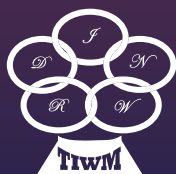


A photograph of a welding process with bright sparks flying out from a central point, set against a dark background.

Transactions on Intelligent Welding Manufacturing

Volume I No. 1 2017



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Transactions on Intelligent Welding Manufacturing

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Volume I No. 1 2017

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ISSN 2520-8519

ISSN 2520-8527 (electronic)

Transactions on Intelligent Welding Manufacturing

ISBN 978-981-10-5354-2

ISBN 978-981-10-5355-9 (eBook)

DOI 10.1007/978-981-10-5355-9

Library of Congress Control Number: 2017943844

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Editorials

Dear Colleagues,

In response to the increasing R&D efforts toward intelligent manufacturing technology in the field of welding, the Robotics and Automation Committee of China Welding Society has successfully sponsored a series of conferences, including the biennial *Chinese Conference on Robotic Welding (CCRW)* since 1996 and quadrennial *International Conference on Robotic Welding, Intelligence and Automation (RWIA)* since 2002. As successful platforms for academic and technical exchanges, CCRW and RWIA series have condensed the consensus of outstanding scientists, engineers, and entrepreneurs in the field of intelligentized welding technology and received attention from the Springer publishing house who has been the publisher for all previous RWIA proceedings. Through the cooperation and careful planning of three scholars, Professor Shanben CHEN of Shanghai Jiao Tong University, Professor Yuming ZHANG of the University of Kentucky, and Professor Zhili FENG of Oak Ridge National Laboratory, as well as the endorsement from Mr. Wayne HU of Springer Shanghai, the Springer officially approved the launch of the series publication “Transactions on Intelligent Welding Manufacturing” (TIWM) in January 2017 to provide a major channel to report and reflect timely advances in intelligent welding manufacturing science and technology through publishing original academic papers, monographs, technical reports, conference proceedings, and other research results. It also is an information platform to promote the steady and rapid development of scientific research and technological innovation of the intelligent welding manufacturing field in the world.

As we all know, welding crafts originated in about 3000 BC. After about 5000 years, with the evolution and development of science and technology, from the original manual welding, automatic welding, and welding robot to modern manufacturing, there are hundreds of kinds and variants of welding processes. Unfortunately, up to today, coordinated operations of human primitive senses and limbs still play a major role in effectively operating them. In the twenty-first century, with the development of robotic technologies and artificial intelligences, it has

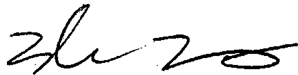
already become the feasible human creative practice to realize the intelligent welding for advanced manufacture by replacing the welder with machines.

It is a widely recognized fact that effectively emulating human welders for their intelligences by machines has not been trivial. It requires breakthrough beyond current boundaries in many scientific and engineering disciplines, including materials, metallurgy, machinery, robotics, information technology, artificial intelligence, computer, automatic control, and management science, as well as their effective coordination. Intelligentized welding manufacturing also certainly sets the latest achievements in the development of human science and technology.

The publication of the TIWM is of great significance to promote the development of modern welding technology. The TIWM is committed to disseminate the advanced science and technology achievements to the world, including welding materials, process, equipment, and all other disciplines related to intelligent welding manufacture. We trust that it will play an important role in promoting the development of advanced welding technology and application.

With heartfelt thanks to fellow colleagues, we look forward to working with you to grow and promote the TIWM to advance the science and engineering foundation for intelligentized welding manufacturing in the world!

Shan Ben Chen



Shanben Chen
Yuming Zhang
Zhili Feng

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Feature Articles

Arc Welding Processes for Additive Manufacturing: A Review

Zengxi Pan, Donghong Ding^(✉), Bintao Wu, Dominic Cuiuri,
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Abstract. Arc-welding based additive manufacturing techniques are attracting interest from the manufacturing industry because of their potential to fabricate large metal components with low cost and short production lead time. This paper introduces wire arc additive manufacturing (WAAM) techniques, reviews mechanical properties of additively manufactured metallic components, summarises the development in process planning, sensing and control of WAAM, and finally provides recommendations for future work. Research indicates that the mechanical properties of additively manufactured materials, such as titanium alloy, are comparable to cast or wrought material. It has also been found that twin-wire WAAM has the capability to fabricate intermetallic alloys and functional graded materials. The paper concludes that WAAM is a promising alternative to traditional subtractive manufacturing for fabricating large expensive metal components. On the basis of current trends, the future outlook will include automated process planning, monitoring, and control for WAAM process.

Keywords: Arc welding · Additive manufacturing · Review · Materials · Automation · Control

1 Introduction

Arc welding has been widely explored for additive manufacturing (AM) of large metal components over the last three decades due to its lower capital investment, an unlimited build envelope, and higher deposition rates [1]. The concept of using arc welding as a means of building up components was initiated in the 1990s from Europe [2, 3]. The capability of arc welding has been demonstrated through building several prototype parts with good structural integrity and mechanical properties [4]. However, WAAM received less attention than other AM processes at that time due to a few reasons: (1) High heat input associated with welding processes can induce residual stress as well as part distortion [5]; (2) Poor accuracy (about ± 0.2 mm) and surface finish of the fabricated part are unacceptable for many applications [1]; (3) Solid layers cannot be filled to form a smooth surface, resulting in inner gaps or voids [6]; (4) Automated CAD-to-part AM system using arc welding processes is immature [7]; (5) Lack of

integrated, reliable process monitoring and control to accommodate variations during the deposition.

More recently, there has been increasing interest in applying AM to titanium alloys due to greater demand for titanium alloys in the aerospace industry, and the difficulty and inefficiency of subtractive manufacturing from billet. There are several alternative approaches including laser [8] and electron beam AM systems [9]. At Cranfield University [10] in UK and University of Wollongong [11] in Australia efforts have been focused on the use of the wire arc additive manufacturing (WAAM) processes due to their high deposition rate, unlimited build envelop, and efficient use of materials, which provide advantages for fabricating medium to large sized components. Over the last ten years, the WAAM process has attracted significant interest, with the search term “wire arc additive manufacturing” being mentioned in 536 documents in the 2017 Scopus database. Many important facets of WAAM have been widely investigated, including processes and machines, materials, path design and programming, process modelling and online control [12]. A review of WAAM technologies is therefore essential for researchers in this area, to summarize the state-of-the-art research outcomes and also to point out the future research interests. A number of existing literature reviews on AM from various aspects can be found [1, 13–20].

This article places emphasis particularly on WAAM technologies, provides a general overview of the most commonly available WAAM processes, lists the mechanical properties of the processed metallic materials as found in the literature, and describes recent development on process planning, sensing and control. The paper ends with conclusions and future research perspective.

2 Wire Arc Additive Manufacturing Systems

The WAAM system consists of a power source, an automatic wire-feed system, a computer numerically controlled work table or a robotic system, and some accessories (e.g. shielding gas, preheating or cooling system). A typical robotic WAAM system is shown in Fig. 1. A computer interface ① is used to programme the experimental process and collect the experimental results. The robot controller ② is used to coordinate both the robot motions and welding processes. A programmable welding power source ③ is used to control the welding process. An industrial robot manipulator ④ implements the movement of the gas metal arc welding (GMAW) torch ⑤ or the gas tungsten arc welding (GTAW) torch ⑥ for metal deposition. Subsequently, a structure is deposited as shown in ⑦.

As indicated in a previous review [1], WAAM technology can be further divided into various categories such as gas metal arc welding (GMAW) based [21], gas tungsten arc welding (GTAW) based [22], and plasma arc welding (PAW) based [23] processes.

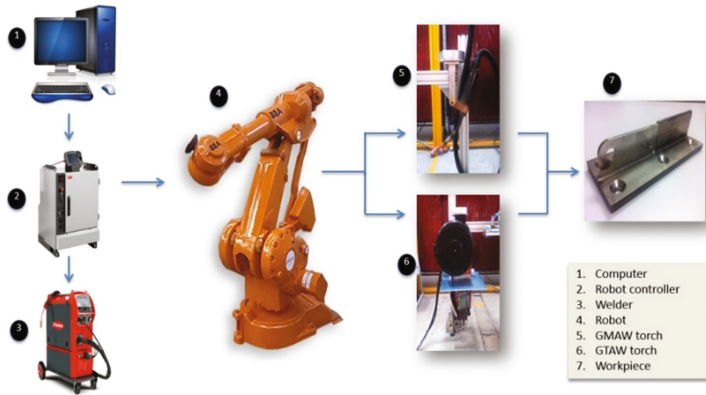


Fig. 1. Schematic diagram of the developed experimental WAAM system

2.1 GMAW-Based WAAM Systems

GMAW is a welding process in which an electric arc forms between a consumable wire electrode and the workpiece metal. The wire is usually perpendicular to the substrate. For a single-wire process, there is no limitation imposed on movement during deposition by the need to rotate the torch. Various transfer modes can be used in GMAW, such as spray and pulsed-spray. Cold metal transfer (CMT), as a modified GMAW variant based on the controlled dip transfer mode, has been widely used for WAAM due to its high deposition rate with low heat input [24]. Tandem GMAW, a twin-wire process, was recently reported for creating metallic objects with high deposition rates [25], as shown in Fig. 2. Although it has been stated that the tandem system has the potential to produce intermetallic alloy as well as the gradient materials, to date there are no reports of this in the literature. To increase the deposition rate and material efficiency, a double electrode GMAW using GTAW torch to provide the bypass current was developed as shown in Fig. 3. It was reported that the coefficient of materials utilization increased more than 10% using DE-GMAW for depositing thin-wall parts within a certain range of bypass current [26]. Note that for any wire-arc system with more than one electrode or wire, the torch must be aligned with the direction of travel, imposing a significant additional constraint on the path planning algorithm.

2.2 GTAW-Based WAAM Systems

GTAW uses a non-consumable tungsten electrode in combination with a separately-fed wire to produce the weld deposit, as shown in Fig. 4. During the deposition process, wire feed orientation influences material transfer and the quality for the deposit. Back feeding, side feeding, and front feeding can be used. Front feeding is normally implemented for Ti-based and Fe-based AM. A mathematical model has been developed to optimise the wire feed direction and position for improved deposition accuracy [27]. Increasing arc length was accompanied by an equal increase in the distance between the shielding nozzle and the workpiece. A gas lens is used to generate laminar

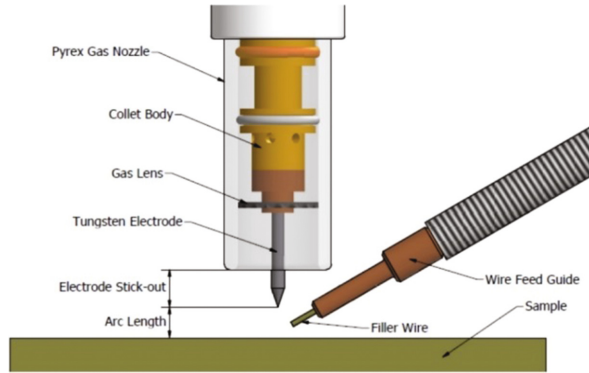


Fig. 4. Illustration of GTAW torch [11]

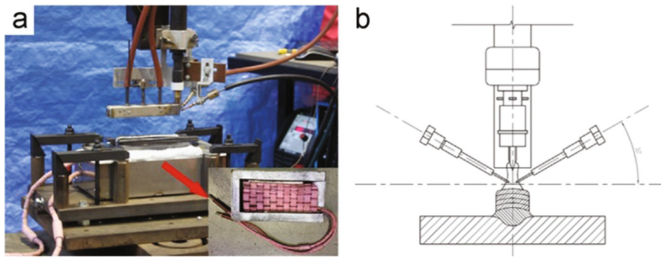


Fig. 5. (a) Experimental setup of twin-wire WAAM system with preheating and trailing devices; (b) Schematic representation of the additive manufacturing process [28]

effects of process parameters on the mechanical properties and surface quality of fabricated parts have been investigated [23].

3 Mechanical Properties of WAAM Processed Metallic Materials

A recent article [19] systematically reviewed the published values for mechanical properties obtained for materials processed by various AM techniques, including powder bed fusion and directed energy deposition technologies. This review focuses on mechanical properties of metallic materials manufactured by WAAM. Based on the limited number of alloy systems for which mechanical properties are published, Table 1 summarizes the existing alloy classes and references to published data, along with the process category.

Titanium alloys have a wide range of desirable mechanical properties including high strength-to-weight ratios, moderate ductility, good fatigue and fracture resistance, and excellent corrosion resistance. The main hurdle for wider application of these materials is their comparatively high manufacturing cost, especially in the aerospace

industry where components suffer high buy-to-fly ratios. With the increasing interest in, and use of, titanium and its alloys, significant efforts are being made to reduce the costs associated with these materials by development of novel production and manufacturing techniques. Ti-6Al-4V is the most popular material investigated using WAAM process [36, 38, 40, 47–52]. Figure 7 shows an additively manufactured wall structure using GTAW-based WAAM process.

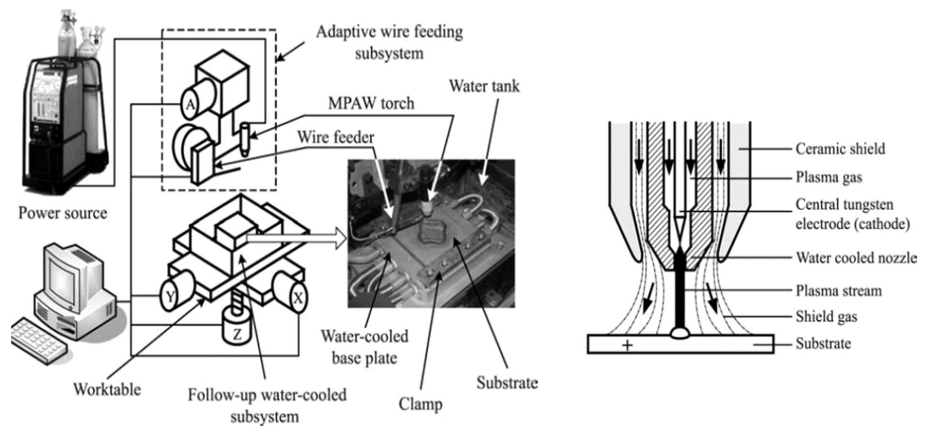


Fig. 6. Schematic diagram of the PAW-based WAAM system and the details of plasma arc [23]

Table 1. Summary of various alloys used in different WAAM process categories, along with references

	GMAW	GTAW	PAW
Titanium alloys		[35, 36, 37, 38]	[33, 39, 40]
Aluminium alloys	[41, 42]	[42]	
Nickel alloys		[43]	[44, 45]
Steel alloys	[46]		[23]
Bonze alloys	[21]		
Intermetallics		[28, 29]	

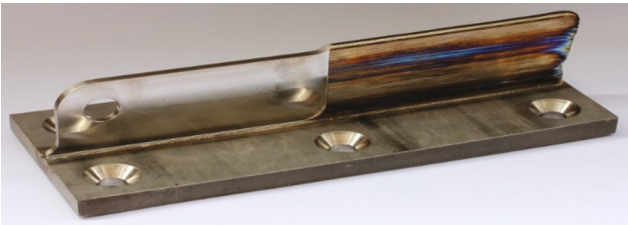


Fig. 7. Additively manufactured Ti-6Al-4V wall structure with partial surface machining [11]

Tables 2–4 provide the mechanical properties of additively manufactured alloys (e.g. titanium alloys, aluminum alloys, nickel alloys and bronze alloys) using different WAAM technologies. Data from ASTM standards are also provided for comparison. A review of the literature reveals that most of the published mechanical property measurements have been focused on tensile testing of titanium alloys, particularly Ti-6Al-4V, as summarized in Table 2. In the tables, the effects of specimen direction on tensile properties are documented using *a* and *b*, representing orientations in build direction and orthogonal to build direction, respectively. WAAM fabricated Ti-6Al-4V parts exhibit lower strength and higher elongation values in the build direction. Figure 8 captures the mechanical properties of WAAM processed Ti-6Al-4V alloy as well as ASTM standards of wrought and cast material. It can be observed from these summarized results that the mechanical properties of additively manufactured materials are comparable to cast or wrought material, demonstrating that WAAM is a promising alternative for manufacturing many metallic materials.

Table 2. Tensile properties of titanium alloy, depending on the microstructure generated by different WAAM process and in different post welding conditions

Process	Condition	Microstructure	YS[MPa]	UTS[MPa]	EL[%]	Reported by
Cast	/	/	758	860	>8	ASTMF1108
Wrought	/	/	860	930	>10	ASTMF1472
GTAW	AF	Columnar prior β grains + Widmanstätten α/β	/	929 $\pm$ 41 ^a 965 $\pm$ 39 ^b	9 $\pm$ 1.2 ^a 9 $\pm$ 1 ^b	Baufeld et al. [35]
	AF	α phase lamella basket weave structures	/	939 $\pm$ 24 ^a 1033 $\pm$ 32 ^b	16 $\pm$ 3 ^a 7.8 $\pm$ 2.3 ^b	Baufeld et al. [36]
	HT (600 °C/ 4 h/FC)	lamellar structure	/	972 $\pm$ 41 ^a 977 $\pm$ 14 ^b	12.5 $\pm$ 2.5 ^a 6 $\pm$ 3 ^b	
	HT (834 °C/ 2 h/FC)	lamellar structure	/	931 $\pm$ 19 ^a 971 $\pm$ 28 ^b	21 $\pm$ 2 ^a 14 $\pm$ 2 ^b	
	AF	Widmanstätten α + banded coarsened lamella α	803 $\pm$ 15 ^a 950 $\pm$ 21 ^b	918 $\pm$ 17 ^a 1033 $\pm$ 19 ^b	14.8 ^a 11.7 ^b	Wang et al. [37]
	AF	/	861 $\pm$ 14 ^a 892 $\pm$ 31 ^b	937 $\pm$ 21 ^a 963 $\pm$ 22 ^b	16.5 $\pm$ 2.7 ^a 7.8 $\pm$ 2 ^b	Brandl et al. [38]
	HT (600 °C/ 2 h/FC)	/	891 $\pm$ 16 ^a 915 $\pm$ 14 ^b	976 $\pm$ 35 ^a 981 $\pm$ 8 ^b	11.6 $\pm$ 2.4 ^a 6.6 $\pm$ 2.6 ^b	
	AN(834 °C/ 2 h/FC)	/	856 $\pm$ 21 ^a 893 $\pm$ 24 ^b	931 $\pm$ 17 ^a 962 $\pm$ 29 ^b	20.4 $\pm$ 1.8 ^a 13.5 $\pm$ 2 ^b	
Plasma	AF 600 °C/ 840 °C	Widmanstätten α/β + Columnar β grains	/	/	/	Martina et al. [33]
Pulsed-PAW	AF	Prior columnar β + Martensite α'	909 $\pm$ 13.6 ^b	988 $\pm$ 19.2 ^b	7 $\pm$ 0.5 ^b	Lin et al. [39]
PAW	AF	Columnar β + martensite α'	877 $\pm$ 18.5 ^b	968 $\pm$ 12.6 ^b	11.5 $\pm$ 0.5 ^b	Lin et al. [40]

AF: as fabricated, HT: heat treated, AN: annealed, FC: furnace cooling.

a: In build direction, b: Orthogonal to build direction.

Titanium aluminide alloys based on intermetallic γ phase are widely recognised as promising structural materials due to their attractive combination of low density,

unique mechanical properties such as high specific strengths and moduli, and good resistance against oxidation and corrosion. The potential of twin-wire WAAM for producing titanium aluminides has been shown in recent studies [28]. Full density γ -TiAl based alloy has been successfully produced using twin-wire WAAM process through separately controlled wire feeding of titanium and aluminium welding wires.

Functionally graded material (FGM) belongs to a class of advanced materials with properties that progressively vary over one or more dimensions. The feasibility of fabricating functionally gradient iron aluminide structures using the twin-wire WAAM process has been demonstrated [29]. The experimental results of Fe-FeAl FGM fabrication demonstrated that variable chemical composition along the height of a buildup wall can be achieved by adjusting the ratio of the wire feed from iron and aluminium wires (Table 3).

Table 3. Tensile properties of aluminium alloy, depending on the microstructure generated by different WAAM process and in different post welding conditions

Materials	Process	Condition	Microstructure	YS [MPa]	UTS [MPa]	EL[%]	Reported by
Al6.3Cu	Wrought (2219)	T851	/	267	390	>4	ASTMB211 M [53]
	CMT	AF	Fine dendrites + equiaxed grains	128 ± 2^a 133 ± 5^b	262 ± 4^a 264 ± 2^b	15.8 ± 0.3^a 18.6 ± 1.5^b	Gu et al. [41]
		HT(T6)	Dispersed θ precipitates	305 ± 6^a 333 ± 6^b	458 ± 3^a 466 ± 3^b	13.6 ± 0.9^a 14^b	

AF: as fabricated, HT: heat treated, AN: annealed.

a: In build direction, b: Orthogonal to build direction.

Table 4. Tensile properties of nickel and bronze alloys, depending on the microstructure generated by different WAAM process and in different post welding conditions

Materials	Process	Condition	Microstructure	YS[MPa]	UTS[MPa]	EL[%]	Reported by
IN 718	GMAW	AF	Nb precipitates + dendritic structure	473 ± 6	828 ± 8	28 ± 2	Baufeld [54]
IN 625	Cast	/	/	350	710	48	ASM [55]
	Wrought	/	/	490	855	50	ASM [55]
	PPAW	AF	Laves phase + columnar dendrite structure	438 ± 38^a 423 ± 22^b	721 ± 32^a 718 ± 19^b	48.6^a 49.2^b	Xu et al. [44]
	PPAW	AF	Laves phase+MC carbides + δ -Ni ₃ Nb	449	726	43	
	PPAW	IC	Laves phase + NbC carbides	480	771	50	Xu et al. [45]
	GTAW	HT(980 °C/ STA)	Coarser Laves particles + Nb precipitates	469	802	42	
		AF	Nb, Mo precipitates + dendrite structure	/	684 ± 23^a 722 ± 17^b	40.13 ± 3.7^a 42.27 ± 2.4^b	Wang et al. [43]
NiAlCu	CMT	AF	α + martensite	350 ± 17	667 ± 15	29 ± 2.6	Ding et al. [21]

AF: as fabricated, HT: heat treated, IC: interpass cooling, STA: direct aging

a: In build direction, b: Orthogonal to build direction.

4 Automated Process Planning for WAAM

AM processes can produce physical objects from CAD models in a completely automated fashion. Complex geometries are sliced into a set of 2.5D layers, resulting in highly automated fabrication of simplified sub-geometries. Although it is argued that there are many potential issues for automatic fabrication of finished functional metal components using AM methods, such as thermal build up, process optimization, and possible fusion defects, the layer-by-layer manner in AM makes full automation of fabricating complex structures easier, especially for certain specialized components that traditional CNC processes could not build due to tool accessibility or collision.

A significant amount of work has been done over the past half century to develop the ability to produce parts from weld deposits using a layer-by-layer approach. However, a fully automated CAD-to-part additive manufacturing system that incorporates an arc welding process has yet to be commercialized [7].

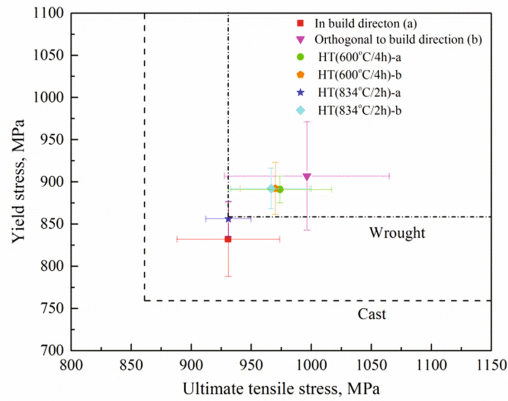


Fig. 8. Summarized mechanical properties of Ti6Al4V components from literatures in WAAM fabrication

4.1 Process Planning for WAAM

The steps involved in building parts with robotic WAAM have been identified as shown in Fig. 9 [56]. The system starts from the CAD model, and ends with the finished component. The input CAD model is sliced into a set of layers using the 3D slicing module. Then deposition paths are generated for each layer through the 2D path planning module. Welding parameters associated with each generated path are automatically selected based on an artificial neural network (ANN) bead geometry model.

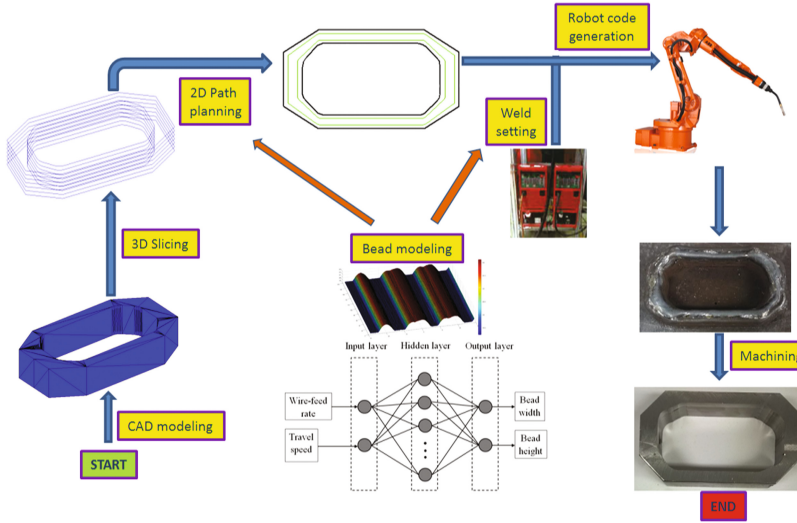


Fig. 9. Steps involved in building parts with WAAM system [56]

Deposition paths together with the determined welding parameters are translated to robot code, proceeding to the fabrication process. Finally, the near-net shape is fabricated and post-process robotic machining is conducted if necessary. By using these step-by-step modules in a robust and autonomous fashion, producing parts using the WAAM processes requires very little human intervention.

Fabricating metallic functional parts using WAAM usually requires more careful process design in order to obtain components with the desired mechanical and material properties. Therefore, advanced design methods for WAAM, particularly slicing and path planning, are essential.

4.2 Slicing Methods for WAAM

Most of the current AM process involves slicing 3D CAD model into a set of 2.5D layers (2.5 D slicing) with a constant or adaptive thickness perpendicular to the build-up direction (usually Z+ direction) [12]. However, to fabricate parts with complex shapes, such a strategy requires supporting structures to be added in order to deposit overhangs (refer Fig. 10a), and deposition in the horizontal plane generates the so called staircase effect for sloping surfaces (refer Fig. 10b). The deposition of sacrificial supports results in the wastage of materials and costly post-processing. The staircase effect concerns the approximate construction of surfaces, which are not aligned along the build direction and is measured as the cusp height (see Fig. 10b).

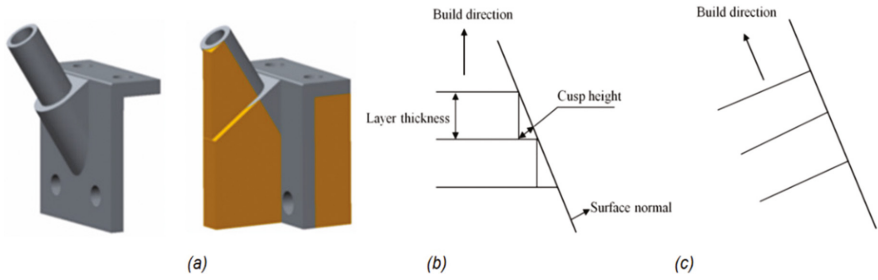


Fig. 10. (a) Supports required (b) Stair case effect (c) Change build direction to eliminate stair case effect

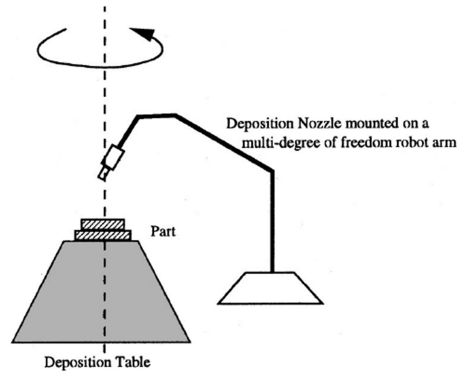
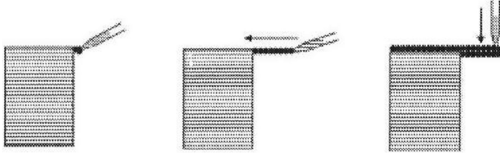
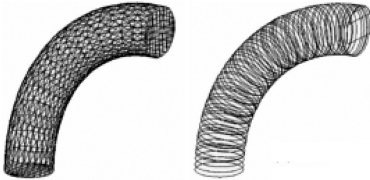
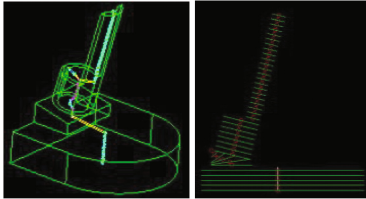
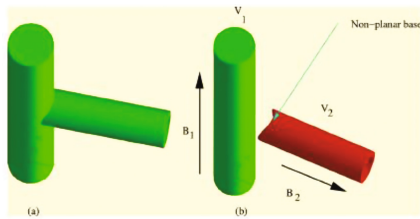
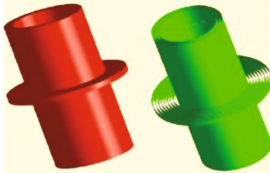
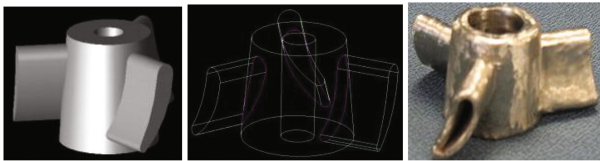
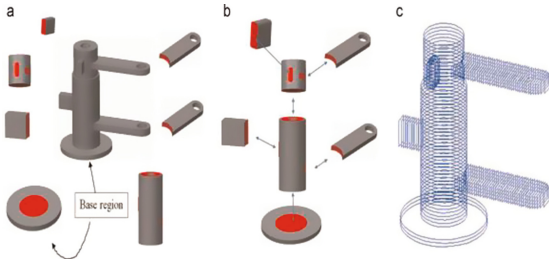


Fig. 11. Multi-direction deposition machine [57]

A possible solution to these problems is to change the slicing/building direction as needed (Fig. 10c). Recently developed AM machines have a deposition nozzle mounted on a multi-axis robot arm, see Fig. 11, which can deposit on the base surface at any orientation and makes depositing on the underside of an overhang possible. This can effectively eliminate the need for supporting structures. As such these machines can be described as Multi-Directional Deposition Systems [57].

Many 3D slicing methods have been focused on minimizing support structures, including transition wall [58], surface tension [59], centroid axis extraction [60], projection based decomposition [57], offset slicing [61], modular boundary models [62], and decomposition-regrouping method [63], as summarized in Table 5. However, each method is only suitable for a subset of part geometries. A key challenge in multi-direction AM is to develop robust algorithms capable of automatically slicing any 3D model into a set of 3D layers which satisfy support-less and collision-free layered deposition.

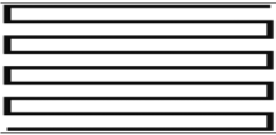
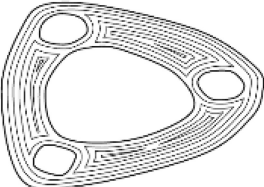
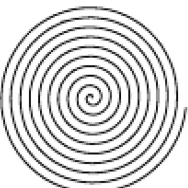
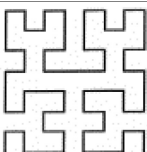
Table 5. Various 3D slicing methods and its typical suitable model

Ref.	Slicing method	Typical examples of the suitable model
[58]	Transition wall	
[59]	Surface tension	
[60]	Centroid axis extraction	
[57]	Projection based decomposition	
[61]	Offset slicing	
[62]	Modular boundary models	
[63]	Decomposition-regrouping	

4.3 Path Planning Strategies for WAAM

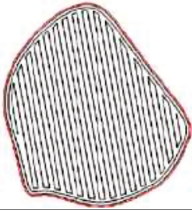
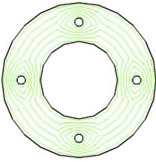
Many types of tool-path patterns have been developed for 2D path planning, as summarized in Table 6. Examples are raster, zigzag, contours, space filling curves, and hybrid tool-path planning approaches.

Table 6. A brief summary of AM tool-path generation methods [64]

References	Tool-path pattern	Examples
[65]	Raster	
[66, 67]	Zigzag	
[68–70]	Contour	
[71, 72]	Spiral	
[73, 74]	Fractal space filling curves	
[73, 75, 76]	Continuous	

(continued)

Table 6. (continued)

References	Tool-path pattern	Examples
[12, 77]	Hybrid	
[6]	MAT-based	
[56, 78]	Adaptive MAT	

Transferring these path planning strategies to a WAAM system is not a straightforward task since the two processes are dissimilar in many ways. The raster scanning path technique is based on planar ray casting along one direction [65]. Derived from the raster strategy, zigzag tool-path generation is the most popular method used in commercial AM systems. While it fills geometries line-by-line along one direction like the raster approach, the zigzag approach combines the separate parallel lines into a single continuous pass which significantly reduces the number of tool-path passes [66, 67]. However, the outline accuracy of the part for both raster and zigzag approaches is poor due to the discretization errors on any edge that is not parallel to the tool motion direction. Contour path generation, which is another typical method, can address this geometrical quality issue effectively by following the geometrical trend of the boundary contours [68, 69]. However, by offsetting the contours, the scheme generates numerous closed curves. The spiral tool-path generation is widely applied in numerically controlled (NC) machining, but is only suitable for certain special geometrical models in the AM process [79]. Another tool-path planning method is based on fractal space filling curves. Bertoldi et al. [73] applied Hilbert curve-based tool-paths to the Fused Deposition Modelling process. However, the large numbers of path direction turning motions that are produced in this strategy are not suitable for wire-feed AM. Continuous path planning can be considered as another tool-path generation method. This method is able to generate filling patterns that allow continuous deposition in a single path to fill any arbitrarily shaped area. The number of welding passes is reduced significantly, thereby minimizing starting-stopping sequences, which is advantageous for the wire-feed AM process. The hybrid path planning strategy is also promising as it shares some merits of various approaches. Generally, a combination of contour and

zigzag pattern is commonly developed to meet both the geometrical accuracy and build efficiency requirements [12, 77]. Reference [6] proposed an innovative path planning strategy, called Medial Axis Transformation (MAT) path, which allows the system to deposit material from the inside towards the outside of a given part geometry. Using this MAT path routine for wire arc additive manufacturing, gaps or voids can be avoided or significantly reduced. As a result, fully dense metal components can be achieved with high productivity and low cost. Based on this “basic” MAT path routine, further studies [56, 78] have proposed adaptive MAT paths to further improve geometrical accuracy and produce void-free deposition. This technique involves continuously altering the deposition width of the wire-feed process to accommodate the component geometry, while simultaneously minimising the number of interruptions to the deposition process at the component boundary. Adaptive MAT-based path planning strategy is particularly benefit for the WAAM of thin-walled structures.

To date, the path planning for WAAM remains empirical and some human invention is required. Depending on the characteristics of the 2D geometries, however, different tool-path patterns are needed.

5 Sensing and Control of WAAM

Current implementations of WAAM through automated process planning are open-loop processes, and the quality of the produced parts relies significantly on the accuracy of the knowledge-based process models (e.g. artificial neural network bead modelling and overlapping model). However, process stability and repeatability are extremely sensitive to the process parameters, building sequences, and welding disturbances. Therefore, to assure desired quality of the deposited parts, sensing and control of the WAAM process is of great importance.

Sensing and control of WAAM is still at a very early stage, and single-bead wall building was a commonly used case study. The main task is to maintain or control the width and the height of the wall using various sensing and control strategies [80–82]. This section reviews the recent developments in sensing technology for the WAAM or arc welding processes.

On-line measurement of the width of the building wall or weld pool is an essential step for control of the process. Visual sensing has commonly been used for quality control of arc welding process, since it has the potential to directly provide dimensional information of weld pool [83]. There were two classes of visual sensing system, namely active visual sensing and passive vision sensing.

Active visual sensing uses laser or structural light as its light sources for the welding area. The key challenge is to overcome the extreme variation in scene brightness created by the welding arc. A stroboscopic vision method was developed to monitor the weld pool as shown in Fig. 12 [84]. The laser energy is transported to the welding site through a single fiber-optic cable. A xenon flash lamp has also been used as a source of intense pulsed light. The laser light reflected from the site is for an instant much brighter than either the direct or reflected light of the welding arc. The system exploits this situation by viewing the welding site with a special-purpose video camera equipped with a CCD video sensor and a very high speed electronic shutter

synchronized with the laser flash and the framing of the video sensor. A narrow-band optical filter to match the laser wavelength is also used to further suppress light from the welding arc. Instead of using an expensive high energy laser illuminator, an innovative vision-based sensing system using 50 mW laser diodes has been used to determine the weld pool geometry [85]. As shown in Fig. 13, the liquid GTAW weld pool, which has a mirror-like specular surface, reflects the incident laser pattern while the surface of the solid base metal is not specular. Therefore, dots or stripes projected on the weld pool are reflected and projected on the imaging screen, enabling indirect measurement of the weld pool geometry.

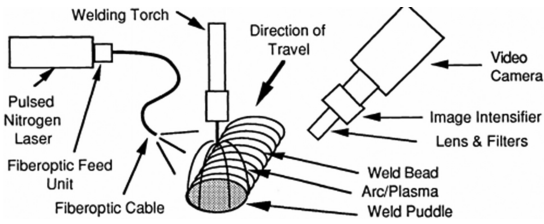


Fig. 12. Control Vision Inc laser video viewing system using a pulsed Nitrogen laser [84]

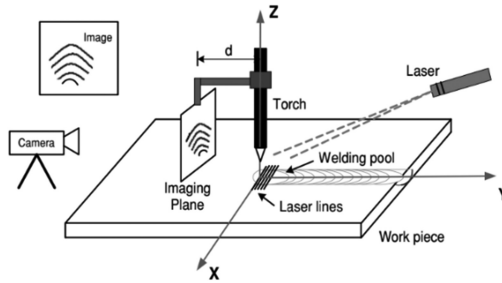


Fig. 13. The vision-based sensing system [85]

Passive visual sensing uses the light from black body radiation of liquid metal and welding arc. As shown in Fig. 14, a typical passive visual sensing system composed of a CCD camera and filters has been used to capture the weld pool information during GMAW and GTAW processes [86]. For the pulsed GTAW process, clear images could be easily achieved during the time when the current is at the lowest (base current), as shown in Fig. 15 [87]. For the GMAW process, where it is more difficult to synchronize the camera with the higher frequency droplet spray transfer, an appropriate dimmer-filter system which significantly suppresses interference from the welding arc is important.

