in all the spot welds. The mapping using energy dispersive spectroscopy of a region of the keyhole/copper rings and the stir zone showed the presence of copper particles in the aluminium matrix. However, Very few aluminium particles were found in the copper rings. Intermetallic compounds were found in some of the spot welds.

Keywords Microstructure · EDS · SEM · XRD · Intermetallic compounds

4.1 Introduction

Friction stir spot welding is a solid state welding technique, which has been fairly frequently used to join different types of materials. Over the years, many efforts have been made to produce friction stir spot welds between aluminium and copper [1–14]. A typical microstructure in a friction stir spot weld comprises different regions: the parent material (PM), the heat affected zone (HAZ), the thermomechanically affected zone (TMAZ), the stir zone (SZ) and the Hook, which is also called the copper ring (in friction stir spot welding Al/Cu) [1, 15]. Many researchers have found the presence of detrimental intermetallics in the produced joints; and those intermetallic compounds affect the mechanical properties of the FSS welds.

A 3 mm thick AA1050 to pure copper was joined using FSSW by Ozdemir et al. [14]. The joints produced did not have any macroscopic defects; and the grains on the copper side close to the Al/Cu interface were finer than those of the copper

parent material. And that was attributed to the effect of the rotating pin, which deformed the grains close to the Al/Cu interface and the recrystallization of the grains in the stir zone of the copper metal, because of the heat input [14]. Furthermore, Ozdemir et al. [14] conducted energy dispersive spectroscopy analyses; and the results revealed the formation of hard and brittle intermetallic compounds of AlCu, Al₂Cu and Al₄Cu₉, which had formed at the interface.

It was noticed that there were not many published articles available on the microstructural evolution and the chemical analysis of friction stir spot welding between aluminium and copper. Therefore, it is important that more research be conducted to fully understand the microstructural behavior and the chemical composition of the joints (Al/Cu). This could lead to the optimization of the process; and this would enable it to be used as an alternative to riveting and resistance spot welding.

This chapter focuses on the microstructural evolution and the chemical composition of friction stir spot welds AA1060 to C11000 produced when using different process parameters and tool geometries. This could provide a platform for further research in the field of FSSW Al/Cu.

4.2 Experimental Procedure

In this study, AA1060 and commercially pure copper C11000 sheets were used for the experiments. The dimensions of the test coupon for each plate were $600 \times 120 \times 3 \text{ mm}^3$. The sheets were friction stir spot welded in a 30 mm overlap configuration.

The Friction stir spot welding process was conducted at rotation speeds of 800 and 1200 rpm; and the tool shoulder plunge depths were 0.5 and 1 mm while using a constant hold time of 10 s. The joints were produced by using an MTS PDS I-Stir at the eNtsa of Nelson Mandela Metropolitan University (NMMU), Port Elizabeth, South Africa, as shown in Fig. 4.1.

The welding tools had a 15 mm-diameter shoulder, a 5 mm-diameter pin and a 4 mm pin length. The tool material is H13 tool steel hardened to 50–52 HRC. Two different tool structures were used to produce the spot welds, Flat Pin and Flat Shoulder (FPS) and Conical Pin and Concave Shoulder (CCS). The samples were prepared by using a standard metallographic procedure [16, 17] and ASTM standard E3-11 [18]. Furthermore, iron III nitrate (Fe (NO₃)₃) added to the suspension was used in the final polishing step; and this assisted in removing the copper scratches on the samples.

The surface morphology of the spot welds was analyzed using scanning electron microscopy (SEM). A TESCAN instrument equipped with Vega TC software Vega TC, was used. The SEM was coupled with an energy dispersive spectrometer (Oxford instrument X-Max); and the latter was used for the chemical analyses. Furthermore, an optical microscope was utilized to study the surface morphology of the spot welds when using an Olympus BX51 M microscope. A solution of FeCl₃



Fig. 4.1 Shows the MTS PDS I-Stir used to produce the friction stir spot welds

(10 g) + HCl (6 ml) + Ethanol (C_2H_5OH) (20 ml) + H_2O (80 ml) was used to etch the copper side of the spot welds; while the aluminium side was etched with H_2O (190 ml) + HNO_3 (5 ml) + HCl (10 ml) + HF (2 ml). X-ray diffraction (XRD) analyses were carried out for the phase identification and to check the possible presence of intermetallic compounds and their composition. The samples were examined by using a D8 Advanced diffractometer with a Cu tube while using a 2 mm collimator; the recording range and step size were 15° – 120° and 0.04° respectively.

The analyses of the intermetallics were done in the SZ, TMAZ and in the HAZ of the fabricated friction stir spot welds.

4.3 Results and Discussion

The top and the bottom of the FSS Welds, produced at different process parameters and using different tool geometries, is depicted in Fig. 4.2. The effect of heat generation during the friction stir spot welding process can be clearly seen at the bottom of the sheets.

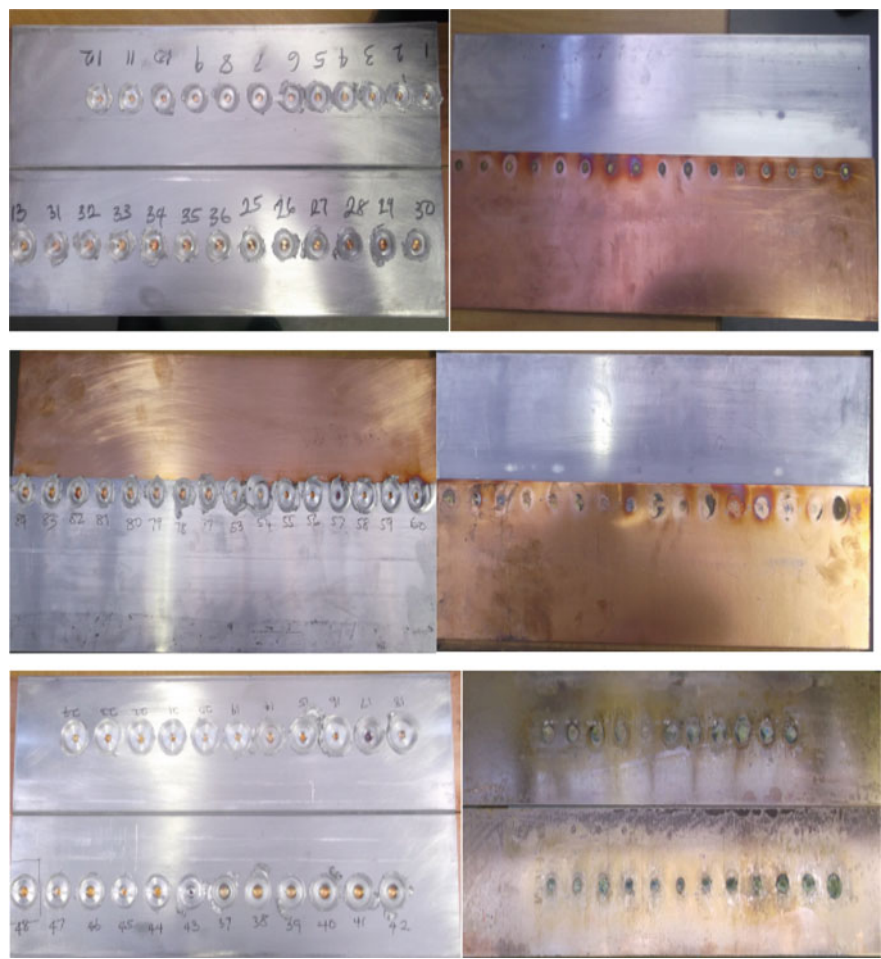


Fig. 4.2 Shows the top and bottom of the FSS welded sheets using different process parameters and tool geometries

4.3.1 Microstructural Evolution

Figure 4.3 shows the cross-section of the welds produced when using different process parameters and the different tools geometries employed.

It was observed in Fig. 4.3, that the shapes of the pin and the shoulder in the cross sections of the produced spot welds, viz. flat pin/flat shoulder and conical pin/concave shoulder, can be clearly seen.

The colour contrast between the two plates welded, namely, aluminium and copper could be seen; copper has a lighter contrast than the aluminium. It was further observed the presence of a keyhole; and on both sides of the welds, there was a presence of copper rings [2] also known as hooks [19], which were formed from the deformed part of the lower sheet (copper) penetrating into the top sheet

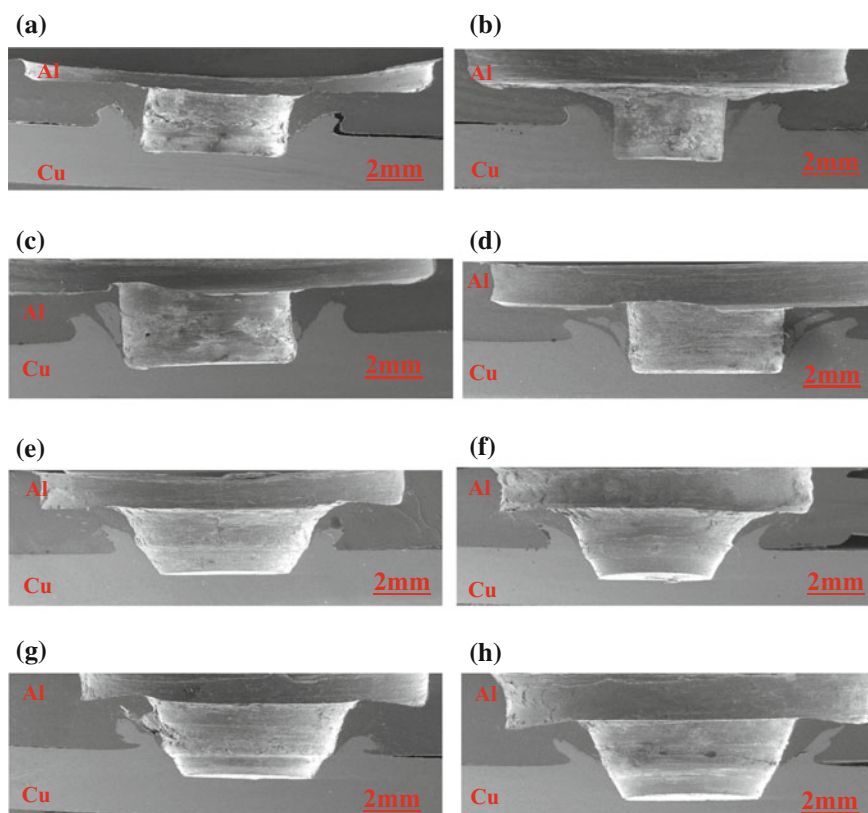


Fig. 4.3 Micrographs of the cross sections of friction stir spot welds produced by using a flat pin and shoulder tool (a CCS_800_0.5, b CCS_800_1, c CCS_1200_0.5 and d CCS_1200_1) and using a flat pin and shoulder tool (e FPS_800_0.5, f FPS_800_1, g FPS_1200_0.5 and h FPS_1200_1)

(aluminium). This observation was in agreement with the results obtained by Ozdemir et al. [14].

Figures 4.4 and 4.5 show the copper rings and the corresponding lengths. Heideman et al. [2] also observed the presence of the copper rings with different lengths in all the produced spot welds.

The length of the copper rings of the spot welds produced at different process parameters using a flat pin/flat shoulder and conical pin a/concave shoulder, are shown in Figs. 4.4 and 4.5. In this study, it was observed the presence of copper rings, which consisted of the copper base material extruded into the aluminium sheet. This suggests that while the copper material was moving around the tool and diffusing into the aluminium, the latter was not diffusing or being pushed into the copper ring [2]. It was also observed that, the thickness of the workpieces was reduced after the friction stir spot welding was used.

In a similar study, Ozdemir et al. [14] observed that the penetration length of the copper into the aluminium was about half of the thickness of the aluminium

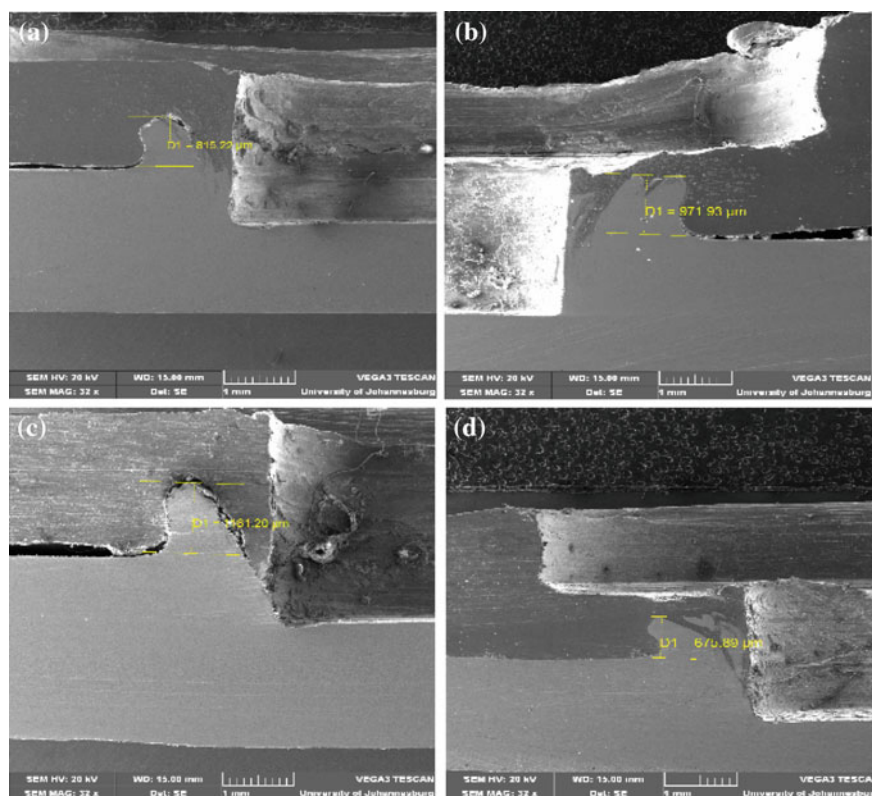


Fig. 4.4 Shows the length of the copper rings of the spot weld produced **a** 800 rpm, 0.5 mm, **b** 800 rpm, 1 mm, **c** 1200 rpm, 0.5 mm and **d** 1200 rpm, 1 mm using flat pin and shoulder tool

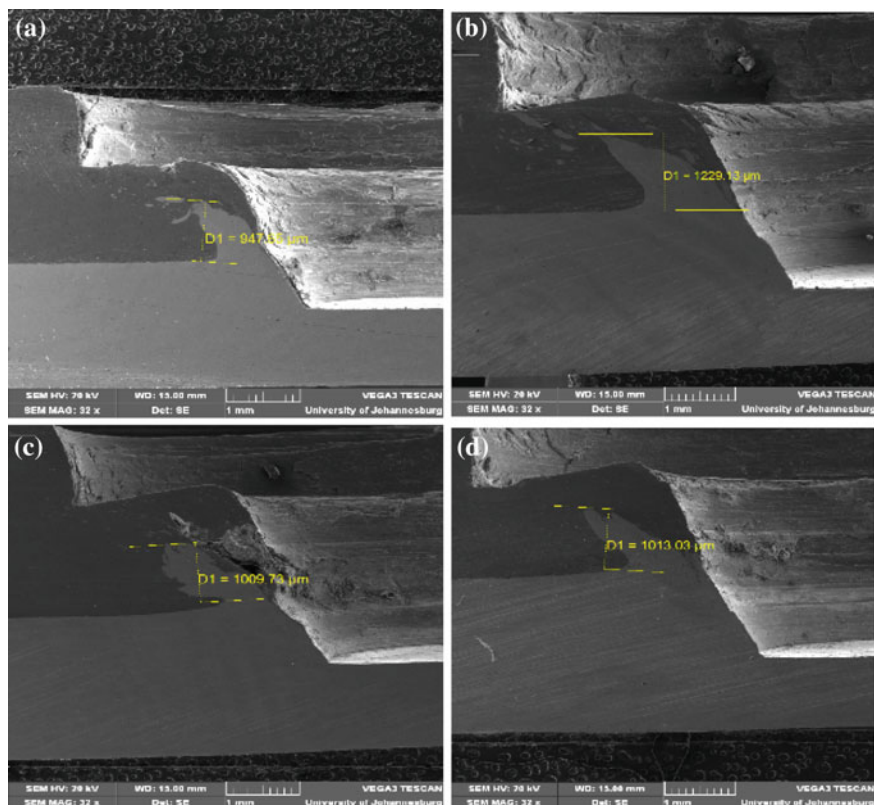


Fig. 4.5 Shows the length of the copper rings of the spot weld produced **a** 800 rpm, 0.5 mm, **b** 800 rpm, 1 mm, **c** 1200 rpm, 0.5 mm and **d** 1200 rpm, 1 mm using a conical pin and concave shoulder tool

workpiece. But this was not the case in the current study; since the obtained copper rings were of different lengths; but they were not half the thickness of the aluminium sheet.

In this study, the penetration length of the copper into the aluminium was also studied. The formed copper rings were measured; and results are shown in Figs. 4.4 and 4.5 for the flat pin/flat shoulder and the conical pin/concave shoulder tools, respectively.

It was observed that the copper ring length increases with the increase of the shoulder plunge depth, except for the spot welds produced at 1200 rpm, using a flat pin and shoulder, where a decrease was observed. The copper ring lengths of the welds produced at 1200 rpm using a conical pin and concave shoulder also showed a slight difference in the copper ring length. This shows that the welds produced at high rotational speed exhibit either a decrease, or a slight increment in the copper ring length. It has been reported that, the copper ring caused interlocking between

the two plates and helped the plates to adhere to each other during tensile testing and reach a high strength before failure [2].

The effect of the process parameters and the tool geometry on the lengths of the formed copper rings can be seen in Fig. 4.6.

Figure 4.7 depicts the microstructure of the parent materials, namely: (a) copper and (b) aluminium using an optical microscope.

The microstructure of the friction stir spot welds analyzed by using an optical microscope are seen in Figs. 4.8 and 4.9. Figure 4.8 shows the microstructure of the

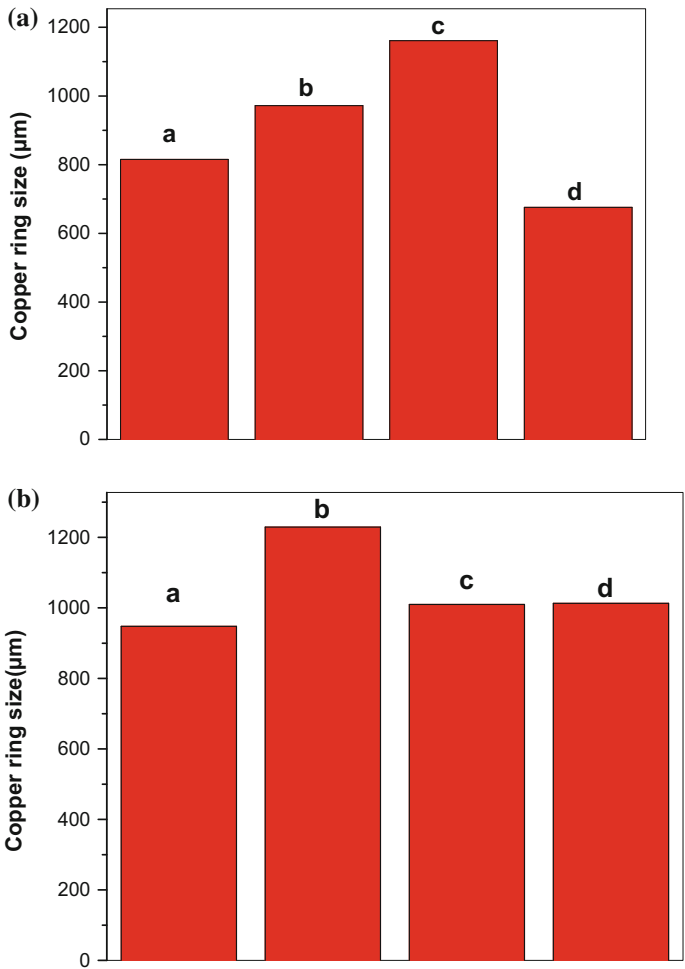


Fig. 4.6 The copper ring lengths obtained using (A) a flat pin and concave shoulder tool at different process parameters, **a** (FPS_800_0.5), **b** (FPS_800_1), **c** (FPS_1200_0.5) and **d** (FPS_1200_1) and (B) using a conical pin and concave shoulder tool at different process parameters, **a** (CCS_800_0.5), **b** (CCS_800_1), **c** (CCS_1200_0.5), **d** (CCS_1200_1)

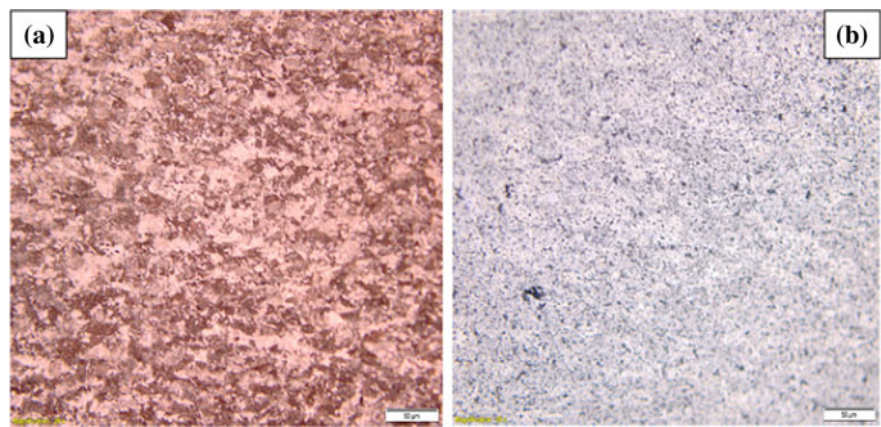


Fig. 4.7 Microstructure of the parent materials **a** C11000 and **b** AA1060

spot weld produced a flat pin/flat shoulder tool at 800 rpm (a) and 1200 rpm (b), shoulder plunge depth of 1 mm. Additionally, Fig. 4.8 depicts the microstructure of the spot weld produced when using a conical pin/concave shoulder tool at 800 rpm (a) and 1200 rpm (b), shoulder plunge depth of 0.5 mm.

It can be seen in Fig. 4.8a that there is the presence of a copper ring and a mixture of Al/Cu particles are present in the stir zone. No obvious welding defect in the joint was observed; and the copper is distributed in this zone with different shapes. Furthermore, in Fig. 4.8a, in the upper part of the joint, the large bulk of copper with irregular shapes can be seen. The tool pin was inserted into the aluminium plate; and the copper ring extruding upwards from the lower copper plate in

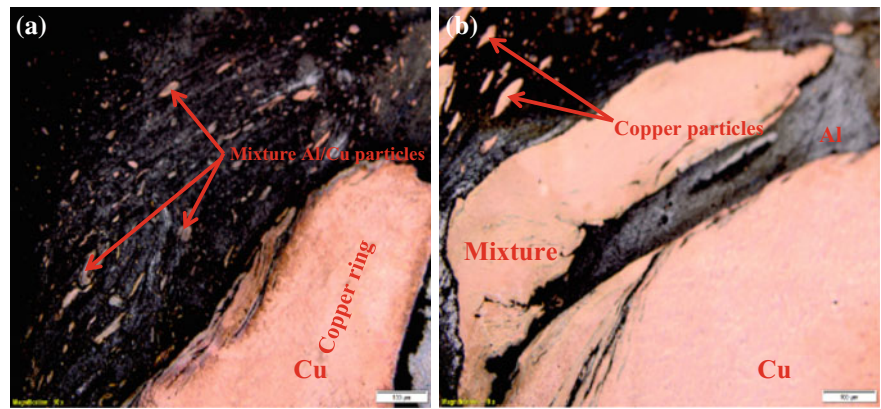


Fig. 4.8 Shows the macrostructure of the welds produced at 800 rpm (a) and 1200 rpm (b), 1 mm shoulder plunge depth using a flat pin/flat shoulder tool

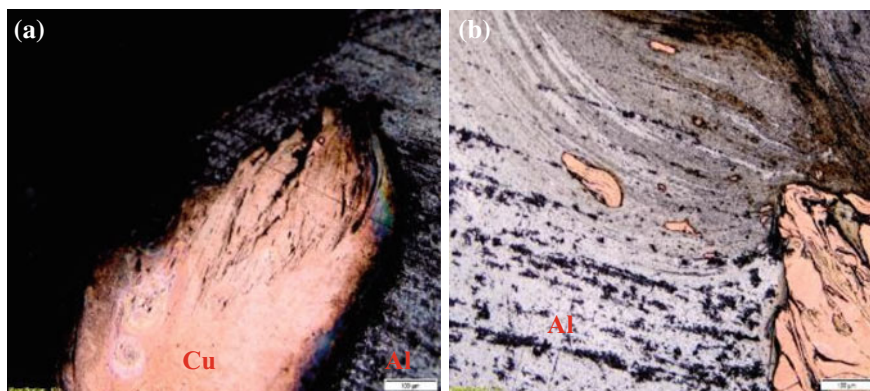


Fig. 4.9 Shows the macrostructure of the welds produced at 800 rpm (a) and 1200 rpm (b), 0.5 mm shoulder plunge depth using a conical pin/concave shoulder tool

the aluminium plate was observed. This was in agreement with a study conducted by Heideman et al. [2].

Also, the intermixing of copper and aluminium is not homogeneous for the different produced spot welds; and different microstructures are formed in different regions of the welds. It has been reported that the FSW of dissimilar materials is distinguished from those of similar materials by the formation of a complex, intercalated vortex-like and related flow pattern [20].

In Fig. 4.9b, a good interlaced structure can be seen. This is formed by aluminium and copper, thereby indicating that the two plates are bonded together firmly in this region; and it is composed of a lamellae structure of copper particles with a streamlined shape of aluminium strips. In that region, it was also observed that there were a few disseminated copper particles.

The energy dispersive spectroscopy (EDS) mapping of a region of the keyhole and the copper ring area was conducted. Figures 4.10, 4.11, 4.12 and 4.13 show the EDS mapping of the spot welds produced at different process parameters, including the rotation speed and the shoulder plunge depth obtained when using a flat pin/flat shoulder. The distribution of copper (red) and aluminium (black) can be seen from Figs. 4.10, 4.11, 4.12 and 4.13.

It was observed that there is a presence of copper particles and fragments in the aluminium matrix; but there was almost no presence of aluminium particles in the copper matrix. This was noticed in the EDS mapping of the spot welds produced at the rotation speed of 800 rpm, which was considered low in this current study; while at the two shoulder plunge depths, only the presence of a large deformed copper material (copper ring) with some small copper particles in its surroundings could be seen.

The EDS mapping of the welds produced at the rotation speed of 1200 rpm, which was considered to be high, and at both shoulder plunge depths, there was besides the presence of the copper ring another large piece of copper material next

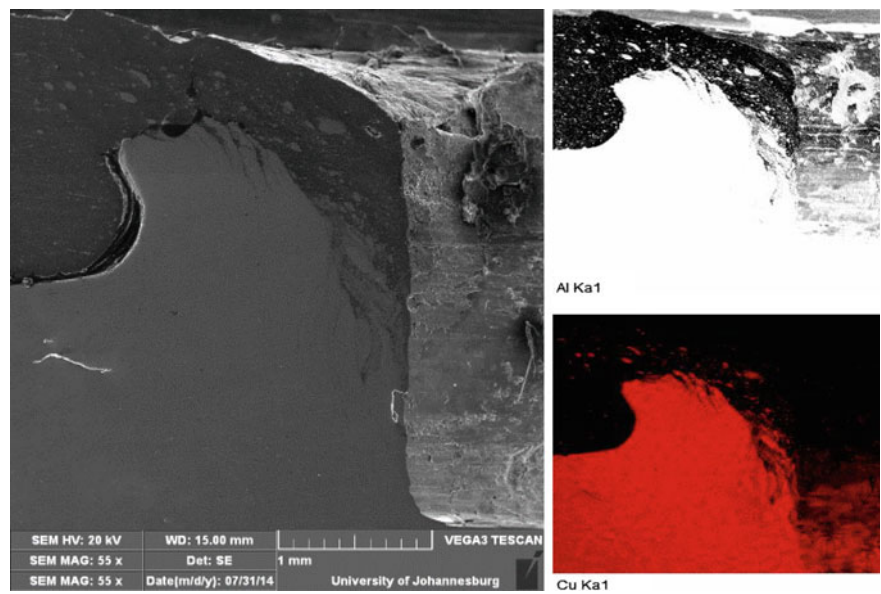


Fig. 4.10 Depicts the mapping of a weld produced at 800 rpm and 1 mm shoulder plunge depth using a flat pin and a flat shoulder tool. Copper is represented in red and aluminium in black

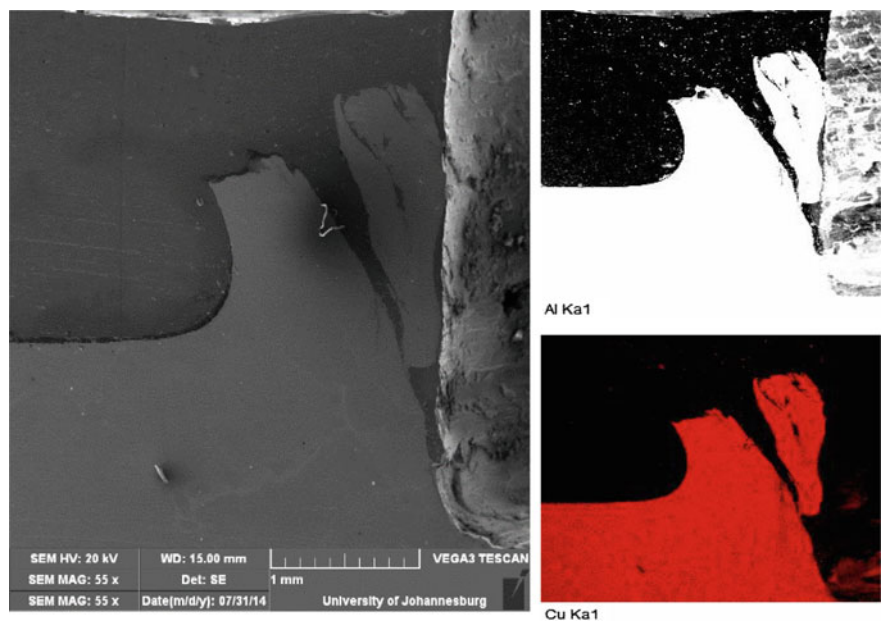


Fig. 4.11 Depicts the mapping of a weld produced at 1200 rpm and 0.5 mm shoulder plunge depth using a flat pin and a flat shoulder tool. Copper is represented in red and aluminium in black

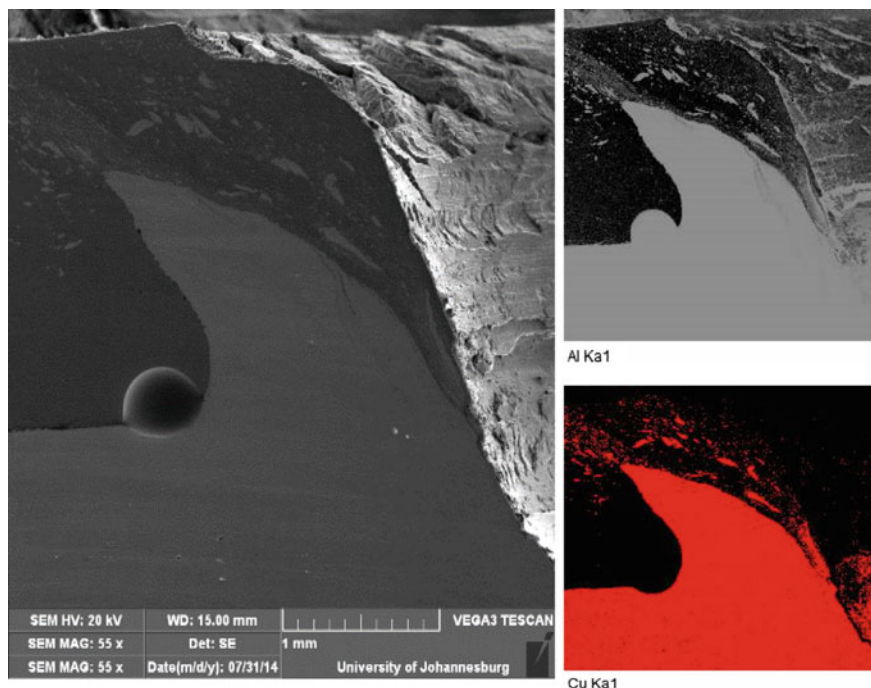


Fig. 4.12 Depicts the mapping of a weld produced at 800 rpm and 1 mm shoulder plunge depth using a conical pin and a concave shoulder tool. Copper is represented in red and aluminium in black

to the copper ring. This could be due to the effect of the rotation speed on the material flow; whereas at 1200 rpm, the copper rings were seen to be sectioned into two. This was observed by the change in the widths of the copper rings of the welds produced at 1200 rpm. This observation should be compared with the welds produced when using a conical pin and a concave shoulder.

Furthermore, the energy dispersive spectroscopy (EDS) mapping was also conducted for the stir zone of the different welds. Figures 4.14, 4.15, 4.16 and 4.17 present the EDS mapping of the SZ for the spot weld produced, when using a flat pin/flat shoulder and a conical pin/concave shoulder tool.

It was seen that the element distribution shows a mixing of copper and aluminium: especially in the stir zone and this was expected; since the stir zone is formed in the vicinity of the keyhole produced by the tool. During the tool rotating movement, it is expected that materials move around the tool pin to produce good mixing. In Fig. 4.14, a large number of copper particles of different sizes and shapes were observed in the aluminium sheet. When the rotation speed is increased (Fig. 4.15), the number of small copper particles in the aluminium matrix is increased. On the other hand, spot welds produced when using a conical pin and a concave shoulder are presented in Figs. 4.16 and 4.17. The presence of large bent

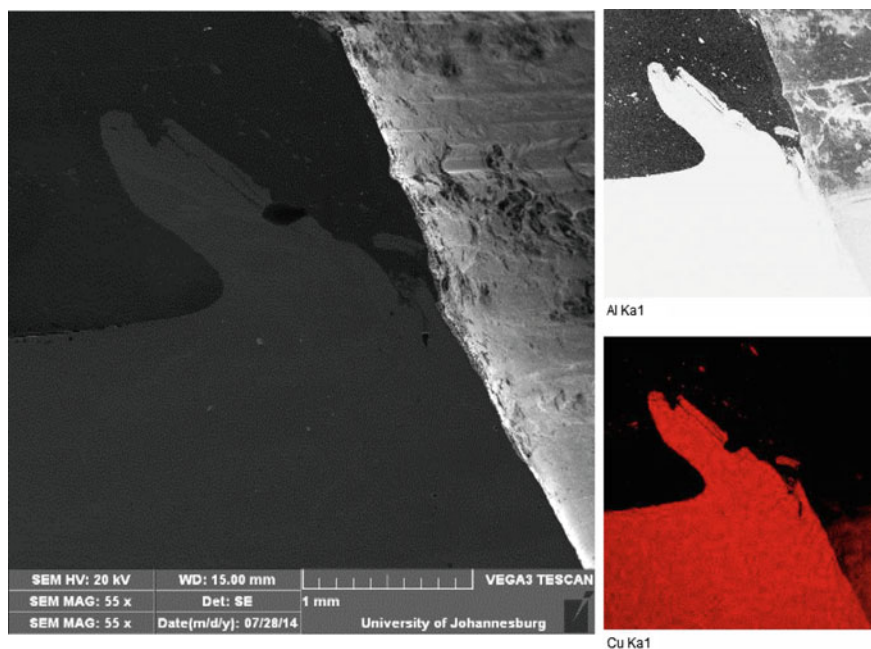


Fig. 4.13 Depicts the mapping of a weld produced at 1200 rpm and 1 mm shoulder plunge depth using a conical pin and a concave shoulder tool. Copper is represented in red and aluminium in black

copper fragments, surrounded by smaller copper particles in the aluminium matrix, was observed in Fig. 4.16.

When the rotation speed was increased from 800 rpm to 1200 rpm, a good mixture (Al/Cu) was seen on one side; whereas the other region contained small particles of copper disseminated into the aluminium (Fig. 4.17).

4.3.2 Chemical Analysis

The chemical composition analyses using the X-ray diffraction technique and energy dispersive spectroscopy were carried out to investigate the effect of process parameters on the formation of hard brittle intermetallic compounds.

Figure 4.18 presents the X-ray diffraction patterns of the aluminium and copper base materials.

The XRD analysis was performed in three different locations of the spot weld samples, viz., the stir zone, the thermomechanically affected zone and the heat-affected zone. This was done by using a 0.8 mm collimator, as shown in Tables 4.1 and 4.2 for the samples produced when using a flat pin/flat shoulder and

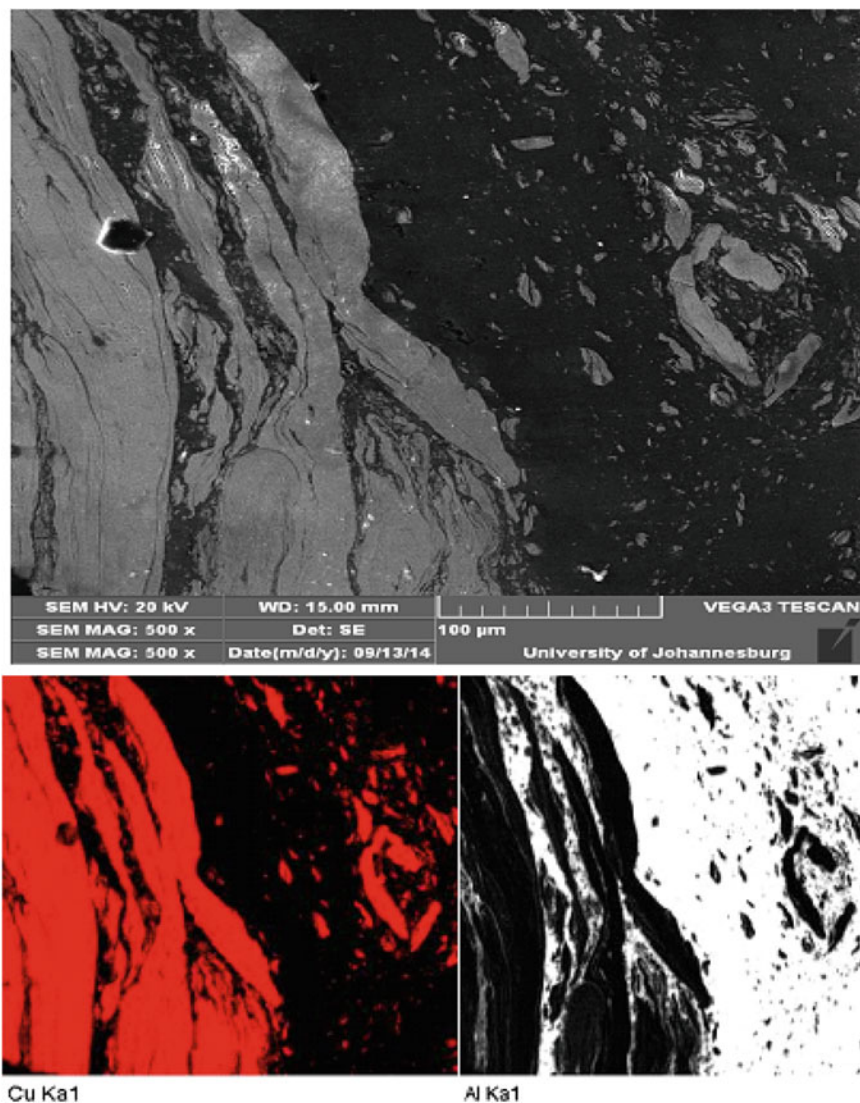


Fig. 4.14 Shows the mapping of the stir zone for the weld produced at 800 rpm and 0.5 mm shoulder plunge depth, using a flat pin and a flat shoulder tool. Copper is represented in red and aluminium in black

conical pin/concave shoulder tool, respectively. The XRD patterns obtained in the three different zones show intense aluminium and copper peaks; while low intensity XRD peaks depict the intermetallic compounds. The presence of intermetallic compounds in the produced friction stir spot welds has been investigated by many authors [13, 14].

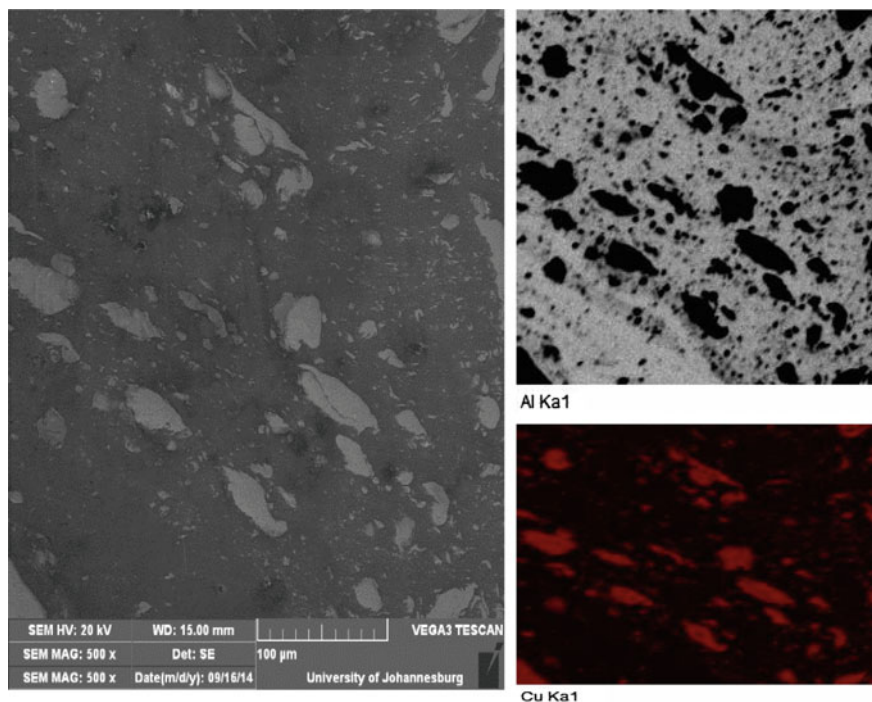


Fig. 4.15 Shows the mapping of the stir zone for the weld produced at 1200 rpm and 1 mm shoulder plunge depth using a flat pin and a flat shoulder tool. Copper is represented in red and aluminium in black

In the current study, intermetallics could not be well identified, due to their low concentrations in the different produced samples. Similar results were obtained by Akinlabi [21]. Additionally, intermetallics were found in all the analysed spot samples. This could be due to the fact that welds were produced at one spot; where the amount of heat generated was high, which could lead to the formation of intermetallic compounds; since they are thermally activated phases [22]. Furthermore, a study conducted by Galvao et al. [23] confirmed and justified the presence of a high melting point for intermetallic compounds, such as Cu_9Al_4 (1030 °C) in the characterized samples when using XRD. They further justified that this was due to the occurrence of the thermomechanically induced solid state diffusion.

It was also noticed that some of the intermetallic compounds' peaks overlapped with the peaks of the base materials. Figure 4.19 shows the X-ray diffractogram for the stir zone of the sample produced at 800 rpm, 0.5 shoulder plunge depth when using a conical pin/concave shoulder tool. It can be seen that the presence of intermetallics includes Al_4Cu_9 , Al_3Cu_2 and AlCu_3 .

A number of different intermetallics were found in the samples of the spot welds. Intermetallics of AlCu_3 , Al_4Cu_9 , Al_2Cu , Al_3Cu_2 , Al_2Cu_3 , AlCu were found in the

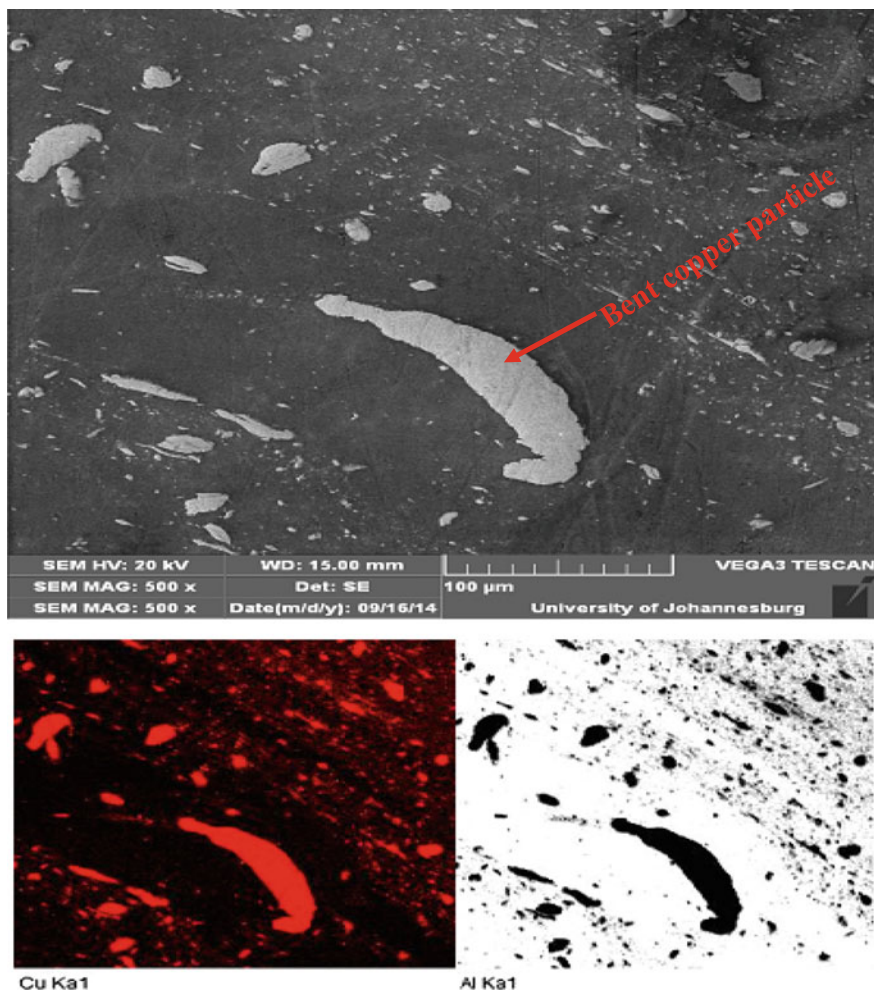


Fig. 4.16 Shows the mapping of the stir zone for the weld produced at 800 rpm and 0.5 mm shoulder plunge depth, when using a conical pin and a concave shoulder tool. Copper is represented in red and aluminium in black

SZ of the weld produced at 800 rpm, 0.5 mm shoulder plunge depth using a flat pin and a flat shoulder tool; whereas AlCu_3 , Al_4Cu_9 , Al_2Cu , Al_3Cu_2 were found in the SZ of the weld produced at the same process parameters, but when using a conical pin and a concave shoulder tool. On the other hand, in the TMAZ of the welds produced at the same process parameters, as indicated above, only the AlCu_4 intermetallic compound was found, while using a flat pin and a flat shoulder; while AlCu_3 , Al_2Cu , Al_2Cu_3 intermetallics were found in the TMAZ of the weld produced, when using a conical pin and a concave shoulder tool.

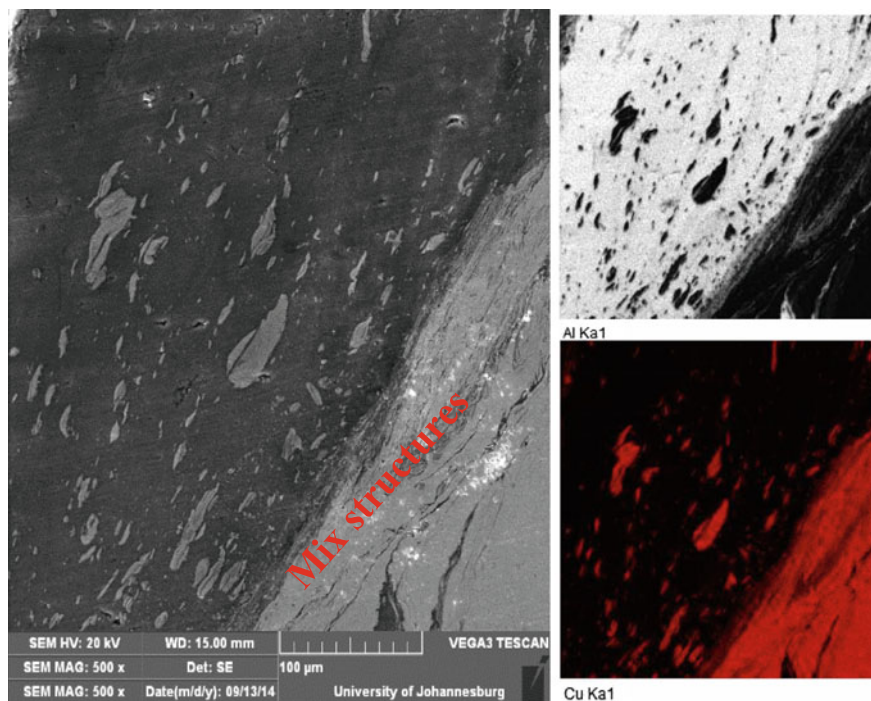


Fig. 4.17 Shows the mapping of the stir zone for the weld produced at 1200 rpm and 0.5 mm shoulder plunge depth, using a conical pin and a concave shoulder tool. Copper is represented in red and aluminium in black

This phenomenon could be linked to the generation of low heat input, which would generate less heat.

It has been reported that low heats in FSW can disfavor the formation of intermetallics [22]. The most common intermetallic compounds formed in the spot weld samples are: Al_4Cu_9 , AlCu_3 , Al_2Cu_3 and Al_2Cu .

4.3.2.1 Energy Dispersive Spectroscopy Analyses (EDS)

The EDS analyses were conducted to investigate and confirm the presence of intermetallic compounds in the spot welds produced when using various process parameters. The analyses were conducted in the keyhole and the stir zone of the cross sectioned samples.