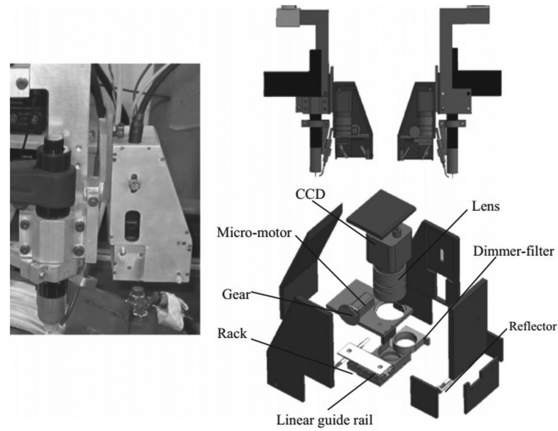


Fig. 14. A typical CCD based passive visual sensing device [86]

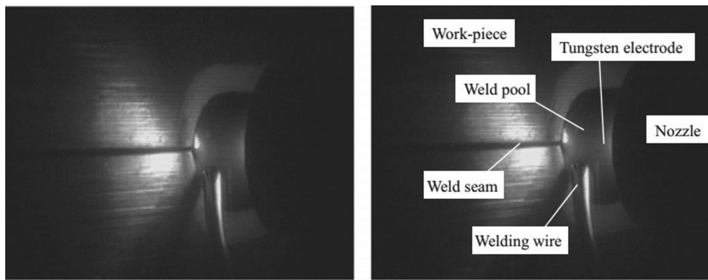


Fig. 15. The welding image during the GTAW process [86]

Although visual sensing for monitoring the weld pool during a conventional (i.e. non-AM) arc welding process has been widely investigated, there is little literature reporting the direct measurement of the weld pool during the WAAM process. To obtain clear images of the WAAM process, more robust sensing devices as well as imaging processing algorithms are required. This additional requirement is due to surfaces adjacent to the weld pool in WAAM not being as regular or predictable as workpiece surfaces normally encountered in conventional single-pass fabrication welding. This also can result in additional instability of the WAAM welding process. Instead of direct measurement of weld pool in WAAM process, active visual sensing [82] and passive visual sensing [80] were used to monitor the area behind the welding area where the influence of the strong welding arc is largely reduced, therefore a certain distance lag was suffered. Another control strategy used for WAAM is to scan the geometry of each deposited layers, then the deviations in the layer height are compensated by adaptively adjusting the wire-feed rate on next deposition layer, based on the 3D scanned data [88]. Through iterative learning control, stable deposition and flat surfaces could be achieved after the deposition of several layers. While most of the

existing literature is focused on simple wall building, in future more attention will need to be paid to the on-line control of WAAM process in the fabrication of complex structures.

6 Conclusions and Future Research Perspectives

Research and development of WAAM for metal components is interdisciplinary, integrating materials science, thermo-mechanical engineering, and process planning. The research conducted in recent years is valuable in characterizing and validating the WAAM of metal components. It is considered that the next progression of WAAM is the automation of the process. Significant research and further understanding are required in aspects of process control and optimization (particularly on-line process monitoring, and control of residual stresses and distortions), and automated process planning (e.g., 3D slicing, path planning, and integrated milling). In terms of industrial manufacturing of large scale structural components, WAAM should not be expected to replace current subtractive manufacturing processes for all, or even most, situations. Rather, the two should complement each other where possible to reduce material usage and final costs.

Acknowledgments. This research was carried out at the Materials Research Lab, University of Wollongong. The work was supported by Defence Materials Technologies Centre (DMTC), which was established and is supported by the Australia Government's Defence Future Capability Technology Centre (DFCTC) initiative.

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Research Papers

Study on Human Welder Behavior by Measuring Local Flow Pattern of Weld Pool and Torch Posture

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Abstract. To study human welder behavior by sensing the welding torch posture and weld pool flow pattern, so as to provide a way to realize intelligent robot welding, a synchronous experiment system is setup with laser vision and a dynamic tilt sensor to precisely obtain the three-dimensional information of weld pool and torch posture. In the downward welding experiment, the data of reflected laser striped image of weld metal fluid flow and the change of torch posture are obtained. The algorithm for extracting weld metal fluid flow characteristic parameters is also written to obtain the weld pool flow pattern. Through the experiment analysis, it is found that the change of weld pool flow characteristic parameters and the change of torch posture have obvious coherence. The change of torch posture reflects the reaction and control ability of the human welder. The change of the weld pool flow characteristic parameters reflects that the welder maintains specific weld metal fluid flow pattern and obtains good weld forming ability.

Keywords: GTAW · Human welder behavior · Laser vision · Local flow pattern · Weld pool · Torch posture

1 Introduction

It is found that through observing the surface of weld pool, skilled welders can adjust the welding torch posture correctly to control certain penetration status, and to control the weld defects so as to obtain homogeneous weld as much as possible [1]. However, it needs a long-term to train human welders for getting skills and experience. Welders' experience is the interaction behavior between people and weld pool. In order to realize intelligent robot welding [2], many scholars of home and abroad have studied the interaction behavior between human welder and weld pool. Liu Yukang, Zhang Yuming [3–6] made some researches on human welder behavior relating to welding current and welding speed, they proposed an adaptive neuro-fuzzy inference system (ANFIS) to correlate the human welder's response to the 3D weld pool surface as characterized by its width, length and convexity. Japan's Aoyama Gakuin University [7] made a research on welder behaviors with four cameras to record the positions of tungsten electrode tips in the TIG welding with filler wire process. British M.S. Erden [8] identified the difference between skilled welder and unskilled welder by analyzing the data of welding torch tip's position which was obtained from a three-dimensional motion capture system, and the result showed that

skilled welders can control the welding torch tip and limit the torch speed to vary in a small range. Liu Yukang, Zhang Yuming [9] also established a virtual welding system, which successfully finished the welding on a pipeline, and they obtained a good weld formation. They established a predictive control algorithm, made the automated GTAW pipeline welding experiment with different welding current and speed. The result showed that the algorithm has a good robustness. However, these studies are all focused on the control or regulation of the energy index of the weld pool. On the one hand, the regulation of energy is easy to make the temperature gradient change relatively, which makes the weld pool unstable. On the other hand, the regulation of energy is easy to make the property of welded joint change greatly, which influences the follow-up service of welds. Therefore, this paper proposes a new experimental scheme that intends to control welding torch posture to change the weld metal flow pattern of weld pool and adjust local heat input of the thermodynamic coupling process. At present, direct measurement of the weld metal flow pattern is very difficult. Although some researchers have investigated the measurements of molten pool fluid flow in metallic melts [10, 11], those processes are not associated with actual welding conditions.

This paper focuses on qualitatively studying the correlation of the welding torch posture and the local flow pattern of the weld pool, which in turn reflects the human welder's responses on the varying weld pool surface, and verifies the proposed scheme to investigate the interactive behavior of welder. To this end, a synchronous acquisition test system, including a five-line-mode-structure laser vision to measure the flow pattern of weld pool and a dynamic angle sensor sensing the data of welding torch posture were established, and the verified experiment was performed.

2 Experimental Principle and System

2.1 Experimental Principle

During TIG welding process, the surface of liquid weld pool carries important welding physical information. However, during the welding process, the change of the weld metal fluid flow cannot be measured directly. Therefore, this paper presents the measuring method of using the striped laser vision to measure the local flow pattern of weld pool. The laser stripes produced by low-power structured laser are projected, covering on the surface of weld pool. The changes of the laser stripes reflected on the surface of the weld pool are observed and recorded by the CCD camera and stored in the computer. Because the laser stripe pattern, which is projected onto the surface of weld pool with a certain geometric parameter and imaged after specular reflection, has a strict optical correspondence with the change of the flow pattern of weld pool on the surface, so the spatial geometrical mapping optical model established between the weld pool and the projected laser stripes can realize the dynamic measurement of the weld metal fluid flow. The principle is shown in Fig. 1.

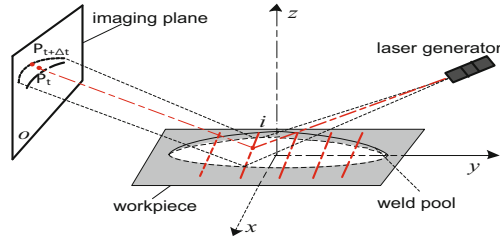


Fig. 1. Experimental principle

2.2 Experimental System

According to the principle of measuring the flow pattern of weld pool by laser vision in Fig. 1, the experimental system of synchronous acquisition in Fig. 2 is established. The experimental system of synchronous acquisition uses the MPU6050 sensor to sense the welding torch posture. In the system, a structured laser with wavelengths of 658 nm, 37.5 mW is placed in plane OYZ, and it was about 90 mm from the weld pool, and about 30° from the work-piece. In the plane OXZ, an imaging screen is vertically or obliquely placed about 53 mm from the weld pool to intercept the striped laser reflected by the weld pool surface. The system uses the high-speed CCD camera to record the reflected laser image. In order to further reduce the impact of the arc exerts on the image quality, CCD camera lens is equipped with a 660 ± 10 nm band-pass filter. It uses AC-DC inverter welding machine TIG315AC/DC as a welding power source. During the welding process, the torch is supported by the universal joint and adjusts the direction and speed of welding trolley by the stepper motor combined with an inverter.

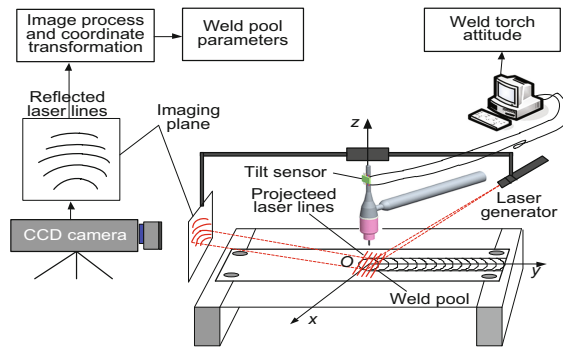


Fig. 2. Experimental system

3 Experimental Procedure and Discussion

3.1 Image Processing Algorithm

In order to extract the laser stripes' curvature radius from the collected laser stripe image, the image should be preprocessed at first. In order to remove the noise signal in the reflected laser stripe image, image filter method was adopted. Through the binarization of image processing, the laser stripe is separated from the image and to study. The edge of the laser stripe contains a wealth of intrinsic information, which is a basis to make a distinction between a laser stripes and another one. In order to facilitate the curve fitting of the laser stripes, it is necessary to perform the image edge detection on the edge of the laser stripe image, and then extract the edge value of the laser stripes, using the least squares fitting method to fit the midpoint between the upper and lower edges of the laser stripes. The fitting steps are as follows.

Fitting Laser Stripe Function

Assuming the general expression of the image fitting function is:

$$y = a_0X^n + a_1X^{n-1} + a_2X^{n-2} + \dots + a_iX^{n-i} \dots + a_{n-1}X + a_n \quad (1)$$

where $a_i (i = 1, 2, 3 \dots n)$ are constants.

Midpoint value should be fitted at first, and each midpoint value should be go on through, and then a_iX^{n-i} can be constructed, and finally the fitting function of the midpoint value in the laser stripe was obtained. Figure 3 shows the laser stripes' midpoint detection, and the detected mid-points were fitted by the above function. The fitted curve can be seen in Fig. 3 red line.

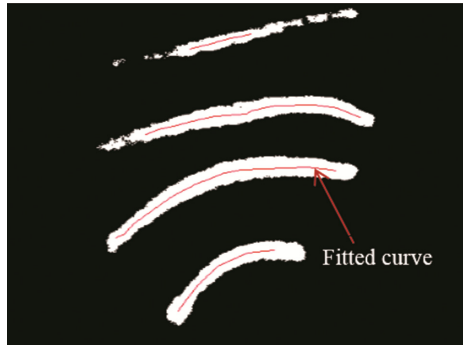


Fig. 3. Midpoint detection of laser stripe (Color figure online)

Solving the Laser Stripes' Curvature Radius. After the function expression that can expresses the laser stripe image is obtained, each a_iX^{n-i} should be goon through and to find the first derivative $(n-i)a_iX^{n-i-1}$. And then each $(n-i)a_iX^{n-i-1}$ should be goon

through to find the second derivative $(n - i - 1)a_i X^{n-i-2}$, finally the first derivative function expression y' of the function, and the second derivative function expression y'' can be obtained.

Then according to the expression of curvature K :

$$K = \frac{|y''|}{(1 + y'^2)^{3/2}} \quad (2)$$

Therefore, the curvature radius:

$$R = \frac{1}{K} \quad (3)$$

Thus the solution of the laser stripes' curvature radius function expression is obtained, which is shown in Fig. 4.

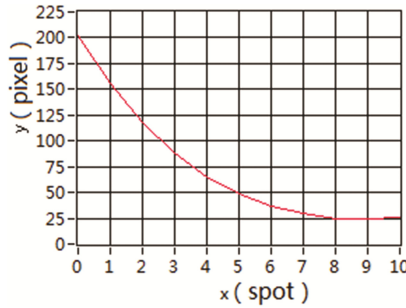


Fig. 4. The curvature radius of the laser stripe

Representation of Local Flow Pattern of the Weld Pool. As shown in Fig. 1, the i th laser stripe reflected by the surface of the weld pool is taken as an example. After an interval time Δt , point $P(t)$ moved to point $P(t + \Delta t)$. Taking a small part of the liquid metal on the surface of weld pool as an example, a micro displacement Δs occurred in the pool. Taking the laser stripe on the imaging screen as the object of study, the reflected laser stripes' curvature radius is changed from $R(t)$ to $R(t + \Delta t)$, so the flow rate of the weld pool is:

$$V = \frac{\Delta S}{\Delta t} \quad (4)$$

Because $\Delta t \rightarrow 0$, so $\Delta s \rightarrow 0$, simply:

$$\Delta S = f(R_{t+\Delta t} - R_t) \approx c(R_{t+\Delta t} - R_t) \quad (5)$$

where c is a constant.

So:

$$V = c \frac{\Delta R}{\Delta t} \quad (6)$$

After the laser stripes curvature radius of function expression is obtained, the curvature radius of each laser stripe. Since the length of the video time is T , the total number of the pictures which obtained after framing is N , the flow rate is expressed as a function between the change of curvature radius and time:

$$V = c \frac{\Delta R}{\Delta t} = c \frac{\Delta R}{\frac{T}{N}} \quad (7)$$

3.2 Experimental Results and Discussion

In order to extract characteristic parameters which reflect the change of flow pattern of weld pool from the changing laser stripes, a program to extract the laser stripes' curvature radius is written in Lab VIEW by using the program flow chart shown in Fig. 5.

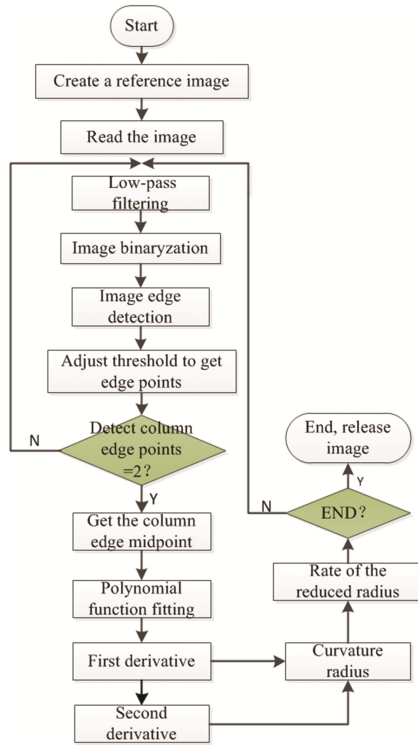


Fig. 5. The program flow chart of laser stripe image processing

The established experimental platform was used to make a bead-on-plate welding experiment with 304 stainless steel, and the experimental parameters are shown in Table 1. When the laser stripes completely covered the surface of the weld pool, the laser stripe images captured on the imaging screen were shown in Fig. 6. In order to study the welders' behavior of adjusting flow pattern of weld pool by adjusting the weld torch posture, the program which was written by the program flow chart shown in Fig. 5 was used to process the laser stripe image.

Table 1. Experimental parameters

Name	Material	Plate thickness $H/(mm)$	Current $I/(A)$	Arclength $l/(mm)$	Welding speed $v/(mm/s)$	Gas flow $Q/(L/min)$
Parameters	304 Stainless steel	3	60	3	1.5	8

Figure 6 shows laser stripe images which reflected by the weld pool surface during the welding process, and the image was formed under the DC current which was obtained every 3 s in the video shot by the high-speed camera with the sampling frequency of 200 Hz. In Fig. 6, during the whole welding process, the shape of the laser stripe image is changing constantly. There are 3 points selected in the second laser stripe image: the point near the center of the weld pool, the point near the edge of the weld pool and the point between the center and the edge of the weld pool. And the Fig. 7 shows the dynamic changing curve of torch posture. Figure 7 shows the weld pool characteristic parameters of local flow pattern, which is obtained from Eq. (7). From the change trend of the whole curve, we can receive the information that closer to the center of the weld pool, the greater of curvature radius change rate will be, indicating that when the position is closer



Fig. 6. The typical reflection of the laser stripe (the time interval of images: 3 s)

to the center of the weld pool, the liquid metal's flow rate will be greater. The comparative analysis between Figs. 7 and 8, it shows that in Fig. 7, weld pool characteristic parameters of local flow pattern change greatly at 30 s–34 s while the angle of torch posture also changes greatly at 30 s–34 s. Correspondingly, weld pool characteristic parameters of local flow pattern at 47 s–51 s in Fig. 7 changed dramatically, while the posture angle at the 47 s–51 s in Fig. 8 changed greatly, and then weld pool characteristic parameters of local flow pattern reaches a steady state again. The results show that when the welding process unstable state is caused by the change of weld pool local flow pattern, welder can adjust the welding torch posture to bring the weld pool to another steady state again. The change relationship between the rate of laser stripe's curvature radius changes and time also reflects the liquid metal's flow state in the plane XOZ to a certain extent. When the position is closer to the center of the weld pool, the liquid metal flow rate will be greater. This result agrees well with that by simulation [12].

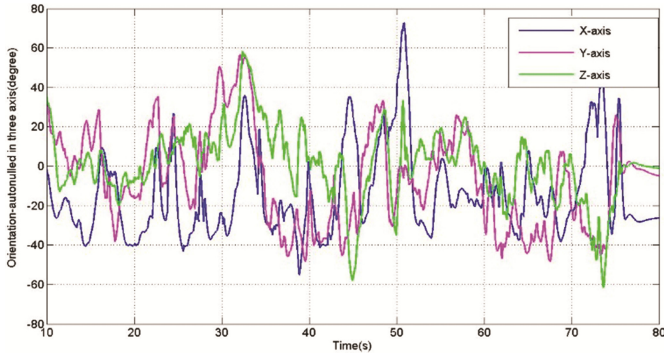


Fig. 7. The posture curve of welding torch

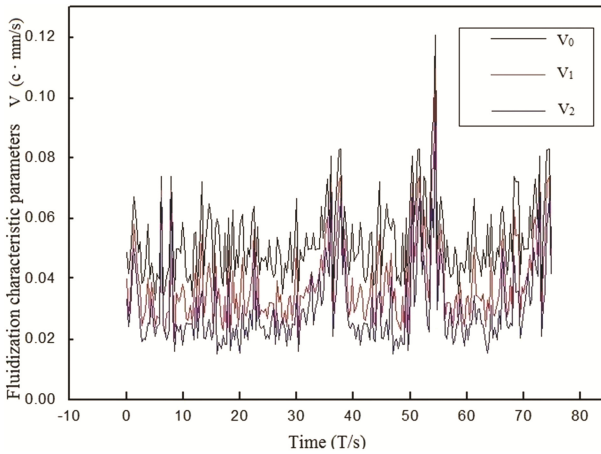


Fig. 8. The fluidization characteristic parameters (v_0 represent central area of weld pool; v_1 represent between central and edge area of weld pool; v_2 represent edge area of weld pool)

4 Conclusions

A new method is proposed in this paper to characterize the local flow pattern of weld pool by mean of measuring the dynamic change rate of the curvature radius of weld pool surface during welding process. The change of weld pool characteristic parameters of local flow pattern and the change of welding torch posture have obvious coherence, therefore it can characterize the human welder behavior in welding operation. The weld pool characteristic parameters of local flow pattern show that liquid metal flow rate at the center of weld pool is greater than that at the weld pool edge. This result agrees well with that by simulation.

Acknowledgement. Thanks for the help of Prof. Zhang Yuming of University of Kentucky in this article. Thanks for the National Natural Science Foundation of China (No. 61365011-2014).

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A Robotic Re-manufacturing System for High-Value Aerospace Repair and Overhaul

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Abstract. This paper describes the necessary elements for the development of a bespoke robotic welding system for aerospace turbofan compressor blade re-manufacturing. The established industry-academia research partnership and project evolution at The University of Sheffield (UK) from 2006 is highlighted in the joint development of a disruptive platform technology for high-value aerospace re-manufacturing. The design process, funding mechanisms, research and development of key components (vision system, high-speed DAQ, advanced GTAW welding system trials) are described in this paper. Interaction of these key components when combined with novel collaborative robotic technology and experienced welding engineers has made this project possible. This industry-academia research intensive collaboration between VBC Instrument Engineering Limited (UK) and The University of Sheffield has received project funding from the Engineering and Physical Sciences Research Council (EPSRC, 2006–2010), the Science and Facilities Technology Council (STFC, 2011–2013) and Innovate-UK with the Aerospace Technology Institute (2014–2018).

Keywords: Welding · Manufacturing · Simulation · Robot

1 Introduction

The European Organization for Nuclear Research, the Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator, based at CERN. The ATLAS Experiment is one of two large scale detectors sited on the Large Hadron Collider. Sited at CERN, 100 m below ground, the ATLAS collaboration conducted the search that led to the Nobel Prize winning Higgs boson discovery in 2012. ATLAS explores extra dimensions and new particles and the detector is the largest volume particle detector ever constructed [1].

The University of Sheffield (TUoS) is heavily involved with the construction, installation and later operation of the Inner Detector (ID) of ATLAS from 1997 to date [2, 3]. To cope with the proposed High Luminosity LHC (HL-LHC) energy rate, the ATLAS inner detector now requires significant upgrades, beginning in 2017, to achieve a factor of 10 higher rate of collisions, essential for probing new physics phenomena.

Particle detector cooling systems require lightweight materials with high strength. The existing design of the ATLAS ID cooling system included thousands of tube and pipe connectors, all a potential single point of failure and source of high materials mass for the detector [4]. For the future ATLAS Upgrade Inner Tracking Detector (ITk) it was desirable to make the cooling connections more robust and, in order to compensate for higher luminosity, further reduce weight & size. A market survey conducted from 2005–2006, on commercial welding equipment highlighted that no off-the-shelf welding system was capable of joining ultra-thin <200 mm wall thickness of 316L stainless steel micro-tubes, the first chosen ATLAS ITk prototype tubing material, and later CP2 Ti micro-tube of 125 mm wall thickness.

Forming a collaboration, the University of Sheffield and VBC Instrument Engineering Limited (VBCie) worked in partnership furthering the development of a unique gas tungsten arc welding (GATW) power source, the “InterPulse HMS” system. Publicity from this new welding system power supply, utilized by the aerospace and power generation industries was brought to the attention of TUoS researchers and automation was added to the InterPulse by means of an orbital weld head. The developed Constricted GATW process solved many issues from previous research papers such as numerous failures observed in space-vehicle propulsion-fuel systems due to failed welds [5, 6] and subsystem electronic component damage [7–12] induced from stray electrical arcs.

In order to maintain a global competitive advantage in the UK manufacturing sector, the UK Government identified the need for rapid development of the next generation of advanced high-value manufacturing. One direction that has huge potential is highly reconfigurable and flexible manufacturing systems and their application to the aerospace industry. Predictable re-manufacturing processes help manufacturers reduce waste by offering raw material reduction, minimizing production downtime and repair costs. Cost of repair is generally the less important factor when considering repair, time to repair is the most important consideration.

The Manufacturing, Repair and Overhaul (MRO) industry relies on significant use of manual welding with existing repair techniques. Current remanufacturing of aerospace turbine compressor blades is carried out on 80% of all recovered blades from a serviced aero engine. Human errors observed in manual welding processes to repair turbofan compressor blades largely attributes to a poor repair yield of only 45%. The robotic re-manufacturing system for high-value aerospace manufacturing is designed to recover a 100% yield of recovered blades. Extending blade life represents large savings to both aerospace engine manufacturers and airline operational costs due to repairs worth from £250 to £7 k per blade dependent on size and material.

Successful TIG welding requires highly skilled engineers who rely on experience when facing welding problems. This practice often results in human error, repetitive strain injury and loss of production control. Implementation of robotics avoids errors, reducing risk to engineers. Furthermore, automated welding solutions reduce dependencies on highly skilled personnel allowing manufacturers to invest in research and innovation.

The following text will present and describe key components of a robotic welding systems for development of a high-value aerospace manufacturing system, Sect. 2 describes industry-academia collaboration between The University of Sheffield and

VBCie, Sect. 3 discusses the system development timeline, Sect. 4 discuss the profiling of an aerospace turbofan compressor blade, Sect. 5 describes the development of high-speed data acquisition system for TIG welding, Sect. 6 highlights the development of a machine vision system for real-time welding inspection, Sect. 7 demonstrates simulations of a six axis robotic manipulator used for welding turbine blades.

2 The Industry-Academia Collaboration

Collaborative industrial research and development supported by Research Agency funding has allowed for TUoS research group expansion and established significant expertise in low heat input fusion welding, real time defect inspection and intelligent robotic systems. In-turn this has allowed successful knowledge transfer back to industry and the continued buildup of expertise.

VBCie, the industrial partner has been able to gain a depth of research knowledge and the ability to conduct blue skies research projects that would otherwise be unobtainable, ultimately using research outputs for product development. The global MRO market is currently valued at £63bn, these projects have strengthened industrial relations with aerospace and the nuclear industry [13], see Fig. 1.

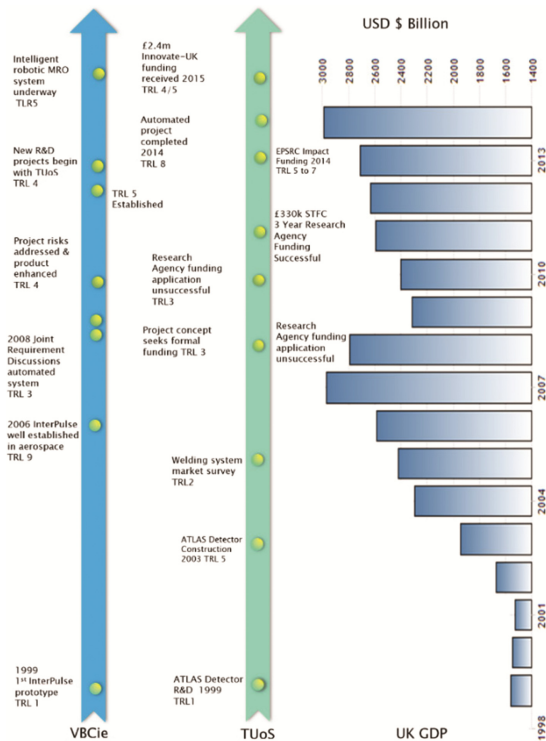


Fig. 1. Industry-academia collaboration with UK economic GDP

Expansion to strategically locate a new VBCie subsidiary (VBCie Asia) in Singapore and the development of a network of affiliates and distributors across South East Asia better serves customers in the region. In the UK, VBCie has benefited from increasing their workforce with new engineers and a general increase of production.

New academic collaboration linking the ARTC (Advanced Remanufacturing Technology Centre) in Singapore with the University of Sheffield came about through involvement with VBCie and existing research programs with TUoS and AStar, Singapore's research agency. This collaboration builds on existing collaborative R&D projects that both Sheffield and ARTC have with Rolls-Royce Aerospace and VBC Instrument Engineering in the UK and Singapore.

Current joint TUoS, VBCie & ARTC post graduate studentships now address novel challenges for the remanufacturing of both large scale (aerospace) and small-scale (ATLAS/CERN) automated low-heat welding systems. These are required for both Particle Physics detectors, nuclear and aerospace applications to work with newly developed lightweight, high strength materials.

This research project has never proceeded in a straight line. Developing new partnerships with robotics companies, vision system manufactures, electrical test and measurement industry has increased the wealth of knowledge available to the partnership. Effectively now a highly skilled cross-disciplinary team can be deployed to rapidly respond to both the needs of industry but also further academic research.

3 System Development Timeline

Variable parameter changes: current, length, angle, manipulation and speed, termed CLAMS are detailed in welding procedure schedules used to provide numerical input for the manual operator to achieve correct results with high yield. Knowledgeable and experienced welding engineers apply their skills almost automatically by subtly fine-tuning multiple welding control parameters dynamically achieve the required results. These dynamic inputs modify the weld deposition characteristics such as; micro-structure, depth, size, and shape.

Effective dynamic weld correction requires intelligence, which has proven exceptionally challenging to develop when welding complex profiles and super alloy materials with minimal heat input and distortion. Widespread use by aerospace engine manufacturers of GTAW technology partially provides a solution [5, 7]. Continuous iterations of variable parameter data enable production of the correct weld deposition with high repeatability but with the inability to respond to a change in dynamics or conditions.

Development of this advanced, intelligent robotic welding system requires the correct relationship between welding parameters and corresponding outputs. Advanced programming of robots, data interpretation from integrated sensory and feedback systems are required to replace a human welder's expertise. Intelligence within the control loop can only be accomplished by key technologies such as electronic sensors, machine vision systems, high-speed data acquisition and control systems.

Timely development of disruptive intelligent robotic technologies for remanufacturing is non-trivial. The cyclic nature of global economies, large manufacturer's

response to investment and subsequent capital expenditure show a wave like effect on how industry-academic research projects slow and expand. The relationship and project development timeline [14–18] is shown in Fig. 2, beginning with requirements for an alternative to joining ultra-thin tubes for the next LHC upgrade to the development of intelligent robotic remanufacturing solutions for aerospace and nuclear sectors.

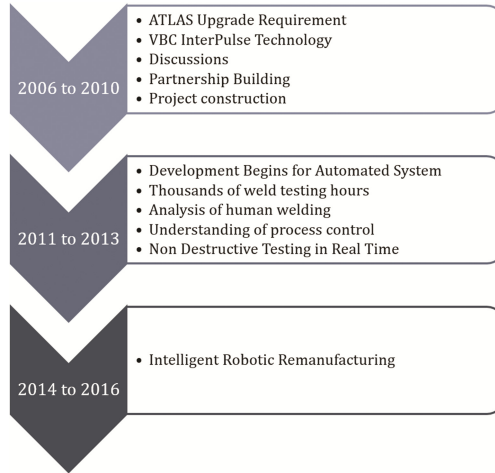


Fig. 2. Project development timeline

In 2006, the technology was simply not available even though the requirements were known. Considerable amounts of research analyzing the specifications of commercial off-the-shelf technologies was conducted. Fortunately, a theoretical solution was proposed by the academy-industry collaboration between TUoS [19, 20] and the VBCie [21] who provided the know-how and technology respectively. The following four years refined concepts as technology matured and by 2010, research funding concepts were made. Construction of the initial demonstrator was funded by the STFC Innovations and Partnerships Scheme in 2011. Progress was made with parallel investigations on the ATLAS Upgrade Experiment both in the UK and CERN, investigating the use of ultra-thin stainless steel tubing for cooling systems. Realization quickly matured, easily applying the technique for orbital welding of stainless steels to titanium alloys. This revolutionized the approach of the project and allowed entry into the aerospace domain for the collaboration.

High value aerospace gas turbine blades are subjected to extreme temperatures during operation, every 30000 h of airtime, engines are entirely overhauled, and worn blades are taken out for repairing and refinishing using manual weld deposition. Only half of all blades are reclaimable, although current yield is only around 80% of that half due to high heat input during welding and poor practice.

The aerospace industry deals with Maintenance, Repair and Overhaul (MRO) in relation to the blade repair systems for aerospace turbofan engine. In 2014, VBCie in

partnership with Sheffield University were awarded significant funding from Innovate-UK and the Aerospace Technology Institute (ATi) to design and develop a robotic aero turbine blade re-manufacturing system [22].

The objective of this industry-academia research project is to identify both wear on the blade and carry out a low heat input weld build up and potentially doubling its existing service life. This automated solution will gather wear data using profile detection and machine vision prior repairing the blade. Real-time welding data will be evaluated using a NDT (non-destructive testing) high-speed data acquisition system [23, 24]. VBCie's InterPulse technology is ideally suited to any application that benefits from low heat input temperature. This data can be fed back to the blade manufacturer to further both service life, design and efficiency to increase throughput and save on scrapping blades.

Intelligent systems for the autonomous re-manufacturing robot are constructed in modules to mirror human cognition and dynamic response. The inspection module dictates the automatic loading and unloading of blades, automatic part recognition, selection of the weld program, weld torch with wire feed and work piece tooling. The system automatically identifies different types of blades continuously and assigns the corresponding welding data to follow (Fig. 3 shows a representative system design). In the following sections, the main unit modules will be explained. Photographic illustration of the final system cannot be shown in this publication due to commercial protection.

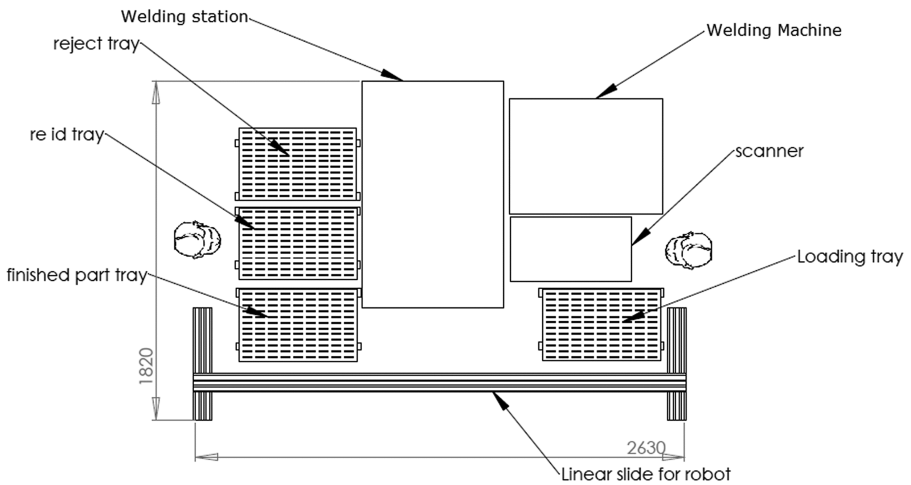


Fig. 3. Graphical representation of modular elements of turboman re-manufacturing system

4 Aerospace Turboman Compressor Blade Profiling

Profile detection is used in the image analysis of turboman compressor blades to locate the blade edges with high accuracy. Edge detection is an effective tool for many machine vision applications and it provides information about the location of the boundaries of objects and the presence of discontinuities, see Fig. 4.

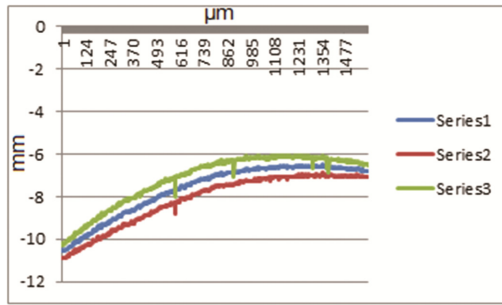


Fig. 4. High-speed blade-profile detection: upper (green), lower (red) and centre (blue) (Color figure online)

Detection helps to determine if a defect is present using line profiles and edge detection. When performing measurements to determine if a blade under inspection is manufactured correctly, the part is either accepted or rejected, depending on whether the main parameters fall inside or outside of the manufacturer tolerance limits. An edge along the line profile is defined by a technique that levels the contrast between background and foreground and the slope of the transition. The position and orientation of the blade can be determined from the profile detection data then used by the tracking control system of the robotic manipulator, see Sect. 6.

5 High-Speed Data Acquisition System

VBCie and the University of Sheffield have developed a novel low-current and automatic GTAW orbital welding system called the Heat Management System (IP50-HMS). The IP50-HMS produces accurate narrow bead welds and offers excellent weld quality and control over the weld process of high quality materials such as titanium and steel super alloys. The use of high frequency pulsing interposed within the pulsed weld current increases arc force and more penetration is achieved with significantly lower input current. This allows for improved heat management on critical welds whilst still attaining full penetration. The machine has proven very successful in the joining of very thin wall, small diameter titanium and stainless steel alloy heat exchanger tubes. Conventional orbital welding systems cannot weld such thin wall material with small diameters. The IP50-HMS produces autogenous butt welded joints showing higher mechanical integrity than conventional orbital welding systems evaluated. The low heat input obtained improves the materials micro-structure because of the decrease in distortion and residual stress. The IP50-HMS proves to have an exceptionally high production yield with very low weld failure rates [23].

The STFC funded an Innovations Partnership Scheme (IPS) project with VBCie & TUoS. The objective was to transfer technology and expertise, developed using STFC research, to the marketplace in partnership with industry. Electrical measurements of arc voltage, current and input power measurements of the VBCie system were obtained using a novel high-speed DAQ system previously developed by the University of

Sheffield to determine system accuracy. The portable signal-conditioning device can be used to measure DC and AC welding current and voltage signals and therefore can be used to evaluate GTAW welding systems. Electrical measurements are obtained and analyzed to determine if a weld deposition has been successful or not in real-time, see Fig. 5. Detailed observations have shown no structural or geometrical imperfections in the weld bead monitored using the developed DAQ. Micro-hardness tests have also been performed according to standard BS EN 1043-2:1997 [25] and all of the welds have successfully passed in accordance with the standard.