AlCu and Al_2Cu intermetallics were found in the keyhole of the spot welds produced at 800 rpm and 0.5 mm shoulder plunge depth (Table 4.3a); whereas, only Al_4Cu_9 was found in the weld produced at 800 rpm and 1 mm shoulder plunge depth (Table 4.3b). Both welds were produced by using a flat pin/flat shoulder tool and were detected in the keyhole (Table 4.3). Table 4.4 depicts the

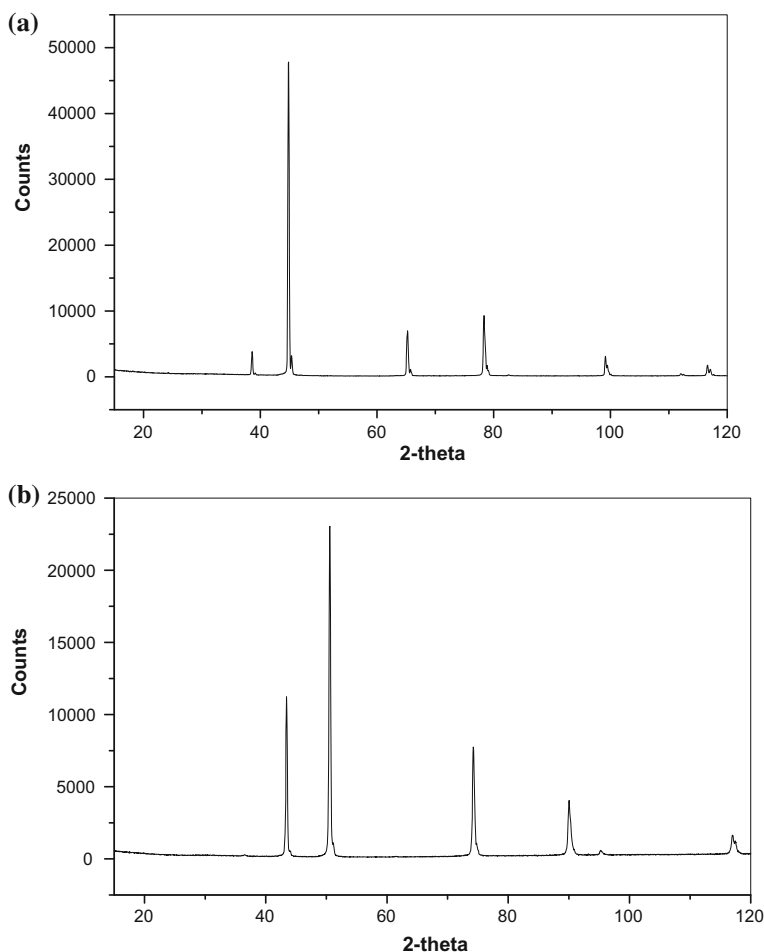


Fig. 4.18 X-ray diffraction pattern of **a** the aluminium parent material (AA1060) **b** the copper (C11000) parent material

EDS analyses of the keyholes for the welds produced when using a flat pin/flat shoulder at 1200 rpm and a shoulder plunge depth of 0.5 and 1 mm. AlCu and AlCu_3 were found in the FPS_1200_0.5 weld (Table 4.4a); whereas only AlCu_3 was found in the FPS_1200_1 weld (Table 4.3b). While using a conical pin/concave shoulder tool, AlCu was found in the weld produced at 800 rpm and 0.5 mm shoulder plunge depth (Table 4.5a). On the other hand, Al_2Cu_3 was found in the keyhole of the weld produced at 800 rpm and 1 mm shoulder plunge depth (Table 4.5b). No intermetallic was found in the keyhole of the spot weld produced at 1200 rpm and 0.5 mm shoulder plunge depth, when using a conical pin/concave shoulder (Table 4.6 a). Al_3Cu_4 and AlCu_3 intermetallics were present in the

Table 4.1 Intermetallics found in different zones of the spot weld samples produced when using a flat pin and a flat shoulder

Weld ID	Zone	Intermetallic compounds
FPS_800_0.5	Stir zone	Al Cu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, Al ₃ Cu ₂ , Al ₂ Cu ₃ , AlCu
	Thermo-mechanically affected zone	AlCu ₄
	Heat-affected zone	AlCu ₄
FPS_800_1	Stir zone	Al ₂ Cu, Al ₃ Cu ₂ , Al Cu ₃
	Thermo-mechanically affected zone	Al Cu ₃ , Al ₂ Cu ₃ , Al ₂ Cu
	Heat-affected zone	Al ₄ Cu ₉ , Al ₂ Cu ₃ , Al ₂ Cu
FPS_1200_0.5	Stir zone	Al Cu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, AlCu
	Thermo-mechanically affected zone	Al ₄ Cu ₉ , Al ₂ Cu, Al ₂ Cu ₃ , Al ₄ Cu, AlCu
	Heat-affected zone	Al Cu ₃ , Al ₄ Cu ₉ , Al ₂ Cu ₃ , AlCu
FPS_1200_1	Stir zone	Al Cu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, Al ₂ Cu ₃ , AlCu
	Thermo-mechanically affected zone	Al ₄ Cu ₉ , Al ₂ Cu, Al ₂ Cu ₃ , Al ₄ Cu
	Heat-affected zone	Al Cu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, Al ₃ Cu ₂ , Al ₂ Cu ₃ , Al ₄ Cu

Table 4.2 Intermetallics found in different zones of the spot welds samples produced when using a conical pin and a concave shoulder

Weld ID	Zone	Intermetallic compounds
CCS_800_0.5	Stir zone	AlCu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, Al ₃ Cu ₂
	Thermo-mechanically affected zone	Al Cu ₃ , Al ₂ Cu, Al ₂ Cu ₃
	Heat-affected zone	Al ₂ Cu, Al ₂ Cu ₃ , Cu ₃ Al, Al ₄ Cu ₉ , Al ₃ Cu ₂
CCS_800_1	Stir zone	Al ₂ Cu, Al ₄ Cu ₉ , Cu ₃ Al, Al ₃ Cu ₂ , AlCu, Al ₂ Cu ₃
	Thermo-mechanically affected zone	Al Cu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, Al ₃ Cu ₂ , AlCu
	Heat-affected zone	Al Cu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, Al ₃ Cu ₂ , AlCu, Al ₂ Cu ₃
CCS_1200_0.5	Stir zone	AlCu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, Al ₃ Cu ₂
	Thermo-mechanically affected zone	Al Cu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, Al ₂ Cu ₃
	Heat-affected zone	Al ₂ Cu ₃ , Al ₂ Cu
CCS_1200_1	Stir zone	Al Cu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, Al ₃ Cu ₂ , AlCu
	Thermo-mechanically affected zone	Al Cu ₃ , Al ₄ Cu ₉ , Al ₂ Cu, Al ₃ Cu ₂ , Al ₂ Cu ₃ , Al ₄ Cu
	Heat-affected zone	AlCu ₃ , Al ₄ Cu ₉ , Al ₂ Cu ₃ , Al ₂ Cu

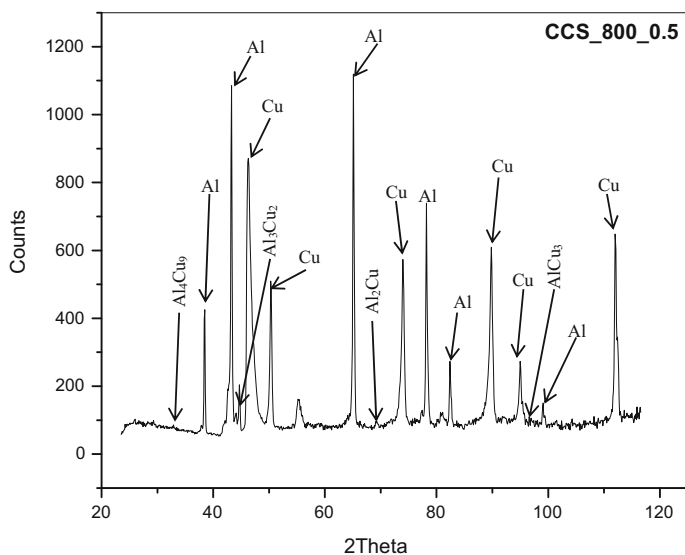


Fig. 4.19 X-ray diffractogram of the stir zone of the weld produced at 800 rpm, 0.5 mm shoulder plunge depth when using a conical pin and a concave shoulder tool

keyhole of the weld produced at 1200 rpm and 1 mm shoulder plunge depth; and this is depicted in Table 4.6b.

According to the results obtained in the keyholes of the spot welds, there was no trend showing the effect of process parameters on the formation of intermetallics.

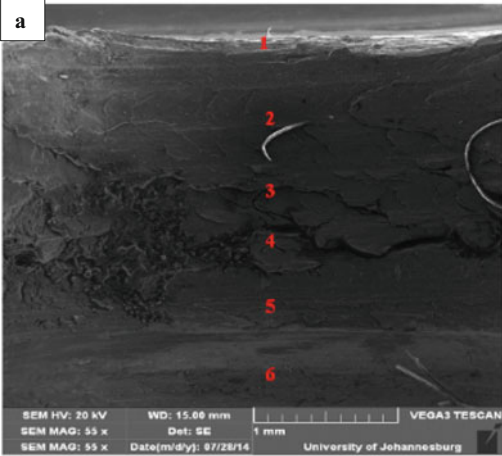
It has been reported that the presence of the intermetallic compounds in the joint interface could preferentially favour the development of a crack during the shear tensile analysis [9]. In various samples, it was noticed that there was a region rich in aluminium, especially in the upper zone (aluminium sheet) of the keyhole, with a lower percentage of copper. This could have been caused by the stirring of the tool pin, which took the copper particles from the bottom plate upwards, and favored the presence of either rich aluminium regions, or the presence of intermetallics.

This was observed by the decrease in the percentage of aluminium from the first analyzed point to the last (eventually in the copper, where the percentage of copper increases considerably). This was observed in all the welds, except for the weld produced at 1200 rpm, 0.5 mm shoulder plunge depth, when using a conical pin and a concave shoulder.

Tables 4.7, 4.8a, b, 4.9a, b and 4.10a, b present the energy dispersive spectroscopy analyses carried out in the stir zones of the fabricated friction stir spot welds.

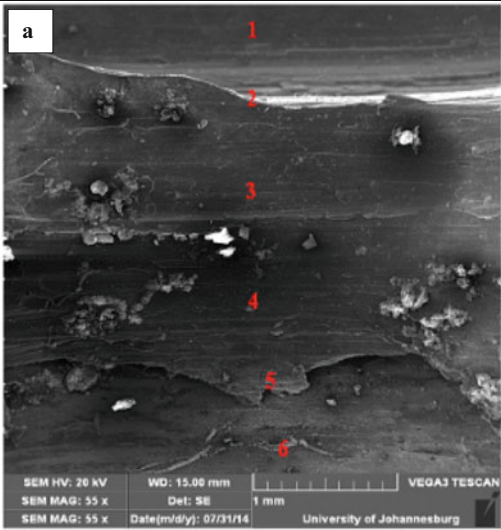
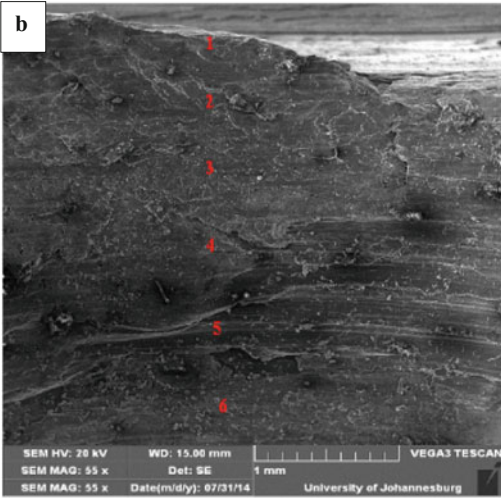
Figure 4.7 shows the presence of AlCu, Al₄Cu₉ and Al₂Cu intermetallic compounds found in the stir zone of the weld produced at 800 rpm, 0.5 mm shoulder plunge depth, when using a flat pin/flat shoulder tool. In Fig. 4.8a, Al₂Cu and Al₃Cu₄ were found in the stir zone of the weld produced at 1200 rpm and 0.5

Table 4.3 Presents the EDS analysis of the keyhole for (a) FPS_800_0.5 and (b) FPS_800_1 spot welds

a	Point	composition		intermetallic compound
		Al	Cu	
	1	99	0.09	-
	2	89	11	-
	3	32	67	AlCu
	4	86	13	-
	5	58	41	Al ₂ Cu
	6	93	7	-
b	Point	composition		intermetallic compound
		Al	Cu	
	1	92	8	-
	2	93	7	-
	3	81	18	-
	4	19	80	Al ₄ Cu ₉
	5	9	90	-
	6	7	93	-

shoulder plunge depth, when using a flat pin/flat shoulder tool; whereas Al₄Cu₉ and AlCu intermetallics were found in the weld produced at 1200 rpm and 1 mm shoulder plunge depth (Fig. 4.8b). In the stir zone of the weld produced at 800 rpm and 0.5 shoulder plunge depth, only Al₄Cu₉ was found (Table 4.9a); while Al₄Cu₉ and AlCu were found in the weld produced at 800 rpm and 1 mm shoulder plunge depth (Table 4.9b). When the rotational speed was increased to 1200 rpm, using two shoulder plunge depths, namely 0.5 and 1 mm, Al₂Cu, AlCu, AlCu₃ and AlCu intermetallics were found, respectively, for CCS_1200_0.5 and CCS_1200_1

Table 4.4 Presents EDS analyses of the keyhole for (a) FPS_1200_0.5 and (b) FPS_1200_1 spot welds

a  SEM HV: 20 kV WD: 15.08 mm VEGA3 TESCAN SEM MAG: 55 x Det: SE 1 mm SEM MAG: 55 x Date(m/d/y): 07/31/14 University of Johannesburg	Point	composition		intermetallic compound
		Al	Cu	
	1	98	1	-
	2	97	3	-
	3	97	2	-
	4	98	1	-
	5	37	62	AlCu
b  SEM HV: 20 kV WD: 15.08 mm VEGA3 TESCAN SEM MAG: 55 x Det: SE 1 mm SEM MAG: 55 x Date(m/d/y): 07/31/14 University of Johannesburg		Al	Cu	
	1	89	11	-
	2	15	84	AlCu ₃
	3	12	87	AlCu ₃
	4	96	2	-
	5	98	2	-
	6	68	31	-

(Table 4.10a). And only AlCu intermetallic compound was found in the spot weld produced at 1200 rpm, 1 mm shoulder plunge depth, when using a conical pin/ concave shoulder (Table 4.10b).

Table 4.5 Presents the EDS analyses of the keyhole for (a) CCS_800_0.5 and (b) CCS_800_1 spot welds

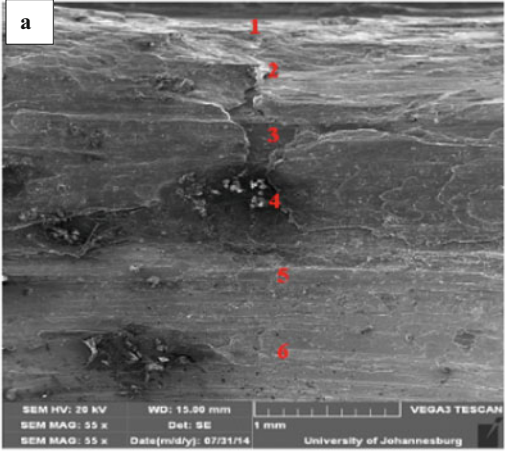
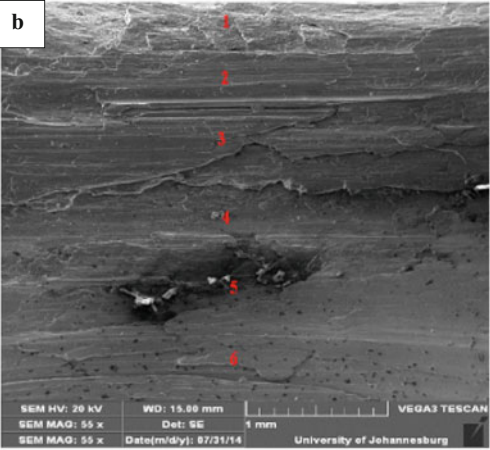
a  SEM HV: 20 kV WD: 15.00 mm VEGA3 TESCAN SEM MAG: 55 x Det: SE 1 mm SEM MAG: 55 x Date(m/d/y): 07/31/14 University of Johannesburg	Point	composition		intermetallic compound
		Al	Cu	
	1	92	7	-
	2	96	4	-
	3	89	10	-
	4	68	32	-
	5	12	88	AlCu
	6	5	95	-
b  SEM HV: 20 kV WD: 15.00 mm VEGA3 TESCAN SEM MAG: 55 x Det: SE 1 mm SEM MAG: 55 x Date(m/d/y): 07/31/14 University of Johannesburg	Point	composition		intermetallic compound
		Al	Cu	
	1	92	7	-
	2	84	15	-
	3	83	17	-
	4	77	23	Al ₂ Cu ₃
	5	71	29	-
	6	4	96	-

Table 4.6 Presents the EDS analyses of the keyhole for (a) CCS_1200_0.5 and (b) CCS_1200_1 spot welds

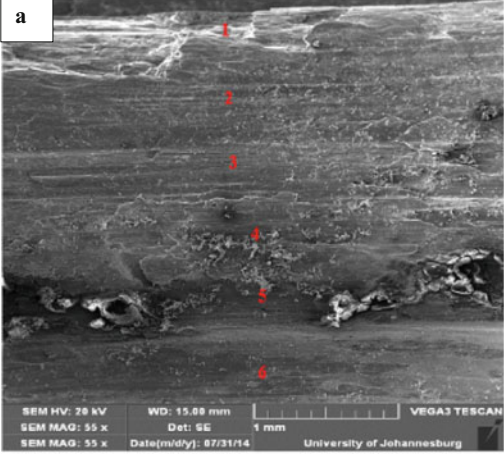
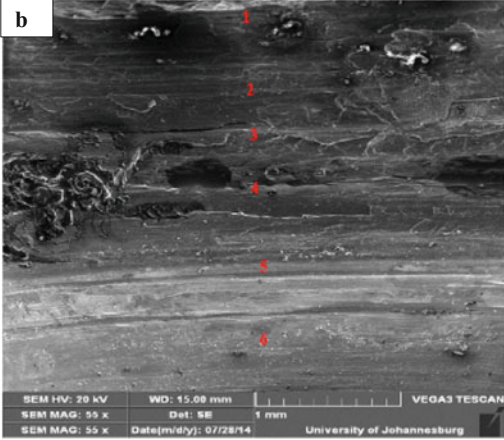
a  SEM HV: 20 kV WD: 15.09 mm VEGA3 TESCAN SEM MAG: 55 x Det: SE 1 mm SEM MAG: 55 x Date(m/d/y): 07/31/14 University of Johannesburg	Point	composition		intermetallic compound
		Al	Cu	
	1	96	3	
	2	97	3	
	3	94	6	
	4	72	27	
	5	90	9	
	6	78	21	
b  SEM HV: 20 kV WD: 15.09 mm VEGA3 TESCAN SEM MAG: 55 x Det: SE 1 mm SEM MAG: 55 x Date(m/d/y): 07/28/14 University of Johannesburg	Point	composition		intermetallic compound
		Al	Cu	
	1	92	8	
	2	95	5	
	3	93	6	
	4	92	8	
	5	24	76	
	6	14	86	

Table 4.7 Depicts the EDS analyses of the stir zone for FPS_800_05 and FPS_800_1 spot welds

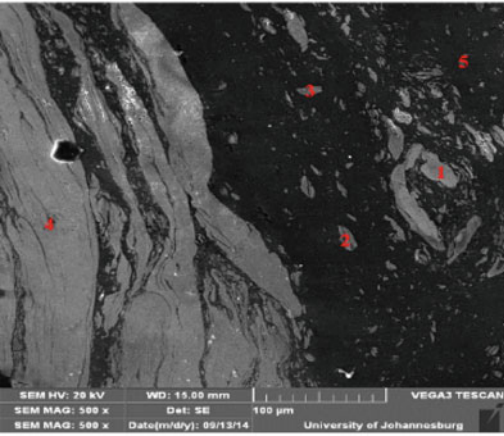
	Point	composition		intermetallic compound
		Al	Cu	
	1	0.72	99.28	-
	2	40.88	58.91	Al ₂ Cu
	3	16.4	83.6	Al ₄ Cu ₉
	4	1.49	98.51	-
	5	35.51	64.49	AlCu

Table 4.8 Depicts the EDS analyses of the stir zone for (a) FPS_1200_0.5 and (b) FPS_1200_1 spot welds

a			Point	composition		intermetallic compound
				Al	Cu	
			1	54.94	45.06	
			2	48.5	51.5	Al ₂ Cu
			3	4.34	95.66	-
			4	24.55	75.45	Al ₃ Cu ₄
			5	41.98	58.02	Al ₂ Cu

b			Point	composition		intermetallic compound
				Al	Cu	
			1	1.46	98.54	
			2	17.71	82.29	Al ₄ Cu ₉
			3	36.27	63.73	AlCu
			4	94.53	5.07	-
			5	16.98	83.02	Al ₄ Cu ₉

Table 4.9 Depicts the EDS analysis of the stir zone for (a) CCS_800_0.5 and (b) CCS_800_1 spot welds

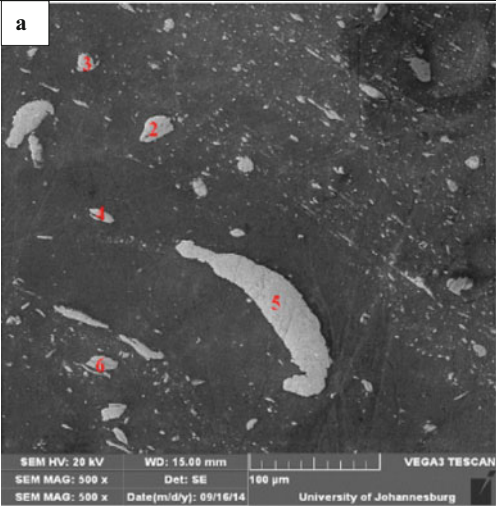
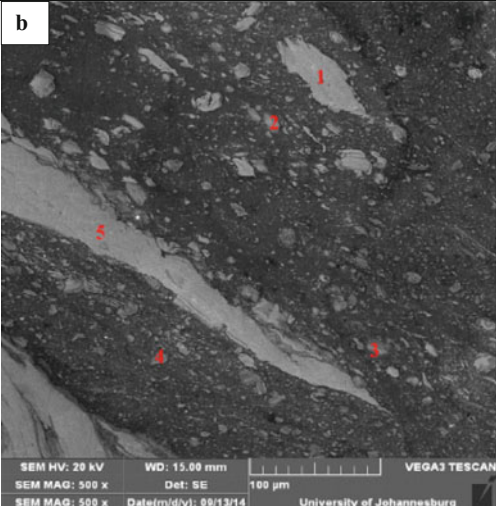
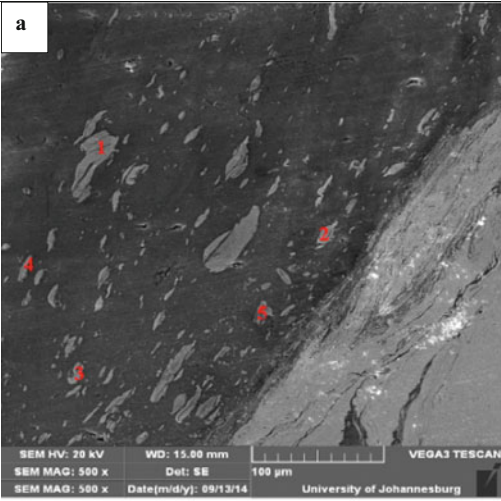
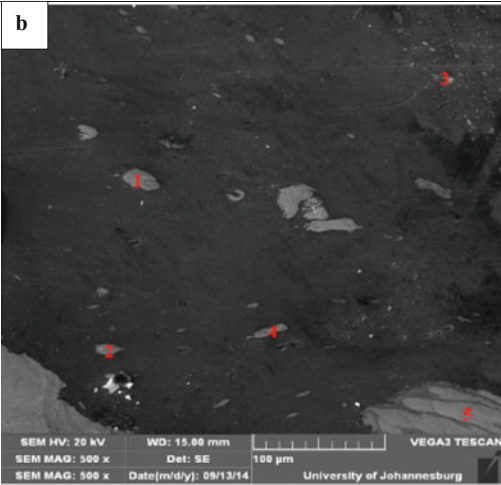
a 	Point	composition		intermetallic compound
		Al	Cu	
	2	6.21	93.79	-
	3	94.79	5.01	-
	4	4.17	95.83	-
	5	0.55	99.45	-
	6	20.45	79.55	Al ₄ Cu ₉
b 	Point	composition		intermetallic compound
		Al	Cu	
	1	5.86	94.14	-
	2	18.74	81.26	Al ₄ Cu ₉
	3	26.55	73.45	AlCu
	4	79.17	20.53	-
	5	2.64	97.36	-

Table 4.10 Depicts the EDS analysis of the stir zone for
(a) CCS_1200_0.5 and
(b) CCS_1200_1 spot welds

a	Point	composition		intermetallic compound
		Al	Cu	
	1	3.1	96.9	-
	2	7.82	92.18	-
	3	49.49	50.27	Al ₂ Cu
	4	29.22	70.78	AlCu
	5	13.77	86.23	AlCu ₃
b	Point	composition		intermetallic compound
		Al	Cu	
	1	2.26	97.74	-
	2	1.33	98.67	-
	3	92.77	6.97	-
	4	37.35	62.65	AlCu
	5	9.15	90.85	-

4.4 Conclusion

Friction stir spot welding between 3 mm thick AA1060 and C11000 was conducted by using two different tool geometries, namely: flat pin/flat shoulder and conical pin/concave shoulder. The microstructural evolution and the chemical analysis of some areas of the spot welds produced at different processing parameters were investigated. The results showed the presence in all the welds of a copper ring on both sides of the keyhole; while the length increases with the shoulder plunge depth. But the joint produced at 1200 rpm for the two tool geometries demonstrated a decrease and a slight increase in the length of the copper ring, when using a flat pin/flat shoulder and conical pin/concave shoulder, respectively.

Furthermore, a good metallurgical mixing was observed in most of the spot welds produced. The mapping of a region of the keyhole/copper ring and the stir zone of the spot weld showed different microstructures with copper particles and fragments in the aluminium matrix. Al_4Cu_9 , Al_2Cu , Al_2Cu_3 and Al_2Cu intermetallics were the most common intermetallic compounds formed in the spot welds. Additionally, the EDS analysis also revealed low peaks for the presence of intermetallics in the keyhole and interfacial regions of the spot welds.

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Chapter 5

Microhardness Profile and Shear Tensile Test of FSSWelds AA1060 to C11000 (Case Study)



Abstract Friction stir spot welding (FSSW) is a solid state welding process; and it is used to overcome the difficulties of joining aluminium and copper alloys. Dissimilar joining of AA1060 and C11000 using friction stir welding was carried out. The microhardness profile analyses were carried out and the probability distribution function (PDF) of the measured microhardness values was determined. Additionally, shear tensile tests were conducted. High microhardness values were obtained in the region close to the keyhole of most of the samples, which could be linked to the presence of intermetallic compounds in the stir zone of the spot welds. For the shear tensile test, only a nugget pull out failure mode took place in all the produced spot welds. The PDF revealed that the process parameters and the tool geometries significantly have an effect on the distribution of the microhardness values.

Keywords Aluminium • Copper • FSSW • Microhardness • Shear tensile
Probability density function

5.1 Introduction

Aluminium and copper are among the widely used materials for engineering structure; and this is due to their performances including higher electric conductivity and heat conductivity. Understanding the joining of aluminium and copper would enable researchers worldwide to understand phenomena, which occur during the joining of the two materials. Friction stir spot welding is a solid state joining technique and a variant of friction stir welding [1]. Investigating welds' properties, such as microhardness and shear tensile strength would provide a good understanding of the different combinations of process parameters employed during friction stir spot welding.

Many researchers have investigated the link between process parameters, tool geometries and the resulting shear tensile values and microhardness profiles of Al/Cu friction stir spot welds [2–7]. On the other hand, the usage of statistical analyses

would assist in evaluating the effect of process parameters and the resulting properties of the produced spot welds. Akinlabi and Akinlabi [8] carried out a statistical analysis, in an attempt to understand the link between the process parameters and the resulting properties of friction stir welds Al/Cu. They found that the downward vertical force has a significant effect on the obtained tensile strength. Furthermore, a strong link between the electrical resistivity and the weld heat input was observed [8].

This chapter focuses on the effect of the process parameters, including rotational speed and shoulder plunge depth on the microhardness profile and the shear tensile strength. The relationship between the microhardness profiles and the process parameters using the Probability Density Function (PDF) was also analyzed.

5.2 Materials and Methods

In this study, AA1060 and C11000 sheets were used, both 3 mm thick, 600 mm in length and 120 mm in width, as depicted in Fig. 5.1. The sheets were friction stir spot welded by using different process parameters and tool geometries. A lap weld configuration was used in this study, as depicted in Fig. 5.2; and a 30 mm overlap configuration was used. The spot welds were produced at rotation speeds of 800 and 1200 rpm, 0.5 and 1 mm tool shoulder plunge depths when using a constant dwell time of 10 s. Table 5.1 presents the chemical composition of AA1060 and C11000.

5.2.1 Vickers Microhardness Profile

A Vickers microhardness analysis were carried out on the parent materials and on the fabricated FSS Welds samples. ASTM standard E384-11^{e1} [9] was used for the

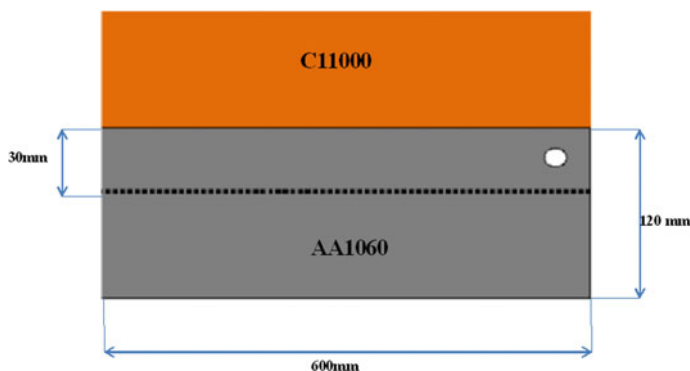


Fig. 5.1 Shows the dimensions of the coupons used in the current study

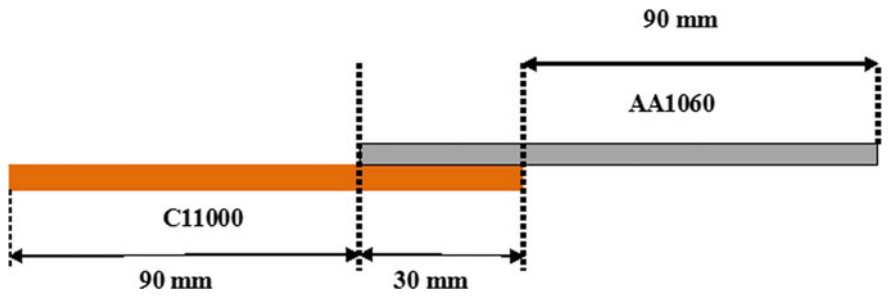


Fig. 5.2 Shows the joint configuration used in the current study

Table 5.1 The chemical composition of AA1060 and C11000 (in wt%)

	Si	Fe	Ga	Others	Al					
AA1060	0.058	0.481	0.011	0.05	Balance					
	Zn	Pb	Ni	Al	Co	B	Sb	Nb	Others	Cu
C11000	0.137	<0.1	0.02	0.023	0.012	0.077	0.036	0.043	<0.492	Balance

preparation of the samples. The measurements were done along the cross sections of the welds with 100 g as the load and 10 s dwell time. Intervals of 0.5 mm were used between the two microhardness indentations. That was done to analyze the microhardness trend on the produced spot welds. The measurements were done using the screw gauge attached to the Dura hardness tester. The recommended standard test method for Vickers microhardness of metallic samples is a 1–120 kgf load; and in this study 100 g was used, based on the literature sources [9–12].

The microhardness profiles were measured from the stir zone in the middle of the copper ring and in the bottom sheet (copper), as depicted in Fig. 5.3.

Furthermore, the obtained microhardness values were used, in order to find the Probability Density Function (PDF) of each one. A Matlab 2014 software program was used.

Fig. 5.3 Shows the microhardness measurement locations on a spot weld (dashed lines to illustrate the two locations)

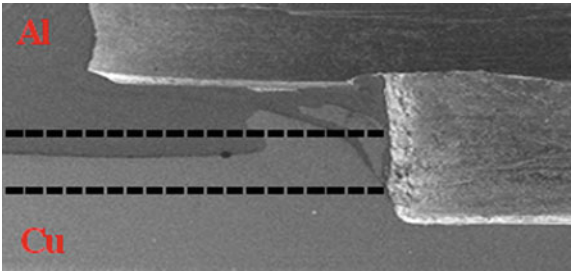




Fig. 5.4 Shows some of the specimens used for the shear tensile test in the current study

5.2.2 Shear Tensile Testing

Lap shear tensile strength tests of the produced weld samples were conducted, in order to investigate the effect of the process parameters on the obtained shear tensile results. Some of the shear tensile specimens used in this study are presented in Fig. 5.4; the lap shear testing was performed by using an Instron screw-driven tensile machine (Model 1195, 5500R) with a load cell of 100 kN and 3 mm/min crosshead speed.

5.3 Results and Discussion

The microhardness values of the copper parent material ranged from 86.7 to 96.3 HV; whereas for the aluminium, the values were between 34.6 and 40.3 HV. Shiraly et al. [3] reported that the presence of hard and brittle intermetallic compounds could be the causal factor for the sudden increase of microhardness in the stir zone. They further stated that the higher microhardness values around the keyhole have good consistency with the copper layers severely broken up into fine particles that are dispersed randomly [3]. Their statement was in agreement with the results obtained in the current research work.

Figure 5.5 presents the microhardness profile of the spot welds produced, when using a flat pin/flat shoulder and conical pin/concave shoulder tools at 800 rpm (rotation speed) and two shoulder plunge depths, namely 0.5 and 1 mm.

The measurements were taken in the top part of the samples (Fig. 5.3). The highest microhardness values of 63.8 HV and 123 HV were obtained for the weld produced at 800 rpm, 0.5 mm shoulder plunge depth using the flat pin/flat shoulder and conical pin/concave shoulder tools, respectively.

On the other hand, the highest microhardness values of 415 HV and 140 HV were measured for the samples produced at 800 rpm, 1 mm shoulder plunge depth, using flat pin/flat shoulder and conical pin/concave shoulder tools, respectively. It was further noticed that in most cases, the microhardness values decreased when the measurements were recorded away from the keyhole. This shows that the presence of intermetallics especially in the stir zone definitely affect the microhardness values.

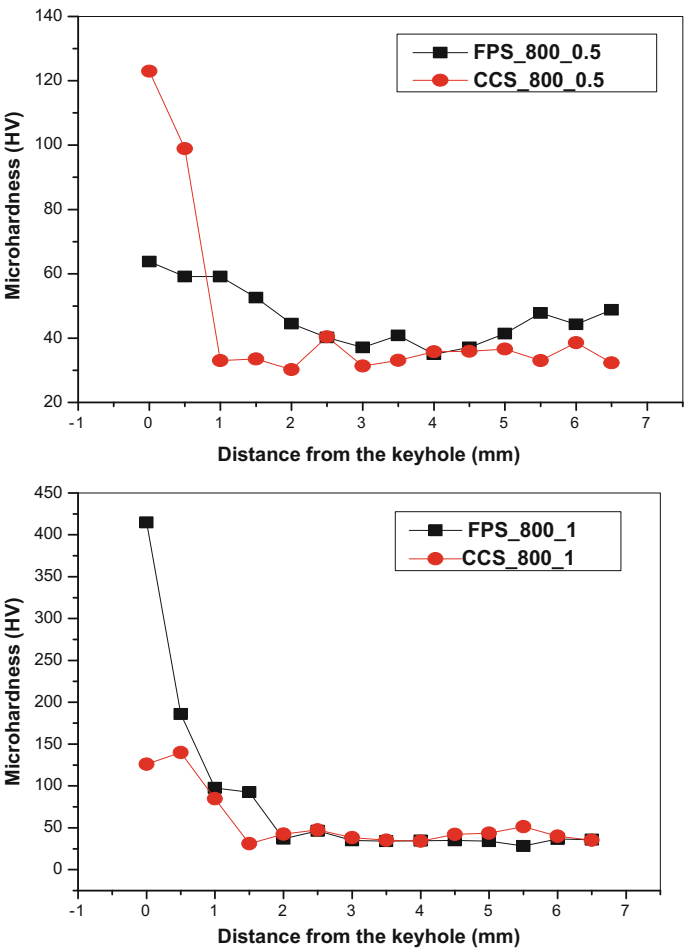


Fig. 5.5 Microhardness profile along welds produced using flat pin/flat shoulder (FPS) and conical pin/concave shoulder (CCS) at 800 rpm and at 0.5 mm and 1 mm shoulder plunge depth at the top

Figure 5.6 depicts the microhardness values for the spot welds produced at 1200 rpm and with a shoulder plunge depth of 0.5 and 1 mm using flat pin/flat shoulder and conical pin/concave shoulder tools. These measurements were recorded in the top part of the welds from the keyhole. The highest microhardness values of 153 HV and 109 HV were recorded for the welds produced at 1200 rpm, 0.5 shoulder plunge depth using flat pin/flat shoulder and conical pin/concave shoulder tools, respectively. On the other hand, the highest values of 154 HV and 93.3 HV were obtained for the welds produced at 1200 rpm, shoulder plunge depths of 1 mm, when using a flat pin/flat shoulder and conical pin/concave shoulder tools.

The microhardness values obtained at the bottom part of the welds, as illustrated in Fig. 5.3 are depicted in Figs. 5.7 and 5.8. The highest microhardness values of 105 HV and 95 HV were obtained in the welds produced at 800 rpm and 0.5 shoulder plunge depth, when using a flat pin/flat shoulder and conical pin and concave shoulder tools, respectively. Additionally, the highest microhardness values of 158 HV and 101 HV were obtained in the welds fabricated at 800 rpm and 1 mm shoulder plunge depth by using a flat pin/flat shoulder and a conical pin/concave shoulder, respectively. No trend was observed to show the effect of process parameters and tool geometries on the microhardness profile.

Figure 5.8 presents the microhardness profile recorded at the bottom part of the samples, when using the two tool geometries at a rotational speed of 1200 rpm and a shoulder plunge depth of 0.5 and 1 mm. 94.4 HV and 96 HV were the highest values of microhardness recorded for the weld produced at 1200 rpm, 0.5 shoulder plunge depth using a flat pin/flat shoulder and a conical pin/concave shoulder, respectively. On the other hand, 96 HV and 96.1 HV were the highest microhardness values obtained respectively, when using the flat pin/flat shoulder and conical pin/concave shoulder tools. The welds were fabricated by using 1200 rpm, as the rotational speed and 1 mm as the shoulder plunge depths.

The statistical analyses using the probability distribution function (PDF) of the microhardness results obtained by using various process parameters and tool geometries is presented and discussed. Schneider et al. [13] stated that all the mechanical tests are subject to large statistical fluctuations, which should be evaluated.

Yurkov et al. [14] reported that the probability distribution function of the Vickers hardness corresponds to a Gaussian (or Normal law). Yanchev and Trifonova [15] stated that it is a log normal. Hassan et al. [16] studied the significance of the process parameters in the friction stir welding of aluminium matrix composites (AMCs). In this study, a Matlab2014a statistical toolbox was employed. It was used to analyze the probability density function of the obtained microhardness results. This was carried out to establish an understanding on how different parameters and tool geometries can affect the probability of obtaining specific microhardness values.

The microhardness measurements were taken from two different locations, as shown in Fig. 5.3. A probability density function (PDF) is a function that describes the relative possibility for a random variable to take on a given value.

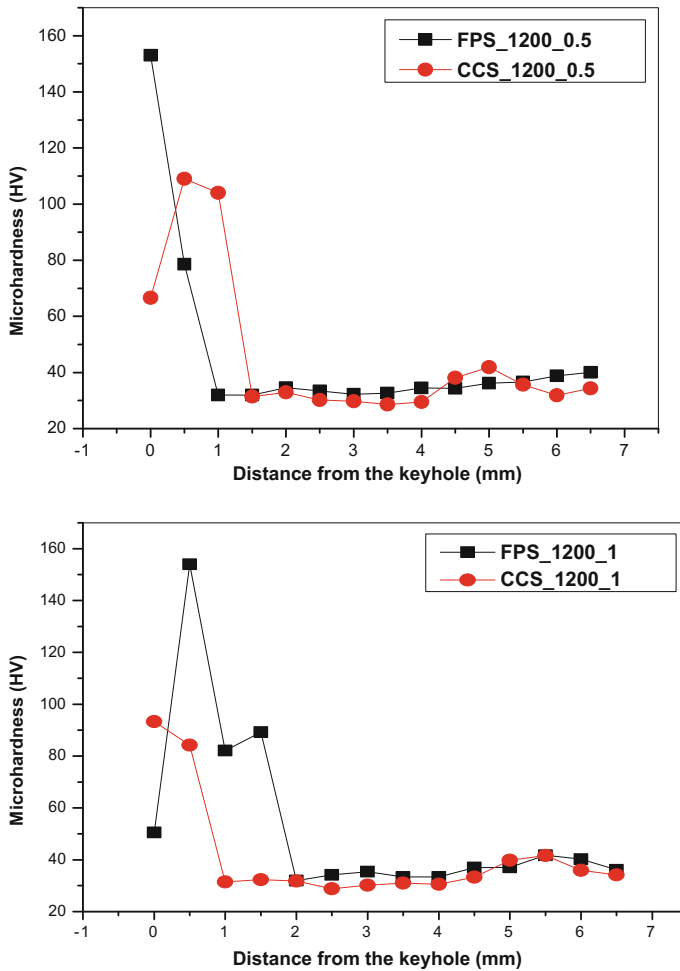


Fig. 5.6 Microhardness profile along welds produced using flat pin/flat shoulder (FPS) and conical pin/concave shoulder (CCS) at 1200 rpm and using 0.5 mm and 1 mm shoulder plunge depths at the top

The probability of the random variable falling within a particular range $[a, b]$ of values is given by a finite integral of the pdf within that range $[a, b]$.

$$p(x) = \int_b^a f(x, \mu, \sigma) = \int_b^a \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (5.1)$$

The PDF histograms of the microhardness values and their fits of the parent materials, namely, aluminium and copper, are depicted in Fig. 5.9a, b, respectively.

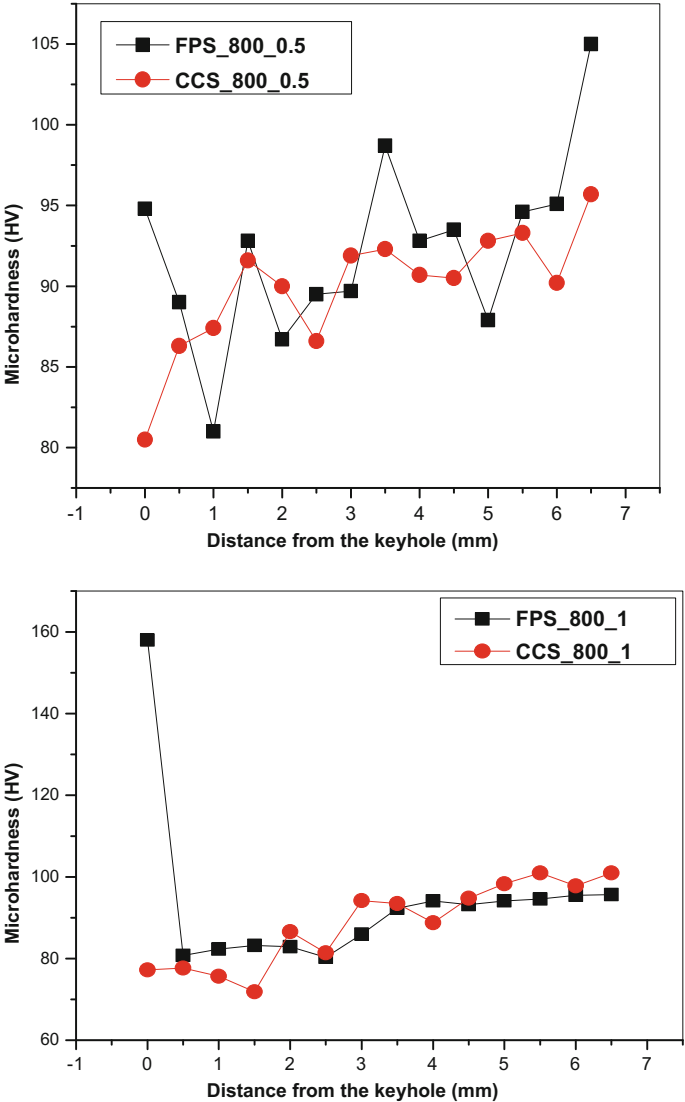


Fig. 5.7 Microhardness profile along welds produced using flat pin/flat shoulder (FPS) and conical pin/concave shoulder (CCS) at 800 rpm and using 0.5 mm and 1 mm shoulder plunge depths at the bottom

The probability density function of the top and bottom microhardness measurements were investigated. Figure 5.10a, b depict the PDF histograms of the microhardness values for the weld produced at 800 rpm, 0.5 mm shoulder plunge depth, when using a flat pin and a flat shoulder tool.

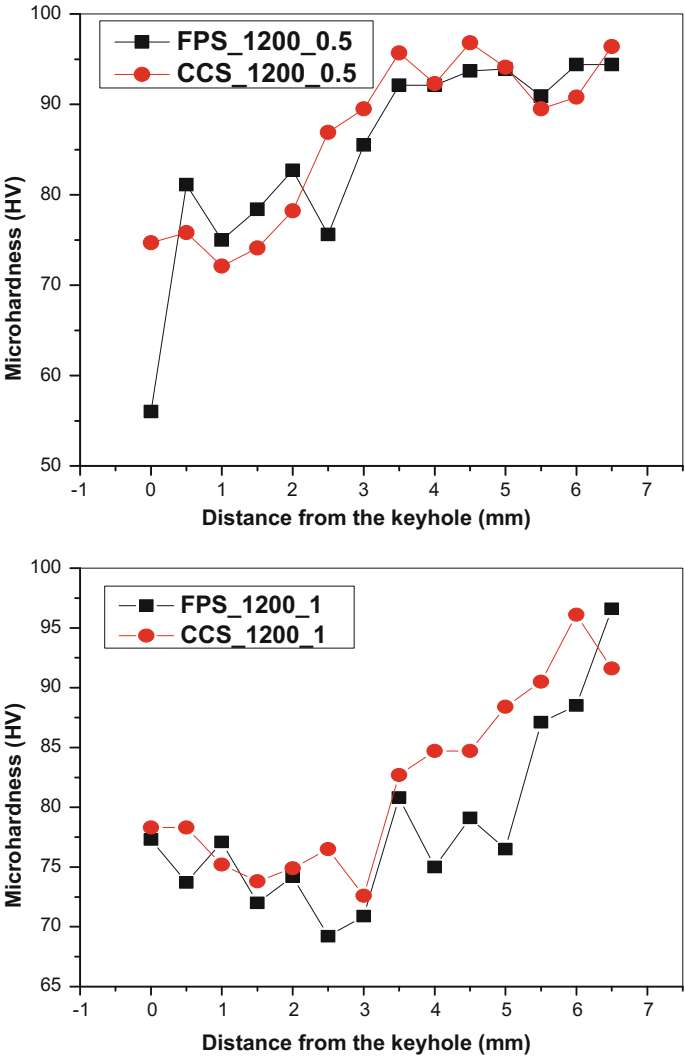


Fig. 5.8 Microhardness profile along welds produced using flat pin/flat shoulder (FPS) and conical pin/concave shoulder (CCS) at 1200 rpm and using 0.5 mm and 1 mm shoulder plunge depths at the bottom

It can be observed that the probability of having microhardness values between 40 and 45 HV is high in the histogram, as shown in Fig. 5.10a, which represents the microhardness measured at the top of the spot weld. This corresponds mostly to the microhardness of the aluminium parent material; whereas, the possibility of getting high microhardness values between 50 and 60 HV is low. On the other hand, the probability density function of the bottom measurement depicted in Fig. 5.10b

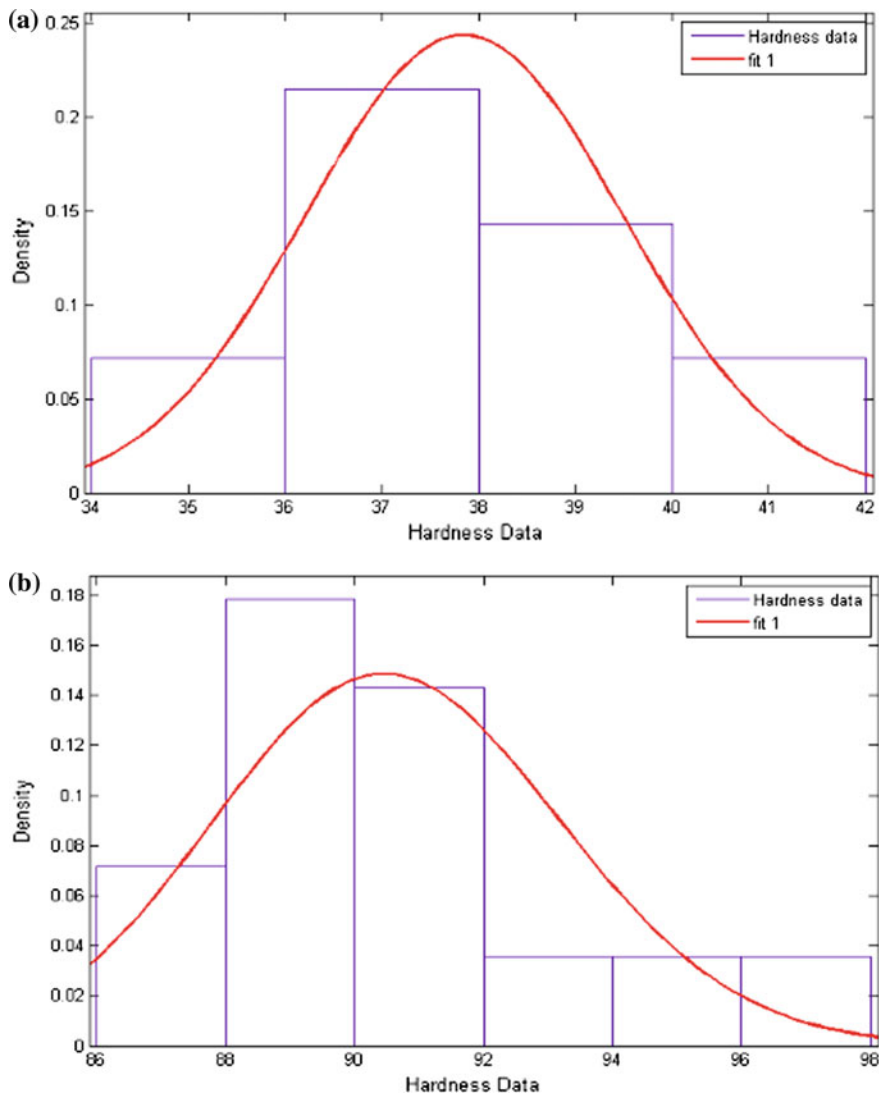


Fig. 5.9 Depicts the microhardness PDF histograms of the parent materials, **a** aluminium, **b** copper

shows that there is a high possibility of getting microhardness values between 85 and 95 HV. This corresponds with the microhardness of the copper parent materials plates; while the microhardness values between 100 and 105 HV are likely to show a lower possibility of being obtained.

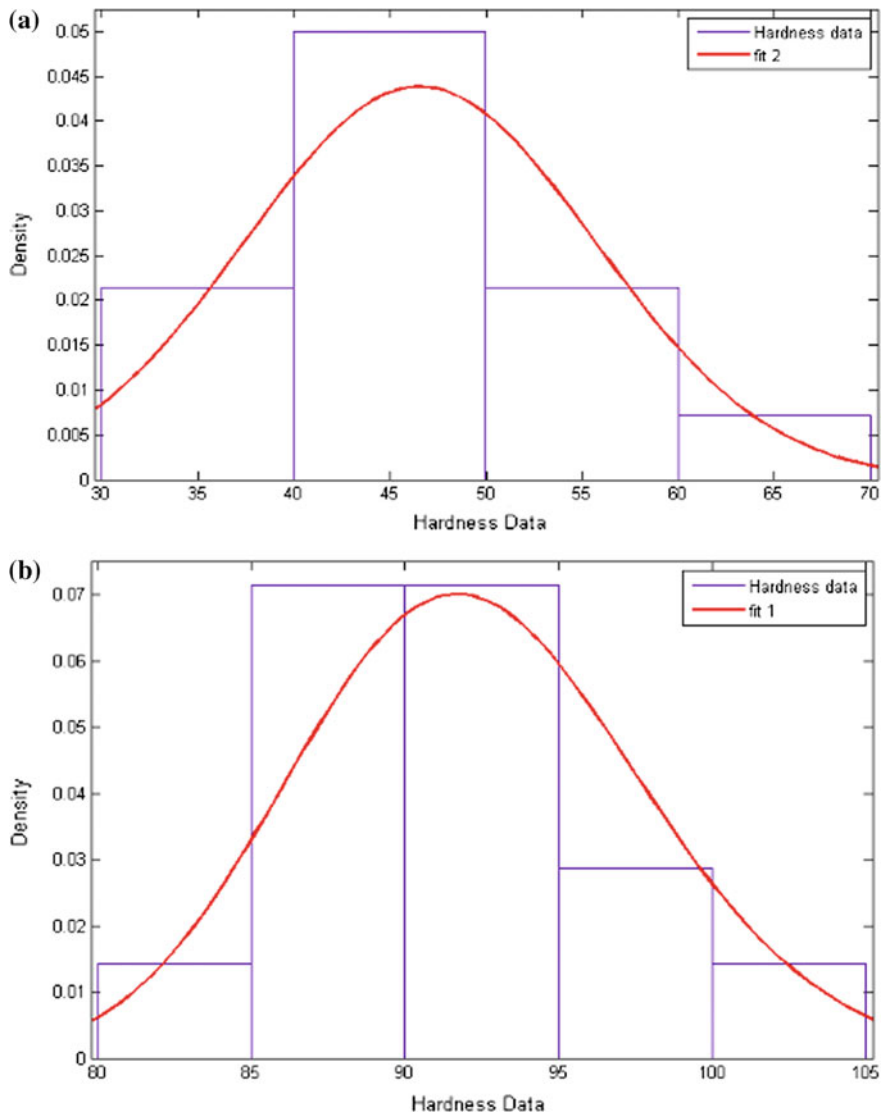


Fig. 5.10 PDF histograms of the microhardness of FPS_800_0.5 spot weld, **a** top and **b** bottom

The possibility of having higher microhardness values compared to the values of the base materials was assumed to be due to the presence of a mixture of copper and aluminium in the vicinity of the keyhole.