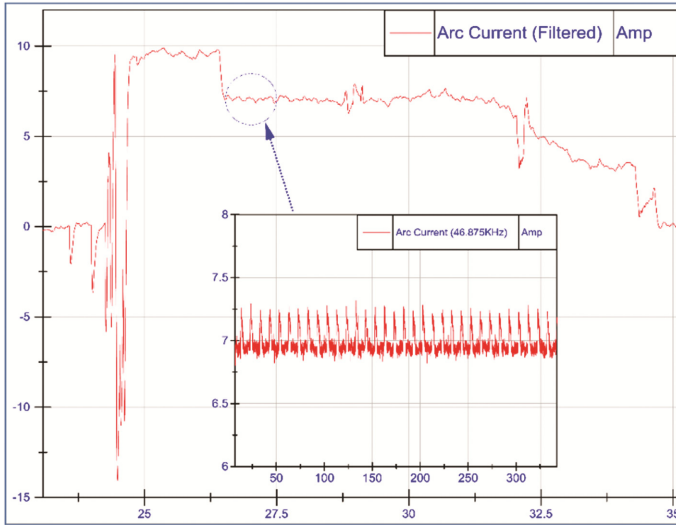


Fig. 5. High-speed current measurement of a successful weld deposition. Inset figure shows a weld region with uniform penetration

6 Machine Vision for Welding Robots

The primary aim of the machine vision system will be to detect the incoming parts and interface to the welding system to ensure it is at the correct position and orientation. This is particularly important in the aerospace industry as most parts are custom-made, consisting of unique shapes and sizes. This means the system will detect faults and defects on the parts and determine the appropriate re-manufacturing or correction procedure required. The vision system will be able to detect cracks and shape deformation on turbofan compressor blades to provide a NDT method of blade testing. This high-resolution stereo camera bar system can also be integrated with the robotic re-manufacturing system for tracking control.

One key aspect to achieve welding process automation is the visualization of the weld. A 3D stereo vision system was used to image the welding process for monitoring and inspection purposes [26]. A camera and lens combination, chosen in order to achieve a resolution able to detect defects of sizes 25 μm , measure the welding process at a speed

of 20 mm/s and image an 8 mm^2 area. A USB3 1.2 MP camera with a $1/3$ in $3.75 \mu\text{m}$ pixel pitch global shutter CMOS sensor and a macro lens with a variable focus from 13–130 mm were used to achieve the required resolution. In addition to the cameras and lenses, an important component of the machine vision system is the illumination and filtering. Following information obtained by spectral measurements of the welding arc, a high-power laser and specifically tuned laser were chosen to minimize the influence of the welding arc on the images.

The vision system relies on using stereo imaging pairs to produce a 3D reconstruction of the target area thereby locating it and produces its topological maps to provide information necessary for the welding to take place. This technology has great potential to be developed not only for robotic welding systems but also for other automated systems that require vision systems.

Figure 6 shows a snapshot of TIG welding during the first stage testing of the vision system. The system is able to image the welding tip, pool and bead. Whilst this is important for testing the capability of the image system in filtering out the high-intensity welding arc, the final system is planned to only image the welding pool and bead as these provide information about the quality of the weld.

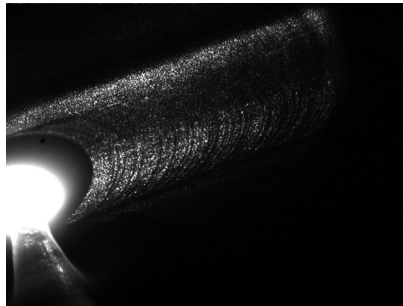


Fig. 6. Snapshot image of the TIG welding tip, pool and bead

A second camera is used to acquire the welding process simultaneously from two separate angles. The images are then processed using a semi-global matching (SGM) stereo algorithm in order to produce a high resolution and accurate 3D reconstruction of the welding process. This will provide high resolution and accurate information for inspection and monitoring of the weld. Such information is used by the welding robot for controlling the welding process by adjusting parameters such as voltage intensity, distance between the arc tip and sample and welding speed.

7 Simulation of Welding Robot Kinematics

Kinematic robot simulation of the robot manipulator and the interaction with key components of the robotic re-manufacturing system (welding machine, vision system, blade tray, etc.) are performed using V-REP and ROS-Industrial. The robot simulator V-REP is based on a distributed control architecture: each model can be individually

controlled via a ROS node or a remote API client. All these make V-REP ideal for simulating algorithms to control the six-axis robot manipulator. V-REP's motion planning module allows handling motion-planning tasks to allow computing a welding trajectory from a start configuration to a goal configuration in S-shape, by taking into account the manipulator kinematics, joint limits and collisions between manipulator and obstacles. When the goal configuration is not directly known, it needs to be computed from the position and orientation in Cartesian space of the end-effector.

ROS, an open-source project, can provide a common framework for robotics applications and is heavily utilized by the research community for service robotics applications, including industrial robotics for manufacturing. ROS capabilities, such as advanced perception, path and grasp planning, can enable industrial robotic applications that were previously technically infeasible or cost prohibitive.

An open-source project that extends the advanced capabilities of the ROS software to manufacturing is ROS-Industrial. The benefits of ROS-Industrial include, custom inverse kinematics for manipulators, including solutions for manipulators with six degrees-of-freedom such as the robotic manipulator. This simplifies robot programming to the task level by eliminating path planning and teaching, optimal paths are automatically calculated given tool path waypoints. Applying abstract programming principles to similar tasks reduces costs. This property is useful in low-volume applications or with slight variations in work pieces, such having different types of blades on the same batch or tray.

An example of the ROS Industrial program when inclusive with modern robotic software generally contains packages that provide nodes for communication with the robot controller, degree of freedom models for the six axis robot arm and associated arm navigation and motion control packages [27], see Fig. 7.

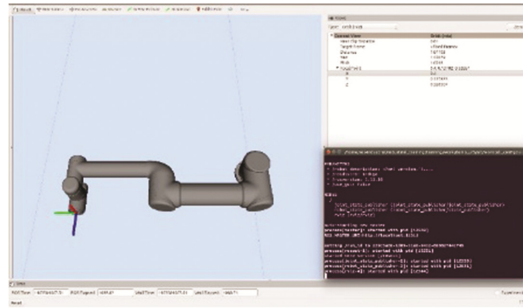


Fig. 7. ROS 6-axis robot arm simulation in a workcell MoveIt environment

8 Conclusions

The challenges of developing a robotic re-manufacturing system for high-value aerospace manufacturing within intelligence and dynamic control are successfully addressed when each key system element is developed in-conjunction with experts in each field (Vision, Robotics and Welding). Industry-Academia collaborative research projects are

challenging as they carry a high risk of failure, however, researchers in academia can aid industrial development jointly mitigating risk using simulation and high fidelity measurements. The knowledge exchange and technology developed since 2006 within this specific partnership has continued to expand into new areas. The collaboration has widened to join with other manufacturing companies, working in partnership to develop high tech, disruptive technologies for flexible manufacturing. The final functional robotic re-manufacturing system will be delivered by 2018.

Acknowledgements. Research supported by EPSRC, STFC, UK-ATLAS, EU FP7 AIDA, EU H2020 AIDA2 and INNOVATE-UK. We are very grateful to Dr. Benjamin Crutchley from Industrial 3D Robotics for aid.

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Automated Programming for Robotic Welding

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Abstract. Robotic welding automation allows manufacturers to increase quality, flexibility and reduce costs. However, the costs involved in programming welding robots for small production runs limits viability for Small and Medium Enterprises to employ arc welding automation. This paper outlines an Automated Offline Programming framework which can be used to generate robot programs directly from Computer Aided Design models with minimal human input, allowing programming costs to be drastically reduced or even eliminated. The key stages of our approach are presented and a specific implementation for welding of complex pipe structures is shown. The results demonstrate the feasibility of our method to enable truly flexible robotic welding automation.

Keywords: Robotics · Welding · Automated programming · Motion planning

1 Introduction

Industrial robotic automation is typically the domain of high volume manufacturers with short cycle times and large batch sizes. The cost of tooling and programming limits the viability of robotic welding automation for low volume and once-off production. This paper presents an Automated Offline Programming (AOLP) approach for generating robotic welding programs directly from Computer Aided Design (CAD) models, reducing or eliminating programming costs.

Arc welding is a key robot application. 13% of robots sold in 2011 were used in arc welding applications [1]. Tooling costs for robotic arc welding are similar to those in manual arc welding, hence the programming costs involved is the key limiting factor for use in low production volumes. By reducing programming time and costs, the presented AOLP framework makes automated robotic welding feasible for Small and Medium Enterprises (SMEs).

There are two primary classifications of robot programming methods: automatic and manual programming [2]; and online and offline programming [3]. Conventionally robots use online manual programming (or lead-through programming), in which an operator uses a teach pendant to guide the robot through the designed welding motions.

These motions are recorded to create the robot program. This approach is simple and low cost, but requires: significant time, a physical robot, and is limited by the skill of the operator. Recent extensions to this focus on programming by demonstration, in

which an operator demonstrates a task to perform which the robot then “learns” using sensors [4].

In contrast, Offline Programming (OLP) uses a model of the robot, cell and work piece to allow a user to generate robot programs using a software package without requiring exclusive access to a physical robot. By taking advantage of software tools and existing CAD data it is possible to rapidly develop and simulate robot programs. However, this programming process has many of the same challenges as conventional programming: it requires a skilled operator, there are challenges translating to a physical robot, and for some cases the costs can be higher than conventional programming [5].

Automated Offline Programming (AOLP) [5] is an approach which extends OLP by using algorithms to automate much of the robot programming process. This can drastically reduce or even eliminate human effort required for robot programming, making robot programming viable for low volume applications. It also allows generating complex motions to access challenging areas, as well as integrating sensing to deal with part placement inaccuracies.

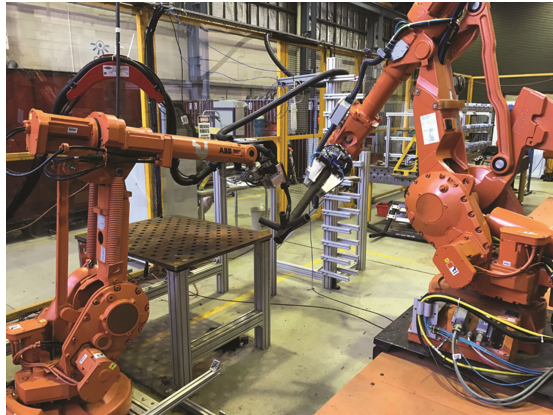


Fig. 1. The robotic welding cell with two 6-DOF manipulators

This paper presents the AOLP framework tailored specifically for arc welding. Previous papers have presented individual components in detail, but this paper aims to cover all the required stages for a full AOLP welding solution. Section 2 outlines the overall approach and Sects. 2.1 to 2.5 detail each stage. Results from a specific implementation are presented in Sect. 3 and conclusions are drawn in Sect. 4.

2 Automated Offline Programming

Automated Offline Programming (AOLP) uses planning algorithms to translate a CAD model directly into a robotic program with little human intervention. The process, introduced in [3, 5], is composed of several key stages as illustrated in Fig. 2. For the specific case of welding, they are:

- (a) **3D CAD Model**
During product design, create a 3D CAD model of the parts to weld.
- (b) **Process Definition**
Define the weld paths, orientations and key process parameters.
- (c) **Process Planning**
Generate robot motions to perform the welding operation.
- (d) **Trajectory Planning**
Plan intermediate motions to move between welds and home positions.
- (e) **Calibration**
Use sensing to account for differences between the CAD model and the part.
- (f) **Post Processing**
Optimize motions, and convert to robot code.

Steps (b)–(f) use algorithms to directly generate high quality welding programs with little or no human intervention. Sections 2.1–2.5 detail approaches to each of these stages.

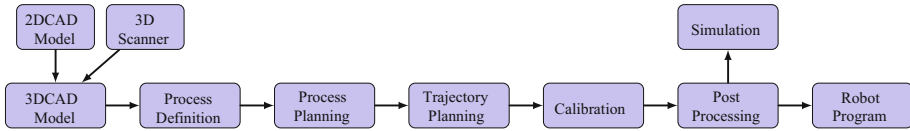


Fig. 2. The Automated Offline Programming (AOLP) process for welding

2.1 Process Definition

The first stage in the AOLP welding process is to define or extract the weld paths and necessary process parameters. This generates weld paths $p(t) \rightarrow SE(3)$, where $t \in [0, 1]$ is the position along the weld. Several methods have been used to specify weld paths for CAD models [6]:

- Define weld paths within the CAD application.
- Pass data to an external program using an Application Programming Interface (API).
- Export CAD models in a universal format for processing in an external application.

Weld paths can be defined within the CAD application, such as the system demonstrated by Neto et al. [7] which uses line primitives in Autodesk Inventor to define welds. Reference [8] also used a similar approach to represent welds within the CAD model which were then extracted using the SolidWorks API. However, this approach relies on manual design work and is not fully automated. It is also difficult to deal with complex cases such as several curved work pieces joining together.

For direct programming, it is necessary to use semi-automated or fully automated methods to extract weld paths from CAD models. Semi-automated methods such as [9] prompt the user to select two plates to join and a straight weld is then generated. For a fully automated system, it is necessary to identify both straight and curved welds with no user interaction.

Automated Weld Path Generation. A fully automated system to identify welds between pairs of triangular meshes was presented in [10]. This is an ideal solution as it allows weld paths and normal to be automatically determined from complex and irregular geometry such as the example shown in Fig. 7. This method relies on repeatedly expanding and intersecting triangular meshes of each part, allowing both the weld paths and wire directions to be identified directly from a CAD model with no special meta-data to define the weld.

2.2 Process Planning

The primary phase in the AOLP process is the generation of the robot motions to achieve each weld defined in Sect. 2.1. The weld path is only partially constrained, and there is freedom to tilt and rotate the torch to achieve a motion. In addition, the torch angles and workpiece position must be optimized to achieve a high-quality weld. This can be formulated as a task space (T-space) motion planning problem as shown in Table 1. T-space planning formulates the planning problem derived from the task being performed, as well as including task-specific constraints.

Table 1. T-space parameters describing the weld planning problem

Parameter	Description
t	Position along the weld path, $t \in [0,1]$
$R_{x,y,z}$	Rotation around the weld torch x , y and z axes. This corresponds to push, tilt and roll angles
$ctwd$	Contact Tip to Work Distance (CTWD)
$configuration$	Robot configuration representing which Inverse Kinematics (IK) solution to use
$positioner$	Configuration of any external robot or work piece positioners

There are several methods to solve T-space motion planning problems. A common method is to discretize the search space and use an algorithm such as A* [11] to generate a resolution-optimal solution. This approach does not work when the problem dimensionality is very high, as is common in robotic welding applications. A simple sampling-based planner implementation cannot be used as the probability of generating configuration space (C-space) samples which satisfy task constraints is very low.

Yao and Gupta [12] describe ATACE, which samples directly in T-space before converting samples to C-space. Shkolnik and Tedrake [13] sample T-space using a Rapidly exploring Random Tree, and then use a controller to grow the tree in C-space. Alternative, approaches such as [12] can repair samples to satisfy task constraints. Other algorithms include CBiRRT2 [14] and tangent-space sampling [15].

Positioner Configuration. One of the key T-space parameters to optimize weld quality is the configuration of the workpiece positioner. Positioners can take many forms, from rotary tables to full 6-DOF robots. Typically, each DOF in the positioner is discretized and candidate configurations are ranked using a cost function. This function is composed of several weighted weld metrics such as:

- Path incline or decline angle.
- Parent geometry profile angle. -Welding torch angle.

This cost function is typically adapted for the welding process being used. For example, with a typical Gas Metal Arc Welding (GMAW) process, the function would balance minimizing incline, maximizing parent geometry profile angle and minimizing welding torch angles (i.e. weld torch pointing down).

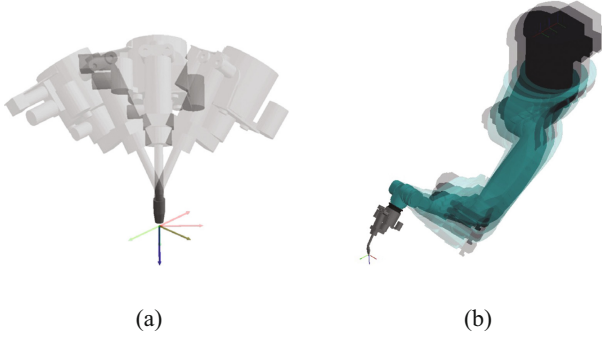


Fig. 3. Inherent redundancy in the (a) R_z and (b) *positioner* T-space parameters as shown in Table 1 [8]

Task Space Weld Planning. For welding, the T-space planning problem is formulated based on the weld path and weld gun angles, as shown in Table 1.

For a welding cell with a standard 6-DOF robotic manipulator and static work piece, the T-space planning problem also has six dimensions. The addition of any external robot axes or work piece positioners increases the problem dimensionality. As in [8] we use an A* [11] graph search to solve this problem while maintaining resolution optimal weld quality. However, the T-space problem is of sufficiently high dimensionality that a straightforward graph search is not possible.

In order to reduce the A* search to a tractable problem, the inherent redundancy of the T-space parameters is exploited as shown in Fig. 3. As can be seen, when changing the R_z torch roll angle, the position of the weld nozzle does not actually change. Another example is changing the *positioner* parameter: when this changes, the position of the entire weld torch does not change. This allows us to decouple the problem into smaller sub-problems which can be sequentially solved as in [8].

2.3 Trajectory Planning

Once the process motions have been generated, collision-free intermediate trajectories between home positions can be planned. In contrast to the T-space planning problem in Sect. 2.2, intermediate trajectories are planned in the robot's configuration space (C-space). A single robot configuration q is a vector of joint angles describing the robot's position, and the C-space C is the space encompassing all possible configurations. A portion $C_{obs} \subseteq C$ is occupied by obstacles, with the free space being defined as

$C_{free} = C - C_{obs}$. Given a start configuration q_{start} and goal q_{goal} , trajectory planning requires finding a path $\tau: [0,1] \rightarrow C_{free}$ such $\tau(0) = q_{start}$, $\tau(1) = q_{goal}$ and any additional constraints are satisfied.

Sampling Based Planning (SBP) uses a graph structure of individual samples drawn from C to approximate the connectivity of the free space. This removes the need to explicitly represent C_{free} and C_{obs} , allowing for effective motion planning for high-DOF robots such as industrial robotic manipulators. The two most common SBPs are the Probabilistic Roadmap Method (PRM) [16] and Rapidly-exploring Random Trees (RRT) [17]. A PRM is a two stage multi-query planner: in the first stage a roadmap of random configurations connected by paths is generated and in the second stage this is queried to see if q_{start} and q_{goal} can be connected. In contrast, RRTs are single query planners which grow a tree from the start configuration q_{start} until q_{goal} is reached.

For an AOLP system, multi-query PRMs [16] are generally the most applicable approach as they benefit from repeated planning queries within the same work cell environment. An example roadmap generated within a manufacturing cell is shown in Fig. 4. There are many PRM variants such as Lazy-PRM [18] which can offer improved performance characteristics. The main challenge of using a PRM for automated welding is the need to plan into narrow passages, as the weld torch must be placed close to the work piece inside challenging areas. This can be addressed using sampling schemes suited to this scenario [19–21].

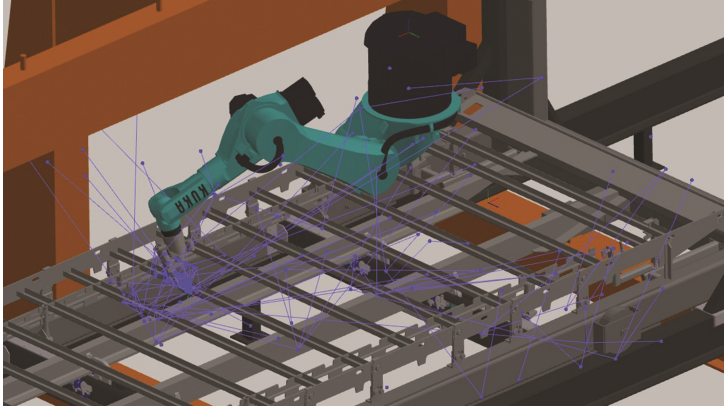


Fig. 4. A roadmap generated during trajectory planning [8]

2.4 Calibration

Calibration is necessary to adapt the weld path from the nominal CAD position to the “as-built” part position. The nominal weld path $p(t) \rightarrow SE(3)$ generated in Sect. 2.1 will differ from the “as-built” weld path $b(t) = p(t) + h(t)$ where $h(t)$ is the error function modelling the difference between the CAD model, the workpiece and robot pose error. Once the error is known the weld path can be adjusted during execution as shown in Fig. 5.

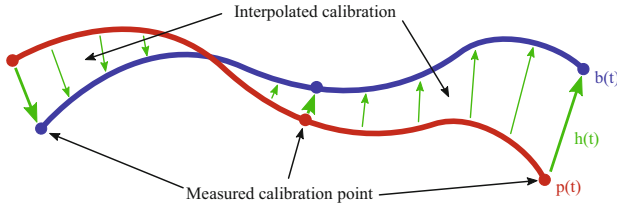


Fig. 5. A nominal CAD weld path $p(t)$, “as-built” path $b(t)$ and the measured error function $h(t)$ used for calibration

$h(t)$ is evaluated using sensors integrated in the robotic package. There are many commercially available solutions. Two common approaches are touch sensing, where the power source detects continuity between the welding system and the workpiece; and laser profilometry, where a 2D profile is evaluated by a dedicated processing system for a particular feature (such as a plane, corner, edge or bound). Other methods include structured light and computer vision [22]. Once the arc is established, seam tracking techniques [23, 24] can also be used.

Often it is not practical to continuously model $h(t)$, so discrete sensing actions are used to sample $h(t)$ and the intermediate values are linearly interpolated.

Also it is not always necessary to model all components of $SE(3)$ for the correction – this is often the case for corrections in the welding direction where an error will not lead to poor weld quality (with the exception of the start or end of a weld).

The online measurement of $h(t)$ involves the creation of sensing actions to be executed on the robotic system. These actions work by identifying feature positions and comparing them to known reference features from the CAD model. Creating these actions automatically involves careful consideration of the parent geometry, the effect of errors, and the sensing method used. We utilize a tiered search algorithm to determine the optimal robot actions to calibrate the weld position where sensing features are evaluated from most to least optimal:

1. Weld seam
2. Features on the parent parts of the weld
3. Nearby weld seams
4. Nearby part features

An important aspect of the calibration process is to evaluate the information gathered by sensing such that the weld can be calibrated in $SE(3)$. For example, additional information is required perpendicular to the welding direction to calibrate the weld start position.

Sensing motions and actions are planned as part of the AOLP process. These motions can be formulated as a T-space problem similar to Sect. 2.2.

Touch Sensing. Touch sensing is a common feature built into industrial welding power sources. It involves moving the robot along a linear path until an output from the power source indicates that continuity between the welding wire and the workpiece has been detected. Once continuity is detected, the robot motion is stopped and the position is

recorded. Touch sensing requires several actions as each sensing operation provides a 1D calibration property.

Laser Profilometry. Laser profilometry typically employs a structured light mechanism and a camera to detect a 2D profile of the target. Common commercially available systems also provide a processing system to evaluate the profile and convert the raw scan data into simple metrics about the profile's type and position. Laser profilometry provides a 2D calibration property.

2.5 Post Processing

The final stage in the AOLP process involves sequencing, optimizing the generated motions and converting the process and trajectory plans to robot code. Sequencing can be based on minimizing cycle time, distributing heat input to minimize distortion, or other factors (Fig. 6).

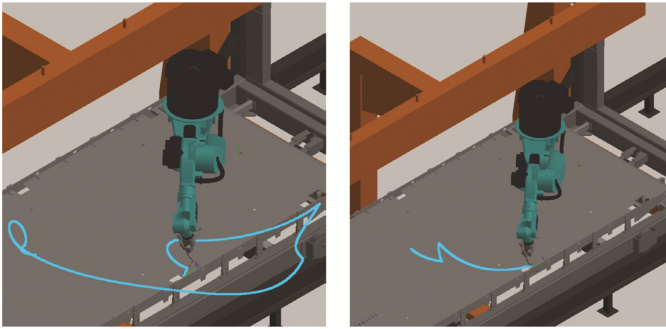


Fig. 6. An end-effector trajectory before (left) and after (right) optimisation [8]

Typical sampling-based planners, as outlined in Sect. 2.3, often produce sub-optimal paths and benefit from post-process optimization [25]. There are several techniques for post-process optimization which short-cut segments of the generated path. References [26, 27] attempt to skip points in the generated path to remove redundant motions. Sánchez and Latombe [28] attempt to skip entire randomly selected portions of the path at a time. Guernane et al. [29] presented a method which skips between the midpoints of path points and Hsu et al. [30] uses a similar technique which adds points to the path. Geraerts et al. [31] developed the partial shortcut method which applies these operations on one DOF at a time, and Polden et al. [25] extended this specifically for industrial robots to guide optimization towards DOFs which deviate the most from an ideal path.

Alternatively, planning variants can be used which embed optimization in the planning process. Algorithm variants such as PRM* and RRT* [32] converge to an optimal solution and can be used to minimize path length or other criteria during the trajectory planning phase. Therefore, post-process optimization may not be required.

As in [8] a path optimization procedure can also be used to generate motions between welds. A path between subsequent welds can be created by joining the path from the

end of the first weld to the home position and the path from the home position to the start of the second weld. The optimization algorithm can then be used to shorten this non-optimal path. This allows acceptable quality intermediate motions to be generated without invoking a full planning algorithm as in Sect. 2.3.

The final step is to convert the generated process and trajectory motions into robot code and insert the relevant welding control commands. Common targets include ABB's RAPID language [33] or Kuka's KRL [34]. The conversion process from generated motions to a robot control program is generally straightforward.

3 Results

We present an AOLP implementation to weld pipe and plate geometry. This implementation utilizes two 6-DOF industrial robotic manipulators as shown in Fig. 1. An ABB IRB 4400 is used for workpiece positioning, and an ABB IRB 1400 is used for welding. Calibration sensing utilizes a ServoRobot DIGI-I/P laser profilometry scanner. For these results we present three scenarios as shown in Fig. 7:

1. a simple pipe-pipe structure,
2. a more complex pipe-plate structure, and
3. a complex multi-pipe node structure.

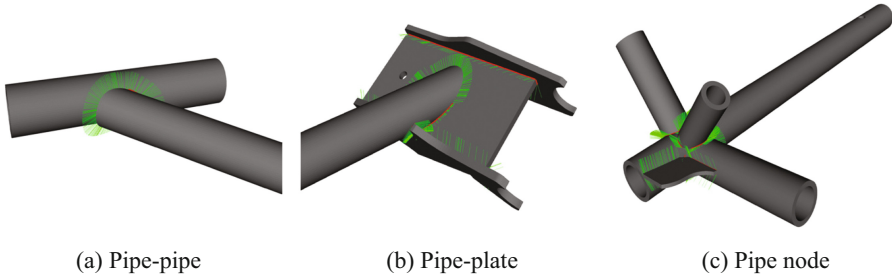


Fig. 7. Generated weld paths for each scenario

The first stage of the AOLP process is to generate the weld paths. The weld paths are then converted to robot motions using the following steps:

1. Workpiece positioning
2. Planning the weld path motion
3. Planning the sensing actions and motions

As the positioner is a 6-DOF robot we cannot naively sample all DOFs to evaluate workpiece positioner configurations. Instead we first rank combinations of (R_x, R_y) angles and then search within (R_z, x, y, z) for the best solution. Many of the welds in these scenarios are made up of complex curves where the weld seams cannot be measured directly for calibration purposes. Instead, the axes of the parent pipe objects are measured and used to create the error function $h(f)$. Welds are sequenced to ensure that

weld starts are not placed on top of existing welds to improve the visual appearance of the fabrication.

The three scenarios shown in Fig. 7 were each planned on a MacBook Pro with a Core i7 CPU and 16 GB RAM. The overall planning time and a breakdown of the time taken for each stage is shown in Table 2. Each of the generated programs was then executed in the robotic welding work cell, resulting in high quality welds as shown in Fig. 8.

Table 2. Planning results for the presented AOLP implementation

	Pipe-pipe	Pipe-plate	Multi-pipe node
No. of bodies	2	4	5
No. of welds	4	11	17
Overall time (s)	153	711	793
Path generation (s)	0.539	1.22	2.22
Process planning (s)	104	506	595
Trajectory planning (s)	40.3	84.3	112
Post processing (s)	8.47	120	83.4

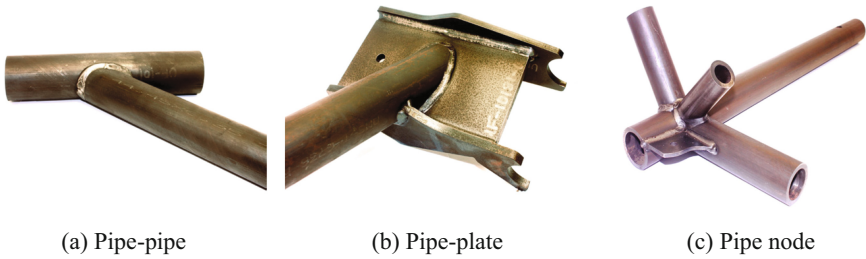


Fig. 8. Resulting welds for each scenario

The time taken to generate these programs is relatively short. The welding program for even the most scenario we tested was generated in under 15 min. This supports the applicability of this weld program generation for complex structures. The breakdown of planning time required for each stage in the AOLP process are as expected. Process planning, which includes generating the weld path motions and calibration positions, requires the majority of the processing time. We consider this to be an artifact of our optimization approach which uses a greedy search algorithm to maximize the final weld quality.

4 Conclusion

Automated Offline Programming enables truly flexible robotic welding capability. We listed the key steps of an AOLP process and explored the underlying technologies and algorithms. We then detailed our specific implementation that automatically generates weld programs for a wide range of simple and complex geometries, and tested the

resulting programs on a robotic welding setup. Our results validate the approach and show the ability of this programming method to produce high quality welding results without human programming effort.

Future developments include applying automated programming techniques to more complex tasks such as integrated pick-and-place, assembly and welding. A limitation of the current approach is the requirement for a CAD model – another extension is to integrate part sensing so a CAD model is not required.

Acknowledgements. The authors would like to acknowledge the support of the Defence Materials Technology Centre (DMTC), which was established and is supported by the Australian Government's Defence Future Capability Technology Centre (DFCTC) initiative. The authors would also like to thank industry partners Thales Australia and Ekebol for their ongoing support and welding advice and expertise.

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Investigation of the Correlation Between Plasma Electron Temperature and Quality of Laser Additive Manufacturing Process

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Abstract. In this paper, a spectral diagnosis method was reported to explore the temperature characteristic of plasma and detect the forming quality in laser additive manufacturing. The spectral data were collected by the spectrum acquisition system under different processing parameters. The plasma temperatures under different processing conditions were calculated using Boltzmann plot of six neutral iron lines between 375 nm and 390 nm, and the influence relationships between laser power, powder feeding rate, traverse speed, cladding layer and plasma temperature were found. Meanwhile, the time domain diagrams (the relationship between the temperature and time) corresponding to the process were established, in which temperatures were respectively calculated by Boltzmann double-line method and Boltzmann plot method, to analyze the correlation between temperature fluctuation and the forming defects. It was found that the results from Boltzmann plot method could reflect the generated defects more clearly.

Keywords: Laser additive manufacturing · Laser induced plasma · Spectroscopic diagnosis

1 Introduction

In recent years, laser processing technology, including laser welding, laser cutting, laser cladding and laser additive manufacturing, has been developing rapidly [1]. In particular, laser additive manufacturing has drawn more and more attentions [2, 3], because of its advantages such as material saving, high efficiency, exact controllability, excellent formation, etc. Many researchers and organizations have conducted a lot of researches on the technical principle, forming process, solidified microstructure and mechanical properties. But physical characteristics of the laser induced plasma and the reaction mechanism have not been well studied. It is well known that laser induced plasma is produced during laser additive manufacturing process, and the quality of the process could be reflected by the characteristics of the plasma [4].

At present, the research of the plasma focuses mainly on laser welding process. Kawahito [5] measured the spectral data of the plasma produced during laser welding of 304 austenitic stainless steel, and a number of metal atomic spectral lines and a few Ar atomic spectral lines were collected, and the plasma temperature was also been figured out which was about 6000 K. Through spectral studies on the plasma produced from the CO₂ laser welding of stainless steel and titanium alloys, Szymanski [6] presented the change laws of the plasma temperature and electron density when the height of plasma changed. Alfier [7] had studied on the relevance of the plasma temperature and penetration depth in the laser welding process, he found that the plasma temperature would decrease when the laser power increased in the CO₂ and Nd:YAG laser welding experiments. Dadras [8] studied the spectral information under different shielding gases or preheating temperatures during welding of copper base alloy. Mazumder and Lober [9] conducted a series of experiments by a 10 kW CO₂ laser for studying the energy transfer of the laser induced plasma. The absorption, refraction of the plasma and the plasma temperature were determined, and they found that the central temperature of plasma was in the range of 14000–15300 K, and the rate of absorption was in the values area of 7.5–29%. Some papers also pointed that the welding defects could be diagnosed by analyzing spectral information. By real-time monitoring the hydrogen spectrum of the welding arc, Shea [10] reached the aim of controlling hydrogen and hydrogen pore. Kong [11] found that the defects existing in welded joints is related to the change of plasma temperature corresponding to the welding process. Sibillano [12] reported that the plasma temperature could reflect the penetration depth of CO₂ laser welding and Nd:YAG pulsed laser welding and Konuk [13] found that the protection conditions had a great effect on the control of welding quality through the spectral diagnosis method. Some spectroscopic researches for welding defects detection were conducted by Ancona [14], in the bead-on-plate experiments of AISI 304 stainless steel. It was found that the temperatures, which were calculated using the Fe I, Cr I, and Mn I, were correlated with crater formation, lack of penetration, welding disruptions and seam oxidation in laser welding. Sibillano [15] found a correlation between spectral characteristics and oxidation layer formation in the CO₂ laser AA5083 aluminum processing.

In addition, there are also some researches of the plasma having been reported in the laser metal deposition process. It was found that the spectral lines ranging from 450 nm to 650 nm were highly related to the stability of the process. However, some problems were not investigated, such as the relation of clad quality and spectral data or the effects of the energy input. As for qualitative analysis, the phase transformation of Cr–Fe and Ni–Fe alloy was connected with the spectral line-intensity-ratio in Song's study [16]. In the further research, Song and Mazumder [17] used the Cr/Fe line intensity ratios, plasma temperature and electron density to monitor the laser induced plasma during direct metal deposition process when chromium composition ranging from 10% to 60%. They found that it was quite accurate to measure the chromium concentration using line intensity calibration curve. And the conclusion that spectral information could reflect the changes of microstructure was also found in [16]. Similarly, Wei Y [18] reported that the electron temperature and the intensity ratio IR could be used to monitor the metallic bonding in laser metal deposition process, using a Nd:YAG laser to create

metallic bonding between Metco 42C clad and AISI 4140 substrate. These researches opened the door for monitoring and process control of laser processing through analyzing laser induced plasma. But, there are very few researches about the effects of manufacturing parameters on the plasma and very few good methods or techniques which could realize the defect diagnosis in laser additive manufacturing.

In this paper, by using an effective spectral diagnosis method, the relationships between the processing parameters and the plasma temperature of laser additive manufacturing process were obtained, and a close connection between the temperature fluctuation and the forming quality was discovered, thereby the defects could be detected by analyzing the time domain curves of plasma temperature. Compared with the Boltzmann double-line method, the results computed by Boltzmann plot method could reflect the actual situation of defects more clearly and accurately. The conclusions will be helpful for the quality control of the additive manufacturing process.

2 Experiment

The series of experiments in this paper were conducted based on coaxial powder-feed direct metal deposition, the system was consisted of an Ytterbium-doped fiber laser (IPG YLS-6000), a powder feeder (GTV PF 2/2), and a deposition head (Precitec YC 52) with the focal length of 250 mm. The maximum output power of the laser used was 6000 W with wavelength of 1060–1070 nm, the Beam Parameter Product (BPP) is greater than or equal to 4.0 and the optical fiber diameter was 600 μm which had a Gaussian profile. An AvaSpec Multichannel Fiber Optic Spectrometer matched with a collecting fiber optic probe, of which the spectral resolution is 0.052 ± 0.001 nm, was used to collect the emission spectra ranging from 315 nm to 420 nm. The schematic diagram of the experimental system is shown in Fig. 1. The substrate used was 316 L stainless steel with dimensions of $120 \times 60 \times 5$ mm, and 316 L powder with size-distribution of was 44–50 μm was used in the experiments.

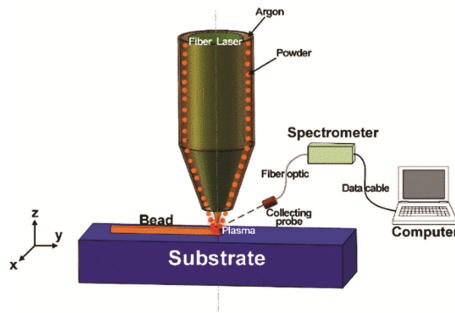


Fig. 1. Schematic diagram of experimental apparatus

To explore the influences of the manufacturing parameters on the plasma temperature, laser power (700–1200 W), powder feed rate (2.17–13.39 g/min), and scanning speed (2.5–10 mm/s) were respectively used as the experimental variables. The specific

test plans are shown in Tables 1, 2 and 3. Argon gas was used as the shielding gas and delivery gas to protect the melting pool from oxidization and delivering the powder. The flow rate of the shielding gas and delivery gas were respectively 9 L/min.

Table 1. Experimental scheme of laser power for a single variable

Experiment	Laser power (W)	Powder flow rate (g/min)	Scanning speed (mm/s)
1	700	7.78	5
2	800	7.78	5
3	900	7.78	5
4	1000	7.78	5
5	1100	7.78	5
6	1200	7.78	5

Table 2. Experimental scheme of powder flow rate for a single variable

Experiment	Laser power (W)	Powder flow rate (g/min)	Scanning speed (mm/s)
1	1000	2.17	5
2	1000	4.98	5
3	1000	7.78	5
4	1000	10.59	5
5	1000	13.39	5

Table 3. Experimental scheme of scanning speed for a single variable

Experiment	Laser power (W)	Powder flow rate (g/min)	Scanning speed (mm/s)
1	1000	7.78	2.5
2	1000	7.78	5.
3	1000	7.78	7.5
4	1000	7.78	10

Because a large amount of forming defects are caused by the relative fluctuation and change of additive manufacturing parameters. To simulate the process, three variables, laser power (1200–700–1200–700 W), scanning speed (5–0–5 mm/s), and Ar gas (with–without), were changed to generate defects during the forming experiments. All these tests were conducted under strict control of a single variable. The aim is to explore the correlation between the temperature fluctuation of the plasma and the defects in the process of laser additive manufacturing.