Figure 5.11 depicts the PDF histogram of the microhardness obtained at the top (a) and bottom (b) for the weld produced at 800 rpm, 0.5 mm shoulder plunge depth, when using a conical pin/concave shoulder.

The results show that there is a higher possibility of microhardness values between 30 and 50 HV; whereas the high values between 120 and 130 HV can be obtained at a low possibility, as shown in Fig. 5.11a.

Moreover, when the rotational speed at 1200 rpm is increased, the possibility of getting high microhardness values between 100–110 HV and 90–100 HV increases

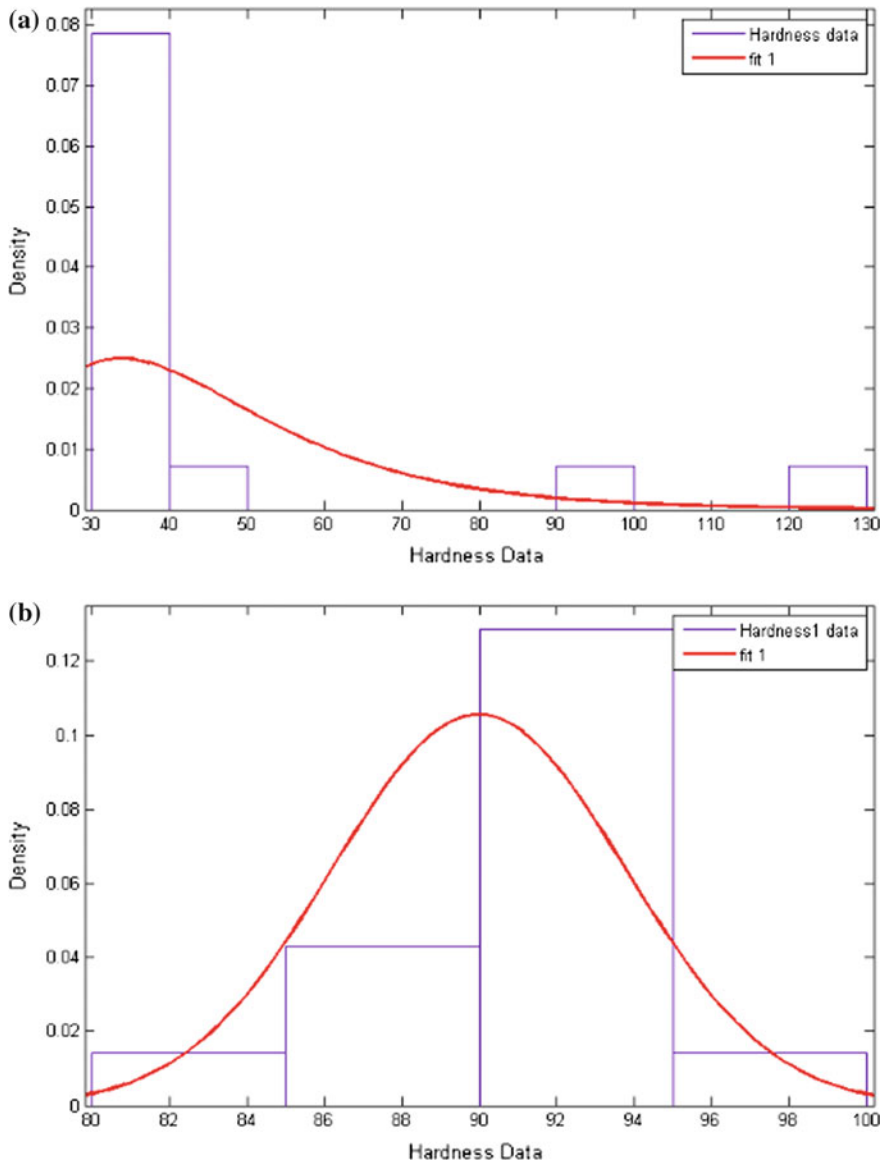


Fig. 5.11 PDF histogram of the microhardness of CCS_800_0.5 spot weld, **a** top and **b** bottom

for the spot weld produced when using a conical pin and a concave shoulder for the top measurement, and for the top and bottom microhardness values, respectively. It can be seen that the rotational speed and the tool geometry can influence the possibility of different probability distributions.

The model shows that in order to get the probability in a certain region, we need to compute the integral of the PDF in the region of interest. The PDF found in the current study is a normal distribution called a Gaussian distribution. In order to get any probability, we can compute the finite integral of the normal distribution of Eq. 5.1.

The goodness of the fit and the residuals were also analyzed. The results show that most of the values of the R^2 ranged between 0.8842 and 0.9999, which is an indication on how well the model fits with the produced experimental data; and these are presented in Tables 5.2, 5.3, 5.4 and 5.5.

Figure 5.12a, b present the goodness of the fit and the residuals for the weld produced at 1200 rpm, 1 mm shoulder plunge depth using a flat pin and a flat shoulder tool (top microhardness measurement). In addition, Fig. 5.13a, b depict

Table 5.2 R^2 and adjusted R^2 of the welds produced using a flat pin and a flat shoulder tool for the microhardness measured on top

Sample ID	R square	R square adjusted
FPS_800_0.5	0.9896	0.9322
FPS_800_1	0.9996	NA
FPS_1200_0.5	0.9999	0.9995
FPS_1200_1	0.9993	0.9952

Table 5.3 R^2 and adjusted R^2 of the welds produced using a conical pin and a concave shoulder tool for the microhardness measured on top

Sample ID	R square	R square adjusted
CCS_800_0.5	0.9924	0.9505
CCS_800_1	0.9976	0.9843
CCS_1200_0.5	0.9893	0.9303
CCS_1200_1	0.9997	0.9978

Table 5.4 R^2 and adjusted R^2 of the welds produced using a flat pin and a flat shoulder tool for the microhardness measured at the bottom

Sample ID	R square	R square adjusted
FPS_800_0.5	0.8842	0.2475
FPS_800_1	0.9999	NA
FPS_1200_0.5	0.9937	0.9589
FPS_1200_1	0.9298	0.5439

Table 5.5 R^2 and adjusted R^2 of the welds produced using a conical pin and a concave shoulder tool for the microhardness measured at the bottom

Sample ID	R square	R square adjusted
CCS_800_0.5	0.9818	0.8819
CCS_800_1	0.9424	0.6258
CCS_1200_0.5	0.987	0.9157
CCS_1200_1	0.9866	0.9126

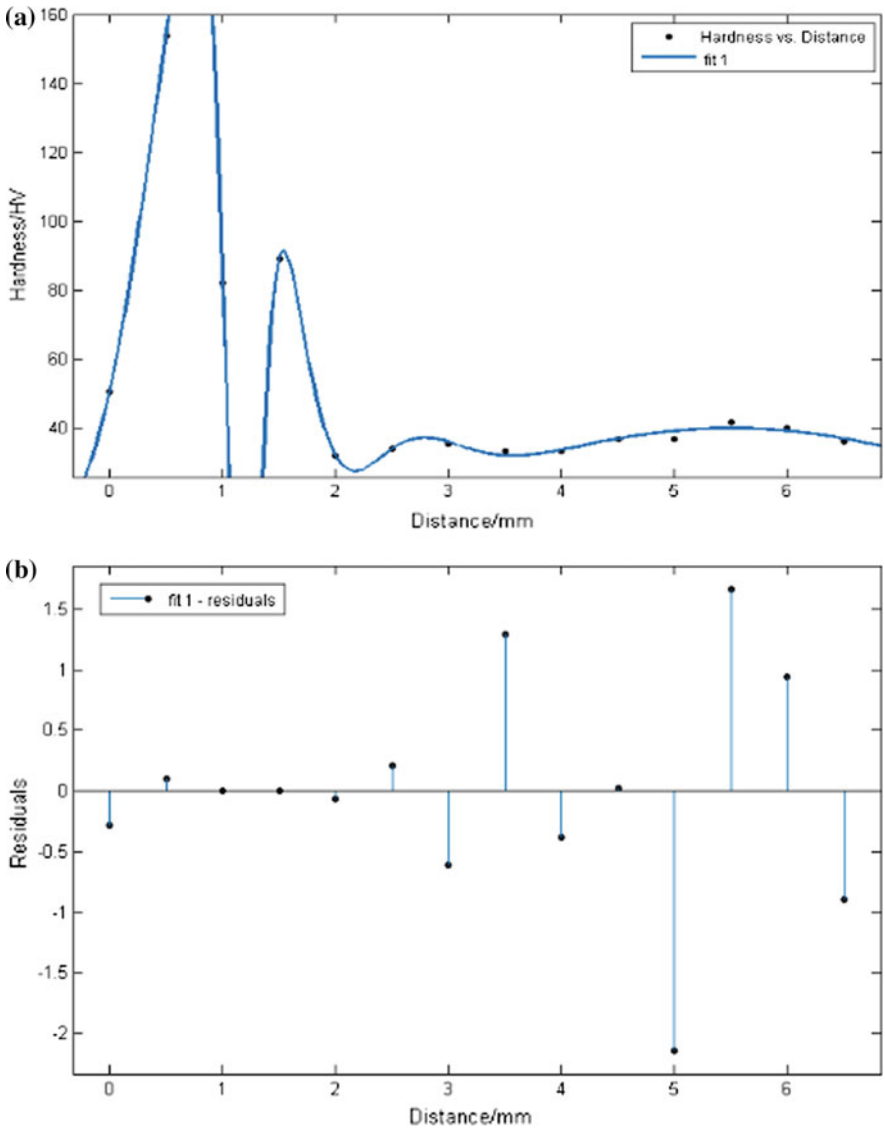


Fig. 5.12 Goodness of the fit (a) and the residuals (b) for the spot weld produced at 1200 rpm, 1 mm shoulder plunge depth using a flat pin and a flat shoulder (top microhardness measurements)

the goodness of the fit and the residuals for the weld produced at 1200 rpm, 1 mm shoulder plunge depth when using a conical pin and a concave shoulder (top microhardness measurement). The residual analysis were employed, in order to check the adequacy of the models. Figure 5.12b and Fig. 5.13b show the residual plots for the microhardness values obtained at the top using a flat pin/flat shoulder

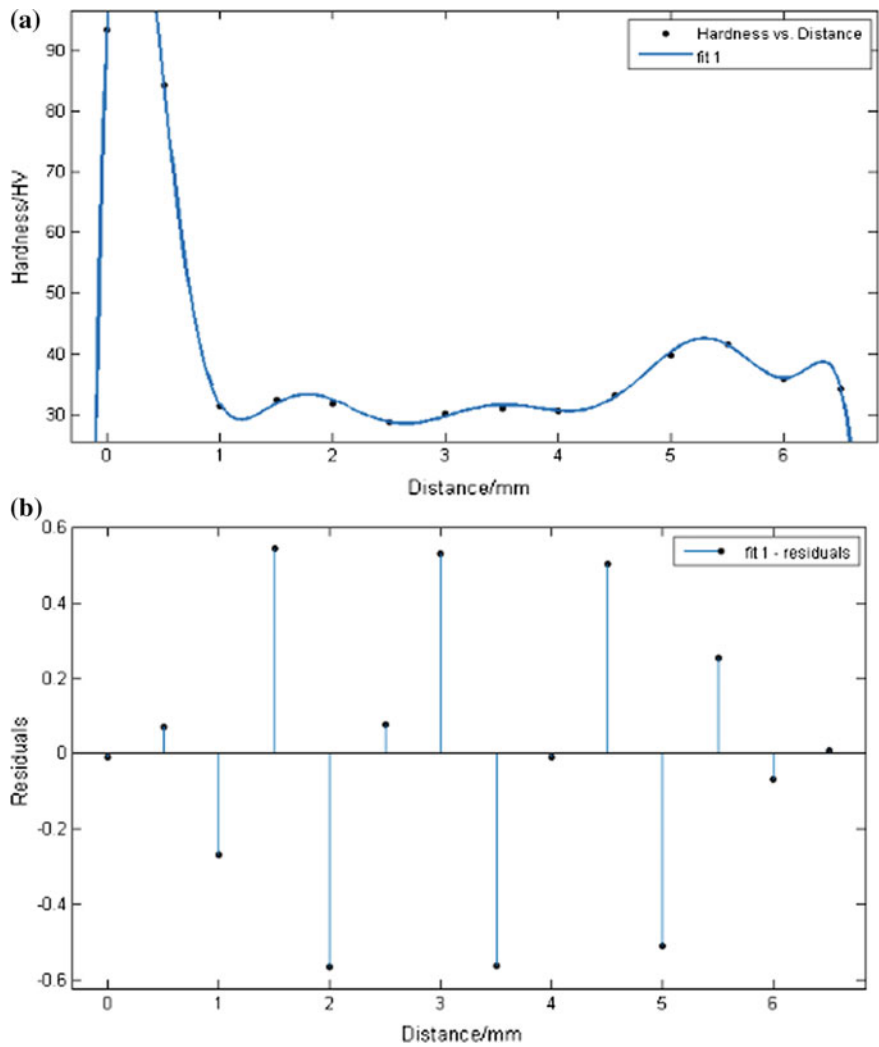


Fig. 5.13 Goodness of the fit (a) and the residuals (b) for the spot weld produced at 1200 rpm, 1 mm shoulder plunge depth when using a conical pin and a concave shoulder (top microhardness measurements)

and a conical pin/concave shoulder when using a 1200 rpm and 1 mm plunge shoulder plunge depth, respectively.

The standard deviation, the variance and the mean obtained from the statistical analyses of the measured microhardness values of the two locations positions are presented in Tables 5.6, 5.7, 5.8 and 5.9.

It should be noted that the mean is equal to μ if the distribution is normal. In some cases in the current study, μ and the mean have different values, which shows

Table 5.6 Mean, variance, mu and sigma of the spot samples produced when using a flat pin and a flat shoulder tool for the microhardness taken on top

Sample name	Mean	σ^2	μ	σ
FPS_800_0.5	46.5429	82.8442	46.5429	9.10188
FPS_800_1	75.0992	4994.97	4.00167	0.79641
FPS_1200_0.5	45.1208	441.806	3.71115	0.44317
FPS_1200_1	51.7308	672.845	3.83391	0.47359

Table 5.7 Mean, variance, mu and sigma of the spot samples produced when using a conical pin and a concave shoulder tool for the microhardness taken on top

Sample name	Mean	σ^2	μ	σ
CCS_800_0.5	44.5748	409.802	3.70341	0.43303
CCS_800_1	55.8872	813.763	3.90757	0.48119
CCS_1200_0.5	45.4532	482.889	3.71166	0.45831
CCS_1200_1	40.9416	248.04	3.64315	0.37148

Table 5.8 Mean, variance, mu and sigma of the spot samples produced using a flat pin and a flat shoulder tool for the microhardness taken at the bottom

Sample name	Mean	σ^2	μ	σ
FPS_800_0.5	92.2338	32.7196	4.52241	0.06196
FPS_800_1	84.7	119.974	84.7	10.9533
FPS_1200_0.5	84.7	119.974	84.7	10.9533
FPS_1200_1	78.4286	58.0637	78.4286	7.61996

Table 5.9 Mean, variance, mu and sigma of the spot samples produced using a conical pin and a concave shoulder tool for the microhardness taken at the bottom

Sample name	Mean	σ^2	μ	σ
CCS_800_0.5	89.9857	14.2859	89.9857	3.77967
CCS_800_1	88.5643	102.307	88.5643	10.1147
CCS_1200_0.5	86.2521	89.6604	4.45128	0.10945
CCS_1200_1	82.0425	54.8519	4.40318	0.09009

that the distributions were not normal in some of the analyses. The standard deviation σ should be close to zero; but in the current work, the value of the standard deviation is not close to zero in some of the cases. This shows that the microhardness values are not close to the expected values; and this could be due to the presence of very far apart measured microhardness values in the different locations of the weld samples.

These results were obtained because of the presence of intermetallics, which could have been the cause of the high microhardness values. It is known that intermetallic compounds are hard and brittle.

Furthermore, in a plot of residual versus distance, it has been shown that the models are adequate to predict the responses in an acceptable manner.

In friction stir spot welding of dissimilar materials, the formation of intermetallic compounds, especially in the stir zone, can significantly reduce the joint strength. Tables 5.10 and 5.11 present the results of the failure loads.

High failure loads of 5225 and 4844 N were obtained when using a flat pin and a flat shoulder at 800 rpm, 1 mm shoulder plunge depth and 1200 rpm and 1 mm shoulder plunge depth, respectively. It was observed that by increasing the plunge depth, strong welds were obtained; this was in agreement with the results obtained by Heideman et al. [2]. Additionally, the two highest failure loads obtained when using a conical pin and a concave shoulder were 2991 and 4606 N; the parameters used were 800 rpm, 0.5 mm shoulder plunge depth and 1200 rpm, 1 mm shoulder plunge depth, respectively.

It was observed that, a strong weld was obtained by using 800 rpm and 0.5 mm shoulder plunge depth; and the welds using the same rotation speed and 1 mm shoulder plunge depth gave a slightly lower failure load. Figures 5.14 and 5.15 show the shear loads and the displacement curves of the friction stir spot welds when using different tool geometries and process parameters.

It was observed that all the fractures were ductile. Moreover, the presence of the copper ring extruded upwards on both sides of the keyhole from the lower copper

Table 5.10 Failure load results for the welds produced with a flat pin and a flat shoulder

Rotation speed (rpm)	Tool shoulder plunge depth (mm)	Failure load (N)			Mean Failure load (N)
		Weld 1	Weld 2	Weld 3	
800	0.5	761	2547	2697	2622
800	1	5225	1281	4498	3668
1200	0.5	245	4459	1271	4459
1200	1	3207	4289	4844	4113

Table 5.11 Failure load results for the welds produced using a conical pin and a concave shoulder

Rotation speed (rpm)	Tool shoulder plunge depth (mm)	Failure load (N)			Mean Failure load (N)
		W1	W2	W3	
800	0.5	1173	1833	2991	2412
800	1	1373	1077	2739	2056
1200	0.5	3454	3978	4086	3839
1200	1	4609	202	2380	3495

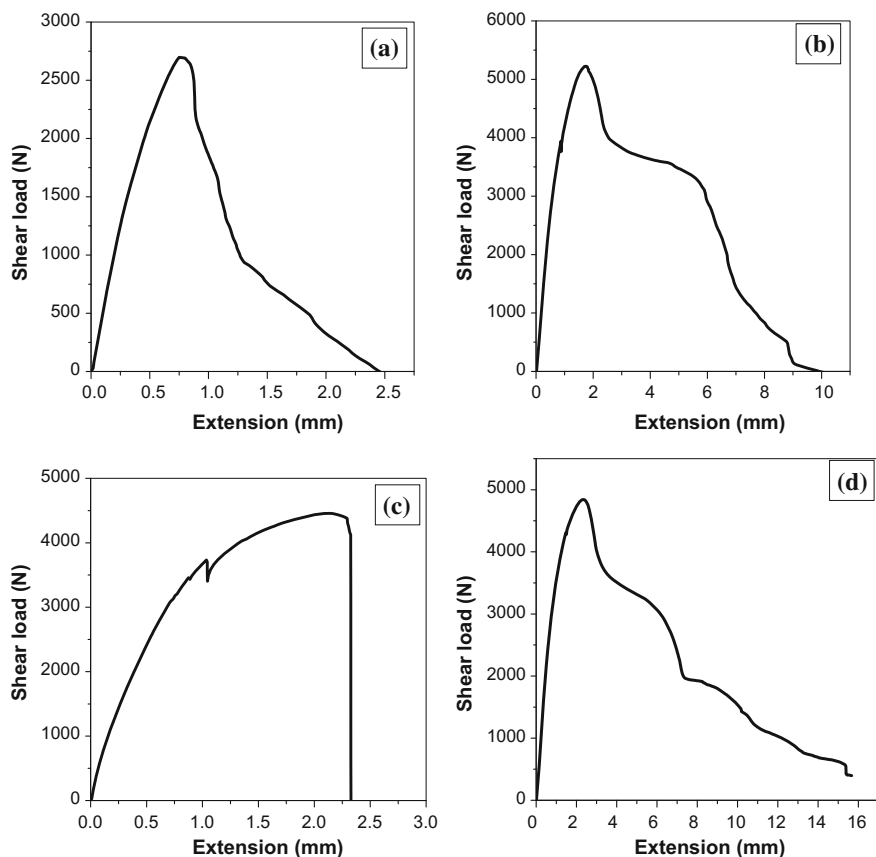


Fig. 5.14 Shear tensile behavior of weld produced at **a** FPS_800_05, **b** FPS_800_1, **c** FPS_1200_0.5, **d** FPS_1200_1 using a flat pin and flat shoulder

plate. This was suspected to influence the fracture mode. The copper ring caused interlocking between the two sheets and helped the sheets adhere to each other during the tensile testing, and to reach a high strength before failure [2]. The effect of the process parameters on the maximum failure load is represented in Figs. 5.16 and 5.17 for the welds produced when using a flat pin/flat shoulder and conical pin and concave shoulder, respectively.

It was observed that as the shoulder plunge depth increases, the failure load increases, except for the weld produced at 800 rpm when using a conical pin and a concave shoulder. On the other hand, Figs. 5.18 and 5.19 show the fractured samples of the welds produced at 1200 rpm, 0.5 mm shoulder plunge depth using a flat pin and a flat shoulder tool, and at 800 rpm, 0.5 mm shoulder plunge depth, when using a conical pin and a concave shoulder tool, respectively.

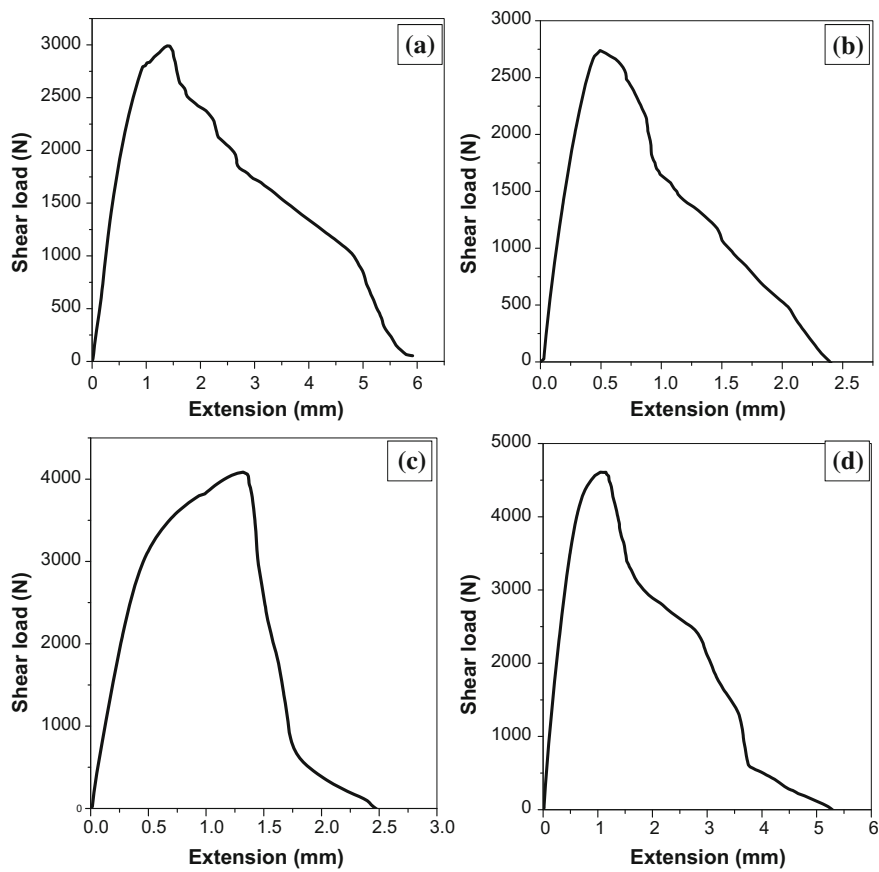


Fig. 5.15 Shear tensile behavior of weld produced at **a** CCS_800_05, **b** CCS_800_1, **c** CCS_1200_0.5, **d** CCS_1200_1 using a flat pin and flat shoulder

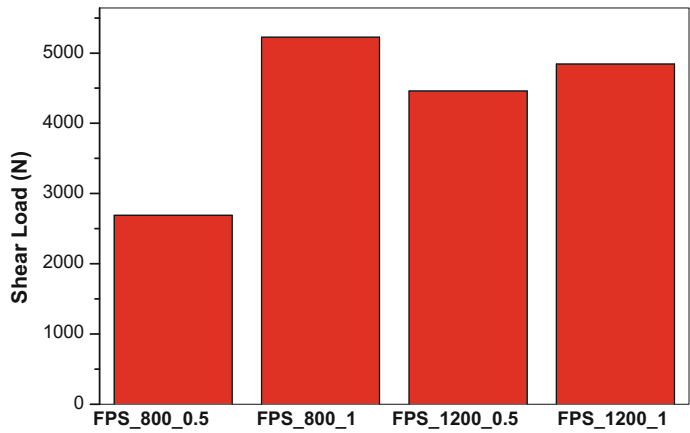


Fig. 5.16 Shows the effect of process parameters on the maximum failure load of the welds produced when using a flat pin and a flat shoulder tool at 800 rpm and 1200 rpm

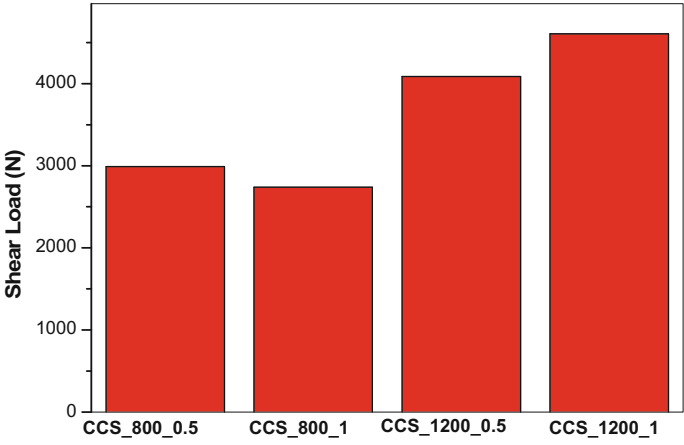


Fig. 5.17 Shows the effect of process parameters on the maximum failure load of the welds produced using a conical pin and a concave shoulder tool at 800 rpm and 1200 rpm

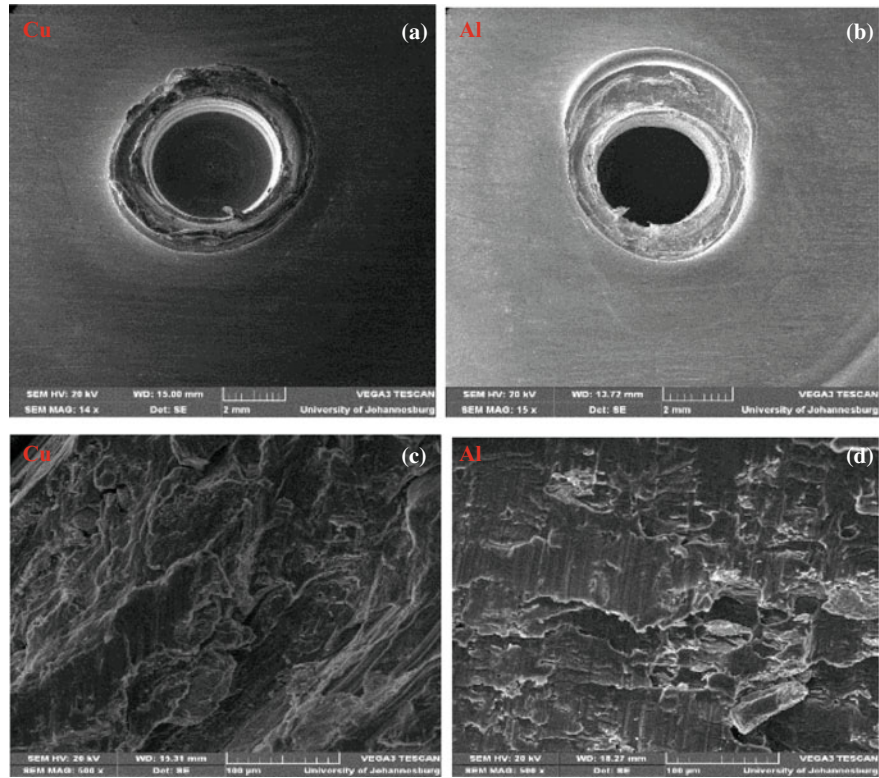


Fig. 5.18 SEM images of spot weld produced using a flat pin and a flat shoulder tool; the rotation speed was 1200 rpm and the shoulder plunge depth of 0.5 mm, **a** failed nugget upper sheet (Cu), **b** the lower sheet (Al), **c** and **d** fractured surface on the copper and aluminium side, respectively

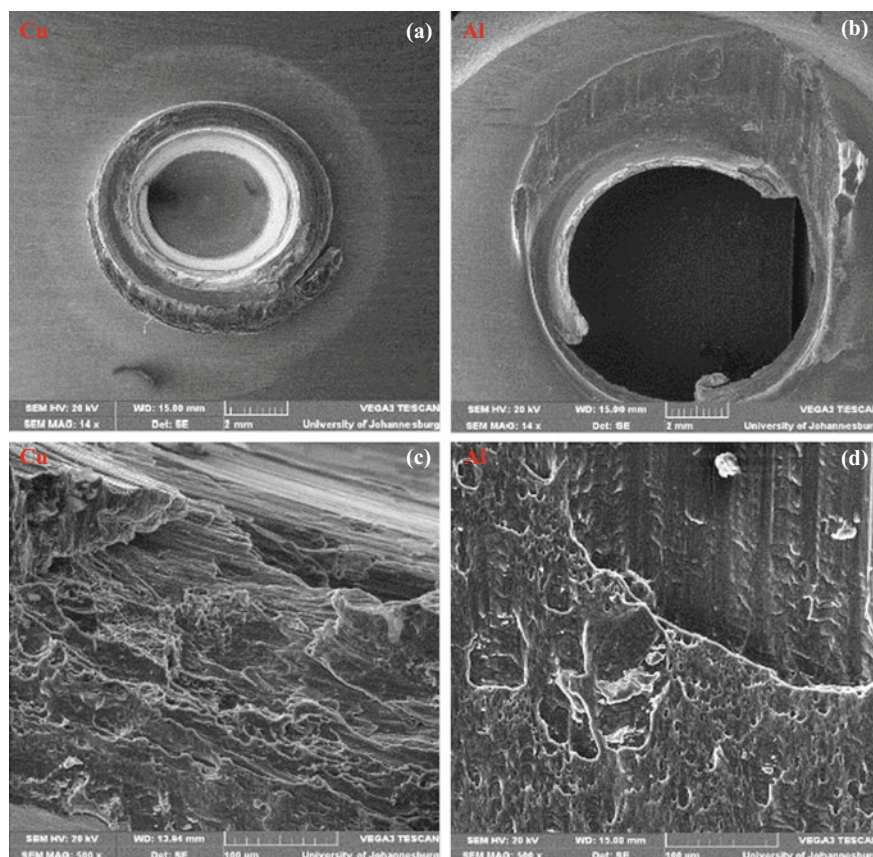


Fig. 5.19 SEM images of spot weld produced using a conical pin and a concave shoulder tool; the rotation speed was 800 rpm and the shoulder plunge depth of 0.5 mm, **a** failed nugget upper sheet (Cu), **b** the lower sheet (Al), **c**, **d** fractured surface on the copper and aluminium side, respectively

According to Lin et al. [17], the shear failure mechanism is the principal failure initiation mechanism of the nugget pull out failure mode in lap-shear specimens from the mechanical point of view. Only the pull-out nugget failure mode was observed in the current research work; and this was due to the difference in properties of the parent materials. The fracture surface of the spot weld revealed a ductile morphology. It can also be seen that the prominent fracture surface includes the presence of small dimples, which may be attributed to the homogeneous microstructure of the small grains at the failure location [18].

The dimples were in different sizes, which can be attributed to the different process parameters and the tool geometries used. The low shear tensile results obtained in some of the experiments could be due to the presence of cavity defects in some of the fractured samples. The results were in agreement with the results obtained by Tan et al. [19].

5.4 Conclusions

A 3 mm thick AA1060 and C11000 were joined by using friction stir spot welding. Different tool geometries: namely, a flat pin/flat shoulder and a conical pin/concave shoulder and different process parameters were used to weld the sheets.

Higher microhardness values measured (top) were observed in all the spot welds and this was in the zone close to the keyhole. Additionally, all the microhardness values measured (bottom) in the zone close to the keyhole, had lower values and were close to the average value of the copper parent material. This was noticed for all the joints produced when using a conical pin/concave shoulder.

The PDF histograms of the measured microhardness values revealed that the process parameters and the tool geometries significantly affect the distribution of the microhardness values in different weld locations.

Furthermore, the goodness of fit values showed that most of the R^2 values ranged between 0.8842 and 0.9999, this is an indication of how well the model fits with the produced experimental tests. The maximum shear tensile failure load increases with an increase in the tool shoulder plunge depth, excluding the weld fabricated at 800 rpm when using a conical pin/concave shoulder tool.

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Chapter 6

Residual Stresses in Friction Stir Spot Welded AA1060 to C11000 Using the X-Ray Diffraction Technique (Case Study)



Abstract Aluminium and copper are widely used in engineering structures, due to their unique performances, such as higher electrical conductivity, heat conductivity, corrosion resistance and mechanical properties even though they have considerable differences in their melting points. In this study, the microstructure of the friction stir spot welds of aluminium and copper produced at various parameter combinations were analyzed by using a scanning electron microscope; while the residual stresses were studied by using the X-ray diffraction technique. Furthermore, the electrical resistivities of the joints was also measured. The evolving microstructure shows a good mixing in the produced spot welds with Cu particles present in the aluminium matrix. The formation of a copper ring/hook was evident in all the spot welds; and the length thereof increased with the shoulder plunge depth variation; while the spot welds produced at 1200 rpm for the two tool geometries exhibited a decrease and a slight increment in the length of the copper ring using a flat pin/flat shoulder and conical pin/concave shoulder, respectively. The obtained residual stresses results were compressive. The maximum residual stress of -116.8 MPa was measured on the copper ring of the welds produced at 800 rpm and 0.5 mm shoulder plunge depth, when using a flat pin and a flat shoulder tool. This was due to the generation of stress, when the copper was extruded into the aluminium sheets. Furthermore, the intensity of all the peaks using different process parameters decreased in comparison to the peaks generated by the parent materials and the effect of shoulder plunge depth on the full width at half the maximum (FWHM) was observed. The values of the measured electrical resistivities of the joints were higher than those of the parent materials.

Keywords Aluminium • Copper • Copper ring • Electrical resistivity
Full width at half maximum (FWHM) • Residual stresses

6.1 Introduction

More than two decades ago, friction stir welding (FSW) was invented; and it has been recognized as a reputable solid-state welding technique. Furthermore, friction stir spot welding (FSSW), which is a variant of FSW, was also developed as a replacement or an alternative joining process for resistance welding. The applications of FSW and FSSW are expanding to various sectors, including the automotive and aerospace industries. This is mainly because FSW and FSSW processes are environmentally friendly techniques; and they produce unique microstructures, which can lead to good mechanical properties. Nowadays, there is an increasing need for high strength, lightweight materials, such as the composites for various applications; and in order to achieve this, a good understanding of the different aspects of their behavior, including the mechanical properties, is critical. One example is residual stresses in materials, which can be created by the utilization of the above mentioned processes.

Residual stresses can be defined as the stresses that persist within a material or body after manufacturing and the material processing in the absence of any external forces or thermal gradients. They can also be produced by service loading, leading to non-homogeneous plastic deformation in the part or sample. Consequently, residual stresses are not caused by loads, such as forces or moments [1].

Differential plastic flow, differential cooling rates, and phase transformations with volume changes can be taken as the different reasons for the occurrence of residual stresses.

On the other hand, residual stresses occur in various manufactured structures and components. Many investigations have been conducted to study this phenomenon and its effect on the mechanical properties of these components [1]. Different methods have been developed to measure the residual stress for different types of components, in order to obtain reliable evaluation. These methods include non-destructive, semi-destructive and destructive methods, as portrayed in Table 6.1.

During the past years, many researchers have investigated residual stress in friction stir welded structures.

Residual stress distributions were determined by using X-ray diffraction on AA 2219 T87 and AA 2219 T851 as the plate and the ring, respectively. This was investigated by Pfeiffer et al. [3] on two different types of components, namely, an 8.5 mm thick plate with the dimensions of 500 mm × 300 mm and a 8 mm thick

Table 6.1 Residual stresses measurement methods [2]

Non destructive	Semi destructive	Destructive
Barkhausen noise method	Hole-drilling technique	Sectioning technique
X-ray diffraction method	Ring-core method	Contour method
Neutron diffraction method	Deep-hole method	
Ultrasonic method		

ring with a diameter of 5.4 m and height of 175 mm. The spot diameters were 1 mm in the case of the plate and 2 mm in the case of the ring segment. $\text{CuK}\alpha$ radiation with an effective penetration depth of $37\text{ }\mu\text{m}$ was used to determine the lattice strains from the diffraction line positions of the $\{422\}$ —lattice planes. Calculation of the stresses was performed on the basis of the $\sin^2\psi$ -technique.

Substantial compressive stresses of $\sim 70\text{ MPa}$ developed in the longitudinal direction at both sides of the remaining specimen, due to cutting. In the transverse direction, the smaller tensile stresses of $\sim 30\text{ MPa}$ were created. Meanwhile, the stresses at the top and root side of the specimen were similar. It may therefore be concluded that no significant bending occurs due to cutting. Furthermore, only small stresses of up to 20 MPa were generated when cutting the circumferential cylinder weld. At the inner side of the ring (the weld root), all the stress components are compressive; whereas at the outer side (the weld crown), the transverse components tend to be tensile. These stress components are included in the results of the subsequent residual stress measurements on the part cut out of the cylinder. The transverse residual stresses are small and generally compressive. The residual stress distribution measured in the weld nugget at the outer surface of the ring-segment (weld crown) indicates a reduction of tensile residual stresses already within the nugget near the fusion line.

This is in contrast with the results for the FSW plates, in which the highest tensile residual stresses were found in the region around the fusion line, with lower residual stresses occurring in the weld centre [3].

Bach et al. [4] reported measurements of residual stress in FSW of AA 2024 T3 using Neutron diffraction. Two test specimens were used in the experiments. These were named: the welded plate and the hammer peened plate.

The as-welded stresses are greater than those in the hammer peened specimen at every slit depth. The maximum tensile stress in the as-welded plate was 239 MPa at a distance of $x = 6\text{ mm}$ to the right of the weld centreline; whereas in the hammer peened specimen, the maximum tensile residual stress was 122 MPa at $x = -8\text{ mm}$ to the left of the weld centreline. Comparing point by point across the weld in the transverse direction, the effects of the hammer peening reduced the tensile residual stresses at every single point, and in most cases caused the stress to change from tension to compression [4].

Fratini et al. [5] determined the residual stress intensity factor K_{Ires} by the cut-compliance method and the residual stress distribution was calculated from the K_{Ires} data with an integral inverse solution based on the Schindler weight function. The AA 2024-T351 plates were friction stir welded. The results showed that K_{Ires} profile for FSW decreases up to a minimum at $\sim 9\text{ mm}$ away from the welding centreline; then, it rises to a positive maximum near the retreating side (R.S.). Weld residual stresses are tensile in the weld, with the external regions being subjected to compressive residual stress; however, this residual stress field did not warp the welded plate out of plane.

Although, the residual stress maximum occurred in the advancing side zone (A.S.), the distribution was quite symmetrical [5].

Furthermore, they recorded a significant reduction in residual stress, up to 90% for the FSW joint after mechanical relief; and thereafter, a very low distribution of K_{Ires} was found; hence, they assumed that there should be very little influence of residual stress on the FCGR (Fatigue Crack Growth Propagation) in the stress relieved specimens. They concluded that the observed residual stress patterns are typical, not only of friction stir welds, but of most welds in general.

Ma et al. [6] friction stir welded AA 2195-T8 plates; and they measured the residual stress, using Neutron diffraction. In order to investigate the influence of the sample dimensions on residual stress profiles, three samples of different sizes were used. The samples were named C (T) for the cracks perpendicular to the weld, and ESE (T) for the cracks parallel to the weld. The X-direction stresses have a double peak tensile residual stress field of similar form in all three specimens. The maximum tensile residual stress parallel to the weld ranged from 120 MPa, for the largest sample, to 47 MPa in the smallest. Remote from the weld line at the notch tip, the minimum stress values varied from about -130 to -20 MPa compression values for the largest and smallest samples.

On the other hand, the Y-direction stresses did not change over the scan line as much as in the X direction; and this was roughly zero (± 10 MPa) at the weld line.

At the notch tip, the residual Y stresses measured -50 MPa compression in the biggest sample, and -20 MPa in the other two samples. Around the notch tip, the residual stresses were always negative for all three sizes: both parallel to, and perpendicular to, the weld.

The residual stress profiles in three sizes C (T) test samples were also investigated. All three C (T) sample sizes showed a double peak in stress, similar to those found in the ESE (T) samples. The maximum residual stress parallel to the weld varied from 110 MPa for the largest sample to 95 MPa for the intermediate to 82 MPa, for the smallest. Furthermore, the residual stresses perpendicular to the weld at this location along the weld line were small, the same as in the ESE (T) samples, with a mean value of about 25 MPa tension, the sample size having little systematic effect.

Ni et al. [7] friction stir welded AA2009 composite reinforced with 17 vol% SiCp. The X-ray diffraction method was used to measure the residual stress of the FSW joints. The results indicated that tensile residual stresses in the weld had a peak value of about 54 MPa in the weld centre. Furthermore, the tensile residual stresses decreased from the centreline to both the retracting side and the advancing side; and they reached about -70 MPa in the heat affected zone. At higher stress amplitudes of above ~ 150 MPa, the parent material showed longer fatigue lives than the FSW joint; but the difference decreased as the stress amplitudes decreased. Both the parent material and the FSW joints showed an equivalent fatigue life at lower stress amplitudes of below ~ 150 MPa [7].

Steuwer et al. [8] carried out studies on the effect of the tool traverse and rotation speeds on the residual stresses by using a synchrotron X-ray method. The parent materials used were AA5083 non-aged hardenable and age-hardenable AA6082 friction stir welds. They found that the region around the weld line was characterized by significant tensile residual stress fields, which are balanced by

compressive stresses in the base material. On the other hand, the rotation speed of the tool has been found to have a substantially greater influence than the transverse speed on the properties and the residual stresses in the welds, mostly on the AA5083 side, where the location of the peak stress moves from the stir zone to beyond the edge of the tool shoulder.

Furthermore, the changes in the residual stress are related to the microstructural and hardness changes. In particular, the larger stresses under the weld tool on the AA5083 side compared to the AA6082 side are related to a transient reduction in yield stress due to the dissolution of the hardening precipitates during the welding prior to the natural ageing after welding [8].

Altenkirch et al. [9] used a synchrotron X-ray diffraction to measure the residual stress distribution in the friction stir welds of AA7449. They investigated the effect of tensioning on the residual stresses. The results showed that by modifying the stress accumulation path, the application of a tensioning stress reduced the tensile magnitude of the final residual weld stresses [9].

Lombard et al. [10], investigated the effect of the varying welding parameters on the residual stress profiles in the friction stir welds of AA5083-H321 using a synchrotron X-ray diffraction method. The results showed that the residual stresses were generally tensile in the weld region, with balancing compressive stresses in the parent material. Furthermore, they concluded that the width of the tensile stress region and the maximum value of the tensile residual stress exhibited a linear dependency, with heat input being calculated by using the different welding process parameters. The heat input appeared to be dominated by the feed rate; and they suggested that the changes in the rotation speed are compensated for by the changes in the measured torque.

Those changes in the heat input directly affected the shape of the residual stress profiles, with more heat input per unit length producing broader residual stress profiles, with lower maxima. The feed rate dominance is supported by a good correlation between the maximum longitudinal residual stress and the feed rate [10].

Peel et al. [11] used the synchrotron X-rays method to measure the residual stress in the friction stir welds of AA5083 sheet. The results showed that the peak longitudinal stresses increased as the traverse speed increases. They attributed the increase to steeper thermal gradients during welding and the reduced time for stress relaxation to occur. Furthermore, the tensile stresses appear to be limited to the softened weld zone, thereby resulting in a narrowing of the tensile region (and the peak stresses) as the traverse speed increases [11].

Prime et al. [12], friction stir welded AA7050-T7451 and AA2024-T351. The residual stresses were measured using the neutron diffraction method; and these researchers concluded that even in friction stir welding of thick, dissimilar, high-strength aluminium alloys, very low residual stresses were attained. The peak stresses of about 43 MPa were less than 20% of the material yield strength. They further said that, such low stresses are virtually unachievable in fusion welding. Even at those low magnitudes, the residual stresses affect fatigue behavior and the measurement of fatigue properties; and therefore, they need to be addressed [12].

Residual stress investigations were conducted by Linton and Ripley [13], when using neutron diffraction. The material used was AA7075-T651 rolled; and in the solution, it was heat-treated and artificially aged via stress relief after heat treatment. The results showed that at all the locations across the weld zone, the highest values of residual stress were recorded in the longitudinal direction; and the lowest values were recorded in the normal direction. For the freshly made weld, all the stress profiles displayed a peak in residual stress in the weld nugget, and a minimum value in the HAZ, just beyond the edge of the tool shoulder [13].

Furthermore, a slightly higher level of stress was recorded on the advancing side of the weld joint [13]. They concluded that, it is important that predictions of anticipated performance and integrity, with regard to resistance to fatigue cracking, should take into consideration the residual stress profiles in aged FSWs, rather than those present in the as-welded samples. This is particularly important for the FSW HAZ, where the as-welded compressive residual stresses become tensile with time [13].

The electrical resistivities of aluminium to copper joints have been investigated by Akinlabi et al. [14] and Savolainen [15]. Akinlabi et al. [14] used AA 5754 to C11000 friction stir welds of 3.175 mm thick; whereas Savolainen used Cu-OF to extruded aluminium alloy EN-AW 6060 T6 of 10 mm thick. Akinlabi et al. [14] found that the electrical resistivities of the produced joints increased as the heat input to the welds increases. The maximum percentage increase in resistivity compared to the average joint resistivity of the parent material was found to be 9.8% [14].

On the other hand, Savolainen [15] found that the resistivity of the welded joint (29 nΩm) is 2.5% higher than the average resistivity of both base materials, which was 28.3 nΩm.

This study is focusing on the measurement of the residual stresses by using the X-ray diffraction technique on FSS Welded AA1060/C11000. The effect of process parameters and tool geometries on the formation of a copper ring and on the full width at half maximum (FWHM) will also be investigated. Furthermore, the effect of process parameters on the electrical resistivities of the produced welds was also investigated.

6.2 Materials and Methods

Sheets of AA1060 (aluminium) and C11000 (copper), each 3 mm thickness, 600 mm length and 120 mm in width were spot lap welded. The chemical composition of the two parent materials was determined by using a spectrometer (Q4 TASMAN). The nominal chemical composition of the aluminium plate is as follow: 0.058 wt% Si, 0.481 wt% Fe, 0.011 wt% Ga, 0.05 wt% others and the rest Al. On the other hand, the chemical composition of the copper plate is, 0.137 wt% Zn, <0.1 wt% Pb, 0.02 wt% Ni, 0.023 wt% Al, 0.012 wt% Co, 0.077 wt% B, 0.036 wt% Sb, 0.043 wt% Nb, <0.492 wt% others and the rest Cu.

The sheets were friction stir spot welded in a 30 mm overlap configuration. The spot welds were produced by using an MTS PDS I-Stir at the eNtsa of Nelson Mandela Metropolitan University (NMMU), Port Elizabeth, South Africa. The tool material is H13 tool steel hardened to 50–52 HRC. The tool pin length and the diameter were kept constant at 4 mm and 5 mm, respectively; while the shoulder diameter was 15 mm. The friction stir spot welds were conducted at rotational speeds of 800 and 1200 rpm; and the tool shoulder plunge depths employed were 0.5 and 1 mm using a constant dwell time of 10 s. Table 6.2 depicts the welding process parameters and the tool geometries used in the current research work.

The presence of copper rings was investigated by using a scanning electron microscope (SEM). A TESCAN Vega TC was used. On the other hand, the residual stress distribution in the friction stir spot welded plates was measured by using the non-destructive X-ray diffraction (XRD) technique. The technique employs inter-planar spacing in the material, which serves as a strain gauge. The principle involves the monitoring of the selected Bragg peak(s) for different tilt angles for each azimuth angle.

By using appropriate elastic constants, the measured strain can be converted to the corresponding residual stress. The residual stress investigations were taken in the SZ and the copper ring area. This was conducted, in order to investigate the effect of the presence of the copper ring extruded upwards from the lower copper plate into the aluminium plate.

The commonly used $\sin^2\psi$ -method was used in the current research study for the determination of the surface residual stresses. The analyses were conducted by using a Bruker D8 Discover diffractometer equipped with $\frac{1}{4}$ Eulerian cradle mounted on a θ – 2θ goniometer. Probing was done by using Cu K_α radiation (with 8 keV energy). The primary optics included a 0.8 mm collimator, as well as a

Table 6.2 Weld matrix and tool geometries

Shoulder plunge depth (mm)	Experiments	Tool rotational speed (rpm)	Shoulder diameter (mm)	Sample designation	Tool features
0.5	1	800	15	FPS_800_0.5	
0.5	2	1200	15	FPS_1200_0.5	Flat pin and shoulder (FPS)
1	3	800	15	FPS_800_1	
1	4	1200	15	FPS_1200_1	
0.5	5	800	15	CCS_800_0.5	
0.5	6	1200	15	CCS_1200_0.5	Conical pin and concave shoulder (CCS)
1	7	800	15	CCS_800_1	
1	8	1200	15	CCS_1200_1	

graphite monochromator. The sample alignment was done by using a laser and video alignment system.

A diffracted beam was collected by using a 2D Vantec 500 detector. The detector was positioned where it coincided with one of the peaks used for the strain measurement. The sample detector distance was 20 cm, corresponding to a range of 32.7° (2θ); and the measurement time per step ranged from 300 to 400 s.

The measurements were performed with the detector positioned at 136° (2θ). In order to have the full stress tensor, the measurements were carried out at six azimuth angles i.e. ϕ and $\phi + 180^\circ$ (0° , 45° , 90° , 180° , 225° , 270°), with the latter allowing measurements at negative tilt angles. For each azimuth angle, a set of eight tilt angles (at 10° increments from 0° to 70°) were acquired. The data thus produced were analyzed by using a LEPTOS version 6.02 software from BRUKER AXS. The analysis was done using the 331 (136.5) Cu reflections. The electrical resistivity of the joint was determined, according to the method used by Akinlabi [16]. This was done by means of a calculation derived from the measurement of the electrical resistance values across the welds. The weld samples were prepared; and a Four-Point probe meter was used to measure the electrical resistance. The electrical resistance of the samples was measured, in accordance with the ASTM standard cited by Akinlabi [16].

6.3 Results and Discussion

6.3.1 *Effect of Process Parameters on the Formation of a Copper Ring (Hook)*

The presence of a keyhole was observed on all the produced spot welds; and on both sides of the welds, there was the presence of copper rings [17], also known as hooks [18], which are a deformed part of the copper material (lower sheet) penetrating into the aluminium (top sheet). This was in agreement with the results obtained by Ozdemir et al. [19]. Figures 6.1 and 6.2 show the copper rings and the corresponding lengths.