3 Results and Discussion

3.1 Plasma Temperature Calculation

The plasma temperature is commonly used to characterize the laser induced plasma during additive manufacturing, which can be calculated by Boltzmann double-line method when the plasma is in the local thermodynamic equilibrium (LTE) assumption state [19]. The Boltzmann double-line method is expressed as follows:

$$\frac{I_1}{I_2} = \frac{A_1 g_1 \lambda_2}{A_2 g_2 \lambda_1} \exp\left(-\frac{E_1 - E_2}{kT}\right) \quad (1)$$

where I_1, I_2 are radiation intensity; A_1, A_2 are transition probability; g_1, g_2 are degeneracy of the excited levels; λ_1, λ_2 are wavelengths; E_1, E_2 are excitation energy; k is the Boltzmann constant. However, there are some certain errors in calculation result of this approach. The Boltzmann plot method was selected for improving accuracy instead of Boltzmann double-line method by using the relative intensities of several emission lines rather than only two lines [20]. It could be described as the following equation [21]:

$$\ln \frac{I_{mn} \lambda_{mn}}{g_m A_{mn}} \propto -\frac{E_m}{kT} + \ln \left(\frac{Nhc}{z(T)} \right) \quad (2)$$

where m is excited level; n is lower state level; λ_{mn} is wavelength; A_{mn} is transition probability; g_m is degeneracy of the excited level; E_m is upper state energy level; T is plasma temperature; N is the number density of the species involved; h is Planck's constant; c is the speed of light; $z(T)$ is the partition function of the element at temperature T . So the plasma temperature can be calculated from the slope of the linear function of Eq. (2).

In this paper, in order to calculate the plasma temperature more accurately, six neutral Fe I emission lines were chosen according to the Boltzmann plot method. They were in the range of 375 nm to 390 nm, which are within 15 nm so that they are close enough

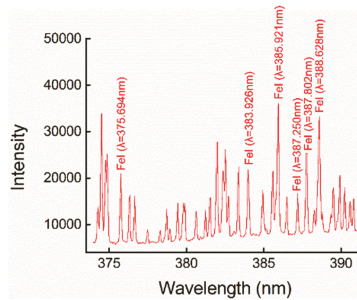


Fig. 2. Spectroscopic parameters of the Fe I emission lines used to calculate the plasma temperature

to be considered as a linear correction on the intensities and have considerable differences of the excitation energy level to minimize the fitting error in the Boltzmann plot. And all of them were summarized in Fig. 2 and Table 4 [22].

Table 4. Spectroscopic data of neutral Fe I emission lines

λ (nm)	A_{mn} (s^{-1})	E_n (eV)	E_m (eV)	g_m
375.694	2.66E+08	3.57	.87	11
383.926	2.55E+08	3.05	6.28	9
385.921	1.11E+08	2.40	5.62	11
387.250	5.25E+07	0.99	4.19	5
387.802	5.41E+07	0.96	4.15	7
388.628	3.71E+07	0.05	3.24	7

Boltzmann plot of a randomly selected sampling point, when 700 W laser power, 7.78 g/min powder feeding rate and 5 mm/s traverse speed were used in single-layer-single-trace experiment, is shown in Fig. 3. The plasma temperature computed was 13764.9 K, as the slope of the linear fit included in the figure is -0.8423 . However, the calculated temperature by the Boltzmann double-line method was 13957.6 K. In this paper, the Boltzmann plot method was mainly used for the research on the parameter influence laws. So, the plasma temperatures under different technical conditions could be similarly acquired.

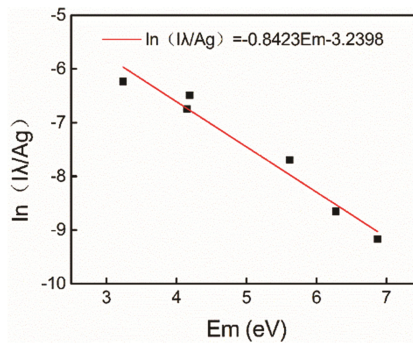


Fig. 3. Boltzmann plot using six neutral iron lines from Table 4

3.2 Influence Relationships Between Different Parameters and the Plasma Temperature

Figure 4 shows the plasma temperatures calculated according to Eq. (2) under different laser powers, it could be seen that the plasma temperature increased with the increment of laser power, and there was a positive linear correlation between them. That was because the increase of the laser power increased the heat input per unit time, so the plasma temperature rose.

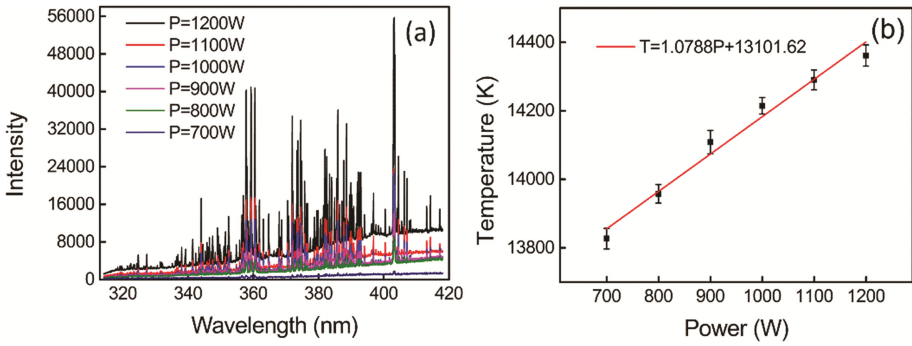


Fig. 4. Relationship between laser power and the plasma temperature: (a) spectral information under different laser powers; (b) relationship between the plasma temperature and laser power

Figure 5 shows the influence relationship of powder feed rate on the temperature of the plasma. It could be seen that with the increment of the powder feed rate, the plasma temperature monotonically decreased and negative linear correlated to it. The reason is that with the increase of powder delivery amount per unit time, while the heat input per unit time remained constant, the powder melted or deposited and the particles ionizing continued to increase per unit time. Thus, it would consume more energy, resulting in the shrink of the plasma temperature.

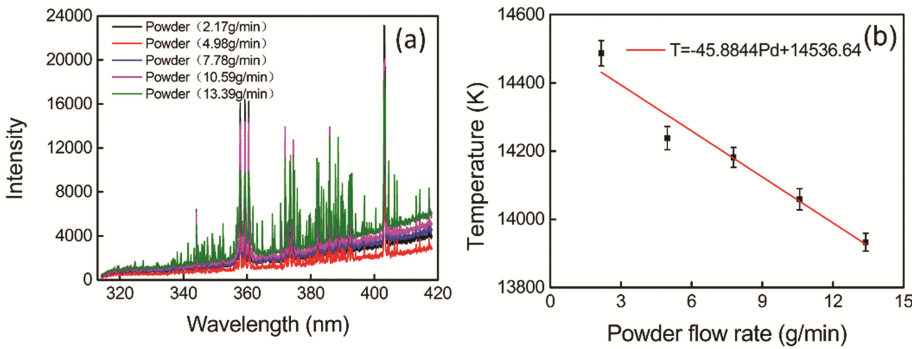


Fig. 5. Relationship between powder feed rate and the plasma temperature: (a) spectral information under different powder feed rate; (b) relationship between the plasma temperature and powder feed rate

Figure 6 shows the influence of the traverse speed on plasma temperature. It could be seen that when other parameters were kept constant, the plasma temperature first increased then decreased with the increment of traverse speed. It is because that the linear energy input reduced with the increment of traverse speed. However, when powder feed rate remained constant, the heat energy loss was reduced due to the reduction of powder consumption and particle ionization. When it was the main influence factor, the plasma temperature increased with the increment of traverse speed. But when

speed exceeded a certain threshold, the reduction of the linear energy input became more active, leading to the decrease in temperature.

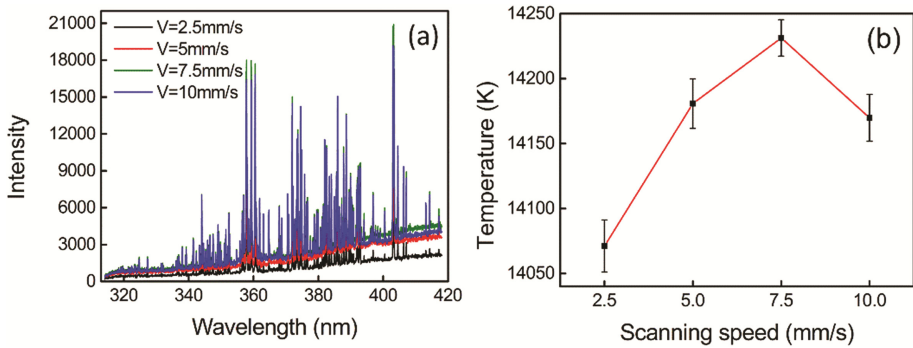


Fig. 6. Relationship between different traverse speed and the plasma temperature: (a) spectral information under different traverse speed; (b) relationship between the plasma temperature and traverse speed

Additive manufacturing is a deposition process layer by layer, it is important to keep every parameter constant at every layer. So, the spectral data and the plasma temperature of different layer were collected and computed in the additive manufacturing process and the results were shown in Fig. 7. It could be seen that the plasma temperature of layer 2 was higher than layer 1; the plasma temperature of layer 3 was significantly lower than layer 2; the temperatures of layer 4 and 5 did not change much compared with layer 3. However, after layer 5, the plasma temperature monotonically increased with the layer number, and had a linear positive relationship with it.

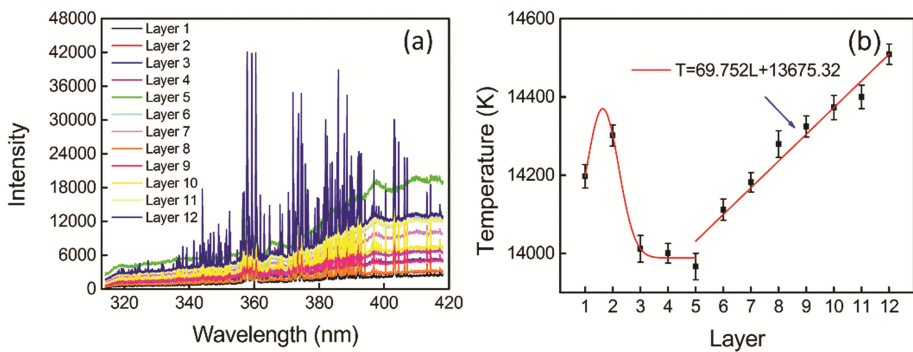


Fig. 7. The plasma temperature at different layers: (a) spectral information under different cladding layers; (b) relationship between the plasma temperature and cladding layer

The reasons for the phenomena could be attributed to the relatively preheating influence of each cladding layer and the energy loss, which was caused by the powder-substrate interactions and the ionization of all types of particles. These two factors are

the primary causes for the change of laser induced plasma temperature in the process. As the first layer was cladded on the substrate, the layer became substrate material for the next layer, because it had a preheating result for the next layer, the plasma temperature of layer 2 was higher than layer 1. With the increase of the layer number, preheating effect was more appreciable, and material characteristics of the newly formed substrates, such as microstructure, were more similar to the powder, which enhanced the possibility of additive manufacturing. Under the concerted action of the two influences, the powder melted or deposited in unit time would increase. And because of the effects of the preheating, the ionization would be exacerbated. So, the energy loss would increase. The comprehensive function made up of heat buildup caused by preheating and the energy loss resulted in the fall of plasma temperature when layer 3 was cladding. For the same reason, the laser induced plasma of layer 3–5 remained relatively low temperature. Nevertheless, with the further increase of the layer number, the heat buildup increased continuously in the additive manufacturing process. When accumulating to a certain level, it would become the major factor affecting the plasma temperature. Thus, after layer 5, the plasma temperature increased linearly.

3.3 Defect Diagnosis Based on the Time Domain Curves of Plasma Temperature

Through the analysis mentioned above, it could be seen that the plasma temperature and processing parameters are closely related. So, it can be inferred that the changes of the parameters could be detected by the variations in plasma temperature. Because the change of the cladding parameters is a major reason that usually lead to some defects, so it is possible to diagnose the forming defects by the plasma temperature fluctuation reflected in the time domain curves. The defects caused by variations of processing parameters were simulated in the following experiments and all spectral data in the process were collected. The time domain curves reflecting the relationship between the temperature and time were established to explore its practical relevance with the forming defects. Meanwhile, the curves were separately charted referring to Boltzmann double-line method and Boltzmann plot method, for the purpose of comparing their accuracies.

Figure 8 shows the changes of the plasma temperature calculated using two discrete Fe I lines at 375.694 nm and 388.628 nm wavelength by Boltzmann double-line method when the laser power changed from 1200 W to 700 W, then to 1200 W and 700 W. Figure 8(a) shows the cladding results in which the cladding width and thickness changed with the laser power. Figure 8(b) shows the changes of the plasma temperature in time domain curves. It could be seen that when the laser power changed, the plasma temperature changed according to the increase or decrease of the laser power and the curves waved more seriously in the higher laser power part, although the changes of the cladding forming were very small. Then, the curves were filtered by the methods of Weighted Average Filter [23] and Savitzky-Golay Filter [24], as shown in Fig. 8(c) and (d). But, no more obviously corresponding relationships were found, though the Savitzky-Golay curve was slightly better

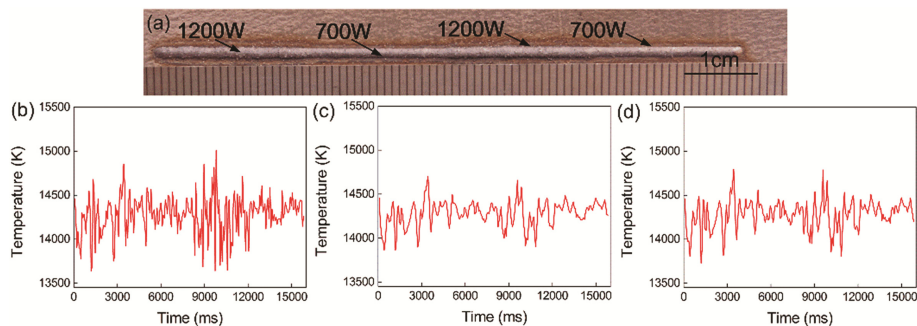


Fig. 8. Changes of the plasma temperature with the change of laser power: (a) photograph of the cladding part; (b) changes of the plasma temperature calculated by Boltzmann double-line method (c) the weighted average filter curve; (d) the Savitzky-Golay curve

During the additive manufacturing process, a few brief stagnations often appear, in which case the sudden drops would reflect in speed, in corners or arcs of the forming path. They tend to induce the protuberance, usually called weld beading, occurring in the cladding layer. Hence, in this paper, a situation that the traverse speed suddenly dropped from 5 mm/s to 0 mm/s was designed to simulate such a case, in order to study whether the defects could be diagnosed by monitoring the plasma temperature fluctuations. The design and results of experiment are shown in Fig. 9 and an overlap was conspicuously visible. Combining the corresponding results of the plasma temperature, there really is a sudden rise in the time domain curve as shown in Fig. 9(b). But the corresponding time of the rise part is such a short period, less than 0.5 s, clearly shorter than the duration when the traverse speed was 0 mm/s, from the sixth second to the tenth second of the whole process. In light of that, the wave peak in the curve is just a little higher than normal fluctuation, even making it extremely difficult to distinguish. And it was even filtered after the filtering process, so far as to be hardly visible in Figs. 9(c) and (d).

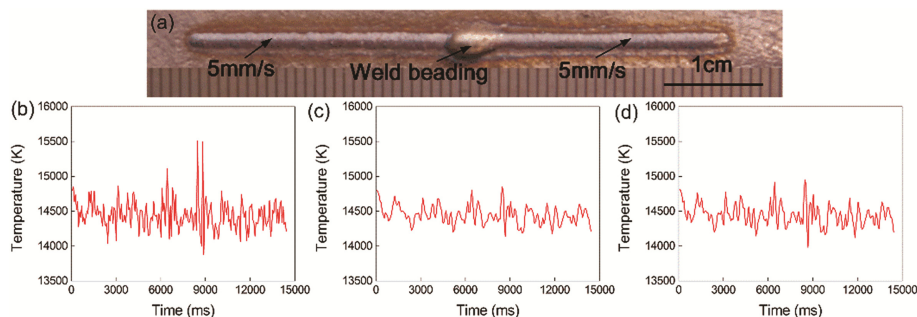


Fig. 9. Relationship between the defects and the plasma temperature: (a) photograph of the cladding part; (b) changes of the plasma temperature calculated by Boltzmann double-line method; (c) the weighted average filter curve; (d) the Savitzky-Golay curve

Shielding gas is an important factor that influences the forming quality, if the manufacturing processes have not been efficiently protected, the manufactured parts would be oxidized seriously, which is considered as one of the most common types of bad moldings. And the volatility of it is one cause which would be very likely bring out defects. Figure 10 shows a test that the shielding argon gas was suddenly stopped during the process of cladding. In the time domain diagrams as shown in Fig. 10(b), it could be nearly clearly seen that the plasma temperature suddenly rose when the shielding gas was turned off, and the curves waved more seriously when the argon gas was shut off. This would mean that the supply disruptions of shielding gas could be recognized by the changes of plasma temperature. That is to say, the time domain curves of plasma temperature could be used to detect this type of defects produced in the additive manufacturing process. The further filter results shown in Fig. 10(c) and (d) presented that the serious oxidation arose from the interruption of shielding gas could be obviously diagnosed according to the fluctuation of plasma temperature, when the noise information had been filtered out. Moreover, it was clarified that the filtering process was necessary in this situation.

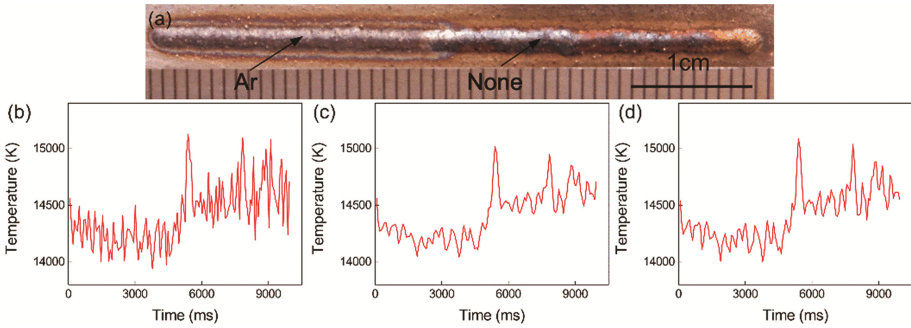


Fig. 10. Relationship between the defects and the plasma temperature: (a) photograph of the cladding part; (b) changes of the plasma temperature calculated by Boltzmann double-line method; (c) the weighted average filter curve; (d) the Savitzky-Golay curve

From above analysis, it could be inferred that the monitoring of plasma temperature could be used to achieve defect diagnosis of the additive manufacturing process caused by the changes of the parameters and other external influential factors. But these diagnostic procedures could not be distinguished very clearly simply by the time domain curves of plasma temperature calculated by Boltzmann double-line method. It is most likely that inaccuracy of the Boltzmann double-line method led to the detection difficulty, although it is easier to compute the real-time temperature and chart the relevant time domain curves in the process through this approach. So, Boltzmann plot method was used to determine more accurate temperatures, removing that uncertainty, for the further research on the correlation between the plasma temperature and the forming defects.

As shown in Fig. 11, the same but more apparent diagnostic result was obtained when the laser power changed as designed, that the plasma temperature was higher and

the curves waved more severely when the laser power was 1200 W. This was because that the higher laser power stood for the more energy input, and the plasma temperature was higher. Meanwhile, the more energy input was provided, the plasma reaction was more violent, and the temperature calculations acquired from the plasma were more instable.

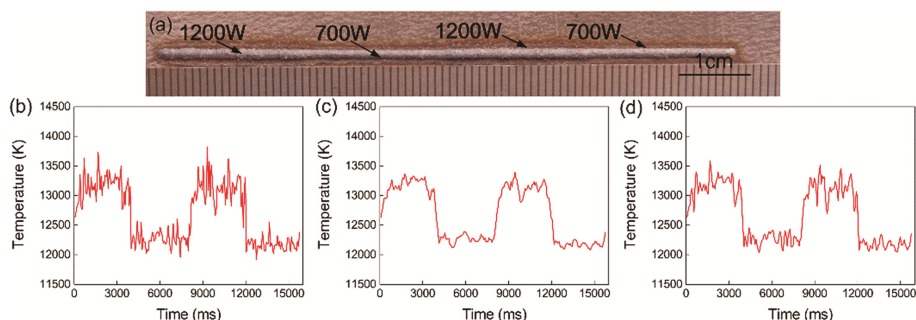


Fig. 11. Changes of the plasma temperature calculated by Boltzmann plot method with the change of laser power: (a) photograph of the cladding part; (b) the plasma temperature curve; (c) the weighted average filter curve; (d) the Savitzky-Golay curve

Compared with Figs. 9 and 12 very clearly showed the apparent variations in plasma temperature when scanning speed changed from 5 mm/s to 0 mm/s and then to 5 mm/s. As shown in the curve, the temperature rose in the sixth second and dropped in the tenth second, fitting well with the residence time during which the scanning speed was zero. Although there was still certain stability in the calculations of plasma temperature, it was enough to accurately judge the overlaps during cladding process using this approach. In the additive manufacturing processes, the shielding gas plays a very important on protecting the specimens from oxidizing. But there is also something that cannot be ignored, that the gas flow determines the cooling effects from heat exchange. Additionally, the supply of shielding gas also provided more gas particles for ionizing, and

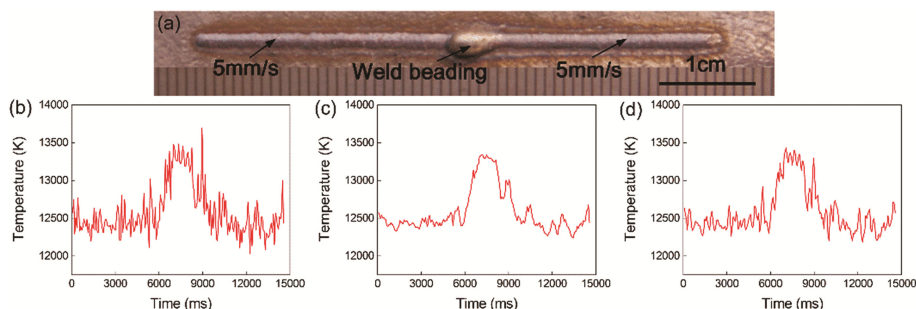


Fig. 12. Relationship between the defects and the plasma temperature calculated by Boltzmann plot method: (a) photograph of the cladding part; (b) the plasma temperature curve; (c) the weighted average filter curve; (d) the Savitzky-Golay curve

so did them. The extra ionization consumed some extra energy, which strengthened the cooling effects on the laser induced plasma. Thus, compared with the results in Fig. 10, even without any filter processing, it could be more clearly observed that the plasma temperature significantly rose when the shielding gas was turned off.

From all the analysis of plasma temperature fluctuation and forming quality, a strong connection was discovered between them. And through the comparison of plasma temperature time domain curves computed by Boltzmann double-line method and Boltzmann plot method, it was found that the defects could not be well recognized with the aid of the time domain curves obtained by the Boltzmann double-line method. However, even without being filtered, the curves obtained from the Boltzmann plot method could still very clearly reflect the appearance and existence time of the forming defects (Fig. 13).

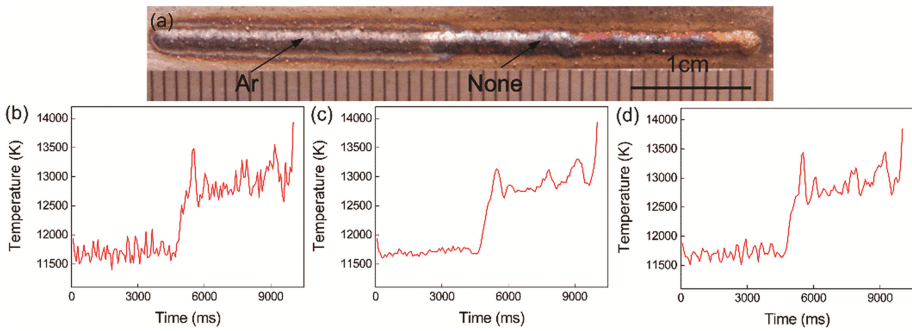


Fig. 13. Relationship between the defects and the plasma temperature calculated by Boltzmann plot method: (a) photograph of the cladding part; (b) the plasma temperature curve; (c) the weighted average filter curve; (d) the Savitzky-Golay curve

4 Conclusions

In this paper, relationships between processing parameters and the plasma temperature during laser additive manufacturing process were studied by spectral diagnosis method. By constructing the corresponding relevance of time and plasma temperatures, the defect diagnosis of the whole cladding process was comparatively accurately realized. The conclusions are as follows:

1. In the case of other parameters being kept constant, the plasma temperature increased linearly with the increase of laser power. With the increase of powder feeding rate, the plasma temperature decreased linearly. With the increase of scanning speed, the plasma temperature first increased and then decreased. After 5 layers, the plasma temperature increased linearly with the cladding layer, but the plasma temperatures of the first 5 layers did not change regularly.
2. The changes or fluctuations of plasma temperature strictly corresponded to the forming defects in laser additive manufacturing process. In other words, the additive

manufacturing defects could be detected by monitoring the time domain diagrams of plasma temperature of the manufacturing process.

3. Compared with the Boltzmann double-line method, the forming defects could be better recognized by Boltzmann plot method, and the formation time of the defects could be clearly recognized by the method.

Acknowledgement. The research is supported by the National Natural Science Foundation of China (51105103, 51504074).

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Welding Technology Analysis of Bypass Coupling Micro Plasma Welding

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Abstract. The method of bypass coupling micro plasma welding was introduced, and used for the research of surfacing welding experiment. Different welding parameters were investigated, the thermal cycling curves were test, and the microstructure was observed. The result shows, with the increase of bypass current, the highest temperature of thermal cycling curves decreased and the microstructure was much fine. Therefore, we could speculate that the heat input to base metal is decreasing with the increase of bypass current. The bypass coupling micro plasma welding can achieve the accurate control of arc heat, balance the heat input to base metal and welding wire. Compared with traditional micro plasma welding, bypass coupling micro plasma welding can accurately control the heat input to base metal under the condition of constant heat input.

Keywords: Bypass coupling micro plasma welding · Heat input · Microstructure

1 Introduction

Thermal input control in Fusion welding has always been the focus of welding research at home and abroad. The welding heat input in Fusion welding has an important effect on the organization and performance of the welded joint. Welding heat input is too large, there will be thick grain joints, joint strength decreased, heat affected area brittle and other issues. The welding heat input is small and can't form an effective welded joint, and easy to produce impermeability and other defects. Reasonable welding heat input can effectively ensure the quality of welded joints, but in general welding, welding heat input is always too large, for which domestic and foreign scholars have studied different methods to control the parent metal heat input, such as: pulse welding [1–3], Double pulse welding [4, 5], cold metal transfer(CMT) welding [6, 7], Double-electrode arc welding [8], and so on. Compared with traditional welding methods, these welding methods can effectively reduce and control the heat input of the base metal, in industrial production has a wide range of applications. Dual-bypass gas metal arc welding (DB-GMAW) [9, 10] is a modified GMAW process, and it is of great potential to reduce the current flow to the base metal while the total welding current is kept constant. This will not only ensure a larger welding rate of wire, while reducing the heat input of the base

metal [11]. According to the different forms of the bypass arc, there are different combination forms: single bypass coupling arc GMAW [12], double bypass coupling arc GMAW [13], pulse bypass coupling arc GMAW [14], double wire bypass coupling arc GMAW [15, 16].

Compared with gas welding, brazing, non-melting arc welding and other welding methods, plasma welding has energy concentration, arc stability and other characteristics, and can conduct small current welding, greatly reducing the base metal heat input [17]. Micro-beam plasma welding is a small current plasma welding with a welding current less than 63A, which can reduce the heat input of the base metal and reduce the heat affected zone of the base metal, improve the weld quality and widely used in thin plate welding [18]. But generally in the process of sheet welding, the need to fill the welding wire to get a good weld, which must increase the welding current to ensure the adequate melting of welding wire, while leading to the increase in the heat input to the base metal and the decline in welding quality. To solve this problem, we proposed a new plasma welding method based on DB-GMAW principle.

In order to precisely control the heat input distribution of the base metal and the welding wire, a method of bypass coupling micro plasma welding method is proposed. In this paper, the plasma coupling method of bypass coupled micro is introduced. Different welding parameters were investigated. During welding, the thermal cycling curves were test for the value of base-metal heat input. Meanwhile, the microstructure was observed by optical microscope to better understand the character of heat input in bypass coupling micro plasma welding.

2 Experiment

2.1 Principle

The basic principle of bypass coupling micro plasma welding is shown in Fig. 1. This welding method consists of welding torch, welding power source, wire feeder, and an adjustable resistor. Compared with traditional micro plasma welding, the difference is that the current flowing through the welding torch is divided into two parts at the tip of the tungsten electrode, part of which flows back to the positive welding power source from the workpiece and the other flows through the wire and the adjustable resistor returns to the positive welding power source. Current satisfies the relationship:

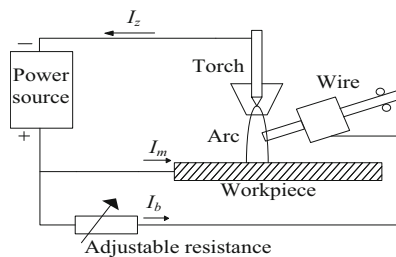


Fig. 1. Principle of bypass coupling micro plasma welding

$$I_z = I_m + I_b$$

where I_z is the total current; I_m is the workpiece current; I_b is the bypass current.

In the constant total current I_z condition, by adjusting the resistance of the adjustable resistor, the bypass current I_b changes, which achieves the workpiece current I_m adjustable. At the same time, the total current I_z can also increase. Through the adjustment of adjustable resistance, the base metal heat input can keep unchanged, which increase the melting wire current, and achieve efficient welding. By using this method, the control of heat input to base metal achieves, while the bypass current also improves the melting speed of the wire and the forming efficiency.

2.2 Experimental System

Bypass coupling micro plasma arc welding experimental system is shown in Fig. 2. It mainly includes welding systems, welding control system and signal collecting system. Among them, the welding system uses LHM-50 precision micro plasma arc welding

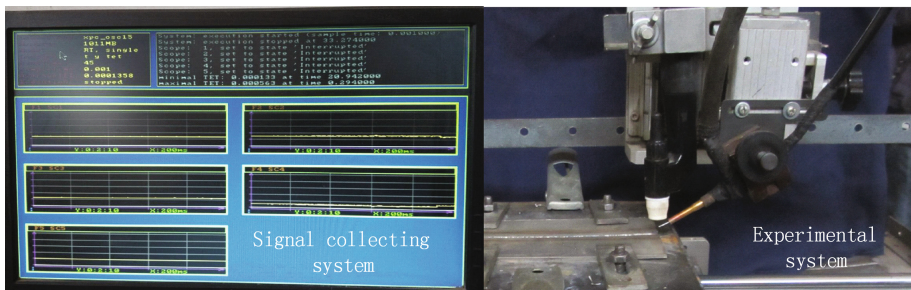
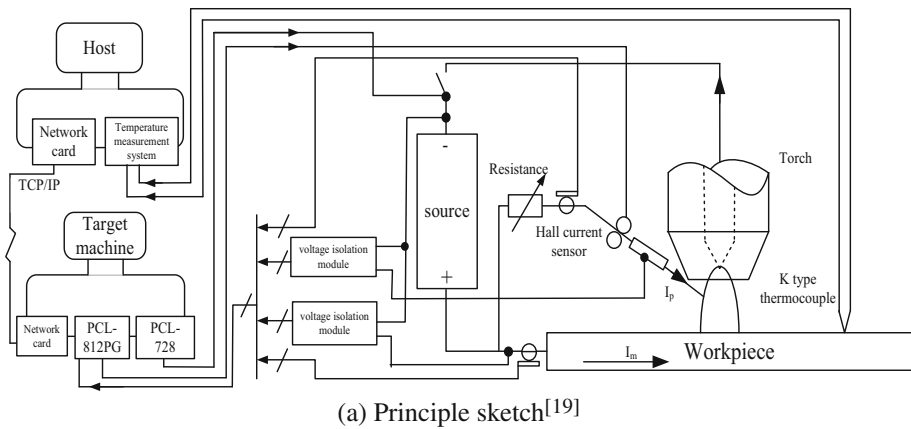


Fig. 2. Bypass coupling micro plasma arc welding experimental system. (a) Principle sketch [19]. (b) Experimental equipment

machine and WF-007A multi-function automatic argon arc filling machine; Welding control system includes three-axis CNC working platform, stepper motor and drive; Signal acquisition system consists of IPC, PCL-812PG data acquisition card, PCL-728 analog output card, Hall current sensor, voltage isolation module and other components. This system can realize real-time automatic control of current, voltage, temperature measurement, starting arc, arc, wire feeding. The real-time measured current and voltage is shown in Fig. 3.

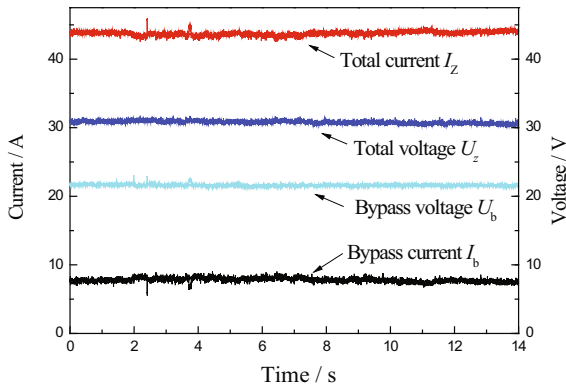


Fig. 3. The measured current and voltage

2.3 Experimental Procedure

The 304-stainless steel plate with thickness of 3 mm was used as base metal. The 0.8 mm ER304L stainless steel wire was used as filler metal. Before welding, polish with sand-paper and clean the stainless-steel plate with acetone to remove surface stains.

The surfacing welding experiment under different parameters was carried out by means of bypass coupling micro plasma arc welding on the 304-stainless steel plate. During welding, the thermal cycle curve was test. The position of test point is shown in Fig. 4. After welding, the seams under different parameter were obtained. The transverse

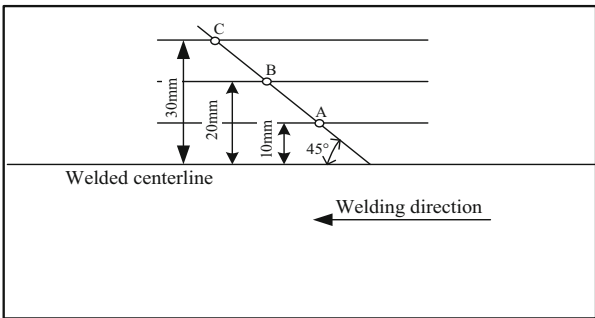
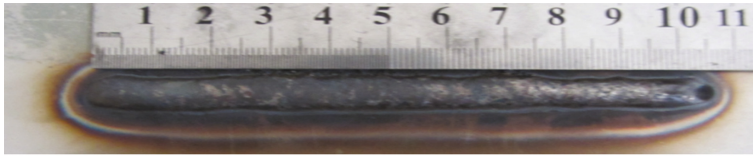


Fig. 4. Distribution of thermocouple measurement points

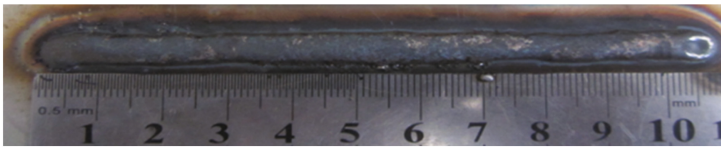
of seam was observed after corrosion. Finally, the microstructure of seam was observed by optical microscope. The total welding current is 50 A; The bypass currents are 0 A/ 10 A/12 A/14 A; The shielding gas flow rate is 10 L/min; The plasma gas flow rate is 0.6 L/min; The wire feeding speed is 280 cm/min; The distance of electrode to workpiece is 10 mm.

3 Results and Discussion

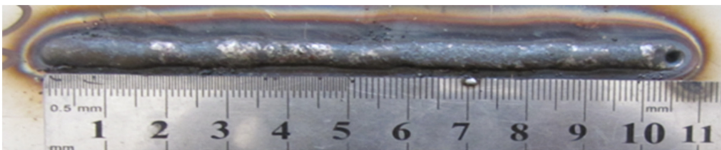
Under the above welding parameters, the welding seams were obtained as shown in Fig. 5. It can be seen that the weld width of seams decreased with the increase of bypass current. Then comparing the transverse of seam like Fig. 6, the weld reinforcement was found increasing with the bypass current, and the weld depth of seam was decreased gradually with the increase of bypass current. The dimension parameters of seam were measured as shown in Table 1. The decrease of weld depth and weld width shows the decrease of heat input of base metal. The weld dilution rate indicates the dilution degree



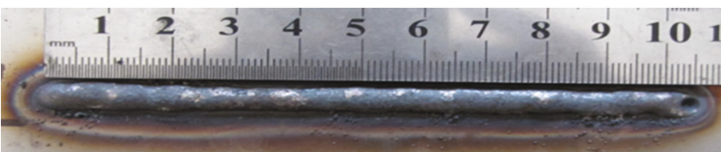
(a) 0A



(b) 10A



(c) 12A



(d) 14A

Fig. 5. The welding seams at different bypass currents

of deposited metal, and expressed as a percentage of the base metal in the weld metal. It can better express the relationship of the fusion quality of the base metal and wire. Therefore, to better understand the influence of bypass current on the heat input of base metal and the fusion velocity of welding wire, the weld dilution rate is used as an eigenvalue to cognize the influences. The weld dilution rate decreased with the increase of bypass current. It shows, when the total current stay in 50 A, the fusion quality of base metal decreased and the fusion velocity and fusion quality of welding wire increased, with the increase of bypass current. The bypass coupling micro plasma welding method can diminish the heat input to base metal, and increase the molten velocity of welding wire.