The presence of the copper ring was also observed by Heideman et al. [17] with different lengths in all the spot welds. The formation of the copper rings, which consist of the copper parent material extruded in the aluminium plate, was observed. This suggests that while the copper material was moving and diffusing into the aluminium, the aluminium was not diffusing or being pushed into the copper ring [17]. The copper ring lengths of the spot welds produced at different process parameters using a flat pin/flat shoulder and conical pin a/concave shoulder, are depicted in Figs. 6.1 and 6.2. There was also a reduction in the workpiece thicknesses in all the produced spot welds. Ozdemir et al. [19] observed that the penetration length of the copper into the aluminium was about half of the thickness of the aluminium sheet; but this was not the case in the current study.

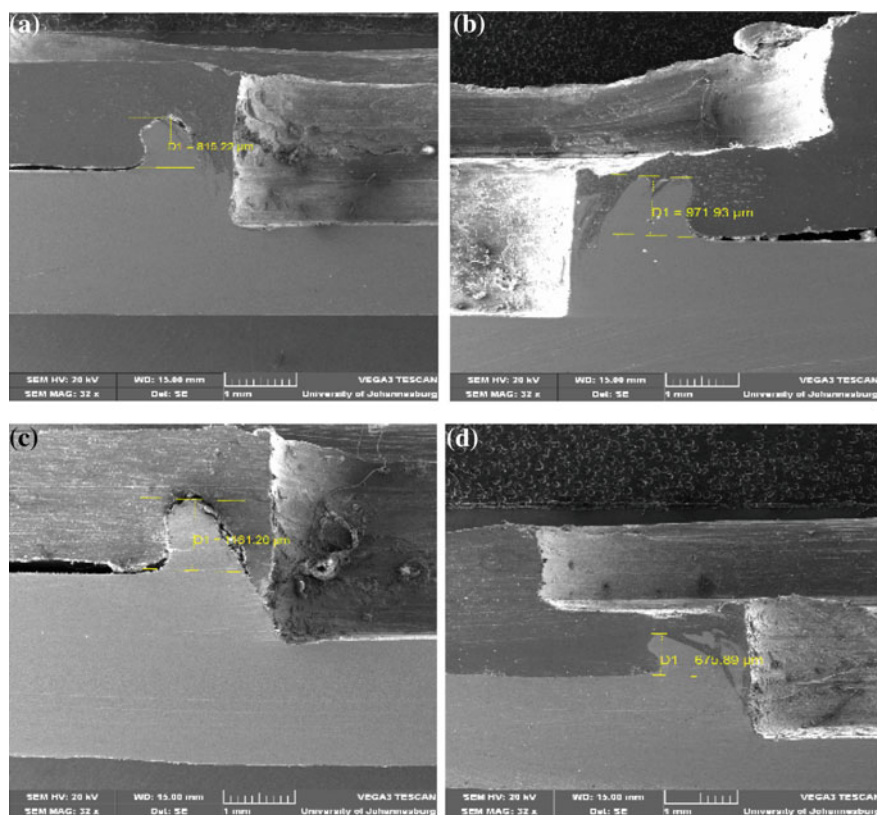


Fig. 6.1 Copper ring length of the spot weld produced: **a** 800 rpm, 0.5 mm, **b** 800 rpm, 1 mm, **c** 1200 rpm, 0.5 mm and **d** 1200 rpm, 1 mm using flat pin and shoulder tool

In the current study, the penetration length of the copper into the aluminium was also studied. The formed copper rings were measured; and the results are shown in Figs. 6.3 and 6.4 for the flat pin/shoulder and the conical pin and concave shoulder, respectively.

It was observed that the copper ring length increases with the increase of the shoulder plunge depth, except for the spot welds produced at 1200 rpm, using a flat pin and shoulder, where a decrease was observed. The copper ring lengths of the welds produced at 1200 rpm using a conical pin and concave shoulder also show a slight difference in the copper ring length. This shows that the welds produced at high rotational speed exhibit either a decrease or a slight increment in the copper ring length. It has been reported that, the copper ring caused interlocking between the two plates and helped the plates to adhere to each other during tensile testing and reach a high strength before failure [17].

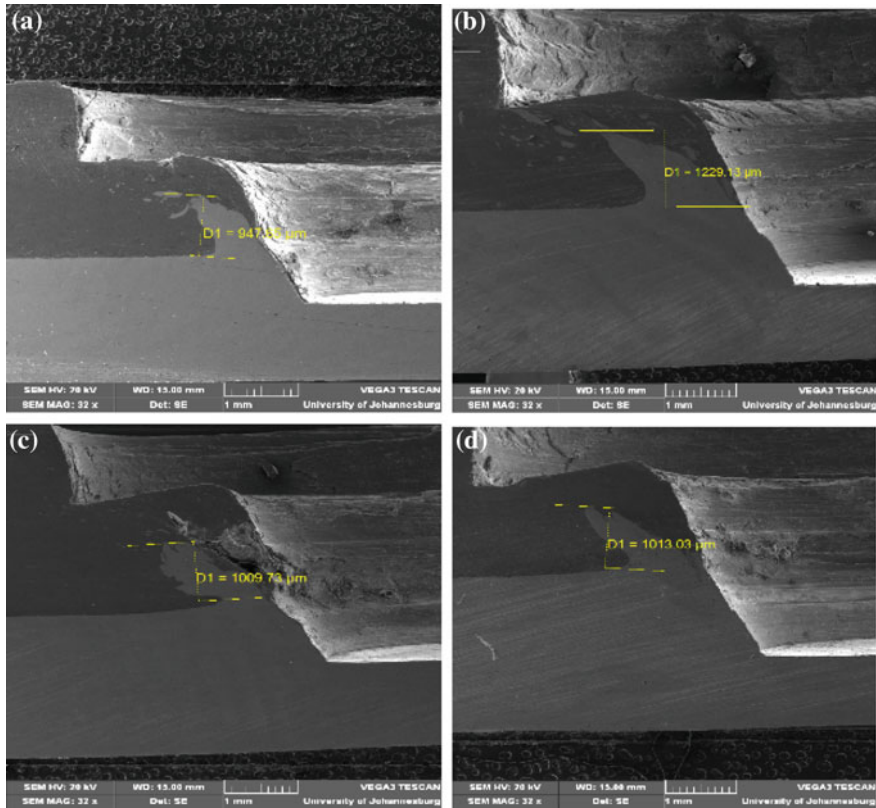


Fig. 6.2 Copper ring length of the spot weld produced: **a** 800 rpm, 0.5 mm, **b** 800 rpm, 1 mm, **c** 1200 rpm, 0.5 mm and **d** 1200 rpm, 1 mm using a conical pin and concave shoulder tool

6.3.2 Residual Stress Analyses Using the XRD Technique

Figure 6.5 depicts a two dimensional image of the residual stress measurement and texture conducted in the current study. It can be seen that the weld had a strong texture. Figure 6.6 shows the residual stress measurement location (SZ) for the welds produced at 800 rpm, 05 mm shoulder plunge depth, when using a flat pin and a flat shoulder and 800 rpm, 0.5 shoulder plunge depth, when using a conical pin and a concave shoulder.

Figure 6.7 presents a typical $\sin^2\psi$ diagram for the (331) diffraction plane of the welds produced at 1200 rpm, 0.5 mm shoulder plunge depth using a flat pin and a flat shoulder tool. The solid line represents the linear least-square fit to a set of data points. Even though the data were slightly scattered, the lattice strain decrease almost linearly with the increase of the $\sin^2\psi$. It was observed that all the residual stresses were compressive (Tables 6.3 and 6.4)

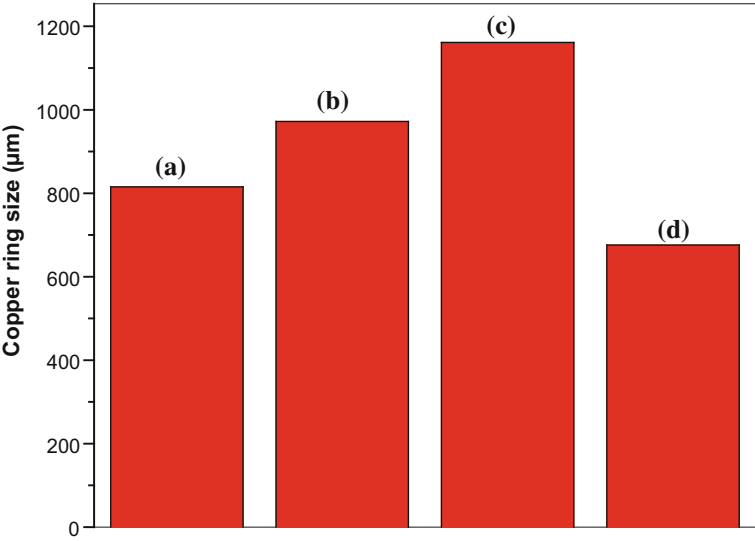


Fig. 6.3 The copper ring lengths obtained using a flat pin and concave shoulder tool at different process parameters, **a** (FPS_800_0.5), **b** (FPS_800_1), **c** (FPS_1200_0.5) and **d** (FPS_1200_1)

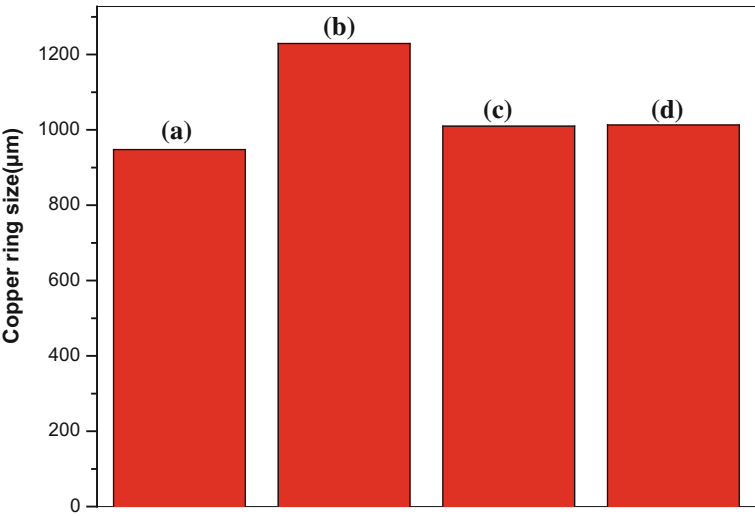


Fig. 6.4 The copper ring (hook) lengths obtained using a conical pin and concave shoulder tool at different process parameters, **a** (CCS_800_0.5), **b** (CCS_800-1), **c** (CCS_1200_0.5) and **d** (CCS_1200_1)

The residual stresses of the welds are shown in Figs. 6.8 and 6.9, respectively, for the welds produced using a flat pin/flat shoulder and conical pin/concave

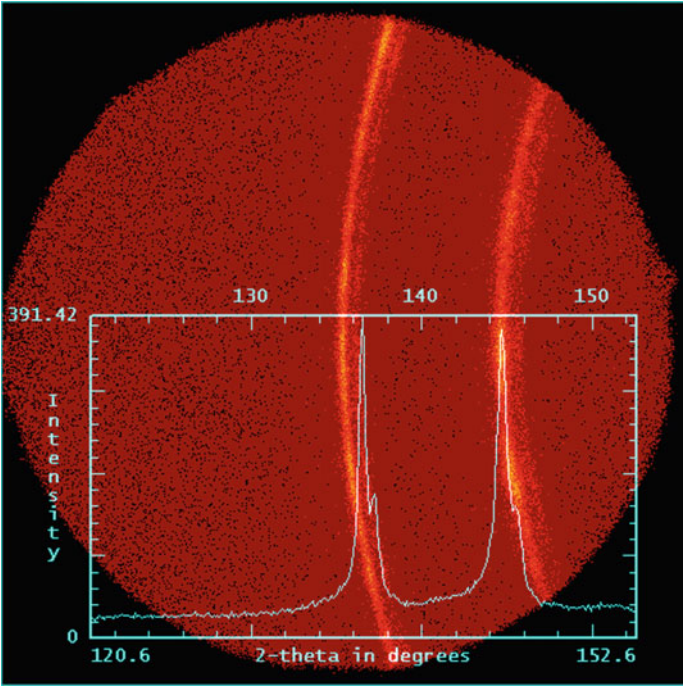


Fig. 6.5 The representative two-dimensional image of one of the welds used in the current study

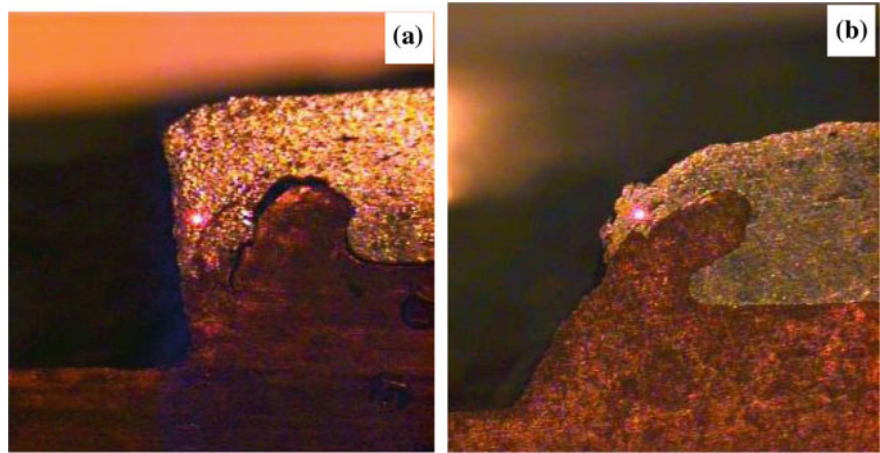


Fig. 6.6 The residual stress measurement position (SZ) of the welds, **a** 800 rpm, 05 mm shoulder plunge depth using a flat pin and flat shoulder, **b** 800 rpm, 0.5 shoulder plunge depth using a conical pin and a concave shoulder

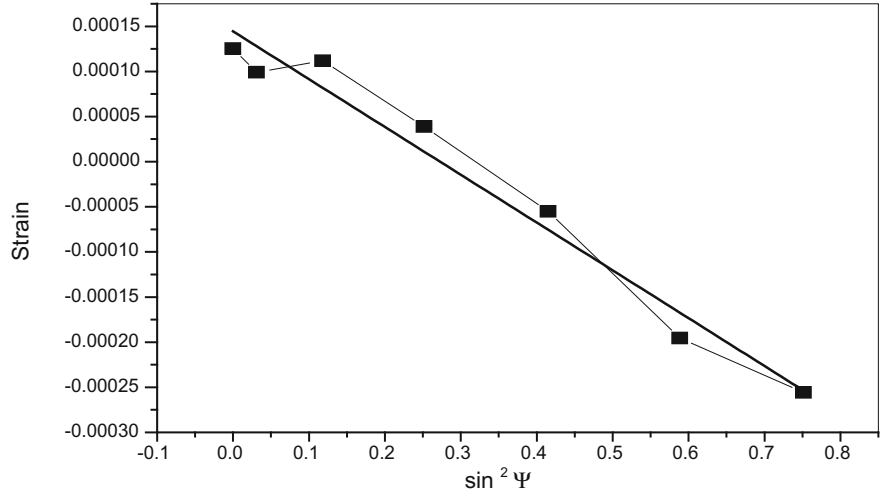


Fig. 6.7 The $\sin^2\Psi$ diagram for the (331) diffraction plane of the weld at 1200 rpm and 0.5 shoulder plunge depth using a flat pin and flat shoulder tool, where the solid line represents the linear least square fit to the data

Table 6.3 Residual stresses (MPa) obtained at different locations of the welds at different process parameters when using a flat pin and a flat shoulder tool

Location	FPS_800_0.5	FPS_800_1	FPS_1200_0.5	FPS_1200_1
SZ	-67	-50.3	-48.2	-53.6
Copper ring	-83.9	-59	-58.8	-81.3
Copper ring	-116.8	-67.1	-62	-99.7
Copper ring	-102.9	-60.4	-70.6	-60.7

Table 6.4 Residual stresses (MPa) obtained at different location of the welds at different process parameters when using a conical pin and a concave shoulder tool

Location	CCS_800_0.5	CCS_800_1	CCS_1200_0.5	CCS_1200_1
SZ	-66.8	-67.4	-63.3	-53
Copper ring	-76.7	-78.4	-58.2	-38.3
Copper ring	-74.6	-72.9	-68.3	-44
Copper ring	-67.5	-68.3	-62.1	-49.7

shoulder. The residual stresses were measured in the SZ (stir zone) and on the copper ring.

It was observed that a residual stress of -67 and -50.3 MPa were obtained in the SZ of the weld produced at 800 rpm using a flat pin and a flat shoulder, when using 0.5 and 1 mm shoulder plunge depths, respectively; while the weld produced at 1200 rpm exhibited an increase. This shows that the shoulder plunge depth has an

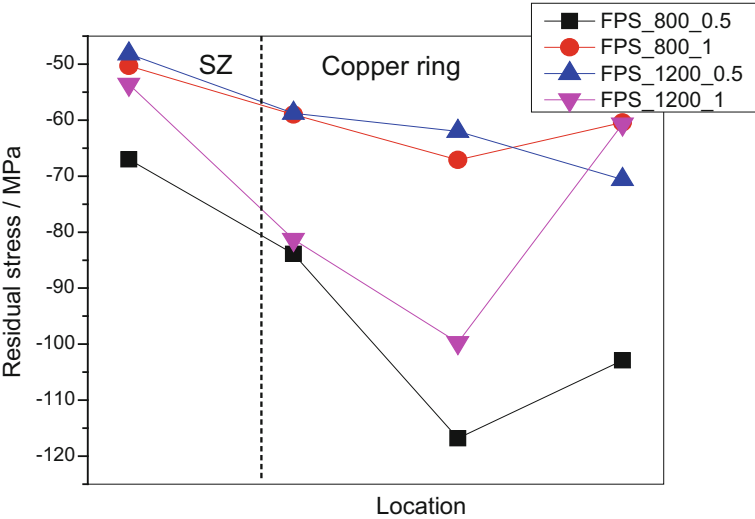


Fig. 6.8 Residual stress distribution of the stir zone (SZ) and on the copper ring of the spot welds produced at different process parameters using a flat pin and a flat shoulder

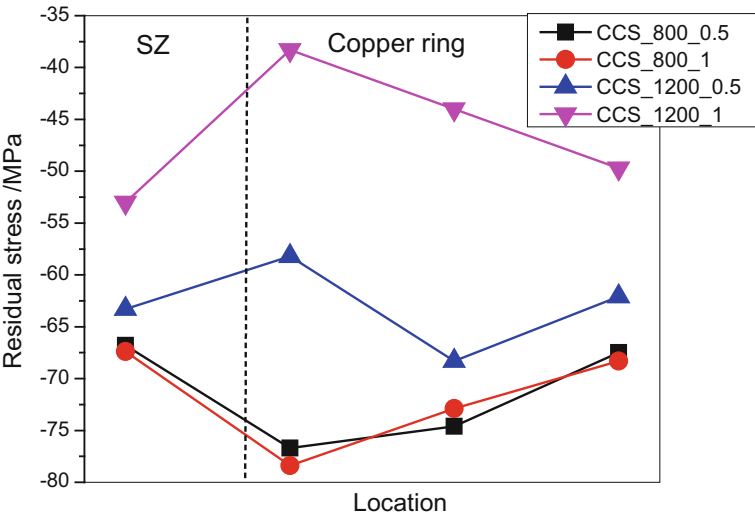


Fig. 6.9 Residual stress distribution of the stir zone (SZ) and on the copper ring of the spot welds produced at different process parameters using a conical pin and a concave shoulder

effect on the residual stress values obtained. As for the weld produced when using a conical pin and a concave shoulder, the residual stresses of -66.8 and -67.4 MPa were obtained in the SZ, respectively. Those welds (800 rpm/0.5 mm shoulder

plunge depth and 800 rpm/1 mm shoulder plunge depth) showed that the two values were similar. A decrease was observed for the weld produced at the high rotation speed of 1200 rpm. Residual stress values of -63.3 and -53 MPa were obtained using 1200 rpm/0.5 shoulder plunge depth and 1200 rpm/1 mm shoulder plunge depth, respectively.

It was further observed that there was no trend in the effect of the shoulder plunge depth on the variations in the residual stresses in the stir zone. The maximum residual stress measurement was found on the copper ring of the welds. A maximum of -116.8 MPa was obtained on the copper ring of the weld produced at 800 rpm, 0.5 mm shoulder plunge depth, when using a flat pin and a flat shoulder tool. The high values of the residual stresses found in the copper ring are due to the stress generated by the extrusion of the copper (bottom sheet) into the aluminium plate (top sheet). Tables 6.3 and 6.4 present the residual stress results obtained at different process parameters and when using different tool geometries.

6.3.3 *Effect of Process Parameters on the FWHM of the Spot Welds*

The full width at half maximum (FWHM) acquired from the diffraction peak widths provides a measure of the microstrain and the plastic deformation in materials (Hutchings et al., as cited by Lombard) [2].

The FWHM of an X-ray diffraction peak also contains valuable information density; since the broadening of the peak shows an accumulation of plastic damage, including the damage caused by dislocation generation during the deformation of the workpiece surface [20]. A diffraction peak from both parent materials was chosen, namely: 44.83° (200) and 50.57° (200) (2 Theta) for aluminium and copper, respectively. Those peaks were used to investigate the effects of the process parameters and the tool geometry on the FWHM. A 2 mm collimator was used to produce the XRD spectrums of the different weld samples when using different process parameters and tool geometries.

Tables 6.5 and 6.6 show the variation of FWHM and the shift in aluminium and copper peaks position of the weld produced at different process parameters and tool geometries; while Figs. 6.10 and 6.11 depict the X-ray diffraction of aluminium and copper peaks used to measure the FWHM of different spot weld samples.

It can be seen that the intensity of all the peaks decreases in comparison to the peaks generated by the parent materials at the same position, and those peaks that were broadened, as shown in Fig. 6.10. This shows that the welding parameters generated stress in the produced spot welds. It has been reported that not only microstrains, but also small grains (microstructure) can broaden the peaks [21]. It was observed that welding parameters affect the position of the peaks compared to the peaks generated from the parent materials. A similar trend was also observed in Fig. 6.11.

Table 6.5 The variation FWHM and the shift in the aluminium peak position of the welds produced at different process parameters and tool geometries

Sample name	2 Theta	FWHM
Aluminium PM	44.83307	0.24875
FPS_800_0.5	43.38238	0.3594
FPS_800_1	43.34289	0.26731
FPS_1200_0.5	43.45799	0.31654
FPS_1200_1	43.01861	0.29351
CCS_800_0.5	43.54	0.3517
CCS_800_1	43.15948	0.23817
CCS_1200_0.5	43.34772	0.23237
CCS_1200_1	43.3729	0.28471

Table 6.6 The variations in FWHM and the shift in the copper peak position of the weld produced at different process parameters and tool geometries

Sample name	2 Theta	FWHM
Copper PM	50.56656	0.29271
FPS_800_0.5	50.48321	0.36551
FPS_800_1	50.46155	0.32128
FPS_1200_0.5	50.6059	0.33443
FPS_1200_1	50.15458	0.33662
CCS_800_0.5	50.64972	0.3749
CCS_800_1	50.27259	0.27384
CCS_1200_0.5	50.47013	0.27202
CCS_1200_1	50.49228	0.29128

The aluminium diffraction peaks had a higher shift than the copper diffraction peaks; this can be attributed to their different properties, such as the melting point. The variations of the FWHM for all the welds can be found in Fig. 6.12.

It can be seen that the FWHM increases at 800 rpm, 0.5 mm shoulder plunge depth; and then it decreases when the shoulder plunge is changed at 1 mm. When the rotation speed is increased, the FWHM of the flat pin/flat shoulder also increases; while a decrease is observed for the conical pin and the concave shoulder when using a 0.5 mm shoulder plunge depth. Furthermore, when the shoulder plunge depth is increased to 1 mm, the FWHM decreases for the flat pin/flat shoulder tool; whereas an increase is observed for the conical pin/concave shoulder tool. This shows that the shoulder plunge depth has an effect on the FWHM.

6.3.4 Electrical Resistivity Measurements

The presence of copper rings and the formation of intermetallics could affect the electrical resistivity of the fabricated friction stir spot welds. The presence of hard and brittle intermetallic compounds in the produced welds by using X-ray diffraction and energy dispersive spectroscopy techniques was observed (see in

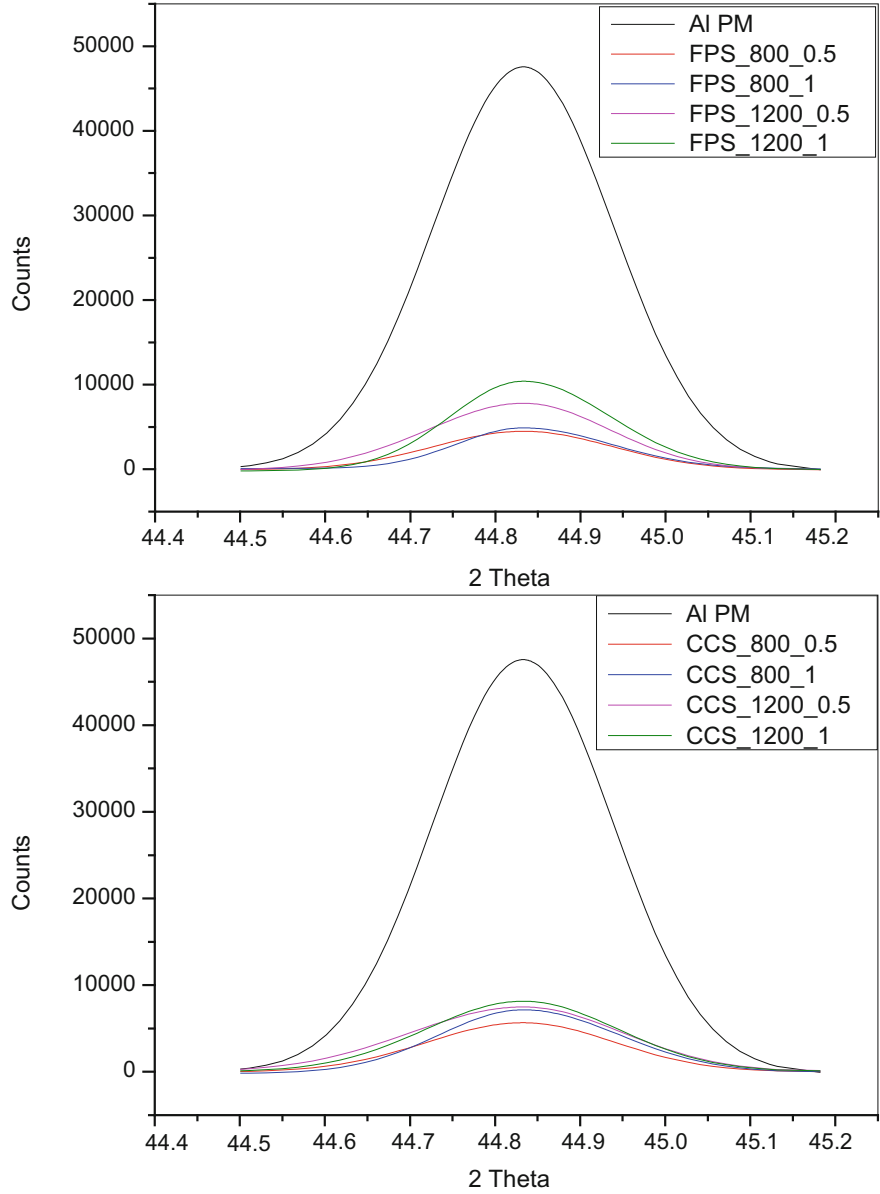


Fig. 6.10 X-ray diffraction peaks of aluminium used to measure the FWHM of the produced spot welds, showing the variation in peak intensity and widths

Chap. 4). The X-ray diffraction analysis was performed in three different regions of the spot weld samples, namely: the stir zone (SZ), the thermo-mechanically affected zone (TMAZ) and the heat-affected zone (HAZ).