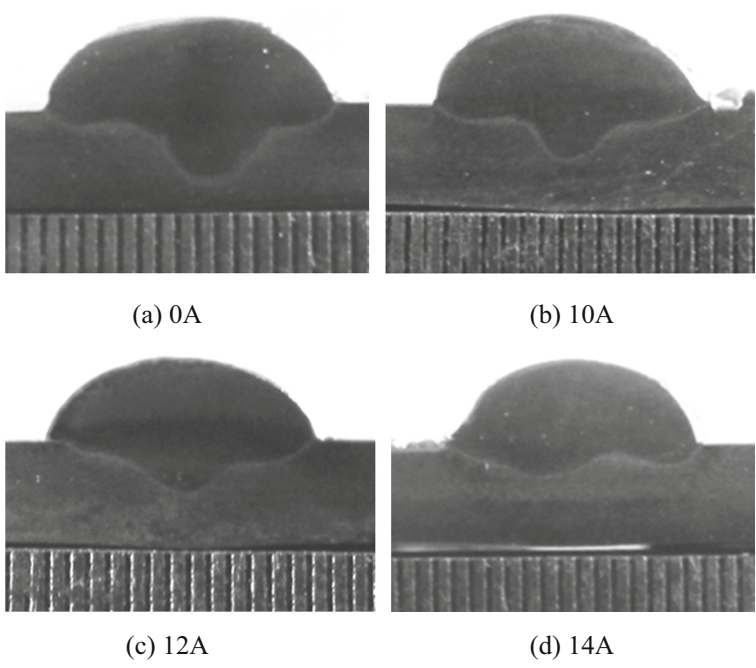


Fig. 6. Transverse of welding seams at different bypass currents

Table 1. The measurement of weld size and welding dilution rate

Bypass current/A	Weld width/mm	Weld reinforcement/mm	Weld depth/mm	Dilution rate/%
0	7.29	2.52	2.36	35
10	6.78	2.66	1.40	27
12	6.375	2.85	1.12	23
14	6.325	2.53	1.10	22

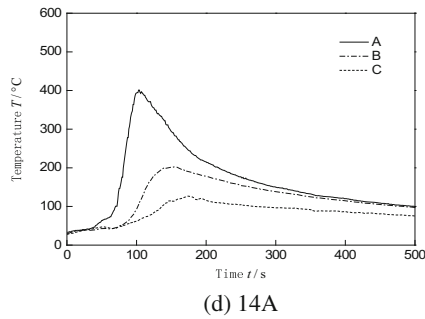
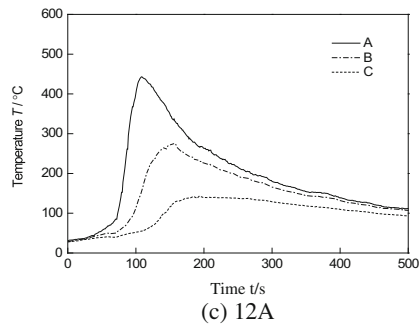
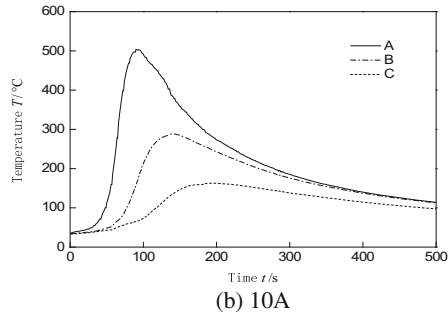
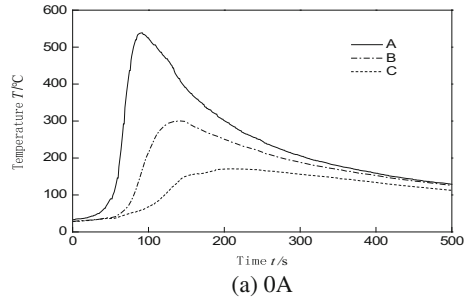


Fig. 7. The thermal cycling curves at different bypass current

To further verify the use of bypass coupling micro plasma welding method whether can diminish the heat input of base metal, the thermal cycling curve was test during the

welding process. The thermal cycling curves were shown in Fig. 7. From Fig. 7, the peak temperatures of each test point under different bypass currents were obtained. Figure 8 is the peak temperature of thermal cycling curves under different bypass currents. In the three thermal cycle curves, the peak temperature of point A at 0 A bypass current is the highest, reaching 538.5 °C. As the bypass current I_b increases from 10 A to 12 A, 14 A, the peak value of the temperature is reduced to 504 °C, 442.9 °C, 401.1 °C. The peak temperature of point B and point C also meet this trend. It can be proved that the heat input to base metal is decreasing constantly with the increase of bypass current.

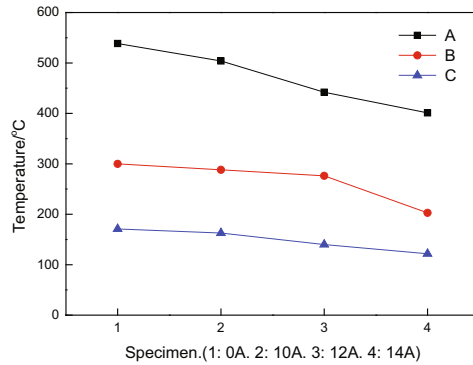


Fig. 8. The peak temperature of Thermal cycling curves under different bypass currents

The heat input to base metal consists of arc heat and resistance heat. When the total current I_z remains unchanged, the base metal current I_m decreased with the increase of bypass current I_b . The decrease of base metal current causes the abatement of resistance heat. Hence due to the abatement of resistance heat, the heat input to base metal is decreased with the change of base metal current. The peak temperature was different at different base metal currents, and reductive with the decrease of base metal current as shown in Fig. 8. The fusion quality of base metal is also decreased as shown in Table 1. Meanwhile, the decrease of base metal current will lead to the increase of bypass current. The bypass current through the welding wire, and generates resistance heat. The resistance heat increases with the increase of bypass current. Therefore, the fusion velocity of welding wire increases. The weld dilution rate decreases with the increase of bypass current as shown in Table 1. The result shows the bypass coupling micro plasma welding can achieve the accurate control of heat input, and balance the heat input to base metal and welding wire. Compared with traditional micro plasma welding, under the condition of constant heat input, it can accurately control the heat input to base metal whether increase or decrease.

Figure 9 is the microstructure around the fusion zone under different bypass current. The effect of heat input on microstructure is great. In turn, Figs. 9(a)–(d) are respectively the microstructure, along with the increase of bypass current. The width of fusion zone is decreasing gradually with the increase of bypass current. And as shown in Fig. 9, the grain size of heat affected zone (HAZ) adjoins Fusion zone decreases with the increase of bypass current. The heat input to base metal will affect the growth of grain. Due to

the increase of bypass current, the current to base metal reduces gradually. The resistance heat of base metal decreases accordingly, which causes the decrease of heat input and the grain refining. The coarse grain will reduce the quality of welded joint, and make the welded joint unreliable. To obtain reliable welded seam, the refined grain is needed. The results show that the bypass coupling micro plasma welding can control the heat input to base metal. Besides, because of the low heat input to base metal, it can alter the size of grain, and improve the microstructure of welded seam.

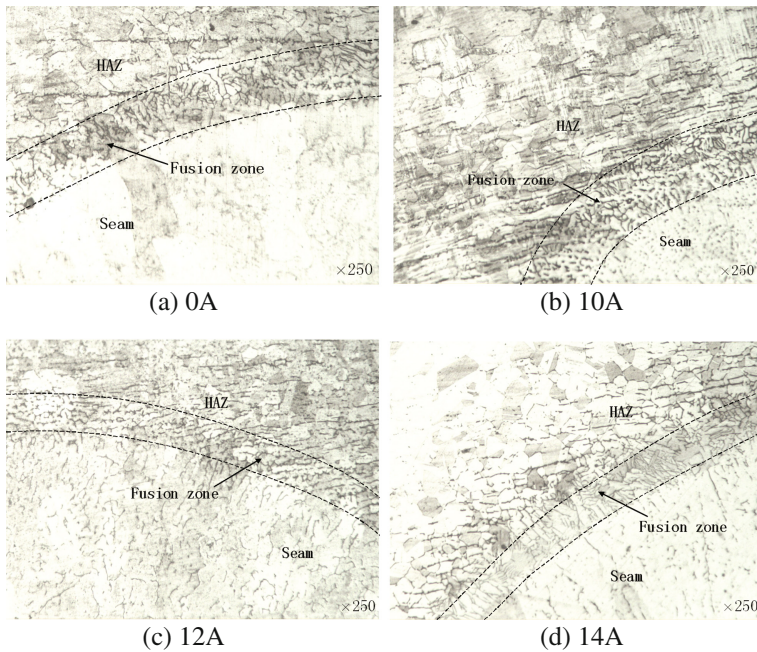


Fig. 9. Microstructure under different bypass current

4 Conclusions

- Through the control of bypass current, the bypass coupling micro plasma welding can achieve the control of arc heat, balance the heat input to base metal and welding wire.
- Under the condition of constant heat input, the heat input to base metal reduces gradually with the increase of bypass current.
- By using bypass coupling micro plasma welding, the microstructure of welded seam can be improved.

Acknowledgement. This research is supported by the National Natural Science Foundation of China (No. 51665034), the authors thank to Maohong Yang, Yonglong Yu for helping in machine repair. Special thanks to Na Wang for guiding in English writing.

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Online Control of Deposited Geometry of Multi-layer Multi-bead Structure for Wire and Arc Additive Manufacturing

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Abstract. A robotic wire and arc additive manufacturing (WAAM) system with active vision sensing capability was implemented to improve the geometry accuracy of multi-layer multi-bead structures. Width and height of the deposited bead were online detected and the accuracies of the designed sensing approaches are 0.25 mm and 0.1 mm, respectively. A double-input-double-output controller with two subsystems was designed to ensure the uniformity of bead width and bead height. The bead width was adjusted by a single neuron self-learning PI controller, while the bead height was controlled based on a rule-based engine. The experimental results indicated that (i) accuracy of the deposited bead width is controlled in 0.5 mm, (ii) accumulation effect of the bead height deviations has disappeared when multiple layers are overlapped, and (iii) the surface finish of each layer was controlled to be flat as well.

Keywords: Wire and arc additive manufacturing · Multi-layer multi-bead structure · Active vision sensing · Bead geometry control

1 Introduction

Additive manufacturing (AM) is a technology to fabricate parts by depositing material on a layer-by-layer basis. AM is capable to realize complex structure design and fabrication, and reduces material and energy at the same time [1, 2]. Wire and arc additive manufacturing (WAAM) is an alternative AM approach for metallic part deposition. The heat source of WAAM is welding arc, while the fed material is wire. It has been proved that WAAM requires lower cost on implementations and fabricates parts with higher efficiency in comparison with other metallic AM technics [3]. The research activities of WAAM regarding advanced material shaping, microstructure and mechanical performance analysis of the deposited part, and path optimization techniques have been reported in the literature succession [4–6].

In general, WAAM contains a planning phase and a deposition phase. In the planning phase, a 3D model of the target part is sliced into multiple layers. For each layer, the deposition path is designed based on the contour of the layer. In addition, manufacturing parameters are deduced according to the planned bead geometries of the layers.

However, geometries of the deposited bead are susceptible to be influenced by the diverse heat sinking conditions and thermo-mechanical coupling effects, which might cause deviations on the bead geometries to the planned values [7, 8]. When the deviations accumulate, the subsequent deposition process cannot advance strictly as planned. Therefore, the WAAM process has the fatal shortcomings of poor continuity and low accuracy.

Improving the accuracy of bead geometry is one of the research challenges in WAAM. To this end, online sensing and control is an efficient way to adjust the bead geometries according to the planned values. The research focusing on process control of WAAM is relative few. Most of the research reported in the literature focused on multi-layer single-bead structures [9, 10]. The work related to multi-layer multi-bead structures is a new research challenge.

This paper aims at improving the geometry accuracy of multi-layer multi-bead structures fabricated by WAAM. A line-structured light vision sensor was employed to measure the bead geometries online. A hybrid controller was designed and implemented to control the bead width and height. The proposed approach was validated by an experiment: fabrication of a multi-layer two-bead structure.

2 System Overview

A WAAM system based on GMAW was designed as shown in Fig. 1. It contains a Motoman HP20D robot, a Panasonic YD500FR welding machine, a GMAW torch, a META SLS-050 line-structured laser sensor, a computer, and some modules for signal transmission. The computer is the core of the system to ensure the coordination of the system components. It receives the stripes aggregated from the sensor, while sending control commands to adjust the manufacturing parameters in the deposition phase. The experimental materials and range of deposition parameters used in this paper are shown in Tables 1 and 2, respectively.

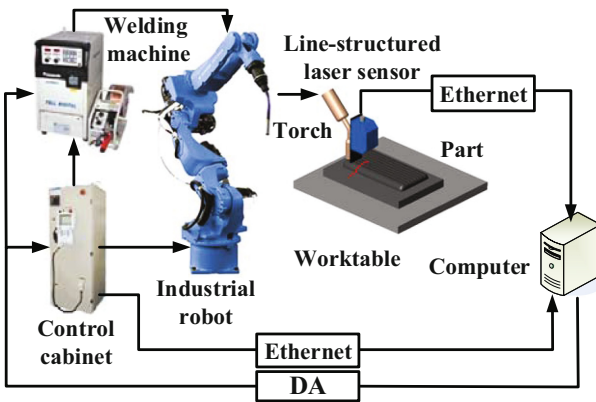


Fig. 1. Schematic diagram of the WAAM system

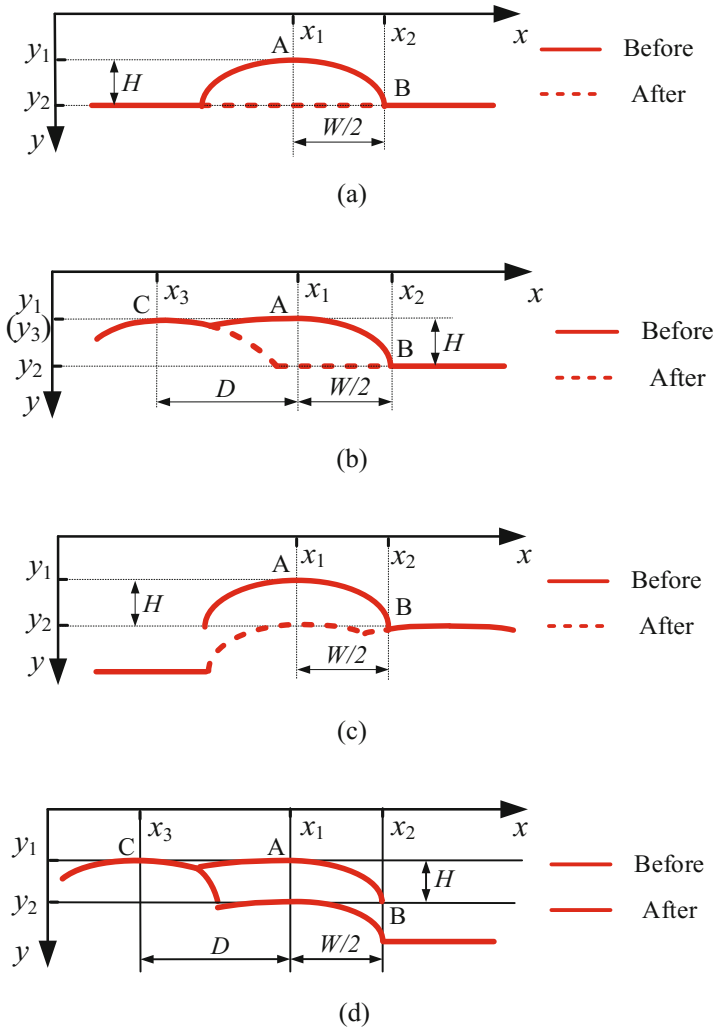


Fig. 2. Typical features of the light stripe of the deposited bead: (a) single bead; (b) overlapped bead; (c) first bead of a lapped layer; (d) last bead of a lapped layer

Table 1. Experimental materials

Substrate		Wire		Shielding gas	
Component	Thickness t/mm	Component	Diameter d/mm	Component	Flow $f/(\text{L}/\text{min})$
Q235 steel	10	H08Mn2Si steel	1.2	95%Ar 5%CO ₂	18

Table 2. Range of deposition parameters

Deposition current I/A	Deposition voltage U/V	Deposition speed $v/(mm/s)$
120–180	20–24	4–8

The reported data of the sensor indicates the cross-sectional profile of the surface of the deposited part. Based on the reported data, an image processing algorithm was designed to acquire the deposited bead geometries. The algorithm includes multiple steps regarding data preprocessing, pattern recognition and feature points extraction (vertex and toe of bead). Based on the designed algorithm the bead geometries are calculated, including bead height (H) and bead width (W). The extracted features of deposited beads are shown in Fig. 2. The detection error of H is ± 0.1 mm, while the detection error of W is ± 0.25 mm.

3 Controller Design

The objective of the controller is to keep H and W of any deposited bead to the planned values: H_{set} and W_{set} . However, H and W are strongly coupled, which implies that the adjustment of any manufacturing parameter, e.g. deposition voltage (U), deposition current (I) and deposition speed (v), changes both H and W at the same time. To solve this problem, it is necessary to separate the control of the width and height into two sub-controllers. A hybrid controller was developed and is shown in Fig. 3, which controls the W as the main goal and controls the H as the second goal.

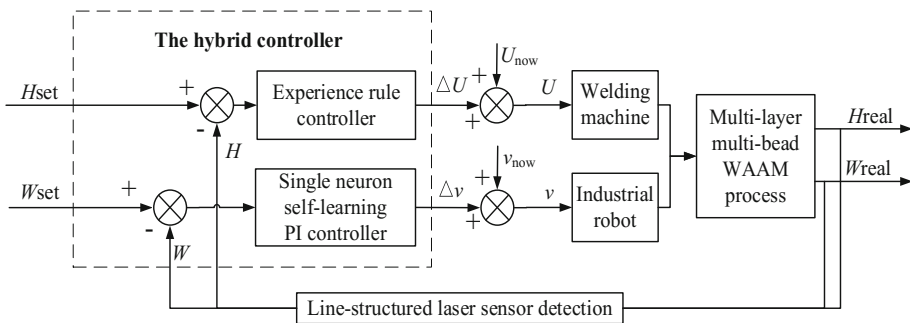


Fig. 3. Schematic diagram of the developed hybrid controller

In this controller, two sub-controllers are combined and work cooperatively. The first sub-controller is used to control W by adjusting v with a single neuron self-learning PI controller, since W is sensitive to the change of velocity. The pure delay of the sensing system was taken into consideration. That is the reason why the differential term of the PID controller is forbidden to avoid oscillation of W . In addition, the single neuron with learning capability was employed to self-tune the PI parameters during the control process based on the learnt experience. The learning capability enables the PI controller

adaptive to the complex WAAM deposition process with high robustness. Furthermore, the objective of the second sub-controller is to prevent the accumulation of H deviations. It works by trimming U with the following experience rules in a low adjusting frequency:

$$R1 : IF H_{set} - H > 0.2 \text{ THEN } U_{n+1} = U_n - 0.5 \quad (1)$$

$$R2 : IF H_{set} - H < -0.2 \text{ THEN } U_{n+1} = U_n + 0.5 \quad (2)$$

$$R3 : IF -0.2 \leq H_{set} - H \leq 0.2 \text{ THEN } U_{n+1} = U_n \quad (3)$$

4 Experimental Results and Discussion

An open-loop experiment and a closed-loop experiment to fabricate a multi-layer multi-bead structure were planned as comparative experiments to validate the developed controller. The target structure was a cuboid component with the cross-sectional size of 13 mm (component width) $\times$ 12.6 mm (component height). The component was designed with 6 layers and 2 overlapped beads in each layer. The planned bead geometries are shown in Table 3. The initial deposition parameters were set as following: the deposition current was 150A, the deposition voltage was 22 V, and the deposition speed was 5 mm/s.

Table 3. The planned bead geometries

Layer	Bead height/mm	Bead width/mm	Center distance/mm	Layer width/mm
1	2.6	7.5	5.5	13
2–6	2.0	7.5	5.5	13

In the open-loop deposition process, the deposition parameters of all beads were kept as the initial values. The detected H and W of several beads are shown in Fig. 4. For simplicity, W_{ij} and H_{ij} are referred to as W and H of the j th bead of the i th layer. It can be seen from Fig. 4 that W_{ij} gets larger while the number of layer increases. In addition, H_{i2} in each layer is higher than H_{i1} when $i > 2$. The heat sinking conditions of the beads in a layer ($i > 2$) is worse than those of the layers below, which results in a lower cooling rate and a longer duration at high temperature of each bead in the layer. That is the reason why bead width increases when the number of layer increases. As a consequence, the center distance between the deposited beads in the second and above layers mismatches to the geometries of the beads, which causes deviation of H .

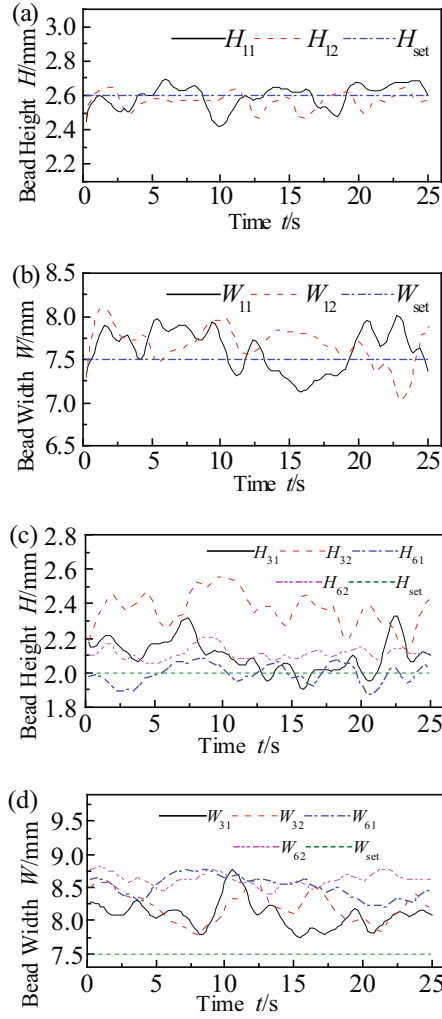


Fig. 4. Detected values in the open-loop deposition experiment: (a) H_{1j} ; (b) W_{1j} ; (c) H_{3j} and H_{6j} ; (d) H_{3j} and H_{6j} , $j = 1, 2$

In the closed-loop deposition experiment, the developed controller was used. The control commands were developed for keeping the bead geometries as planned. The control cycle of W is 2 s, and that of H is 5 s. The detected values of the manufacturing parameters and bead geometries are shown in Fig. 5. With the proposed controller, W was kept to be stable around the planned value, while H deviation is smaller than that in the open-loop experiment. The accuracy of W in the controlled section was better than 0.5 mm.

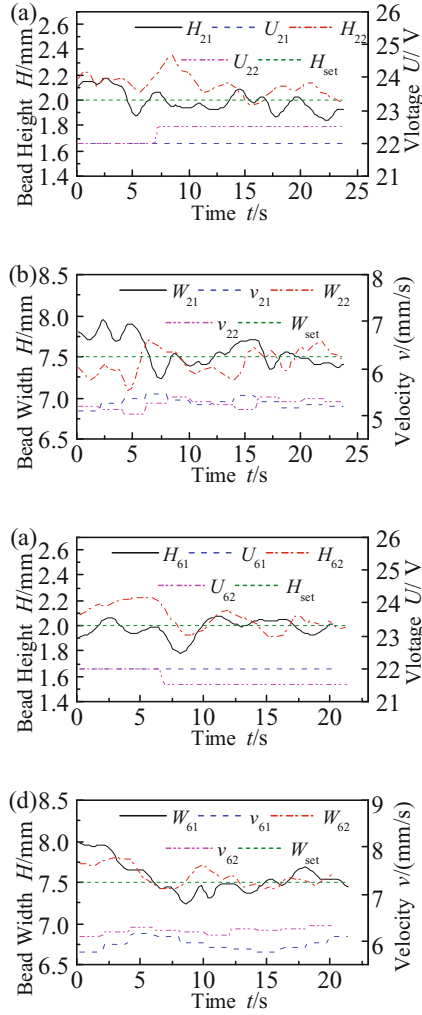


Fig. 5. Detection curve of closed-loop deposited bead sizes: (a) W of the 2nd layer 1st bead; (b) H of the 2nd layer 2nd bead; (c) W of the 6th layer 1st bead; (d) H of the 6th layer 2nd bead

The cross-sectional profiles of the deposited parts in the experiments are shown in Fig. 6. The width deviation of the deposited part in the open-loop experiment is up to 1.24 mm (9.5% of the layer width), while that in the closed-loop experiment was 0.52 mm (4% of the layer width). Furthermore, the top surface of the structure fabricated in the closed-loop experiment is smoother as well. The results indicated that the controller designed in this paper is suitable to improve the geometry accuracy of multi-layer multi-bead structures fabricated by WAAM.

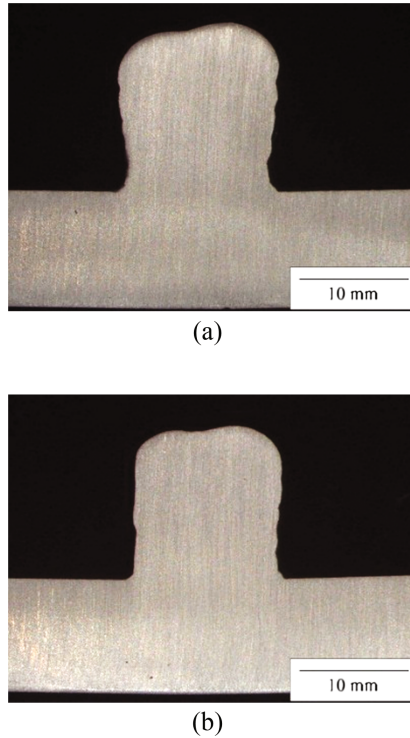


Fig. 6. Section of the formed structures: (a) open-loop experiment; (b) closed-loop experiment

5 Conclusions

A robotic WAAM system with an active vision sensor and a hybrid controller has been built for fabrication of multi-layer multi-bead structures. The conclusions are:

- The active vision sensor is able to detect the cross-sectional profile of a deposited bead in a multi-layer multi-bead structure. Based on the proposed image processing algorithm for extracting feature points of light stripes, the W and H of a deposited bead are known. The detection error of H is less than 0.1 mm, while that of W is less than 0.25 mm.
- The designed controller is suitable to keep the bead geometries as planned. The error on W is controlled within 0.5 mm. The controller also prevents accumulation of H deviations, which results in a flat surface of the fabricated structure.

Acknowledgement. The authors would like to thank Prof. Hongming GAO for his support on the implementation of the robotic WAAM system and Mr. Dongqing YANG for his technical assistant. This work was supported by National Natural Science Foundation of China, No. 51575133.

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The Research on Welding Sources and Ni Interlayer Synergy Regulation in Laser-Arc Hybrid Welding of Mg and Al Joints

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Abstract. Mg and Al alloys were joined by a laser-arc hybrid welding method with addition of Ni interlayer. The macrostructure and elements distributions of the joints were observed by the SEM and EPMA, and the plasma forms of the laser-arc hybrid welding sources were analyzed by the high speed camera. The results showed that the welding mode in Al fusion zone changed from conductive mode to keyhole mode, the intermetallic in the Al fusion zone increased obviously, which still influence the property of the joints evident. The effect of the laser induced arc was changed with the varying of laser and arc welding parameters, which made influence on the welding mode and reactions in the welding process. The regulation of the hybrid welding sources between the elements reactions was an important factor for the joining of dissimilar metals.

Keywords: Laser-arc hybrid welding · Intermetallic · Welding mode · Magnesium · Aluminum

1 Introduction

The joining technology of dissimilar metals were paid more attentions with the improvement of the materials property. If the two materials with different characteristics could be joined favorable, the advantages of the materials would give better expression. The intermetallic makes obviously influence on the property of the dissimilar welding joint. It has been reported that the formation of the intermetallic was mainly decided by the joining methods, welding parameters and interlayer [1, 2].

The joining technology of the Mg and Al alloys was the one of typical problems in dissimilar welding joining process. The Mg-Al intermetallic made harmful effect on the joint, which should be controlled carefully [3, 4]. A Ni interlayer was used by the W.S. Chang in Hybrid Laser-Friction process, and the property improvement of the joint was mainly based on the formation AlNi and MgNi₂ instead of brittle intermetallic compound [5]. Jian Zhang et al. used Ni interlayer in diffusion bonding Mg to Al process [6]. P. Penner et al. [7] reported the resistance spot welding of dissimilar Al/Mg combinations with Au-Ni interlayer, and the Mg₃Au intermetallic compound layer and gold-magnesium eutectic structure made obviously effect on the

joint. Gao, M. et al. had used the Ti interlayer in laser welding Mg to Al process, and the IMC layer consisted of Al-Ti was stronger than Mg-Al IMCs [8]. It could be found that the addition of the interlayer eliminate the Mg-Al intermetallic, which made active effect on the dissimilar Mg/Al joint. Still, some new intermetallic formed during welding process, which influenced the property of the joint directly.

It was well known that the interlayer made obviously effect on the property of the joint, which changed the reaction process of the different elements [9]. However, the reactions between the dissimilar metals and the interlayer were not only decided by the interlayer, but also the thermal cycling and the solidification in the welding process, which was often decided by the welding source and the welding parameters. Therefore, there should be a synergy regulation between the welding source and the interlayer, which was helpful for the control of the reaction process.

In this study, the laser-arc hybrid welding technology was used to joining the Mg alloy to Al alloy. The hybrid welding source was used to regulate the temperature gradient in the fusion zone. The arc source was mainly used to weld the upset plate, and form the Mg fusion zone. The laser source was mainly used to weld the lower plate, and form the Al fusion zone, which was obviously smaller than that of Mg fusion zone. The interlayer was applied to control the intermetallic at the interface of the dissimilar Mg/Al joint. The objective of the current study was to explore the effects of the heat source on the bonding modes and the reactions in laser-arc hybrid welding process.

2 Experiments

A 1.5 mm thick AZ61 Mg alloy sheet and a 1.5 mm thick 6061Al alloy sheet were used in this study. The chemical compositions for the AZ61 Mg alloy and 6061 Al alloy are Mg-6 wt% Al-1 wt% Zn-0.2 wt% Mn-0.1 wt% Si and Al-1 wt% Mg-0.8 wt% Si-0.7 wt% Fe-0.3wt% Cu, respectively. A 0.1 mm thick Ni foil (99.5% purity), was elected as the interlayer. The schematic diagram for the laser-TIG hybrid welding technology is illustrated in Fig. 1.

The welding process was performed using the laser-TIG hybrid welding technique. Argon gas (15 L/min flow rate) was employed to protect the welding zone. The optimum parameters were as follows: 450 W pulse laser power (pulse peak value 7500 W); pulse width 2 ms; frequency 30 Hz; 60 A, 80 A and 100 A TIG currents; and 800 mm/min welding speed. The microstructure was examined using a scanning electron microscope equipped with an energy dispersive spectroscopy (EDS) system. The elemental distribution in the joint was determined via Electronic probe micro-analyzer (EPMA). Phase identification was performed via X-ray diffraction (XRD) from 20° to 100° at 0.02° step. Tensile test perpendicular with size of 100 mm × 20 mm was cut to the weld direction after welding which was shown in Fig. 1, too. Tensile shear tests of samples are performed at room temperature using an Instron-type testing machine with 2 mm•minute⁻¹ cross-head speed.

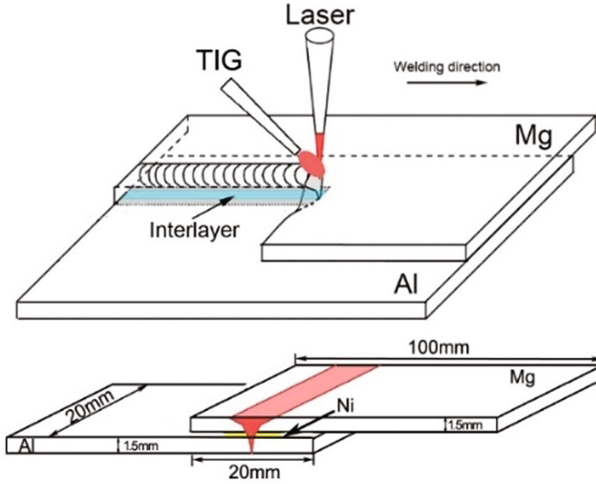


Fig. 1. Schematic diagram for laser-arc hybrid welding Mg to Al joint with Ni interlayer

3 Results and Discussion

3.1 The Welding Shape and Property of Hybrid Welding Joint

Figure 2 shows the macrostructure of the laser-arc hybrid welding Mg to Al joints with different arc welding currents. It was found that the welding penetrations were as increasing as the arc currents. When the welding currents was 60 A, the Ni interlayer was partly melted, and the tensile shear load of the joint was only 1.2 kN. As the welding currents was 80 A, the Ni interlayer was completely melted in laser area, and the tensile shear load of the joint was 2.2 kN. When the welding current was 100 A, the area of the melted Ni interlayer and the penetration were enlarged, and the tensile shear load of the joint was 1.6 kN.

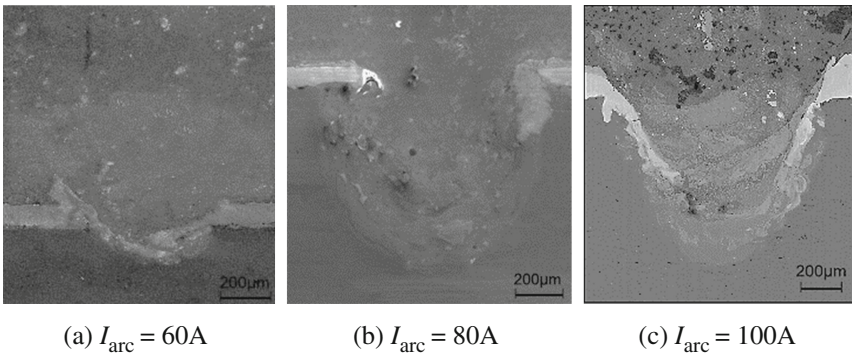


Fig. 2. Macrostructure of the hybrid welding Mg to Al joints with different arc welding currents

3.2 The Reaction in Welding Joint

The element Ni could react with both elements Mg and Al, which formed the Mg-Ni and Al-Ni intermetallic. In order to understand the reaction process, the elements distributions of the joints are observed by the EPMA, as shown in the Figs. 3 and 4. The joint with the 60 A current was not analysis, because the Ni interlayer was only partly melted and the property of the joint was relatively lower.

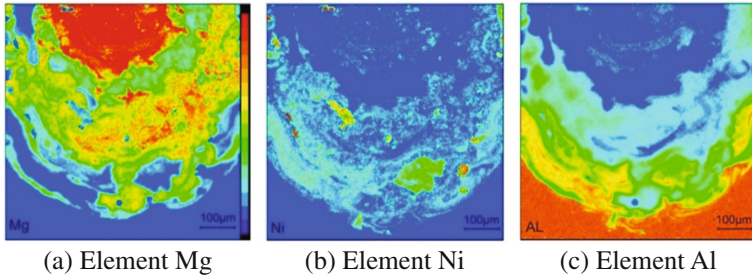


Fig. 3. Elements distributions in the hybrid welding Mg to Al joints with arc current 80 A

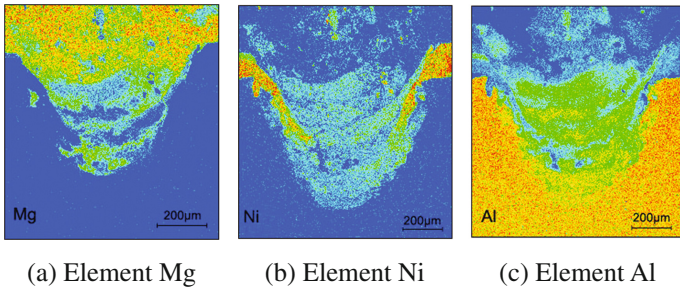


Fig. 4. Elements distributions in the hybrid welding Mg to Al joints with arc current 100 A

Seen from the Fig. 3 the concentration of element Ni approaching to the Al fusion zone is higher than that of the area approaching to the Mg fusion zone. The composition of the joint was tested and analyzed by the EDS, the results showed that it consisted of 75.86 at. % of Mg, 11.85 at. % of Ni and 12.29 at. % of Al, and the microstructure of the joint were mainly the Mg-Mg₂Ni and Mg-Mg₁₇Al₁₂ hypoeutectic microstructure. The element Ni and Al in these areas were distributed in high concentration, and nearly no element Mg. This kind of layer structure was firstly found in the laser-arc hybrid welding joint. In laser induced arc hybrid welding process, the welding mode for Al fusion zone was in a conducive mode. Therefore, the joint showed a layer structure. It meant that in this situation the lower laser power made little impacting and mixing effect on the fusion zone. Thus, the melted Ni interlayer was reacted with Mg and Al alloys slowly.

Figure 4 presents the elements distributions in the laser-arc hybrid welding Mg to Al joint with Ni interlayer, as the arc current is 100A. With increasing of the arc current, the welding mode in the Al fusion zone changed to the keyhole mode. Therefore, the

temperature in the fusion zone would be increased, and the reactions among the elements Mg, Al, Ni were changed. In this condition, the Ni interlayer was melted drastic, and the element Ni distributed in the whole Al fusion zone dispersed, replacing the layer structure in Fig. 3. From the EDS analyses of the transition zone, it consisted of 13.15 at. % of Mg, 14.40 at. % of Ni and 72.45 at. % of Al, which were mainly composed of the Al-Ni and Mg₁₇Al₁₂ phase. More Al-Ni and Mg₁₇Al₁₂ intermetallic formed in the Al fusion zone that made harmful influence on the property of the joint obviously, and the results was nearly same with that of Chang [5]. Except the reaction in the fusion zone, the welding mode in the laser-arc hybrid process was decided by the heat source.

3.3 The Hybrid Welding Source in Welding Process

In different welding arc currents, the hybrid sources of the laser and arc were different. The pulse laser was used in the experiment. Although the average power of the laser beam was less than 500 W, the pulse peak value was about 7500 W, thus the effect of the pulse laser on the welding source varied with the arc currents obviously. In order to understand the influence of the welding arc on the hybrid mechanism, the plasma behavior of laser-arc welding is observed by the high-speed camera, as shown in the Fig. 5. When the arc current was 60 A, the plasma form was relatively small. In this situation, the welding fusion zone in the Mg alloy was comparatively small, and the enhanced effect of the low power pulse laser on the arc was exist but not obvious, thus the welding penetration was low. When the arc current was 80 A, the plasma form of the hybrid source was enlarged, because of the increasing of the arc current. When the arc current was 100 A, the plasma form was even larger. The temperature of the fusion zone was increased, more Mg alloy melted with the increase of arc current. There should be more Mg plasma forming the welding process, which made influence on the hybrid effect between the laser and arc [10].

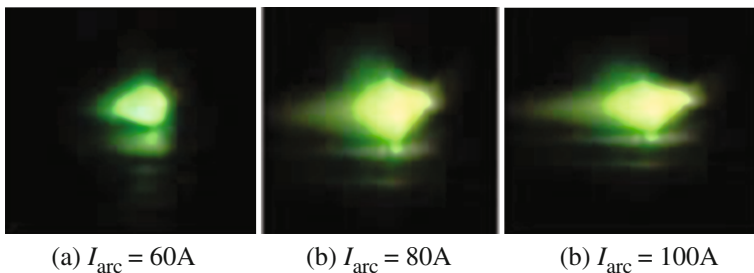
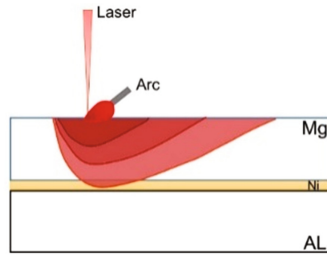


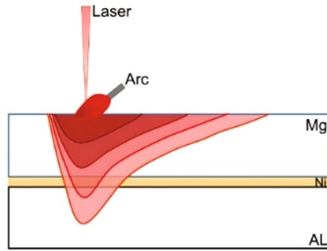
Fig. 5. The plasma behavior of the laser-arc hybrid welding Mg to Al processes

Different heat source models had different energy distributions, and different energy stated that influences the reaction and solidification process of the molten pool, eventually affecting the formation and distribution of intermetallic compounds in the fusion zone of the welded joints. Under the condition of thermal conductivity welding, the laser energy and arc power were relatively low, and the compression on arc and mixing effect

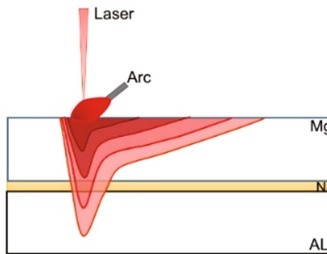
of the laser beam on the fusion zone were not obvious. The main function of the laser was stabilizing the arc with the high welding speed. The arc heat source model was shown in Fig. 6(a). Under the condition of keyhole mode welding conditions, the compression of the laser to the arc would be significant due to the increase of the laser beam power. The keyhole welding mode formed and the heat source model is showed in Fig. 6(c). At this time, the distribution of arc energy was vertical downward projection. The effect of the pulse laser was enhanced by the welding arc. Therefore, the reaction in the fusion zone would be more sharply, and formed a number of intermetallic. Still, the laser induced arc could regulate the heat source power distribution. When the arc



(a) $I_{\text{arc}}=60\text{A}$



(b) $I_{\text{arc}}=80\text{A}$



(c) $I_{\text{arc}}=100\text{A}$

Fig. 6. Laser-arc hybrid heat source model with different arc currents

current was 80 A, the hybrid welding source had a certain penetrating power, but not forming the keyhole, which formed conductive mode welding, as shown in the Fig. 6(b).

4 Conclusions

The Mg and Al alloys were joined successfully by the laser-arc hybrid welding technology. The best tensile shear load joint was 2.2 kN (110 MPa), which was obtained with laser beam power 400 W and arc current 80 A. The welding mode in the Al fusion zone changed from the conductive mode to the keyhole mode with the increasing of the arc currents, and the reactions in the fusion zone altered. More intermetallic was found in the keyhole mode joint. In conductive mode welding joint, the elements distribution in the fusion zone showed the layer structure, and dispersed distribution in the keyhole mode joint. The welding mode in the Al fusion zone was influenced by the hybrid effect of the laser and arc. The welding mode in the fusion zone could be controlled through the regulating of laser induced arc mechanism.

Acknowledgement. The authors gratefully acknowledge the support of National Natural Science Foundation of China (11375038), Science Fund for Creative Research Groups of NSFC (51621064).

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Effects of Laser Welding Parameters on the Characteristics of Deposition Layer

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Abstract. Laser welding with filler wire makes welding more cost efficient due to its properties. However, fluctuation of welding parameters seriously affects the stability of welding process and the quality of deposition layer. Based on the high speed camera system and welding process test, this paper focuses on effects of welding parameters on the laser-wire coupling behavior, the transition behavior of molten metal and the characteristics of deposition layer. The results showed that the transition behaviors of liquid metal were decomposed into globular transition behavior, liquid-bridge transition behavior and spreading transition behavior, among which the liquid-bridge transition behavior was most stable relatively. Different dynamic welding processes in different circumstances were established to interpret the laser-wire coupling behaviors and the transition behaviors of liquid metal while the D was zero. It was found that the coupling behavior and the transition behavior of liquid metal belonged to different dynamic process with the variable welding parameters. The optimized welding parameters were obtained by analyzing the stability of welding process and the characteristics of deposition layer.

Keywords: Laser welding · High-speed camera · Coupling behavior · Transition behavior · Deposition layer

1 Introduction

Laser Additive Manufacturing with Metallic Materials is a research focus because of the urgency of decreasing manufacturing cycle and costs. Meanwhile, it also has broad application prospects in the aerospace, defense military and other fields owing to its good properties such as high flexibility, integration, and high degree of automation [1, 2]. Over the past 20 years, some researchers have mainly studied Laser Additive Manufacturing technology based on metallic powder and achieved some results. However, because of its high cost of raw materials and low utilization rate, the use of metallic powder is limited seriously [3]. Compared with metallic powder, Laser Additive Manufacturing with Filler Wire takes laser heat as a heat source, which has high density of heat input and the smaller heat affected area so as to improve the stability of the welding process. Moreover, by using the metallic wire, no dust pollution as well as material saving are expected with this technique. In this circumstance, laser welding with filler wire has gained worldwide popularity for its capacity of increasing economy [4, 5]. At

present, to obtain the well-shaped deposition layer, previous researches of technology have performed. Many researchers have reported effects of welding parameters on characteristics. To our knowledge little has been focused on the laser-wire coupling behavior and the transition behavior of molten metal.

The research focus on the effects of welding parameters on the laser-wire coupling behavior, the transition behaviors of molten metal and the characteristics of deposition layer by means of high speed camera technology and process test.

For our purposes, the process test with variable welding parameters was carried out and the welding process was gathered with high speed camera accordingly. Then the dynamic welding processes were established to analyze the experimental results. Finally, the size of deposition layer was measured and analyzed.

2 Material and Method

A $180 \times 70 \times 4$ mm Q235 carbon steel sheet is processed for the experiment, and E501T-1 low alloy steel filler wire is employed as the welding consumable, which diameter is 1.2 mm and its chemical composition is shown in Table 1.

Table 1. Chemical compositions of E501T-1

Elements	C	Mn	Si	P	S
Content (%)	0.036	1.40	0.52	0.013	0.011

The schematic diagram of experimental system can be seen in Fig. 1, the Dlight3 semiconductor lasers is used for providing the welding heat source, whose main parameters are as follows: maximum power 1.5 kW, wavelength 976 nm, spot size $3 \text{ mm} \times 1 \text{ mm}$, working distance 275 mm, and working mode CW. In order to reduce the damage of laser heat to the laser device and other components, the central axis of the laser is deflected against the welding direction at a small angle in welding process. The modified SB-10 wire feeder system is adopted and the wire feeding speed is adjusted to vary from 0 m/min to 5 m/min stably. To keep the high temperature welding pool and molten metal from being oxidated, Ar at a constant flow rate of 5 L/min is applied for shielding. The air supplying pipe locates at the rear end of welding direction; moreover, it is coplanar with laser beam and filler wire fed in. Four-axis linkage walking mechanism

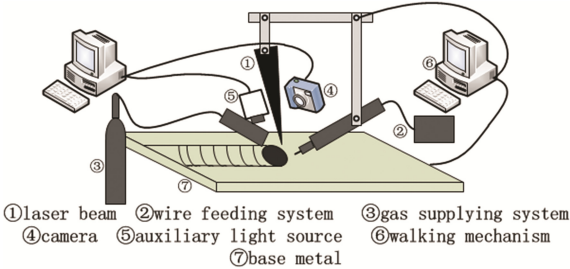


Fig. 1. Schematic diagram of experimental system

was designed for experiment. To gather the welding process real-timely, the high-speed camera system is applied at 1000 frame rate. The NBT's HSX-F300 xenon lamp is used as an auxiliary light source in order to improve the clarity of acquisition area.

3 Results and Discussion

3.1 Effect of the D on the Characteristics of Deposition Layer

As shown in Fig. 2, the D (distance between the laser and the filler wire) is the spacing between laser spot and the contact point of wire ends to workpiece [6], which affects the liquid metal transition, the stability of welding process and the characteristics of deposition layer indirectly by affecting the laser-wire coupling behavior directly.

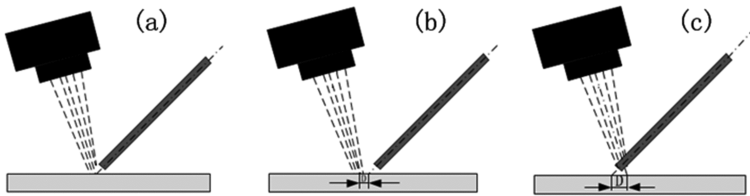


Fig. 2. Schematic diagram of the D : (a) $D = 0$; (b) $D > 0$; (c) $D < 0$

Based on the high-speed camera system, the effect of variable D on the laser-wire coupling behavior and stability of welding process was studied. The welding parameters were given in Table 2.

Table 2. Welding parameters

Parameters	P/W	$V/(mm/min)$	$V(f)/(cm/min)$	Angle/(°)	$S/(mm)$	Gass/(L/min)
Values	1500	120	120	45	8	5

The mechanism of the interaction between laser heat and filler wire is complicated. The transition behavior of liquid metal was liquid bridge transfer when the D varied from -1 mm to 0.5 mm. At the beginning of welding process, a portion of laser heat was used to melt filler wire and others melted base metal so as to form a welding pool, the reason for this was that laser beam was partially overlapped by the filler wire. With the progress of welding process, the absorption rate of laser heat increased accordingly because of the increased liquid metal in welding pool, filler wire was melted adequately by the interaction of laser heat and thermal conduction of liquid metal. Finally, molten metal was transferred into welding pool by way of liquid bridge transfer, which caused the stable welding process and the well-shaped deposition layer. The transition behavior of liquid metal was globular transfer when the D below or equal to -1 mm. Most of the laser heat was absorbed by filler wire since the filler wire happened to lie almost directly over laser beam, which resulted in the relatively small penetration owing to the lesser laser heat transferred to the surface of base metal. Furthermore, because of the larger

distance between the molten metal and the surface of base metal, the volume of liquid metal increased as filler wire fed in. Finally, liquid metal was transferred into welding pool by way of globular transfer when the gravity of droplet was greater than surface tension. As a result of impact effect of liquid metal to welding pool, the welding process was unstable and the deposition layer was discontinuous. The liquid metal transition behavior was spreading transfer while the D varied from 0.5 mm to 1 mm. The reason for this was that the most of laser heat was mainly used to melt the base metal, which resulted in the increase of the penetration and width of deposition layer. Meanwhile, the end of filler wire reached the edge of welding pool, which made filler wire bent and hindered the continuous wire feeding. Then the bent filler wire fed in welding pool was melted fully by the thermal conductivity of liquid metal and formed a deposition layer. The transition behaviors of liquid metal and the appearance of deposition layer with variable D are shown in Figs. 3 and 4.

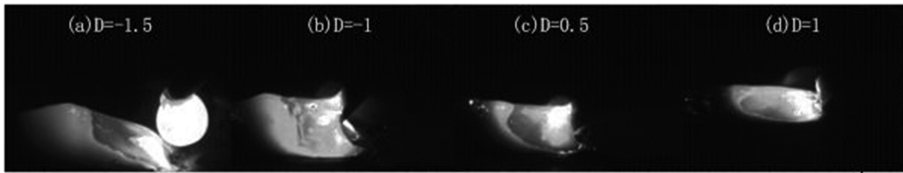


Fig. 3. The transition behavior of liquid metal with different D

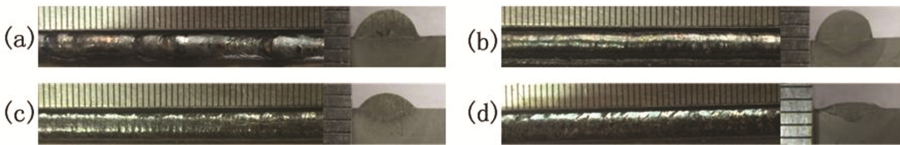


Fig. 4. Appearance and cross-section of deposition layer with different D : (a) $D = -1.5$ mm; (b) $D = -1$ mm; (c) $D = 0.5$ mm; (d) $D = 1$ mm

3.2 Effects of Welding Parameters on the Characteristics of Deposition Layer

The welding parameters are of great significance for the stability of welding process and characteristics of deposition layer. While the D is zero, stable welding process and well-shaped deposition layer can be obtained under the optimized parameters. However, the fluctuation of welding parameters affects the stability of welding process and the characteristics of deposition layer by affecting the filler wire melting mechanism and the liquid metal transition behaviors. Combined with high-speed camera technology and process test, the effects of welding parameters on the laser-wire coupling behaviors, the transition behaviors of liquid metal and the characteristics of deposition layer were studied.

Different Dynamic Welding Processes

In one case, owing to the coincidence of the laser spot and the tip of filler wire, a portion of laser heat was used to melt filler wire and others melted base metal to form a welding pool while the D was zero. On the premise that welding heat-input is greater than the heat required for melting filler wire, the filler wire was melted completely by laser heat and formed a droplet at the beginning of welding process. But the droplet was attached to the end of filler wire instead of transferring into welding pool, the reason for this was that the surface tension between filler wire and liquid metal was larger than the gravity of droplet due to the smaller size of droplet. With the progress of welding process, the volume of molten metal and the size of droplet increased accordingly. And the lower surface of droplet contacted with the upper surface of molten metal at a moment, which formed a liquid bridge. Meanwhile, liquid metal was transferred into welding pool under the combined effects of gravity, surface tension and blow force of gas. The dynamic welding process shown in Fig. 5(I) is used to interpret the laser-wire coupling behavior and transition behavior of liquid metal in this case.

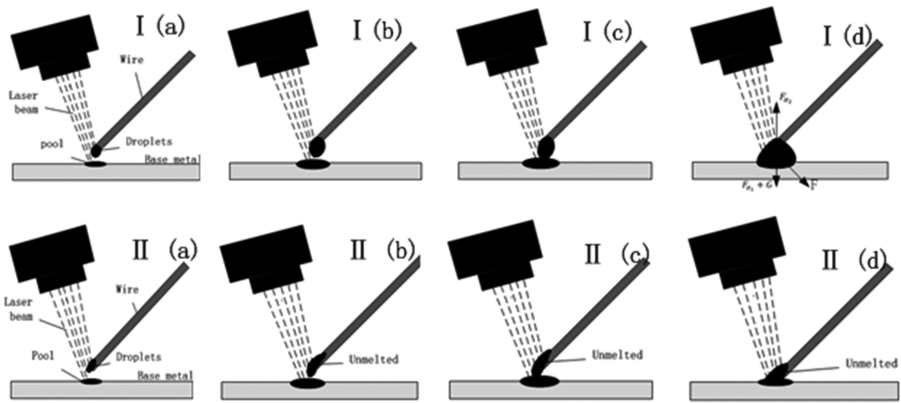


Fig. 5. Different dynamic welding processes: (a) wire melting process; (b) droplet growth process; (c) contact process; (d) liquid bridge transition

In another case, filler wire was melted partly while the heat-input was less than the heat required for melting filler wire, which was different from the case mentioned above. As the welding progressed and filler wire fed in, the volume of unmelted filler wire increased accordingly. Finally, molten metal formed by filler wire was transferred into welding pool similarly while the unmelted filler wire inserted into welding pool and formed a deposition layer under the thermal conductivity of molten metal. The dynamic welding process shown in Fig. 5(II) is used to interpret the coupling behavior and transition behavior of liquid metal in this case.

The condition of liquid bridge transition behavior can be discussed as follows:

$$F_{\sigma_1} + G + F \sin \alpha > F_{\sigma_2} \quad (1)$$

where F_{σ_1} is the surface tension between molten metal and upper surface of base metal; G is the gravity of molten metal, F_{σ_2} is the surface tension between molten metal and tip of filler wire while F is the blow force of gas.

Effect of Laser Power on the Characteristics of Deposition Layer

To verify the effect of laser power on the characteristics of deposition layer. In this experiment, laser power was set to vary from 900 W to 1500 W, welding speed and wire feeding speed were 120 mm/min and 100 cm/min respectively while other parameters were equal to Table 2.

As shown in Figs. 6(a) and 7(a), filler wire fed in was melted completely by laser heat and transferred to base metal while the laser power was 900 W. However, the laser heat that transferred to base metal was not enough to form a welding pool, which led to the solid-state heated physical process. Moreover, molten metal transferred to base metal by way of liquid bridge transition behavior and cooled quickly, which caused the weld defect of incomplete fusion. Figures 6(b)–(d) showed that the surface of base metal began to be melted gradually when laser power was larger than 900 W and the molten metal formed by filler wire transferred into welding pool, which could be described clearly in the dynamic welding process(I). As laser power increased, the size of welding pool and penetration increased accordingly, which resulted in the increased absorption rate of laser heat. The volume of molten metal also increased due to this reason. Owing to the sufficient interaction between molten metal and welding pool, stable welding process and well-shaped deposition layer were obtained, the appearance and size of deposition layer with variable laser power are shown in Figs. 7 and 9(a).

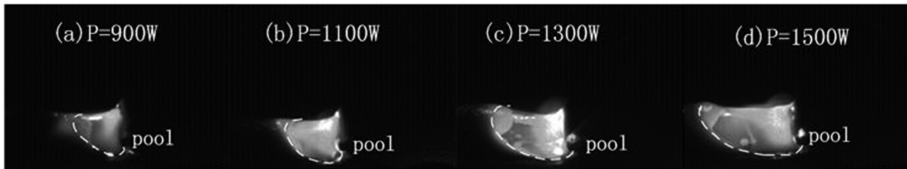


Fig. 6. Transition behavior of liquid metal with variable laser power

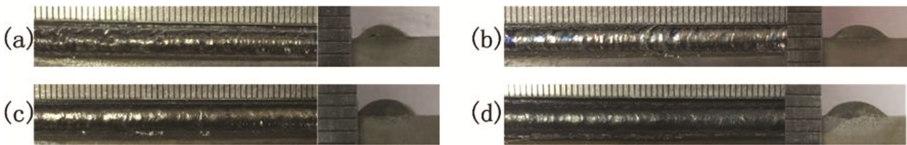


Fig. 7. Appearance and cross-section of deposition layer with variable laser power: (a) $P = 900$ W; (b) $P = 1100$ W; (c) $P = 1300$ W; (d) $P = 1500$ W

Effect of Welding Speed on the Characteristics of Deposition Layer

The welding speed mainly affects the width of liquid bridge and the solidification rate of liquid metal.

As seen clearly in Figs. 8(a)–(b), owing to the higher welding heat-input, filler wire fed in was melted adequately and transferred into welding pool through a relatively wide liquid bridge while welding speed was less than 150 mm/min, which could be interpreted by the dynamic welding process (I). Meanwhile, the welding pool existed relatively for a long time and froze slowly because of the higher energy of welding pool, which made molten metal interact sufficiently with welding pool. Owing to this, the width of deposition layer increased while the height reduced relatively. With the increase of welding speed, the filler wire fed in was melted slowly by the interaction of molten metal and welding pool, the reason for this was that the welding heat-input transferred to base metal reduced relatively. It is shown in Figs. 8(c)–(d) that molten metal transferred into welding pool through a relatively narrow liquid bridge, which was interpreted by the dynamic welding process(II). Meanwhile, the welding pool existed relatively for a short time and froze quickly, which made molten metal spread in a narrow area. As a consequence, the width of deposition layer reduced while the height increased with the increase of welding speed, the size of deposition layer with variable welding speed can be seen in Fig. 9(b).

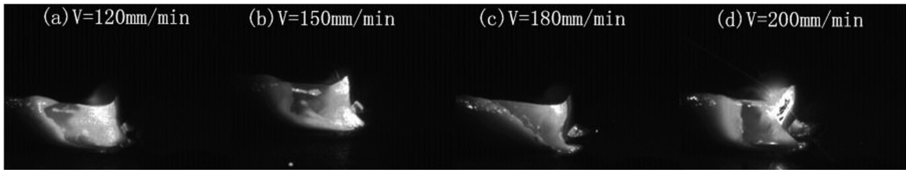


Fig. 8. Transition behavior of liquid metal with variable welding speed

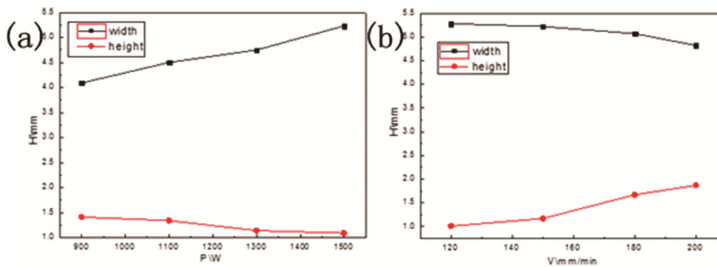


Fig. 9. Effects of welding parameters on the size of deposition layer: (a) effect of laser power on the size of deposition layer; (b) effect of welding speed on the size of deposition layer

Effects of Filler Wire Feeding Speed and Angle on the Characteristics of Deposition Layer

In order to obtain the stable welding process and a well-formed deposition layer, wire feeding speed must be matched well with laser power and welding speed.

On the premise that other things being equal, it is seen in Figs. 10(a)–(b) that the filler wire was fully melted by laser heat and transferred into welding pool while wire feeding speed was less than 150 cm/min, which could be interpreted by the dynamic welding process (I). As the wire feeding speed increased, the heat required to melt filler

wire increased accordingly due to the increased length of wire fed in per unit of time, which resulted in the decreased heat transferred to base metal. As a result, the height of deposition layer increased while the penetration reduced, the appearance and cross-section of deposition layer are shown in Figs. 11(a)–(b). In the condition that wire feeding speed was larger than 150 cm/min, laser heat is not enough to melt filler wire fed in so that unmelted wire inserted into the welding pool. On the one hand, as shown in Figs. 10(c)–(d), unmelted wire was melted fully and formed a deposition layer by the thermal conductivity of molten metal, which was the same as the dynamic welding process (II) discussed in Sect. 3.2. On the other hand, the actual wire feeding speed was smaller than the value set in experiment because of the resistance of welding pool. In consequence, it is seen in Figs. 11(c)–(d) that the height of deposition layer and penetration were almost unchanged.

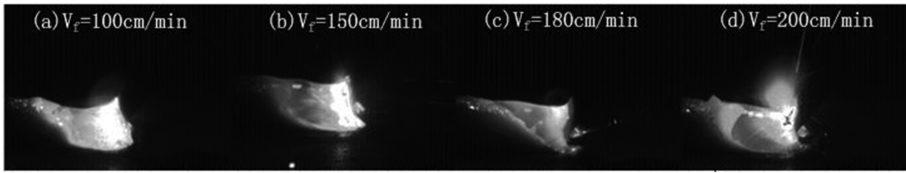


Fig. 10. Transition behavior of liquid metal with variable filler wire feeding rate

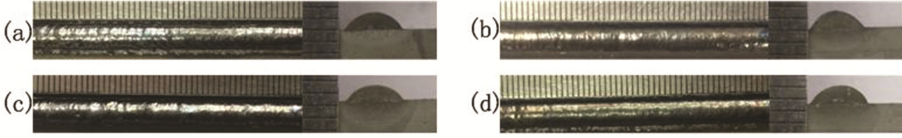


Fig. 11. Appearance and cross-section of deposition layer with variable filler wire feeding rate: (a) $V_f = 100$ cm/min, (b) $V_f = 150$ cm/min, (c) $V_f = 200$ cm/min, (d) $V_f = 250$ cm/min

As shown in Fig. 12, the wire-feeding angle α is the acute angle between the filler wire and the base metal, and the wire feeding speed V_f can be decomposed into the velocity component V_{f_x} that is perpendicular to the direction of laser beam and the velocity component V_{f_y} which is parallel to the direction of laser beam [6]. V_{f_x} affects the absorption rate of laser heat by changing the length of filler wire fed in per second while V_{f_y} decides the impact action of molten metal on welding pool. As shown in Fig. 13(a), filler wire was melted incompletely while the wire feeding angle was small ($\alpha = 30^\circ$) relatively. The reason for this was that laser heat acted on the unit length of filler wire reduced relatively due to the smaller velocity component V_{f_x} in this case. Moreover, the wire extension was stretched, which caused the deteriorated wire directivity and unstable welding process. With the increase of wire feeding angle, it is showed in Figs. 13(b)–(c) that V_{f_x} decreased while V_{f_y} increased, and filler wire fed in was melted fully by the increased laser heat acted on the unit length of filler wire. Finally, molten metal was transferred into welding pool through the liquid bridge transfer behavior, which could

be described clearly by the dynamic welding process (I). The welding process was stable and the deposition layer was well shaped. Figure 13(d) shows that the filler wire was melted incompletely while the wire feeding angle increased continuously ($\alpha = 75^\circ$). The reason for this was that the length of filler wire along the direction of laser beam increased accordingly. Moreover, the distance between the molten metal and welding pool increased due to the oversized wire feeding angle. As a result, the impact action of molten melt on welding pool became stronger accordingly. It is worth noting that stable welding process and well-shaped deposition layer can be obtained while the wire feeding angle varied from 40° to 70° .

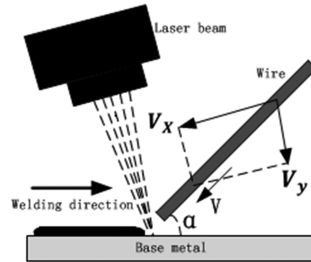


Fig. 12. Schematic diagram of filler wire feeding components

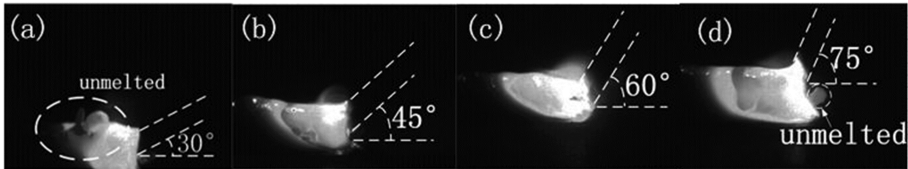


Fig. 13. Transition behavior of liquid metal with variable filler wire feeding angle

4 Conclusions

1. Owing to the different D , the transition behaviors of liquid metal were decomposed into three transition behaviors and the liquid-bridge transition behavior was most stable relatively. Two dynamic welding processes can be used to interpret the laser-wire coupling behavior and transition behavior of liquid metal while the D was zero.
2. The welding process was solid-state heating physical process while laser power was less than 900 W. With the increase of laser power, the size of welding pool and width of deposition layer increased while the height of deposition layer decreased.
3. The welding speed had a great influence on the width of liquid bridge and the solidification rate of molten metal. Molten metal interacted with welding pool sufficiently when welding speed was less than 150 cm/min. With the increase of welding speed, molten metal froze quickly; the width of liquid bridge became narrower; the width of deposition layer and penetration decreased while the height increased.

4. The wire feeding rate could be decomposed into the velocity component V_{f_x} that affected the absorption rate of laser heat and the velocity component V_{f_y} that decided the impact action of molten metal on welding pool. With the increase of wire feeding angle, V_{f_x} decreased while V_{f_y} increased. The stable welding process and well-shaped deposition layer can be obtained while the wire feeding angle varied from 40° to 70° .

Acknowledgements. The results presented in the paper were supported through the National Natural Science Foundation of China (51675256).

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Measurement of the Dynamic and Liquid Weld Pool Under Glaring Arc Light with Femtometre Accuracy

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Abstract. Accurate measurement of the 3D shape of the dynamic weld pool is of great importance for on-line welding process control and off-line welding phenomenon study. However, it remains challenging due to the following reasons. Firstly, the weld pool is dynamic and liquid with extremely high temperature, which requires a nondestructive single-shot measurement technique. Secondly, the specular surface and the ambient strong arc light prevent direct imaging by cameras. Here, we present a structured light technique that yields closed form solutions with femtometre accuracy to measure the dynamic shape of the weld pool produced by gas tungsten arc welding (GTAW). This technique makes use of the band-pass filter and the high penetrability of lasers to overcome the glaring arc light. The sampling points on the weld pool surface are measured by computing the intersections of the projected laser rays and the corresponding reflected laser rays analytically. A conformal mapping transforms the physical world into the virtual world to make the measurement free of optics aberrations. As a result, the achieved measurement accuracy is up to 10^{-13} mm, which is significantly superior to state of art methods.

Keywords: Measurement · Structured light · Conformal mapping · Single shot · Weld pool

1 Introduction

Three-dimensional surface measurement, monitoring and imaging techniques [1–14] are very important in many applications such as biological study, material examination and industrial manufacturing. Based on the surfaces that these techniques are suitable for measuring, these techniques could be divided into two categories: techniques of measuring the specular surfaces [1–5] and techniques of measuring the diffusive surfaces [8–14]. For the specular surface measurement, the reported accuracy includes 0.04 mm [2], 0.22 μm [3] and 0.018 mm [5]. For the diffusive surfaces, the reported accuracy is 12.49 nm [12] for tiny micrometer region, 7 nm [13] and 5 nm [14] for large distance. The one-shot-projection method [5] measures the sampled surface point with exact analytical solution and this method could achieve zero error accuracy in theory. Unfortunately, the aberrations [15–17] introduced by the projector and the cameras decrease the

measurement accuracy dramatically. In addition, the geometry of light propagation in the air is not linear [18, 19], which could affect the measurement accuracy further.

In [5], we have proposed a one-shot method to measure the specular surface. In this paper, we want to increase the measurement accuracy of the proposed method in [5] during measuring the specular weld pool of the GTAW process. To remove the aberrations during measuring the specular weld pool, we present a conformal mapping method in this paper. A conformal mapping $w = f(z)$ is used to connect the physical z -space and the virtual w -space. The measurement is conducted in the virtual space where the light travels linearly and free of aberrations that are introduced by the optics. During practical implementations, it is difficult to calculate the mapping between the physical space and the virtual space. Here, we propose a pattern registration method to map the physical space and the virtual space. In the virtual space, the projected pattern is designed as a set of laser dots and adjacent dots have equal distances along both the row and column directions. In the physical space, the projected laser rays are intercepted by a horizontal diffusive plane during calibration and yield an interception pattern. To find the conformal mapping between the designed pattern and the captured interception pattern, we model the projected rays based on the designed pattern in the virtual space and use an interception plane $P(a, b, c)$ to generate a virtual interception pattern. An affine transformation A is used to map the virtual interception pattern to the captured interception pattern in the physical space. During the experiments, measurement of the specular weld pool with conformal mapping from the virtual space achieved the femto-metre accuracy (1.26×10^{-13} mm) which is superior to all the state of art methods [1–14].

In the proposed measurement system, the surface being measured is not directly viewed by the cameras. Instead, the diffusive planes are viewed after a pattern a laser rays are projected onto and reflected by the specular weld pool surface onto the diffusive planes which are installed with mandatory distances from the specular weld pool surface and glaring arc light. The needed power of the projected laser is thus relatively small despite the extreme arc light illumination and no pulsing for the laser is needed to increase the power. As a result, a continuous low power laser can be used such that the imaging of the reflected laser on the two planes is a continuous process. The dynamic weld pool surface with glaring arc light can thus be imaged continuously. Together with high speed cameras, the analytic solutions for the reflection rays obtained in this paper establish the foundation to measure and calculate dynamic weld pools during different welding processes.

It should be noted that measurement and monitoring [7, 8] of the weld pool is an essential step for the next generation intelligent welding machine to improve the welding quality as monitoring the semiconductor etching [9]. The presented technique in this paper could be a source of reference for the microscopy imaging techniques [9–12] to improve the monitoring or measurement accuracy. With the advent and development of nano-welding [20–22], the presented technique might be able to measure the nano weld pool in the future.

2 Methods

Figure 1 shows the diagram of the welding system with the measurement system set up on it. The front surface of the beam splitter is placed at $y = -115$ mm and the thickness of the beam splitter is 3 mm. Diffusive plane 3 is placed at $y = -30$ mm. Two Dragonfly2 cameras synchronically record images on the two diffusive imaging planes at 60 frames/sec. During the welding process, a 4" schedule 10 stainless steel pipe is used as the workpiece and its outside diameter is 114.3 mm (4.5 in) and the wall thickness is 3.1 mm (0.12 in). The used tungsten, which is fixed on the robotic arm is 2% ceriated and its diameter is $3/32$ ". The tip of the tungsten is shaped into a cone with cone angle 30° and its distance to the work piece is 6 mm. Pure argon is used as the shielding gas and the flow rate is 8.5 L/min (18 ft³/h). The welding power supply operates in the CC (constant current) mode and the current is 70A.

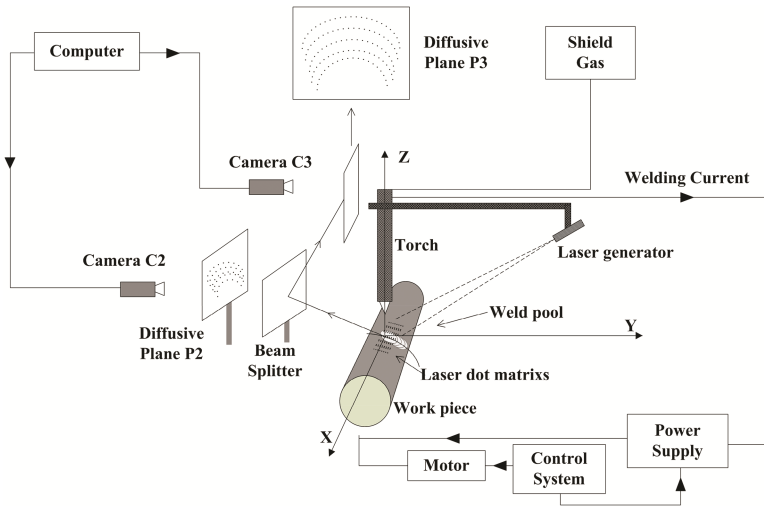


Fig. 1. Diagram of the welding system with the measurement system

The measurement system is illustrated in Fig. 2. Figure 2(a) shows the illustration of how the equations of the projected laser rays are computed. A set of laser rays are projected onto the horizontal reference plane that is placed on a metric lab jacks and produce a set of interception points. The calibrated camera C1 calculates the x and y coordinates of these interception points and the z coordinates of these points are assumed to be $z = 0$. Different sets of interception points are acquired by adjusting the height of the metric lab jacks one millimeter each time vertically. The equation of each projected laser ray is computed by the least square fitting of its interception points with horizontal reference planes at different heights. After all the projected rays are determined, the projection center (x_c, y_c, z_c) is obtained as the point that is nearest to all the projected rays.

$$\begin{bmatrix} V_1^1 & V_2^1 & V_3^1 \\ \vdots & \vdots & \vdots \\ V_1^i & V_2^i & V_3^i \\ \vdots & \vdots & \vdots \\ V_1^N & V_2^N & V_3^N \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \begin{bmatrix} b_1^1 & b_2^1 & b_3^1 \\ \vdots & \vdots & \vdots \\ b_1^i & b_2^i & b_3^i \\ \vdots & \vdots & \vdots \\ b_1^N & b_2^N & b_3^N \end{bmatrix} \quad (1)$$

where $(V_1^i, V_2^i, V_3^i, b_1^i, b_2^i, b_3^i)$ are the differentiating coefficients of the i th laser ray and the total number of the laser ray is N .

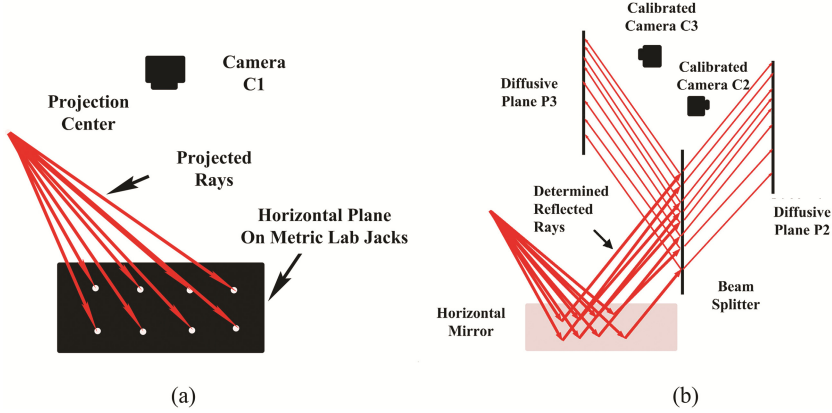


Fig. 2. System calibration: (a) Computation of the projected rays; (b) Computation of equations of the two diffusive planes and their mappings with the corresponding camera image planes

After the projection center is computed, the horizontal reference plane is replaced with a mirror plane and the height of the metric lab jacks is adjusted to be at $z = 0$. The projected rays are reflected by the mirror plane and the reflected rays are determined by the law of reflection. Each reflected ray transmits through a beam splitter and is split into two parts that intercept the diffusive planes P2 and P3 respectively. The symmetry of the projected rays relative to the mirror plane forms a virtual camera that aims at the beam splitter. The equation, π_2 of the diffusive plane P2 is computed by camera C2 and the virtual camera while the equation, π_3 of the diffusive plane P3 is computed by camera C3 and the virtual camera [5]. During on line measurement, the mirror plane is replaced with the specular surface to be measured. The 3D world coordinates of the two interception points of each reflected ray with the two diffusive planes are computed with the equation of the diffusive planes, the Homography between the cameras and the diffusive planes and the camera coordinates of the interception points. The camera coordinate (u_i, v_i) of the i th interception point is transformed to the world coordinate (X_i, Y_i) by Homography. The z coordinate of this point is computed as:

$$Z_i = \frac{\pi(1)X_i + \pi(2)Y_i + \pi(4)}{-\pi(4)} \quad (2)$$

where (X_i, Y_i) is the camera coordinate of the i th point after Homography transformation and π is the equation of plane P2 or P3.