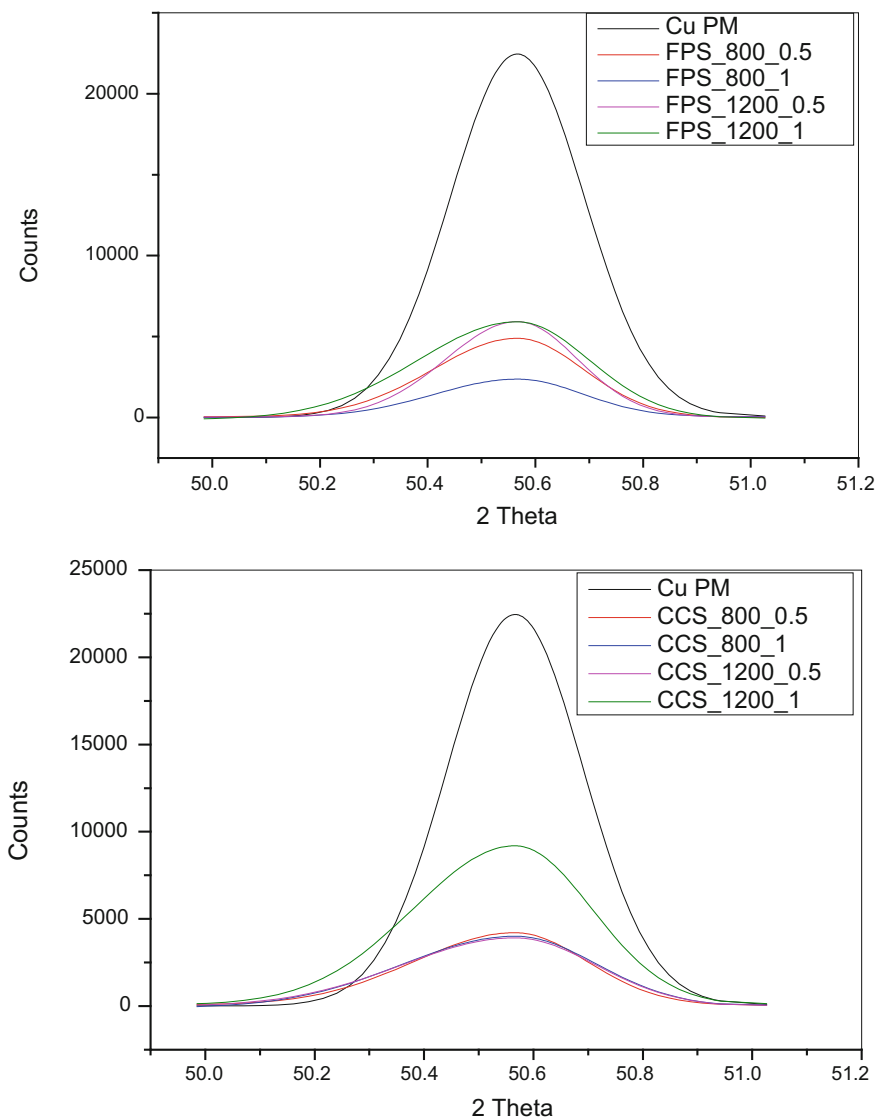


Fig. 6.11 X-ray diffraction peaks of copper used to measure the FWHM of the produced spot welds, showing the variation in peak intensity and widths

The results show the presence of various intermetallic compounds and the most common intermetallic compounds formed in the spot weld samples were: Al_4Cu_9 , Al Cu_3 , Al_2Cu_3 and Al_2Cu and their peaks had low peak intensity values. Additionally, the carried out energy dispersive spectroscopy (EDS) analysis also revealed the presence of intermetallic compounds in the keyhole and interfacial

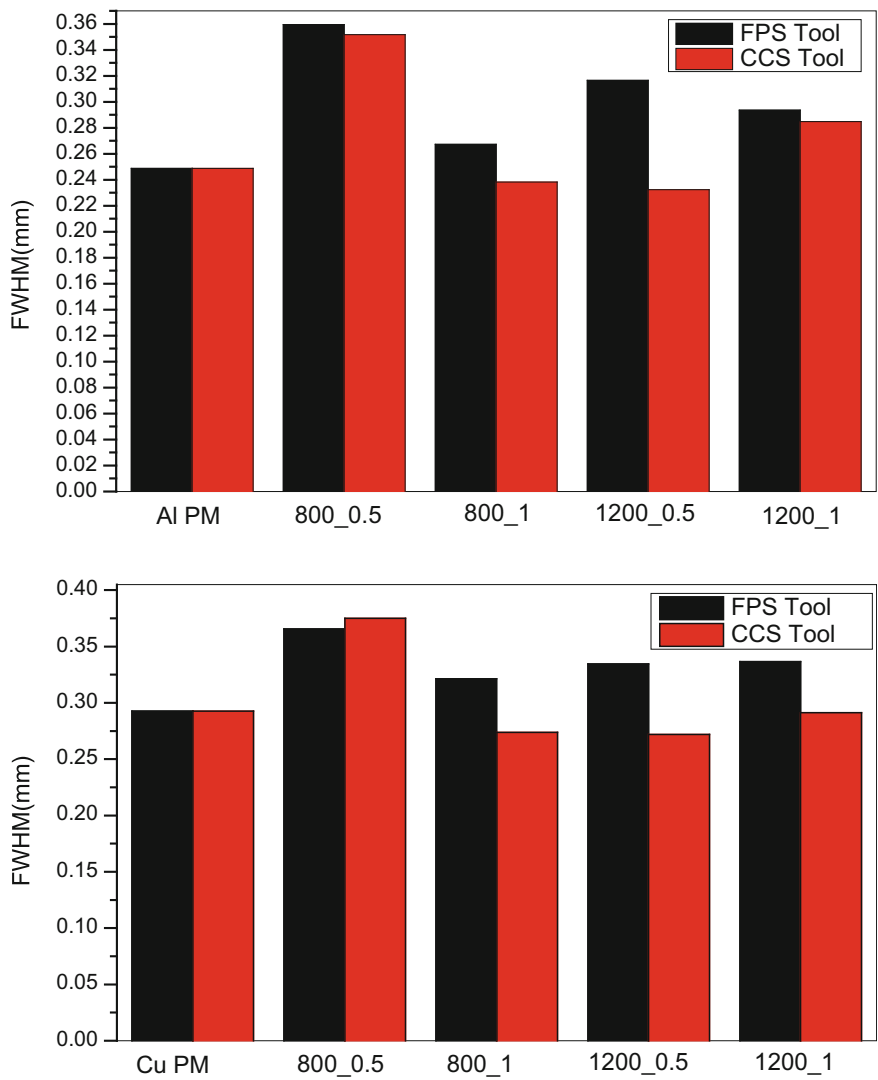


Fig. 6.12 Variation in FWHM of the X-ray diffraction peaks of the Al and Cu using different parameters and tool geometries

regions of the welds, which correlated to the X-ray diffraction analyses (see in Chap. 4).

It has been reported in the literature that intermetallic compounds at the joint interface of aluminium and copper are known to exhibit high levels of electrical resistivity [22].

The electrical resistivity of the aluminium/copper dissimilar material friction stir spot welds was measured at the joint interface and then investigated. The electrical

Table 6.7 Electrical resistivity results using a flat pin and a flat shoulder tool

Spot welds ID	Resistivity $\rho(\mu\Omega)$
Parent material_Al	0.014
Parent material_Cu	0.025
Average ρ	0.02
FPS_800_0.5_1	0.064
FPS_800_0.5_2	0.064
FPS_800_0.5_3	0.063
FPS_800_1_1	0.035
FPS_800_1_2	0.033
FPS_800_1_3	0.033
FPS_1200_0.5_1	0.034
FPS_1200_0.5_2	0.032
FPS_1200_0.5_3	0.032
FPS_1200_1_1	0.032
FPS_1200_1_2	0.031
FPS_1200_1_3	0.03

resistivity measurement results are depicted in Tables 6.7 and 6.8 for the flat pin/flat shoulder, and for the conical pin/concave shoulder tools, respectively.

The results showed that by increasing the rotational speed and the shoulder plunge depths, the electrical resistivity decreases when using the flat pin and a flat shoulder tool (Table 6.7). It was further noticed that there is a big difference between the values of the electrical resistivity of the parent materials compared to most of the spot welded samples. This could be due to the presence of defects in the stir zone, such as micro cracks. The highest electrical resistivity value of $0.064 \mu\Omega$ was found for the sample produced at 800 rpm, 0.5 mm shoulder plunge depth, when using a flat pin and a flat shoulder. It was also observed that most of the welds had an electrical resistivity of between $0.029 \mu\Omega$ and $0.035 \mu\Omega$; but when compared with the average of the parent materials, they showed a depreciation between $0.009 \mu\Omega$ (45%) and $0.015 \mu\Omega$ (75%), respectively, for $0.029 \mu\Omega$ and $0.035 \mu\Omega$.

On the other hand, a depreciation of 220% was found for the sample produced at 800 rpm, 0.5 mm shoulder plunge depth when using a flat pin and a flat shoulder tool.

The electrical resistivity results for the welds produced with a conical pin and a concave shoulder (Table 6.8) showed different trends. A low resistivity value of $0.009 \mu\Omega$ was found when using 800 rpm and 1 mm shoulder plunge depth, which shows an appreciation of $0.011 \mu\Omega$ (55%). However, the results obtained when using the other parameters showed values varying from 0.029 to $0.035 \mu\Omega$. This result was obtained for the sample at 800 rpm, 1 mm shoulder plunge using a conical pin and a concave shoulder; and it has low electrical resistivity when compared to the other spot welds; and this could be an attractive option for electrical conductivity purposes.

Table 6.8 Electrical resistivity results using a conical pin and a concave shoulder tool

Spot welds ID	Resistivity $\rho(\mu\Omega)$
Parent material_Al	0.014
Parent material_Cu	0.025
Average ρ	0.02
CCS_800_0.5_1	0.035
CCS_800_0.5_2	0.032
CCS_800_0.5_3	0.033
CCS_800_1_1	0.011
CCS_800_1_2	0.009
CCS_800_1_3	0.011
CCS_1200_0.5_1	0.033
CCS_1200_0.5_2	0.033
CCS_1200_0.5_3	0.034
CCS_1200_1_1	0.034
CCS_1200_1_2	0.032
CCS_1200_1_3	0.029

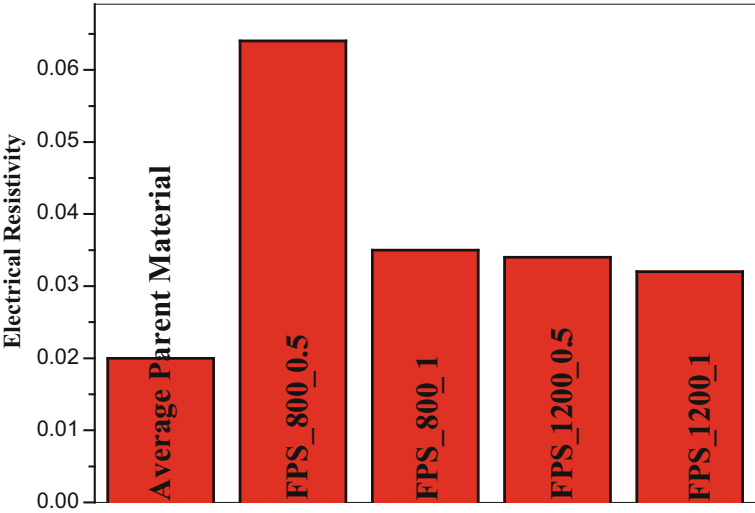


Fig. 6.13 The effect of process parameters on the electrical resistivity of the spot welds when compared to the average resistivity of the parent materials produced when using a flat pin and a flat shoulder tool

Figures 6.13 and 6.14 depict the effect of welding process parameters and tool geometry on the electrical resistivity of the produced spot welds.

It can be seen that the electrical resistivity of all the welds is higher than those of the average parent materials. Akinlabi [16] calculated the electrical resistivity of the

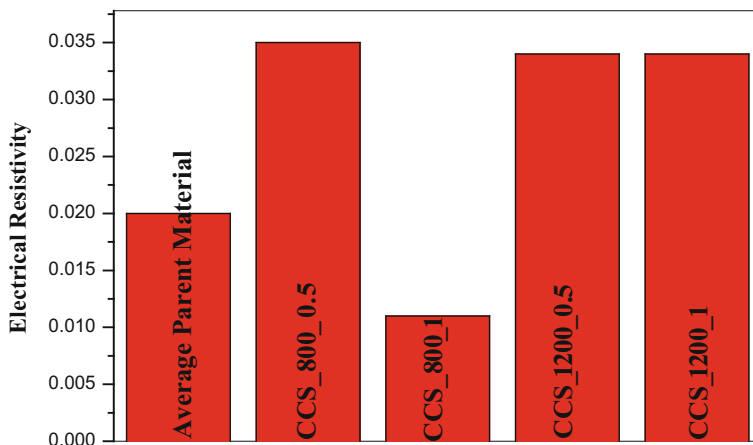


Fig. 6.14 Effect of the process parameters on the electrical resistivity of the spot welds compared to the average resistivity of the parent materials produced when using a conical pin and a concave shoulder tool

friction stir welding between commercially pure copper to AA5754. She concluded that the presence of intermetallics affects the electrical resistivity. This was seen in the welds, where intermetallics were not found [16]. The high values of the electrical resistivity obtained except for the welds produced at 800 rpm and 1 mm shoulder plunge depth in the current research work could be due to the presence of intermetallics in the vicinity of the keyhole. This was confirmed with XRD and EDS analyses, and also with the high values of the microhardness in the vicinity of the keyhole.

6.4 Conclusions

The current study has depicted the microstructure and the residual stresses of the friction stir spot welds produced by using different tool geometries and process parameters. The main conclusions are summarized as follows:

- The AA1060 and C11000 sheets were successfully joined by using the FSSW technique. The microstructure was investigated. The presence of a copper ring was observed in all the spot welds produced. A good material mixing, showing a distribution of Cu particles and fragments with irregular shapes and various sizes was observed. The stir action of the tool pin, which has worn out copper pieces from the copper parent material, breaking them up and dispersing them into the aluminium parent material explained the presence of the copper particles in the aluminium matrix. The intermixing of the copper and the aluminium is not homogeneous for the various welds; and different microstructures were

formed in different regions of the welds. It can be said that the presence of the copper ring could be the reason for the presence of different residual stresses found in the produced spot welds.

- High values of residual stresses are found on the measurements taken on the copper rings and the maximum residual stresses were obtained in the copper ring of the welds produced at 800 rpm, 0.5 mm shoulder plunge depth using flat pin/flat shoulder tool. These high values of the residual stresses found in the copper ring are due to the stress generated by the extrusion of the copper into the aluminium sheet.
- The intensity of all the peaks decreased in comparison to the peaks generated by the parent materials at the same position and those peaks were broadened; and this demonstrates that the shoulder plunge depth has an effect on the full width at half maximum (FWHM).
- The electrical resistivity results revealed high values for all the spot welds compared to the parent materials; but the electrical resistivity of the spot welds produced at 800 rpm, 1 mm shoulder plunge depth when using a conical pin and a concave shoulder exhibited lower values when compared with those of the parent materials. It was noticed that the welds produced at 800 rpm and 1 mm shoulder plunge depth using a conical pin and a concave shoulder tool exhibited a low electrical resistivity, which was more appropriate for use in the electrical industry.

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Glossary

Alloy A substance having metallic properties and being composed of two or more chemical elements, of which at least one is a metal.

Alloying element The alloying element is an element added to and remaining in the metal, which changes its structure and properties.

Backing plate A layer of material that is placed below the joint interfaces of the materials to be welded. It provides a surface to oppose the vertical downward force on the material; and it protects the machine bed.

Bending stress If a beam is subjected to a bending moment, the fibres in the upper part are extended; and those in the lower part are compressed. Tensile and compressive stresses are thereby induced, which vary from zero at the neutral axis of the beam, to a maximum at the outer fibres. These stresses are called bending stresses.

Breaking load The load at which fracture occurs.

Brittleness The tendency of a material to fracture without first undergoing significant plastic deformation.

Brittle fracture Rapid fracture preceded by little or no plastic deformation.

Clamping System Is the device used to hold, locate and prevent the workpiece from moving during the large forces involved in the FSW process.

Coalescence The merging of two or more materials (metals) into one.

Defect A discontinuity or discontinuities that accumulate to render a weld or part thereof unable to meet the minimum acceptance standards or criteria of the design specifications.

Deformation Is a change in the form of a body due to stress, heat, or other causes.

Diffraction The scattering of electrons by any crystalline material, through discrete angles, and depending only on the lattice spacing of the material and the velocity of the electrons.

Ductility The ability of a material to deform plastically before fracture.

Dwell time The period of time after the rotating tool has been plunged into the work and for which it remains stationary, generating frictional heat and plasticizing the materials, before commencing the traverse along the joint (seconds).

EDM (Electrical discharge machining) This is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks).

Elastic region A material is said to be stressed within the elastic region, when the working stress does not exceed the elastic limit.

Elastic deformation This is the deformation of the material that is recovered when force is applied to it.

Elastic limit This is the greatest stress, which a material is capable of sustaining without any permanent strain remaining upon complete release of the stress.

Elongation The increase in gauge length of a body subjected to a tension force, referenced to a gauge length of a body. Usually expressed as a percentage of the original gauge length.

Elongation (%) The total percent increase in the gauge length of a specimen after a tensile test.

Engineering strain This is a dimensionless value that is the change in length (ΔL) per unit length of the original linear dimension (L_0) along the loading axis of the specimen; that is $e = \Delta L / L_0$, the amount that a material deforms per unit length in a tensile test.

Equilibrium A state of dynamic balance between the opposing actions, reactions, or velocities of a reversible process.

Etchant A chemical solution used to etch a metal to reveal the structural details.

Etching Subjecting the surface of a metal to preferential chemical or electrolytic attack to reveal the structural details for metallographic subsequent examination.

Extrusion The process whereby a material is shaped by force or squeezed through a die or nozzle.

Filler metal Metal added in making a welded, brazed, or soldered joint.

Force control A mode in the friction stir welding process, in which a known force from previous welds is added to other input process parameters, in order to produce a weld.

Fusion The melting together of filler metal and base metal, or of base metal only, which results in coalescence.

Fusion welding Any welding process that uses fusion of the base metal to make the weld.

Friction The force required to cause one body in contact with another to begin to move.

Friction stir welding and friction stir spot welding This is a process developed at The Welding Institute (TWI) that utilizes local friction heating to produce continuous solid-state seams. It allows butt and lap joints to be made, without the use of filler metals. The solid-state low distortion welds produced are achieved with relatively low costs, using simple and energy-efficient mechanical equipment.

Grain An individual crystallite in metals.

Grain growth This is a phenomenon, which occurs when the temperature of a metal is raised; the grains begin to grow and their size may eventually exceed the original grain size.

Grain size A measure of the areas or volumes of grains in a polycrystalline metal or alloy, usually expressed as an average when the individual sizes are fairly uniform. Grain size is reported in terms of the number of grains per unit area or volume, the average diameter, or as a number derived from the area measurements.

Grain boundary An interface separating two grains, whereby the orientation of the lattice changes from that of one grain to that of the other. When the orientation change is very small, the boundary is sometimes referred to as a sub-boundary structure.

Grinding Removing material from the surface of a workpiece by using a grinding wheel or abrasive grinding papers.

Hardness This is a term used for describing the resistance of a material to plastic deformation.

Hardness test This measures the resistance of a material to penetration by a sharp object.

Hardening Increasing the hardness by means of a suitable treatment.

Heat affected zone The portion of the base metal which has not been melted, but whose mechanical properties have been altered by the heat of welding or cutting.

Homogeneous The chemical composition and the physical state of any physical small portion, and one, which is the same as that of any other portion.

Hot working A deformation under conditions that result in recrystallization.

Indentation hardness This is the hardness, as evaluated from the measurements of an area of an indentation, made by pressing a specified indenter into the surface of a material under specified static loading conditions.

Intensity (X-rays) The energy per unit time of a beam per unit area, which is perpendicular to the direction of propagation.

Interfacial region A weld joint boundary of the workpieces indicating the positions of the pin and shoulder diameters during the welding process.

Intermetallic compounds These are any solid materials, composed of two or more metal atoms in a definite proportion, which have a definite structure, which differ from those of its constituent metals.

Joint efficiency The ratio of the strength of a joint to the strength of the base metal, expressed as a percentage.

Keyhole This is an exit hole, which is left behind by the friction stir spot welding process after the weld has been done.

Lap Joint A welded joint in which two overlapping metal parts are joined by means of a fillet, plug or slot weld.

Macrograph A graphic reproduction of a prepared surface of a specimen at a magnification not exceeding 25 $\times$.

Macrostructure The structure of metals, as revealed by macroscopic examination of the etched surface of a polished specimen.

Magnification The ratio between the length of a line in the image plane to the length of a line on the imaged material.

Mechanical properties These are the properties of a material that reveal its elastic or inelastic behaviour, when a force is applied, indicating the suitable mechanical applications.

Microstructure The structure of a prepared surface of a metal, as revealed by a microscope at a particular magnification.

Oxidation The addition of Oxygen to a compound.

Parameter The minimum and maximum parameters that would describe the operating range of a variable.

Parent material This is the sheet-metal plate in its 'as manufactured form', as supplied.

Plastic deformation This is the distortion of material continuously and permanently in any direction. The deformation that remains or would remain permanent after the release of the stress that caused it.

Polished surface This is a surface that reflects a large proportion of the incident light in a peculiar manner.

Plunge depth This is the maximum depth that the tool shoulder penetrates into the weld plates.

Recrystallisation This is a change from one crystal structure to another, such as that occurring upon heating and/or cooling through a critical temperature.

Residual stress This is the stress in a body, which is at rest, in equilibrium, and at a uniform temperature in the absence of any external force.

Retreating side The retreating side of the tool is where the local direction of the weld surface, due to tool rotation and the direction of the traverse, is in the opposite direction.

Rotation speed The tool rotation speed is the rate of angular rotation (usually specified in rpm) of the tool around its rotational axis.

Scanning electron microscope An electron microscope, in which the image is formed by a beam operating simultaneously with an electron probe scanning the object.

Solid phase A physically homogeneous and distinct portion of a material system in the solid state.

Spindle speed This is also referred to as the rotational speed; and it is the speed of the work holding device (chuck), measured in revolutions per minute.

Spindle torque This is the spindle torque required to rotate the FSW tool, when plunging it into and traversing through the workpiece along the joint (Nm).

Stress This is the load applied to a piece of material; and it tends to cause deformation, which is resisted by the internal forces set up within the materials, which are referred to as stresses. The intensity of the stress is estimated as the force acting on the unit area of the cross-section, namely: as Newtons per square metre, or as Pascals.

Tensile strength This is the maximum tensile stress, which a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried out to rupture, and from the original cross-sectional area of the specimen.

Tensile test This measures the response of a material to a slowly applied axial force. The yield strength, tensile strength, modulus of elasticity and ductility are thereby obtained.

Tool displacement This refers to the offset of the tool at a certain distance from the weld centre line.

Tool shoulder This refers to that part of the welding tool, which rotates, and is normally disk-shaped.

Tool pin This refers to that part of the tool that rotates in contact with the surface of the workpiece.

Tool plunge This is the process of forcing the tool into the material at the start of the weld.

Tool tilt angle The angle, at which the FSW tool is positioned relative to the workpiece surface; that is, when zero tilt tools are positioned perpendicular to the workpiece surface (degrees).

Traverse speed This is also referred to as the feed rate; it is the speed at which the rotating FSW tool is translated along the joint line (mm/min).

Vickers hardness number This is a number related to the applied load and the surface area of the permanent impression made by a square-based pyramid diamond indenter.

Void This is the space that exists between the particles or grains. Normally, in welding, voids are associated with defects.

Unaffected material This refers to the bulk of the material, which is not affected by either heat or deformation, during the welding process.

Welding This is the process of joining, in which the materials are enabled to form metallurgical bonds under the combined action of heat and pressure.

Weld nugget or stir zone This refers to the recrystallized central area of the joint interface.

Welding speed This is also known as the traverse speed; this is the speed (usually specified in mm/min) of the tool traversing along the workpiece per specified time.

Workpiece The component to be welded.

Wormholes This refers to a defect in a FS weld, usually on the advancing side of the rotating tool, due to the lack of mixing and re-bonding of the plasticized material.