With two points on each reflected ray determined, the ray is determined uniquely with analytic solution. The interception points of the projected pattern on the specular surface are computed as the intersections between the projected rays and the reflected rays. Thus, N sampled points on the specular surface are obtained with analytic solutions. The specular surface could be reconstructed by polynomial interpolation because the specular surface usually changes gradually and smoothly.

The above measurement principle could work perfectly and achieve zero error accuracy in theory. Unfortunately, the optical property of the medium through which light passes affects the geometric paths of the rays and they are not as linear as in vacuum. A conformal mapping [18, 19] $w = f(z)$ is useful in connecting the physical z -space and the virtual w -space. It would be convenient for the measurement to be conducted in the virtual space where the light travels linearly. However, when the aberrations [15–17] are introduced by the optics, it becomes difficult to calculate the mapping between the physical space and the virtual space. Here, we present a pattern registration method to map the physical space and the virtual space.

Both the camera and the projector obey the rule of central projection during imaging. All the rays intersect at the projection center $C(x_c, y_c, z_c)$ and the angle between any two rays can be computed by the following equation.

$$\theta_{ij} = \cos^{-1} \left[\frac{(x_i^p - x_c, y_i^p - y_c, y_i^p - z_c) \cdot (x_j^p - x_c, y_j^p - y_c, y_j^p - z_c)}{|x_i^p - x_c, y_i^p - y_c, y_i^p - z_c| |x_j^p - x_c, y_j^p - y_c, y_j^p - z_c|} \right] \quad (3)$$

where (x_i^p, y_i^p, y_i^p) and (x_j^p, y_j^p, y_j^p) are the i th point and the j th point in the physical space.

In the virtual space, the center point (x_o^v, y_o^v) of the designed 2D pattern is assumed as the center projected ray. The angle, θ_i between the center ray and the i th ray is fixed and is computed by the following equation.

$$\theta_i = \tan^{-1} \frac{d_i}{D} \quad (4)$$

where d_i denotes the distance between the center point and the i th point and D denotes the distance between the projection center and the interception plane that is vertical to the center ray. After d_i and D are determined by Eq. (3), we model the laser rays with points of the designed pattern and the projection center (x_o^v, y_o^v, D) in the virtual space. The modeled rays are formulated as:

$$\frac{X^v - x_o^v}{X_i^v - x_o^v} = \frac{Y^v - y_o^v}{Y_i^v - y_o^v} = \frac{Z^v - D}{Z_i^v - D} = t_i^v \quad (5)$$

where (X_i^v, Y_i^v, Z_i^v) is the i th point of the designed pattern in the virtual space.

We then use the plane $P(ax + by + cz = 1)$ to intercept the modeled rays and compute the distances between the center point and other points on the interception pattern.

$$d_i^v = \sqrt{(X_i^v - X_o^v)^2 + (Y_i^v - Y_o^v)^2 + (Z_i^v - Z_o^v)^2} \quad (6)$$

where (X_o^v, Y_o^v, Z_o^v) is the center point of the interception pattern in the virtual space.

For the pattern in the physical space, we compute the distances between the center point and the same set of points.

$$d_i^p = \sqrt{(x_i^p - x_o^p)^2 + (y_i^p - y_o^p)^2 + (z_i^p - z_o^p)^2} \quad (7)$$

where (x_o^p, y_o^p, z_o^p) is the center point of the pattern in the physical space.

Find the optimal interception plane $P(ax + by + cz = 1)$ that makes Δd minimum.

$$\bar{P} = \arg \min_P \sum |d_i^m - d_i^p| \quad (8)$$

Instead of replacing the point (x_i^p, y_i^p, z_i^p) in the physical space with the point (X_i^v, Y_i^v, Z_i^v) in the virtual space directly, we need to transform (X_i^v, Y_i^v, Z_i^v) from the virtual space into the physical space by an affine matrix A .

$$\begin{bmatrix} x_i^v \\ y_i^v \\ z_i^v \\ 1 \end{bmatrix} = \omega \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} X_i^v \\ Y_i^v \\ Z_i^v \\ 1 \end{bmatrix} = \omega A \begin{bmatrix} X_i^v \\ Y_i^v \\ Z_i^v \\ 1 \end{bmatrix} \quad (9)$$

where (x_i^v, y_i^v, z_i^v) is the mapping point from the virtual space to the physical space. The affine matrix A is computed as:

$$\bar{A} = \arg \min_A d_r \quad (10)$$

$$d_r = \sum_{i=1}^N \sqrt{(x_i^v - x_i^p)^2 + (y_i^v - y_i^p)^2 + (z_i^v - z_i^p)^2} \quad (11)$$

where ω is a constant and N denotes the total number of points in the registered pattern.

The points $(x_i^v, y_i^v, z_i^v); i = 1, \dots, N$ are free of optics aberrations and used for system calibration⁵ and on line measurement of the weld pool.

3 Results and Discussion

A flat mirror is reconstructed by the measurement system and the reconstructed points versus the mapping points from the virtual space are shown in Fig. 3, where the blue circles denote the mapping points and the red crosses denote the reconstructed points. The average reconstruction error is 3.4681×10^{-14} mm in x coordinate, 6.6771×10^{-14} mm in y coordinate and 2.4653×10^{-14} mm in z coordinate. The average reconstruction error between the reconstructed points and the modeled points in the

Euclean space is defined as the sum of the reconstruction error in three dimensions and it is 1.26×10^{-13} mm, which is consistent to the simulation results with MATLAB5. As can be seen, the measurement accuracy of the proposed method could achieve is up to 10^{-13} mm in the practical applications. The reason why the practical system could not achieve the zero error as the MATLAB simulation does is that none of the practically used hardware is perfect. During measurement of the dynamic and liquid weld pool, the accuracy might be reduced further because of additional arc light effect and welding movement/vibration. However, the potential accuracy of the proposed method in measuring the weld pool is femtometer.

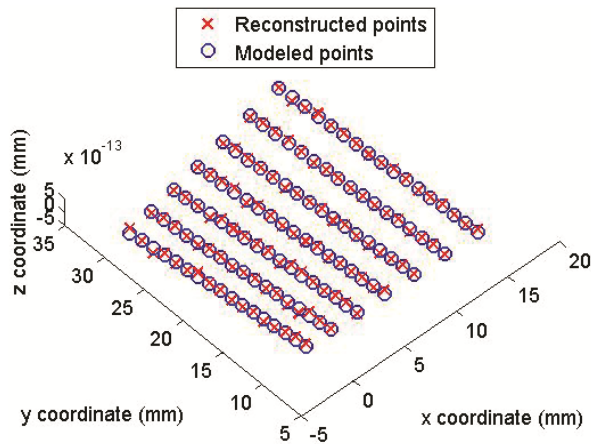


Fig. 3. Computation of the reconstruction accuracy with a flat mirror

To measure the weld pool on line, the challenges include: (1) The arc light radiation is strong and its power is much greater than that of a possible illumination laser; (2) Two diffusive planes are needed and must be placed with a distance. If the used laser is not “focusless”, the focus brings an additional issue for imaging at two diffusive planes at different distances. To overcome the first issue, a spectral band-pass filter [23] is used to decrease the effect of arc light and diffusive planes P2 and P3 are placed with a sufficient distance such that the arc light intensity decays significantly when reaching the diffusive planes P2 and P3. To overcome the second issue, we used the “focusless” (Pico Laser) projector [24].

Weld pools at different times during the gas tungsten arc welding under glaring arc light are measured on line and the reconstructed weld pools at different times are shown in Fig. 4(a) and (b). As can be seen, the change of the shape of the weld pool during welding is vividly presented. These results could be used for study of the welding phenomenon or used for the feedback control of welding processes. The reconstructed weld pool in this paper is from the GTAW process that is relatively stage compared to gas metal arc welding (GMAW) process. The weld pool of the GMAW process is much more complicated and unstable compared to that of the GTAW. Consequently, it might be difficult for the proposed method to achieve similar high accuracy in measuring

GMAW's weld pool. In addition, the projected laser dot pattern should be replaced with line pattern because of the disturbance of the filler metal.

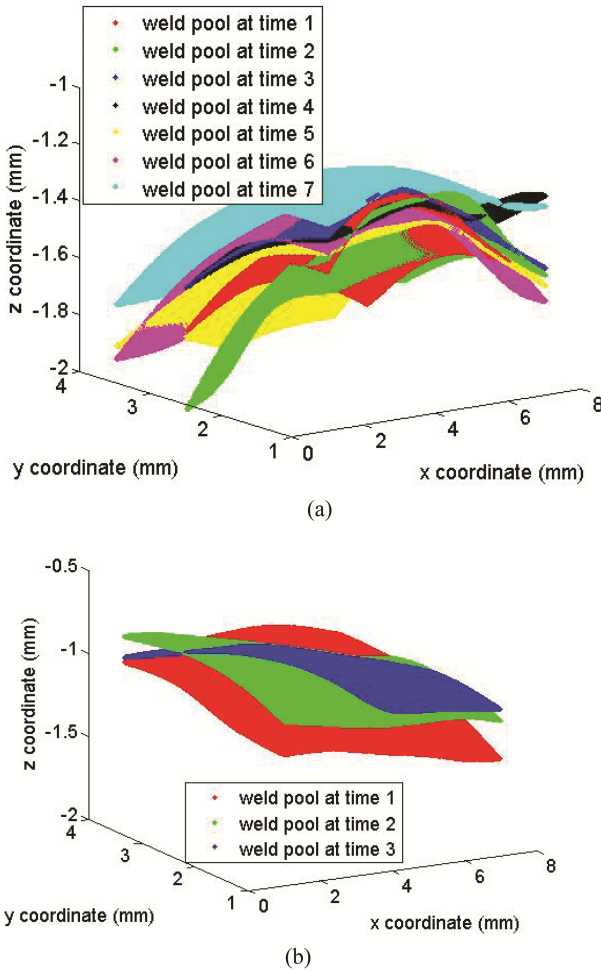


Fig. 4. Reconstructed weld pools at different times: (a) weld pool at one specific location on the steel pipe; (b) weld pool at another location on the steel pipe

4 Conclusion

A technique for measurement of the dynamic and liquid weld pool with femtometre accuracy is presented in this paper. This technique could measure the specular weld pool under glaring arc light significantly more accurately than state of art methods, which is important for the study and improvement of welding processes.

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Study on Microstructure and Mechanical Properties of Ti6Al4V Titanium Alloy Joint with Ultrasonic Consolidation

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Abstract. Lap joint test of the Ti6Al4V titanium alloy with 0.3 mm thickness was conducted by ultrasonic consolidation. The effects of different consolidation time on welded joint microstructure and mechanical properties were studied by optical microscopy(OM), energy dispersive spectrometer (EDS), universal testing machine and other analytical methods. The results showed that the; Mechanical embedment which occurred at the primary stages of ultrasonic consolidation would disappear with the consolidation time increased; dislocation diffusion is the main diffusion way of interfacial atoms, the diffusion of gap and vacancy are less affected. The influence of pretreatment of the oxide film on the tensile shear strength reduced with the increase of welding time. The maximum shear force of the joint is 1940 N, the interface hardness reaches the maximum value when the welding pressure is 0.5 MPa and the welding time is 125 ms.

Keywords: Ultrasonic consolidation · Ti6Al4V titanium alloy · Microstructure and mechanical properties · Consolidation time

1 Introduction

Rapid Prototyping (RP), as a layer stacking technology, integrates the latest achievements in the field of modern CNC technology, CAD/CAM technology, conventional processing technology and material science, which can turn design ideas into the prototype of a certain structure and specific function automatically and quickly or manufacture parts directly [1–3]. Because of its high specific strength, good corrosion resistance and high heat resistance, titanium alloys have been paid more and more attention by the industry, especially in the aerospace and automobile industry [4–8]. Such as the structure of titanium alloy Ti₆Al₄V has been widely used in aircraft, missiles, and has been transferred from the secondary structure to the main structural parts. At present, the mainly been used for rapid prototyping technology of titanium alloy are selective laser sintering technology and selective electron beam sintering technology [9–11]. However, the traditional technology of the laser cladding and the electron beam sintering are easy to

cause metal loss due to the high temperature in the forming process, and the larger residual stress formed during the connection process can easily change the size of the structural parts.

Ultrasonic consolidation technology (UC), as a new type and considered to be very promising rapid prototyping technology, combines ultrasonic welding and CNC milling technology to manufacture three-dimensional metal parts [12–15]. It is layer by layer processing, the ultrasonic welding makes the metallurgical bonding between the layers, the workpiece is machined by plane milling according to the AutoCAD data after the connection of each layer, and then stacked to connect the next layer until the completion of parts and mould manufacturing. This new technology achieves the goals of high precision, high efficiency and low cost. Compared with other rapid manufacturing technologies, ultrasonic consolidation does not require metal melting (only 25%–50% of the melting point) to achieve the purpose of connection [16–18]. This technique uses ultrasonic vibration to generate interfacial friction and to achieve metallurgical connections under pressure (<50 MPa), which avoids liquid solid phase transition, residual stress generation, dimensional change and metallurgical incompatibility, moreover, it is possible to realize the connection between many difficult welding metals. The use of the ultrasonic consolidation technology can produce titanium alloy structural parts and repair the damaged titanium parts simultaneously, which has a broad application prospects.

2 Experiment

The Ti₆Al₄V (TC4) titanium alloy was studied in this experiment, which thickness was 0.3 mm and tensile strength was 902 MPa. The alloy phase is $\alpha + \beta$ type titanium alloy and the chemical composition is shown in Table 1. The CX-20S ultrasonic metal seam welder was used in the experiment, the maximum output power of the device was 3600 W and vibration frequency was 20 KHz, which produced by Foshan Chuxin Electromechanical Co., Ltd.

Table 1. Chemical composition of experimental material (wt%)

Al	V	Fe	O	Si	C	N	H	Ti
5.5-6.5	3.5-4.5	0.3	0.02	0.15	0.10	0.05	0.05	other

In this work, lap joint of welding joint was adopted. In order to evaluate the effect of consolidation time on the forming performance of welded joints, the process parameters of ultrasonic consolidation were: ultrasonic amplitude was 35 μ m, cylinder pressure was 0.5 MPa and welding time was 75 ms–135 ms. Before welding, the 320 mesh sandpaper was used to polish the surface oxide of the workpiece, and the acetone was used to remove the oil at 15 mm near the lap joint. The microstructure of the welded joint will be changed with the combined action of high frequency vibration, surface effect and volume effect, so based on this change to evaluate the influence degree of consolidation time. The principle diagram of ultrasonic consolidation was shown in Fig. 1. The cross section of the welded joint after pre grinding, polished and corroded by etchant (HF: HNO₃: glycerol = 1: 1: 3) was used to observe the metallographic

structure to evaluate the weld forming quality. The weakening of the cross sectional interface and the situation of interface connection were analyzed by SEM. The interfacial diffusion mechanism of titanium alloy and pure nickel was analyzed by EDS. The mechanical properties of joints were evaluated by Micro-Vickers hardness test and tensile test. The Micro-Vickers hardness test was performed at room temperature, the load was 25 gf and the holding time was 15 s. The axial load was applied to the workpiece and the loading speed was 3 mm/min in the tensile test.

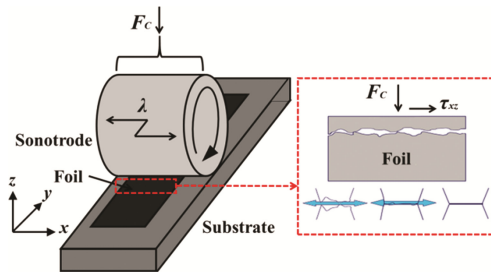


Fig. 1. Diagram of the ultrasonic consolidation principle

3 Results and Discussion

3.1 Microstructure Analysis

The interfacial microstructure of the welding joint of TC4 titanium alloy without surface pretreatment in the condition of the welding pressure was 0.5 MPa and the welding time was 85 ms as shown in Fig. 2. It can be seen from Fig. 2 that the contact interface produces a serrated mechanical embedment and the consolidation interface is visible, which due to the rough surface texture structure of the ultrasonic probe and anvil produce the compressive stress on the workpiece. The metal atoms in the weld zone were activated with the combined effect of the high-frequency friction [19], ultrasonic softening and metal matrix plastic flow in the contact interface during the consolidated process, which is conducive to the formation of metal bonds. Widmanstatten structure, basket-weave microstructure, duplex microstructure and equiaxed α microstructure are the

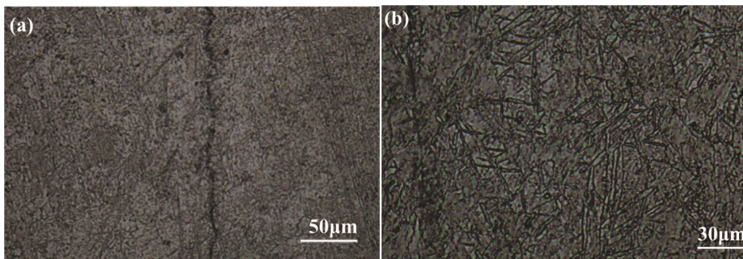


Fig. 2. Microstructure of titanium alloy ultrasonic consolidation joint

common microstructures of TC4 titanium alloy. After welding where near the seam area is the basket-weave microstructure of good comprehensive mechanical properties.

3.2 Effect of Welding Time on Interface Forming

Figure 3 shows the cross section of the welding joint of TC4 titanium alloy without surface pretreatment in the condition of the welding pressure was 0.5 MPa and the welding time was 115 ms, 125 ms. From Fig. 3, the not actual connection area of the joint was reduced and the degree of weakening of cross section was increased along with the welding time. This due to the interface does not produce sufficient plastic deformation in the short time, the actual connection area and the degree of weakening of the cross section increases with the welding time increased.

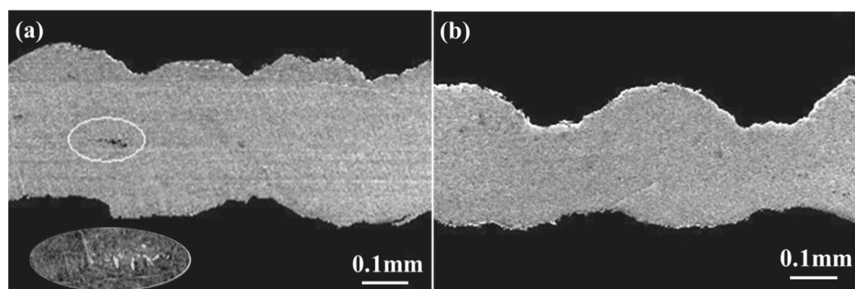


Fig. 3. The cross section of the welded joint under different welding times (a) welding time 115 ms (b) welding time 125 ms

3.3 Effect of Pretreatment on Ultrasonic Consolidation Time

After mechanical testing, the tensile strength of joints (welding pressure was 0.5 MPa, welding time was 105 ms) with and without the oxide film pretreatment was 106.9 MPa and 97.5 MPa respectively, the tensile strength of the joint was increased about 10% after surface pretreatment. The SEM image of joints was shown in Fig. 4. Compared Fig. 4(a) with (b), the actual connection area of the weld was increases and the weld was closer connected that remove the oxide film at the same welding parameters, so the mechanical properties of the joint were improved. In addition it was consistent with the effect of welding time on 125 ms, which indicated that the pretreatment of contact interface can reduce the welding time. The weld metal oxides in Fig. 4 (a) were detected by EDS, as shown in Fig. 5. The results reveal that the metal oxides are Ti oxides and trace amounts of Al_2O_3 where the Al content was 3.07%, which weakened the strength of the joint. Ultrasonic consolidation technology has the advantage of breaking and dispersing the oxide. With increasing of the welding time, the oxide was dispersed in the matrix metal during the plastic flow of the workpiece, but at the same time, it is possible to produce more defects such as crack, adhesion and burn-through. The experiment showed that titanium alloy ultrasonic consolidation was not sensitive to pretreatment, but pretreatment can reduce the welding time.

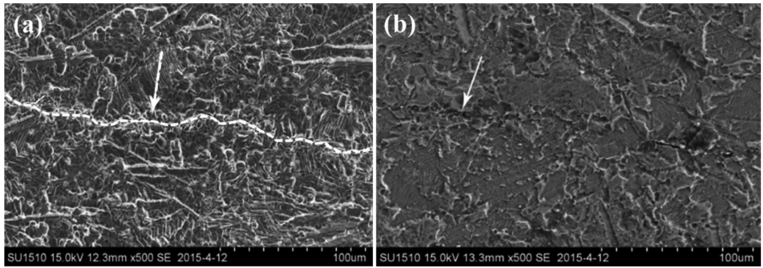


Fig. 4. SEM image of titanium alloy ultrasonic consolidation joint (a) not pretreated (b) pretreatment

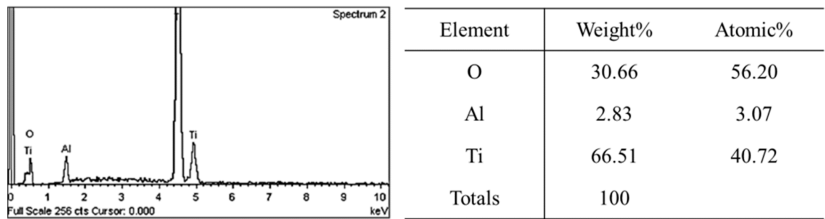


Fig. 5. EDS results of joint interface metal oxide

3.4 Effect of Welding Time on Tensile Shear Force and Microhardness

Figure 6 showed the effect of different welding time on the tensile shear force of the joints with the welding pressure was 0.5 MPa. It can be seen from the Fig. 6 that the tensile shear force of titanium alloy welded joints was increasing along with the welding time. When the welding time was 125 ms, the welded joint reached the maximum shear force of 1940 N, but the shear force was decreased when the welding time continues to increase. This was because with the increase of welding time, the ultrasonic consolidation thermal softening and surface effect made the welded joint soften fully, and the

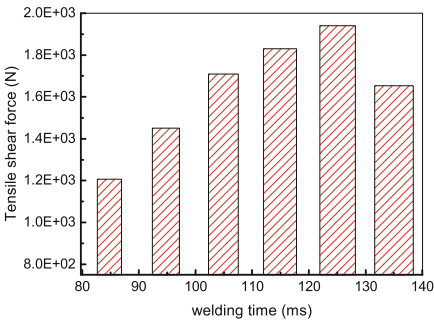


Fig. 6. Tensile shear force of the welded joints at different welding time

action of continuous compressive stress made the ultrasonic probe furrow embedded in the workpiece, which weakened the cross-sectional area and lead to strength decreased.

Figure 7 shows the effects of different welding time on the Micro-hardness of the joint with the welding pressure was 0.5 MPa. It is shown from Fig. 5 that the Micro-hardness increased along with the welding time, the hardness at the connection interface reached the maximum value and higher than the hardness of the base metal. Because the plastic flow of metal matrix was sufficient, and the density of lattice dislocation increased along with the welding time, so that the resisting power of plastic deformation was increased. The plastic flow of the weld joint is the intensest during the consolidation process, therefore the Micro-hardness of the weld is the highest.

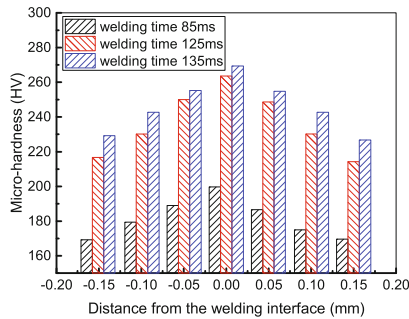


Fig. 7. Micro-hardness of the welded joints

The embedding of the ultrasonic probe during the consolidation process weakened the effective cross-sectional area of the welded joint severely and reduced the joint strength. So how to soften the titanium alloy foil is the key issue. Considering that titanium alloy has good resistance welding performance, the current can be applied to the workpiece during preloading process of ultrasonic consolidation as shown in Fig. 8. This reduces consolidation energy consumption and increases the effective cross-sectional area possible.

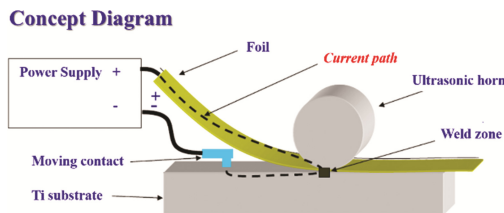


Fig. 8. Ultrasonic Consolidation of titanium alloy under assisted current

3.5 Analysis of Interface Atomic Diffusion Mechanism

The titanium alloy and nickel were carried to ultrasonic consolidation at the welding pressure was 0.5 MPa and welding time was 115 ms, and the interface diffusion

mechanism was analyzed. Figure 9 showed the EDS line scan of the joint interface area, which indicated that the interface appeared obvious phenomenon of atomic diffusion and the width of the diffusion region reached 3 μm , so that ultrasonic consolidation can achieve interdiffusion between elements within 200 ms of welding time. The main reasons are as follows:

- (1) The interface area of the workpiece created a dramatic plastic flow with the combined action of the thermal and ultrasonic softening effect, which will be led to the increase of gap, vacancy and dislocation density in the joint area. The diffusion of metals is caused by internal structural defects such as gaps, vacancies and dislocations.
- (2) The interface to achieve mechanical embedment in the process of preloading of ultrasonic consolidation, which increased the contact area of the interface and was favorable for the interdiffusion of elements.
- (3) During the process of ultrasonic consolidation, the friction heat and deformation energy can promote the temperature rise and increase the atomic diffusion coefficient, which accelerates the diffusion between the elements.

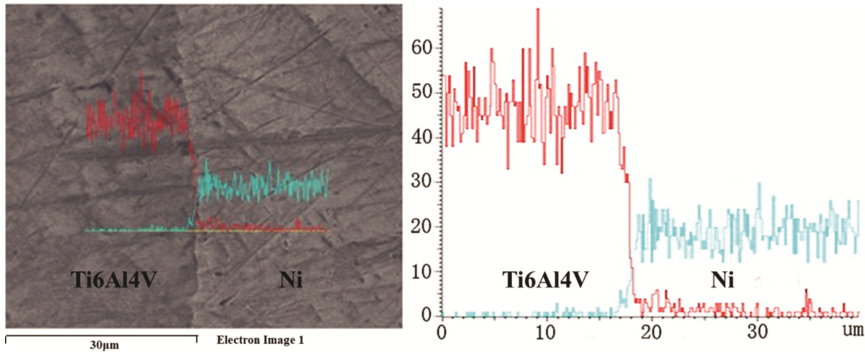


Fig. 9. EDS graph of Ti6Al4V-Ni welded joint

Krzanowski J [20] showed that the interface atomic diffusion distance was 1 $\text{\AA}$ through calculating the diffusion of atoms in the ultrasonic welded joint of aluminum-copper wire, the diffusive distance was less than the diameter of aluminum atoms and suggested that the elements can not achieve diffusion when the welding time was under 60 ms. In this paper, the results of EDS analysis of titanium alloy-nickel welded joint showed that the interface atoms can realize the interdiffusion of elements in the welding time less than 200 ms and formed a transition layer of 3 μm . The diffusion calculation was carried out by Krzanowski J's theory of calculating the diffusion distance in this work.

$$D = D_0 \exp \left(-\frac{Q}{RT} \right) \quad (1)$$

where D is diffusion coefficient (m^2/s); T absolute temperature; R is gas constant ($8.413 \text{ J}/(\text{mol} \cdot \text{K})$); Q is diffusion activation energy ($283000 \text{ J}/\text{mol}$); D_0 is diffusion constant ($4.4 \times 10^{-5} \text{ m}^2/\text{s}$).

The diffusion coefficient of nickel atoms is $D = 9.475 \times 10^{-17} \text{ m}^2/\text{s}$ at temperatures below 1000°C . The Fick's law was adopted to calculate the diffusion distance, however, due to the lack of known conditions, the Einstein empirical formula was used in this work.

$$X = \sqrt{2Dt} \quad (2)$$

where X is diffusion distance (m); t is diffusion time (s).

When the welding time is 125 ms, the diffusion distance is 4.867 nm. The results are in the same order of magnitude as those obtained by E. Krzanowski et al., but the results of the test are less than experimental result, which is mainly due to:

- (1) Diffusion of the gap and the vacancy was only taken into account in this calculation, ignored the defects such as dislocations, grain boundaries and free surfaces. The atomic transition frequencies are higher than those inside the lattice in these regions, which is the high diffusion channel of atoms. Simultaneously, the diffusion activation energy of atoms along the dislocation diffusion does not exceed half of the lattice diffusion, which accelerate the diffusion rate.
- (2) In the gap and vacancy diffusion, the interstitial atoms was adsorbed on the defect to form the Cottrell atmosphere, these atoms need more activation energy to break away from the defects, so the diffusion rate was slowed down.

The results indicated that the dislocation diffusion is the mainly diffusion way during ultrasonic consolidation and the diffusion of the gap and the vacancy have little effect.

4 Conclusion

In this paper, the microstructure and mechanical properties of ultrasonic consolidation joints of titanium alloy at different welding time were studied, and the effect of interface pretreatment on ultrasonic consolidation time and the mechanism of atomic diffusion in the interface were analyzed. The conclusions are as follows:

- (1) The weldment of TC4 titanium alloy without surface pretreatment produced an irregular mechanical embedment at the contact interface of ultrasonic consolidation joint with the welding was 0.5 MPa and welding time was 85 ms, and the welding where near the seam area was the basket-weave microstructure of good comprehensive mechanical properties.
- (2) With the increase of welding time, the not actual connection area of workpiece was reduced, and the microhardness and the weakening degree of cross section was increased. When the welding time was 125 ms, the welding joint achieved the maximum shear force of 1940 N and the hardness reached the maximum value at the connection interface, which was higher than the hardness of the base metal. During the preloading process of ultrasonic consolidation, the current softening of

the base material during the preloading process of ultrasonic consolidation can effectively reduce the degree of cross section weakening.

- (3) Ultrasonic consolidation of titanium alloy was not sensitive to pretreatment, but the pretreatment can reduce welding time.
- (4) The dislocation diffusion was the mainly diffusion way during ultrasonic consolidation, and the diffusion of the gap and the vacancy have little effect.

Acknowledgement. The authors gratefully acknowledge the National Natural Science Foundation of China (51365039) for the financial support of this research work.

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Finite Element Analysis of GTAW Welding Arc Based on Rotational Arc Sensor

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Abstract. A three-dimensional mathematical model of rotational gas tungsten arc welding (GTAW) was established according to magnetohydrodynamics (MHD) theory, the welding arc of conventional GTAW and rotational GTAW were simulated by FLUENT to get the arc plasma's temperature field, velocity field and the static pressure field. The results show that the centrifugal force has little influence on the arc plasma because it's far weaker than the electromagnetic force, and the arc shape as well as physical quantity distribution of these two kinds of welding methods are essentially consistent.

Keywords: Rotational GTAW · Welding arc · FLUENT · Numerical simulation

1 Introduction

GTAW process has been widely used in industrial welding applications [1–6]. Rotational GTAW welding is a promising welding method. This method not only has the advantages of conventional GTAW welding but also the rotational arc sensor that can realize seam tracking and welding automation. Rotational arc sensor can avoid the effects of arc light, high temperature and high magnetic field. The sensor and arc are unified whole, so the sensor has good real-time performance and tracking effect as the arc voltage is sensing signal. Rotational arc sensor has compact structure and low cost, mainly apply to arc welding robot and cross slider. Stable arc can obtain good surface appearance and excellent internal quality. Rotational GTAW welding plasma is subjected to centrifugal force which may affect the arc plasma basic phenomenon. Because of the particularity of rotational GTAW welding, stable arc is the premise of seam tracking and welding automation. So, it is important and useful to understand the basic phenomena in arc plasma. But, it is very difficult to clarify these phenomena experimentally [4, 7, 8]. Due to the rapid development of computer technology, it promoted a deeper understanding of arc plasma by Numerical Simulation. Many studies pay attention to numerical simulation of conventional GTAW welding arc [9–13], but not to rotational GTAW welding arc. In order to provide more theory evidence of application in practical production by using rotational arc sensor, this paper did some research about rotational GTAW with the help of commercial CFD software FLUENT.

Mathematical model been established based on MHD theory and physical prototype. Due to the large temperature variation range in arc zone, and the thermal physical parameters of Ar present highly nonlinear variation in different temperature. Those parameters have great influence on current density distribution, electric potential distribution, temperature field distribution, arc formation and stability. In addition, the current continuity equation is added by UDS (User Define Scalar), and the current density equation is obtained. Using the redevelopment technology of FLUENT based on UDF to connect the physical parameters of argon at high temperature to the mathematical model. Conventional GTAW welding arc and rotational GTAW welding arc have been simulated separately, and the comparative analysis has also been made. Arc temperature field, velocity field and plasma pressure field of rotational GTAW welding not only have great influence on welding process, melting efficiency and melting pool behavior but also can provide basic data of investigation on arc stability. A high-speed camera platform was built, and the arc shapes of those two kinds of welding methods are compared. Because the other physical field of arc plasma is difficult to experimentally verified, and arc shape have close relationship with arc temperature field [14]. So, only the experiment to verify whether rotational arc will have great influence on arc shape been experimentalized.

2 Establishing the Physical Model

GTAW welding arc system which is based on rotational arc sensor (0–40 Hz) was taken as physical prototype to establish mathematical model. The physical prototype is shown in Fig. 1. Tungsten electrode sticks out from ceramic nozzle, and doesn't rotate itself. When tungsten electrode revolves around central axis, GTAW welding arc will be driven to revolve too. Argon was used as protective atmosphere. Because the asymmetry and the centrifugal force during Tungsten electrode's revolution process, it is necessary to use three-dimensional mathematical model to simplify the physical prototype. Mathematical model is shown in Fig. 2.

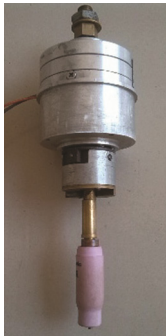


Fig. 1. Physical prototype of rotational arc sensor

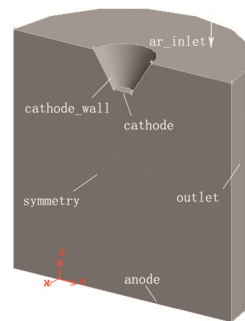


Fig. 2. Simplified mathematical model

This model's cathode is tungsten and anode is workpiece. Tungsten's diameter is 3.2 mm, cone angle is 60° , and it revolves around Z axis. The distance between tungsten's axis and Z axis is 2 mm, which means revolving radius is 2 mm. The distance between the end of the tungsten and anode, is 10 mm that means arc length is 10 mm.

3 Governing Equations

Several basic hypothesis have been made during calculation process: (1) arc plasma is incompressible continuous fluid; (2) arc plasma is in local thermal equilibrium (LTE) state; (3) arc plasma is optically thin, and it's flow state is laminar flow; (4) protective atmosphere is pure argon, and it's physical parameters change with temperature; (5) the effects of the electrode sheath can be ignored.

Based on the above hypotheses, incompressible fluid's Navier Stokes equations under three-dimensional Cartesian coordinate system and Maxwell's electromagnetic equations were chosen as the basic equations of arc simulation.

Fluid's continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

X, Y, Z direction's momentum conservation equation:

$$\rho(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z}) = \frac{\partial}{\partial x}(\mu \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(\mu \frac{\partial u}{\partial y}) + \frac{\partial}{\partial z}(\mu \frac{\partial u}{\partial z}) - \frac{\partial P}{\partial x} + S_x \quad (2)$$

$$\rho(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z}) = \frac{\partial}{\partial x}(\mu \frac{\partial v}{\partial x}) + \frac{\partial}{\partial y}(\mu \frac{\partial v}{\partial y}) + \frac{\partial}{\partial z}(\mu \frac{\partial v}{\partial z}) - \frac{\partial P}{\partial y} + S_y \quad (3)$$

$$\rho(u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z}) = \frac{\partial}{\partial x}(\mu \frac{\partial w}{\partial x}) + \frac{\partial}{\partial y}(\mu \frac{\partial w}{\partial y}) + \frac{\partial}{\partial z}(\mu \frac{\partial w}{\partial z}) - \frac{\partial P}{\partial z} + S_z \quad (4)$$

Energy conservation equation:

$$\rho C_p(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z}) = \frac{\partial}{\partial x}(k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k \frac{\partial T}{\partial z}) + S_H \quad (5)$$

$$S_H = \frac{j_x^2 + j_y^2 + j_z^2}{\sigma} + \frac{5k_B}{2e}(j_x \frac{\partial T}{\partial x} + j_y \frac{\partial T}{\partial y} + j_z \frac{\partial T}{\partial z}) - S_R \quad (6)$$

where ρ is fluid density; u , v , w are the velocity of x , y , z direction respectively; μ is dynamic viscosity coefficient; S_x , S_y , S_z are momentum equation's source terms of x , y , z direction respectively; T , C_p , k are temperature, heat capacity at constant pressure, thermal conductivity respectively; j_x , j_y , j_z are current density of x , y , z direction respectively; σ is electrical conductivity; k_B is the Boltzmann constant; e is electronic power; S_R is radiation heat loss; S_H is the source term of energy equation. The three items on the right of formula 6 represent Joule heat, electron heat and radiation energy loss

respectively. Current density can be calculated by current continuity equation and Ohms law.

Current continuity equation:

$$\frac{\partial}{\partial x}(\sigma \frac{\partial \varphi}{\partial x}) + \frac{\partial}{\partial y}(\sigma \frac{\partial \varphi}{\partial y}) + \frac{\partial}{\partial z}(\sigma \frac{\partial \varphi}{\partial z}) \quad (7)$$

Ohms law:

$$j_x = \sigma \frac{\partial \varphi}{\partial x}, j_y = \sigma \frac{\partial \varphi}{\partial y}, j_z = \sigma \frac{\partial \varphi}{\partial z} \quad (8)$$

where φ is scalar potential; μ_0 is magnetic medium constant; j_x, j_y, j_z represent current density of x, y, z direction respectively.

Magnetic induction intensity can be calculated by introducing magnetic vector potential. The components of x, y, z directions respectively are:

$$B_x = \frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}; B_y = \frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}; B_z = \frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} \quad (9)$$

Momentum equation's source terms are composed of the following equations:

$$S_x = j_y B_z - j_z B_y + F_{lx}; S_y = j_z B_x - j_x B_z + F_{ly}; S_z = j_x B_y - j_y B_x - \rho g \quad (10)$$

where F_{lx}, F_{ly} are the components of centrifugal force on x, y directions, source terms were added by UDF to FLUENT solver [15].

Rotational GTAW welding arc are influenced by centrifugal force, and the formula of centrifugal force is:

$$F_l = m r \omega^2 \quad (11)$$

where m is plasma's mass; r is radius of gyration; ω is rotation frequency. When centrifugal force is loaded as source term, it must firstly be transformed into body component force of x, y directions.

4 Model Construction and Mesh Generation

Based on the above mathematical model, using GAMBIT that is pre-processing software of ANSYS to establish for 3D geometric modeling and generate mesh of the mathematical model. GAMBIT software is simple to operate, flexible and convenient, as well as has a strong ability for mesh generation. The special mesh generation algorithm can directly divide the complex geometrical area into high quality tetrahedron, hexahedron and hybrid grid [16].

Conventional GTAW welding arc and rotational GTAW welding arc share a mathematical model, the difference between two welding process is whether to load centrifugal force source term. In order to improve the mesh quality, those two mesh models

all use good accuracy hexahedral mesh, including wedge mesh in suitable positions. Mesh model is shown in Fig. 3. For the regions with large related physical quantity gradient, self-adaptive mesh refinement functions in FLUENT can be used for local refinement.

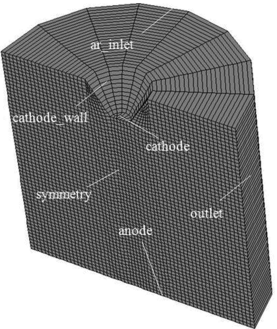


Fig. 3. Mesh model

After modeling and meshing, the boundary type of this model in GAMBIT was set. Among them, cathode_wall, anode and cathode were setup as no slip wall, namely there are no loss of material and energy on these walls. ar_inlet was setup as velocity-inlet boundary condition, outlet was setup as pressure-outlet boundary condition, and symmetry was setup as symmetry plane boundary condition.

5 Setting of the Boundary Conditions

In this paper, boundary conditions were set up according to the actual situation and the previous assumptions. Boundary conditions are shown in Table 1. In Table 1, v_{giv} represents inflow rate of protective gas. Argon thermodynamic parameters, such as density, viscosity, conductivity, specific heat capacity and thermal conductivity in this paper come from the literature [17].

Table 1. Setting of the boundary conditions

Boundary name	Boundary type	V	T	φ	A
ar_inlet	velocity inlet	$v_z = v_{giv}$	1000	$\partial\varphi/\partial n = 0$	$\partial A/\partial n = 0$
cathode_wall	wall	0	1000	$\partial\varphi/\partial n = 0$	$\partial A/\partial n = 0$
cathode	wall	0	3000	$-\sigma \cdot \partial\varphi/\partial z = I/(\pi r^2)(r < 0.5)$	$\partial A/\partial n = 0$
outlet	pressure outlet	$\partial V/\partial n = 0$	1000	$\partial\varphi/\partial n = 0$	0
symmetry	symmetry	$\partial V/\partial x = 0$	$\partial T/\partial x = 0$	$\partial\varphi/\partial x = 0$	$\partial A/\partial n = 0$
anode	wall	0	5000	0	$\partial A/\partial n = 0$

6 Simulation Results and Analysis

After completing the above related settings, the model was introduced into FLUENT to calculate for solution. In this paper, numerical simulation of conventional GTAW welding arc and rotational GTAW welding arc were carried out respectively with welding current 200 A. The welding current polarity is straight polarity direct current. Rotational frequency of rotational GTAW welding arc is 40 Hz, and the direction is counter clockwise. Iterative calculation was carried out based on SIMPLE (semi-implicit method for pressure-linked equations) [18] algorithm in the FLUENT until convergence.

Since the arc plasma can only keep local thermal equilibrium when the temperature is above 10000 K [19], Fig. 4 shows the comparison between experimental and simulation temperature contours in rotational GTAW welding arc above 10000 K. As can be seen from Fig. 4, arc temperature field shows bell shaped, and in the two electrodes temperature gradient is bigger. Furthermore, the highest temperature appears near cathode. Arc temperature reaches the maximum value near cathode. The reason for this phenomenon is that maximum current density in the end of tungsten electrode induced maximum heat production, and tungsten emission electron has a cooling effect on it. So the highest temperature doesn't appear on tungsten electrode. It's difficult to measure arc temperature under high temperature gradient. So, experimental value that has already been made is used for comparing with simulations value, and those two shapes of contour are basically the same. The experiment results (200 A at 10-mm arc length) come from Hsu et al. [20]. Figure 5 shows the distribution map of arc temperature distribution of tungsten electrode axis in two different welding modes. From the diagram, the temperature distribution on the axis of two welding modes is basically same.

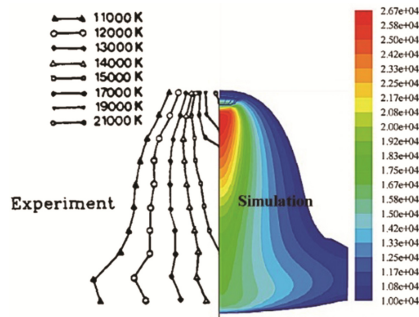


Fig. 4. Comparison between experimental and simulation temperature contours in rotational GTAW welding

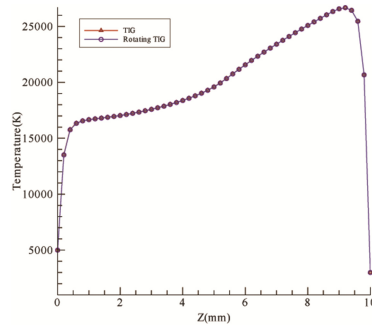


Fig. 5. Arc temperature distribution of tungsten electrode axis

Figure 6 is the velocity field distribution cloud picture of arc plasma in rotational GTAW welding arc. The pressure difference between two electrodes induced plasma fluid force, so the plasma in Fig. 6 flows from cathode to anode at a high speed. The velocity of plasma near cathode is faster, which is due to the larger current density near cathode leads to a larger plasma fluid force and a large force on the plasma of this zone. The velocity of arc plasma reaches maximum under the influence of plasma flow force, and then decreases with the barrier of workpiece. Figure 7 shows the velocity distribution curve of conventional GTAW welding and rotational GTAW welding on the axis of tungsten electrode. The integrated speed of conventional GTAW welding on the axis of tungsten electrode is slightly higher than that of the rotational GTAW welding. The reason is that plasma of rotational GTAW welding is subjected to centrifugal force but the conventional GTAW welding not, so the plasma of rotational GTAW welding tends to be spun off. What's more, the integrated speed of rotational GTAW welding on the tungsten electrode axis is slightly lower, but the velocity fields of those two different welding modes don't have much difference, and can be regarded as the same.

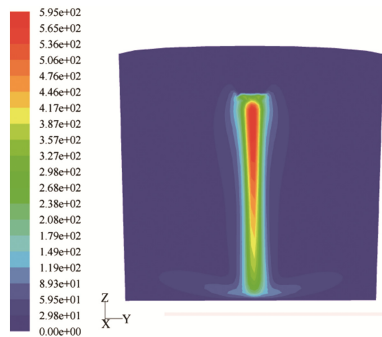


Fig. 6. Velocity field of rotational GTAW welding arc

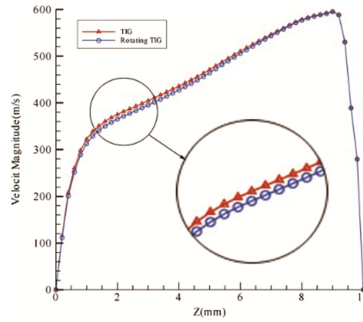


Fig. 7. Velocity distribution of tungsten electrode axis

Figure 8 shows the distribution cloud picture of arc plasma pressure field in rotational GTAW welding. The arc pressure is higher in anode and cathode zones, and decreases with the distance from two electrodes in arc column region. The reason of great pressure in cathode region is that the large gradient of current density in this zone caused the large electromagnetic pinch force. The large pressure in the anode region is mainly caused by the plasma rush to the workpiece at a high velocity. Figure 9 shows distribution curve of arc pressure on the surface of workpiece with conventional GTAW welding and rotational GTAW welding, From the diagram, it can be seen that the distribution curve of two different welding modes are basically in coincidence. Because of plasma velocity on the surface of workpiece decreases with the distance away from the axis ($y = 2 \text{ mm}$) of tungsten electrode, the arc pressure of two different welding modes are all double exponential distribution.

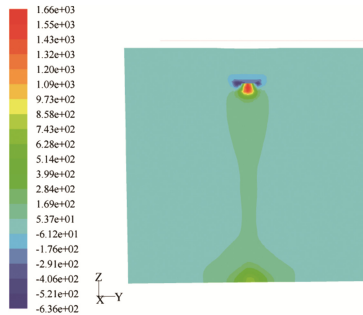


Fig. 8. Pressure field of rotational GTAW welding arc

The arc temperature field, velocity field and plasma pressure field distribution cloud picture of these two different welding modes are compared, it can be seen that the conventional GTAW welding is basically the same with rotational GTAW welding. The reason of this phenomenon is that the centrifugal force is much smaller than the electromagnetic force when rotational frequency is 40 Hz (the maximum frequency of the rotational arc sensor). The highest temperature, the biggest velocity of plasma, the

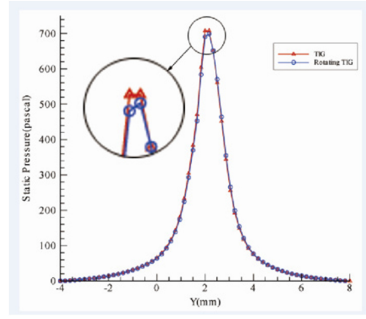


Fig. 9. Pressure distribution of workpiece surface

biggest arc pressure and the gradient of those physical quantity all appears near cathode. It shows that there is a correlation between those three physical quantity.

On the YZ plane of rotational GTAW welding, the centrifugal force distribution from the end of tungsten to workpiece along Y axis is shown in Fig. 10. On this curve, centrifugal force increases with the distance away from the axis of revolution, but the maximum value is only 238 N/m^3 , which can almost be neglected compared with the electromagnetic pinch force (105 N/m^3). It can be concluded that the arc shape and the related physical quantities in rotational GTAW welding within rotational frequency range is basically the same as conventional GTAW welding.

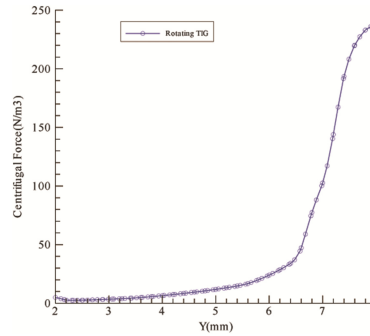


Fig. 10. Centrifugal force distribution along Y axis

7 Experimental Verification

However, it is difficult to monitor arc temperature field, velocity field and plasma pressure field, because GTAW welding arc is an instantaneous physical process at high temperature. The strong arc light also causes interference. There is a close relationship between the arc shape and arc temperature field distribution [14]. So, the arc shape is obtained by high-speed camera system to verify the above conclusions. High-speed camera shooting frame count is 500 frame/s. Conventional GTAW welding arc and

rotational GTAW welding arc which rotational frequency is 16 Hz were photographed respectively. GTAW welding arc shape are showed in Fig. 11. It can be learned from the graphs that both of them are bell shaped, and the simulation results are reliable.

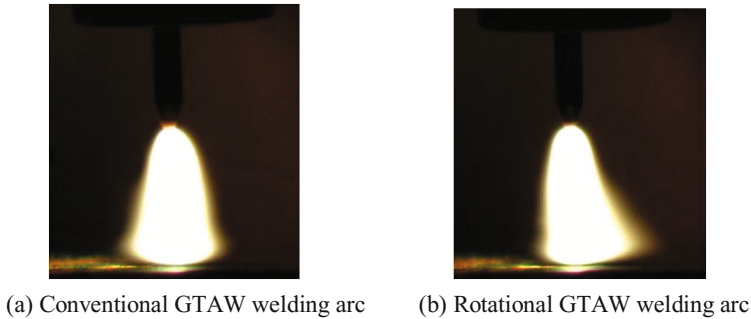


Fig. 11. GTAW welding arc shape

8 Conclusions

- (1) Mathematical model of rotational GTAW welding arc has been established based on MHD theory. Numerical simulation of rotational GTAW welding arc was carried out with the welding current of 200 A and the rotational frequency is 40 Hz. Arc temperature field, velocity field and plasma pressure field distribution cloud picture were obtained.
- (2) In order to compare and analyze, the conventional GTAW welding arc has also been simulated. Arc temperature field, velocity field and plasma pressure field of the two different welding modes are basically the same. The reason of this phenomenon is that centrifugal force is far less than electromagnetic pinch force. So, centrifugal force can almost be neglected.

Acknowledgement. The research is supported by the province science and technology of Jiangxi offend pass item (20142BBE50062). Innovative fund for graduate students of Nanchang University (cx2016075).

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Short Papers and Technical Notes

Analysis of Spreading of the Melt in Diode Laser-TIG Hybrid Cladding Process

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Abstract. A diode laser-TIG hybrid cladding process was proposed in this study to make further improvement on wettability and spreadability of cladding layer. Cladding layers fabricated with different heat sources were wire-cutted to observe their cross section so as to characterize the wettability. The role of TIG arc in this process is analyzed and illustrated in detail through the cladding process recorded by a high-speed camera. The functions of TIG arc in this process are elevating thermal input to reduce surface tension and exerting extra forces on the melt to help it spread out.

Keywords: Cladding · Wetting · Contact angle · TIG arc

1 Introduction

In order to obtain components with improved surface performance and extended service life, laser cladding has been applied to deposit high-performance material on the substrate for many years. However, many problems such as balling (the molten cladding material does not spread out and wet the substrate), pore and crack etc. may occur in the process of laser cladding. These unfavorable formations can severely limit the application of laser cladding, especially in the field such as petrochemical and machinery industries which require an excellent formation of cladding layers. Balling is the most undesirable formation among them all, since it will cause porosity and will be obstacle for the fabrication of subsequent tracks of cladding layer. The traditional method to solve this problem is optimizing process parameters or adding a trace of active elements to reduce the surface tension of molten cladding material. A. Simchi have studied the effects of laser sintering process parameters and reported that balling can be avoided by reducing scanning spacing [1]. J.P. Kruth et al. found that the element P can lower the surface tension of the melt, thus improving wetting, and balling can be suppressed by applying very high pulse energy [2]. But these methods bring up higher demands for powder manufacturing and laser devices, and improvements on wetting by these methods are limited. As the optimizing of powder components comes to meet its limitation, it is time to improve wetting in another way.

By the inspiration of laser-TIG hybrid welding, which has shown clear advantages such as increased welding speed and penetration [3], a diode laser-TIG hybrid cladding

process was proposed in this study. High power diode laser has been proved to be an ideal heat source for cladding because of its high absorption degree by metals and high efficiency [4], compared with the early adopted laser in cladding such as CO₂ laser or Nd:YAG laser. But with higher power comes more intensive thermal input and higher crack tendency [5]. A TIG arc was coupled with diode laser to reduce the required laser power. It can also change the heat distribution and forces exerted on the melt. The functions of the two heat sources in this process are going to be analyzed in this paper.

2 Experimental

A 1.5 kW Focus Light diode laser and a Panasonic TIG welding machine were used in this experiment to melt pre-placed Ni60 powder on Q235 steel. The cladding process was recorded by a high-speed camera manufactured by PointGrey from an angle perpendicular to the scanning direction. The experimental setup of this system is shown in Fig. 1.

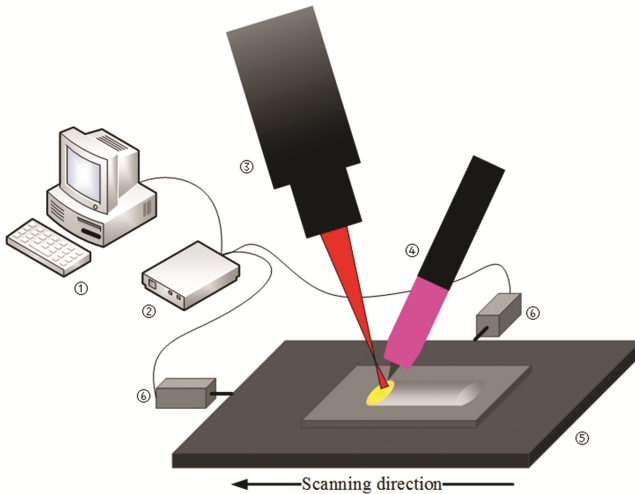


Fig. 1. Schematic of the experimental setup: ① computer for controlling the work table movement; ② stepper motor driver; ③ diode laser; ④ TIG torch; ⑤ worktable; ⑥ stepper motor

Ni60 powder was pre-placed on the Q235 plate with the thickness of 1 mm by a laying powder device. The composition of Ni60 powder used in this experiment is shown in Table 1. Q235 plates were polished to remove the oxide film before cladding. The cladding layers a, b, c and d were obtained by laser, TIG arc and laser-TIG hybrid heat source, respectively. The process parameters used in this experiment is shown in Table 2. After cladding, specimens with dimensions of 15 mm × 15 mm × 4 mm were wire-cutted from the cladded Q235 plates. And then specimens were polished and etched by nitric acid alcohol solution so as to observe the contact angle.

Table 1. Composition of Ni60 powder

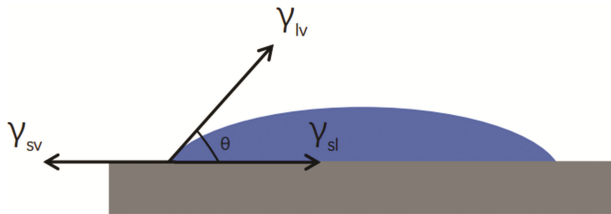
Element content/wt. %	C	Cr	Si	W	Fe	B	Ni
Ni60	0.8	15.5	4.0	3.0	15.0	3.5	Bal.

Table 2. Process parameters

Sample number	Laser power (W)	Defocusing distance (mm)	TIG arc current (A)	Shielding gas flow rate (L/min)	Scanning speed (mm/s)
a	–	–	50	3	2
b	1000	+20	–	–	2
c	1500	+20	–	–	2
d	1000	+20	50	3	2

3 Results and Discussion

Wetting of liquids on surfaces is a complex phenomenon, due to its sensitivity to a great number of factors. Contact angle is a well-accepted measure to characterize the degree of wetting of a surface by a liquid. It is defined as the angle between tangent drawn at the triple point between the three phases and the substrate surface, as shown in Fig. 2. A generally accepted theory is that the smaller the contact angle, the better the wettability. Wettability in this study was characterized by the contact angle from the cross section and macroscopic appearance from above.

**Fig. 2.** Illustration of contact angle

The four single track cladding layers fabricated with TIG arc, laser and laser-TIG hybrid heat source and their cross sections are shown in Fig. 3. It can be seen in Fig. 3(a) that the cladding layer fabricated with a 50A TIG arc is discontinuous mainly due to the lack of thermal input. Besides, the arc force and shielding gas flow blew away a large amount of powder. In that case, only a small amount of powder was melted and then attached to the substrate. That is the main reason why TIG arc is not a suitable heat source for pre-placed powder cladding unless the pre-placed powder is mixed with special binder to be adhered to the substrate, which will make the process far more complex. Figure 3(b) shows the cladding layer obtained by a 1000 W diode laser, the

melt did not spread out well, resulting in high contact angle and bad formation on the edge of cladding layer. This would present an obstacle to the subsequent deposition of material in multi-track cladding. It is a common observation that the surface tension of the liquid decrease with increase in temperature. Hence wettability should improve in any systems with increase in temperature [6]. This can explain why the formation of cladding layer fabricated with a 1500 W diode laser, as shown in Fig. 3(c), is better. However, cracks can be found on the cladding layer. The trapezoid temperature gradient of diode laser, as shown in Fig. 5, and comparatively high thermal input are the main reasons why cracks occurred. Besides, an obvious penetration into the substrate can be found from the cross section. This indicates dissolution of the substrate in the melt occurred, which can reduce the observed contact angle by decreasing the surface tension of the liquid and forming a crater under the melt [7]. Substrate melting is necessary for cladding, since it indicates a metallurgical bond is formed between cladding layer and substrate. However, with substrate melting comes the dilution of cladding layer by substrate, which will compromise the cladding layer performance. Hence keeping the dilution rate as low as possible is vital to the cladding layer performance. A perfect dilution rate was obtained by laser-TIG hybrid cladding process, as shown in Fig. 3(d). Moreover, the contact angle is far smaller than that in Fig. 3(b), even smaller than that in Fig. 3(c), which indicates an excellent wettability.

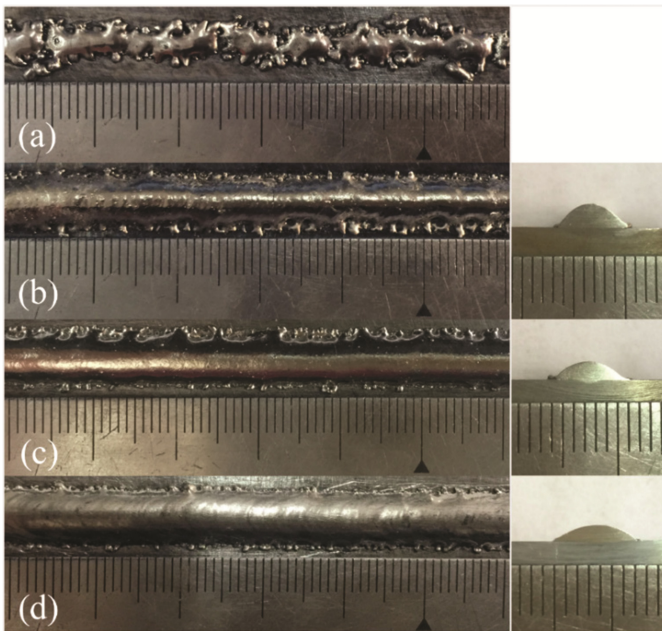


Fig. 3. The macroscopic appearance and cross section of cladding layer fabricated with different heat sources: (a) cladding layer obtained by a 50A TIG arc; (b) cladding layer obtained by a 1000 W diode laser; (c) cladding layer obtained by a 1500 W diode laser; (d) cladding layer obtained by a 50A TIG arc coupled with a 1000 W diode laser

The classic Young's equation gives the basic formulation of contact angle in terms of interfacial tensions:

$$\cos \theta = (\gamma_{sv} - \gamma_{sl}) / \gamma_{lv} \quad (1)$$

where γ_{sv} , γ_{sl} and γ_{lv} are the interfacial tension of the solid/vapor, solid/liquid and liquid/vapor interface, respectively, and θ is the equilibrium contact angle.

According to this formulation, a good wettability can be achieved when γ_{sv} is as large as possible while γ_{sl} and γ_{lv} are as small as possible. γ_{sv} in this equation is considered an invariant constant for given substrate and atmosphere. γ_{sl} and γ_{lv} need to be focused on, in order to improving wettability. The most important factors that affects the solid/liquid interfacial tension γ_{sl} is the formation of reaction products at solid/liquid interface. Most interfacial products can improve wetting and dramatically reduce the contact angle. As for the liquid/vapor interfacial tension γ_{lv} , the factor that influences it most is temperature. The influence of different heat sources on the heat distribution and forces exerted on the melt is going to be analyzed in terms of the two interfacial tensions, γ_{sl} and γ_{lv} in the following paragraphs.

From the cladding process recorded by a high-speed camera, as shown in Fig. 4, the different wetting and spreading process can be analyzed to illustrate why the introduction of TIG arc can greatly improve wetting while maintaining a smaller contact angle.

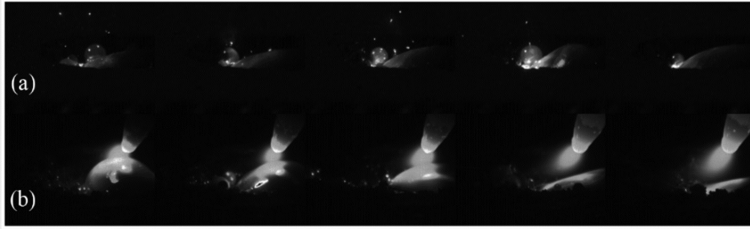


Fig. 4. Screenshots extracted from the video recorded by a high-speed camera: (a) a 1000 W diode laser cladding; (b) a 1000 W laser coupled with a 50A TIG hybrid cladding

In the 1000 W diode laser cladding process, as shown in Fig. 4(a), powder was melted into small balls by laser first. And then, these small balls gathered together and became a bigger ball. With the movement of the workpiece, the molten ball spread out and eventually became a single-track cladding layer.

Since diode laser irradiates a rectangular-shape spot, a trapezoid temperature gradient can be formed, as shown in Fig. 5 which led to a low surface tension in the middle while high surface tension on both sides of the melt. The presence of surface tension gradient, caused by temperature gradient, can naturally cause a flow from the low surface tension area to high surface tension area, as shown in Fig. 6, since a liquid with high surface tension pulls more strongly on the surrounding liquid than one with a low surface tension. That is what have been called Marangoni effect. Because of this effect, the melt tended to spread out. It need to be noted that, although the effect of gravity is normally not taken into account in wetting process according to the many

investigation, gravity in this experiment cannot be neglected. Gravity helped the melt spread and formed a plane contact instead of a spot contact with the substrate, which accelerated the thermal conduction between the melt and substrate. With the high temperature gradient mentioned above and the accelerated thermal conduction, the temperature of the melt decreased rapidly and surface tension γ_{lv} increased. These are the main reasons why contact angle of the cladding layer obtained by laser cladding is relatively high.

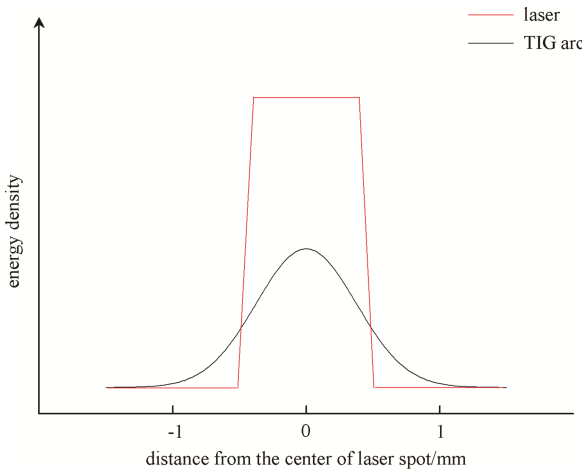


Fig. 5. Heat distribution of diode laser-TIG hybrid cladding process

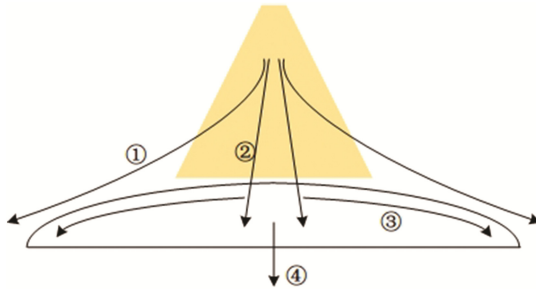


Fig. 6. Schematic of the forces exerted on the melt and the Marangoni flow in the melt: ① plasma flow force and shielding gas flow; ② axial component of electromagnetic pinch force; ③ Marangoni flow arising from surface tension gradient; ④ gravity

In the hybrid cladding process, as shown in Fig. 4(b), the TIG arc was ignited after a molten ball was formed and it quickly flattened the molten ball. In this process, laser melted powder ahead while the following TIG arc helped to spread out the liquid metal.

When TIG arc was introduced in this process, it can exert extra forces on the melt. According to the electromagnetic pinch effect due to the same direction electricity in arc column, there would be an electromagnetic pinch force on the arc, which would yield

an axial component to flatten the melt. The plasma flow force and shielding gas flow force also had a positive effect on the spreading. The schematic of the three forces is illustrated in Fig. 6. These forces can also stir the weld pool to improve its wetting. Laser in this process can stabilize and compress the arc to make arc force more concentrated. This is the how TIG arc improves wetting and spreading in the force aspect.

While in the heat aspect, the most obvious one is that the introduction of TIG arc elevated the thermal input and reduced surface tension γ_{lv} of the melt. TIG arc also affected the heat distribution on the melt. Since TIG arc is a Gauss heat source, it altered the unfavorable heat distribution to a complex but mild distribution, as shown in Fig. 5. There was no steep gradient on both sides of the laser spot, which helped to slow down the heat conduction from processing area to nearby area. Hence the temperature of the melt was comparatively high and surface tension was low. With all the lowered surface tension mentioned above, smaller contact angle can be formed. Besides, the elevated thermal input also intensified interfacial reaction which yielded interfacial products to reduce γ_{sl} and improved wettability. The mild heat distribution also helped to reduce crack tendency.

4 Conclusions

Wetting of a solid by a liquid is of great application importance and affected by a large number of factors including liquid properties, substrate properties and system condition, and wettability is generally measured in terms of contact angle. High power laser must be applied in order to obtain cladding layers with a smaller contact angle since the surface tension gradient, or so called Marangoni stress, resulted from temperature gradient is the only driving force for spreading in laser cladding. However, the attendant high dilution rate and crack tendency are inevitable. A TIG arc can be coupled with laser to reduce required laser power and exert extra forces on the melt to help it spread out. The main function of TIG arc in laser-TIG hybrid cladding process can be explained in two aspects, which is force and heat. In force aspect, it is mainly about the forces that helped to flatten the spherical melt. While in heat aspect, the introduction of TIG arc increased thermal input and reduced liquid surface tension.

Acknowledgment. This work was supported by the National Natural Science Foundation of China (51675256).

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Numerical Simulation of Droplet Transfer of AZ31B Magnesium Alloy Based on FLUENT

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Abstract. According to electromagnetic theory and fluid dynamics theory, the AZ31B magnesium alloy GMAW droplet transfer was simulated in the paper, by VOF model of FLUENT software to track the free interface of gas-liquid, use UDF order to add source term of momentum and energy equation. The simulation results show that when welding current is 100 A, the type of transfer belongs to globular transfer, and the type of droplet transfer of 280 A belongs to projected transfer; the critical transition current from globular transfer to projected transfer is about 220 A. With the increase of welding current, the diameter and length of droplet become small, the ratio of long axis length to the short axis length become more and more small, and the shape of droplet changes from long-oval to round. The neck part produces the maximum pressure, maximum pressure coefficient, maximum droplet velocity; the temperature gradient increases along with the axial direction; those factors will accelerate formation of the pencil tip and promote the droplet transfer.

Keywords: AZ31B · GMAW · VOF · UDF · Droplet transfer

1 Introduction

With the development of the society, every industry has put forward increasingly requirement to products about reducing mass, magnesium and magnesium alloy are used widely as a result of the smaller density of metal, magnesium alloy not only has light density, high specific strength and stiffness, can also reduce shock and unnecessary noise; owing to the high heat conduction rate and high expansion coefficient and lower melting and boiling points of the magnesium alloy, those physical property bring more difficult for magnesium alloy welding [1]. In order to improve the magnesium alloy welding quality and efficiency, this paper utilizes the electromagnetic theory and the fluid dynamics theory, and based on the computational fluid dynamics (CFD) software FLUENT14.5 to simulate the droplet transfer procedure of AZ31B magnesium alloy Gas Metal Arc Welding (GMAW), by simulating different welding currents to gain the characteristic and regulation of droplet transfer, welding parameter of simulation has a certain reference value for magnesium alloy welding test.

According to literature [2–7], the theory of droplet transfer simulation included static force balance theory (SFBT), pinch instability theory (PIT), mass-spring theory, the

minimum energy theory, volume of fluid (VOF) theory; comprehensively compared with five kinds of theories, this paper choose the VOF theory to simulate the droplet transfer procedure, through user defined function (UDF) order to add the source term of the Navier-Stokes equation. In order to track the morphology of droplet, the droplet falling speed, the distribution of pressure and pressure coefficient distribution and temperature distribution in different moments, we need to establish a transient GMAW droplet transfer model under the condition of using VOF theory, the biggest advantage of VOF theory is that you can use VOF model track the free surface of the gas-liquid. The formation and stability of metal transfer depends on the comprehensive effect of various forces which act on the end of liquid metal; according to the appearance and characteristics of the transition, metal transfer mode is usually divided into two basic types: contact transfer and free-flight transfer, the former included short-circuiting, the latter included globular transfer and projected transfer and spay transfer, this paper simulated globular and projected transfer.

2 Numerical Simulation

Figure 1 is a two-dimensional axial symmetry model that imported into FLUENT software to calculate, the level is Y direction, the distance is 8 mm which is equal to nozzle diameter, the vertical is X direction, the distance is from nozzle to the workpiece surface which is 7.5 mm. Calculation region included the gas phase and liquid phase, the grid region means the first phase which is shield gas (Ar), the purity of Ar is 99.99%, the liquid magnesium alloy was regarded as the second phase that added by initialization, the rectangular area of BCDE is the series of AZ31B magnesium alloy welding wire which diameter is 1.2 mm, all of the above data are in accord with the test process.

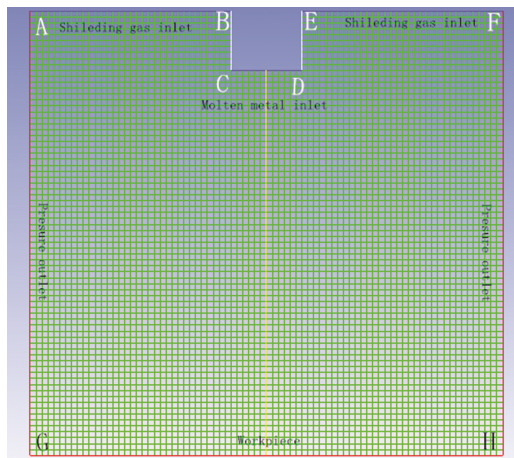


Fig. 1. Mathematical model of droplet transfer

2.1 Assumptions

In order to facilitate the simulation of the complex process of droplet transfer, put forward the following hypothesis [8]:

1. The droplet transition simplify into a two-dimensional axial symmetry problem (mathematical model as shown in Fig. 1).
2. The liquid metal is incompressible Newton fluid.
3. The liquid metal physical parameters are assumed as constant.
4. The welding protective gas (Ar) at atmospheric pressure, and ignore the influence of the pressure change of surrounding.

2.2 Mathematical Equation

During the simulation process of droplet transfer based on FLUENT, the liquid droplet is acted as incompressible Newton fluid, the fluid was manipulated mainly by the equation of mass conservation, momentum conservation and energy conservation [9], those are given below:

Mass conservation equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

Momentum conservation equation:

$$\frac{\partial u}{\partial t} = X - \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\mu}{\rho} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \quad (2)$$

$$\frac{\partial v}{\partial t} = Y - \frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\mu}{\rho} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad (3)$$

In the above equations: u and v are the velocity of the fluid in the direction X and Y , respectively; ρ is the liquid metal density; p is the pressure on the fluid; μ is the Kinematic viscosity of liquid metal; X and Y is the body force, which conducted in the indirection of vertical and level, respectively.

In the process of simulation of droplet transfer, because it involved gas-liquid two phase fluid, we need use VOF model in the module to track the change of free interface. VOF model is equal to the cell fluid volume function $F(x, y, t)$, which satisfied the following conservation equation:

$$\frac{\partial F}{\partial t} + (\nabla \cdot \nabla) F = 0 \quad (4)$$

If $=0$, means no liquid metal fluid in the cell; if $=1$, means liquid metal fluid filled with cell completely; if $0 << 1$, indicate the cell contain two phase fluid.

2.3 Droplet Force Analysis

The metal transfer process is mainly controlled by the gravity, electromagnetic force, surface tension, and the plasma flow, owing to the mass density of AZ31B magnesium alloy is light (1780 kg/m^3), so the effect of promoting droplet transfer of gravity is trivial, the surface tension was controlled by the surface tension coefficient of the first phase and the second phase, in order to simplify calculation, the surface tension coefficient is set as 1.0. Therefore, we can infer that the decisive force for metal transfer process of GMAW is the electromagnetic force, before we imported the physical model into FLUENT, we need add the source term of the momentum equation by UDF order, which was compiled by C program, the main contest of UDF order is about electromagnetic force, calculation formula of the electromagnetic force was given below:

$$F_{em} = \frac{\mu_0 I^2}{4\pi} \left[\ln \frac{R \sin \theta}{r} + \frac{2}{(1 - \cos \theta)} \ln \frac{2}{1 + \cos \theta} - \frac{1}{1 - \cos \theta} - \frac{1}{4} \right] \quad (5)$$

where μ_0 is the Magnetic permeability; R is the radius of wire; I is the welding current; θ is the arc root angle; r is the radius of droplet at any time.

2.4 Boundary Condition

This paper simulated 11 groups data, every simulation group executed under different voltage and current; what's more, the boundary condition of each group are shown in Table 1, is equal to the Wire Feed Speed (WFS), is the velocity of shield gas, T is the temperature, is the volume of second phase; Table 2 is the physical parameters about AZ31B magnesium alloy [1]; Table 3 is the value of voltage and WFS under different currents.

Table 1. Boundary condition of the model

Boundary	u (m/s)	v (m/s)	T (K)	F
AB/EF	vg	0	300	0
CD	vf	0	1380	1
AG/FH	0	0	300	0
GH	0	0	1680	0

Table 2. Material properties of AZ31B Magnesium alloy

Property	Value
Mass density ρ	$1780 \text{ kg} \cdot \text{m}^{-3}$
Kinematic viscosity μ	$0.006 \text{ m}^2 \cdot \text{s}^{-1}$
Magnetic permeability μ_0	$4\pi \times 10^{-7} \text{ H} \cdot \text{m}^{-1}$
Electrical conductivity σ	$7.7 \times 105 \Omega^{-1} \cdot \text{m}^{-1}$
Gravitational acceleration g	$9.81 \text{ m} \cdot \text{s}^{-2}$

Table 3. The voltage and wire feed speed

Current (A)	Voltage (V)	WFS (m/s)	Current (A)	Voltage (V)	WFS (m/s)
100	19	0.05	220	25	0.093
120	20	0.0566	240	26	0.103
140	21	0.0632	260	27	0.123
160	22	0.0698	280	28	0.133
180	23	0.0764	300	29	0.144
200	24	0.083			

3 Results and Discussion

Figure 2 is the droplet transfer process when the welding current is 100 A, voltage is 19 V, the type of droplet transfer belongs to typical globular transfer, as it's depicted in Fig. 2, when the welding current is 100 A, the period of droplet transfer is about 144 ms. Through the initialization to add a semi-circle at the end of wire, the radius of the circle is 0.6 mm, in addition, we regarded this moment as the initial time, namely the time is 0 ms; from 0 to 136 ms, the liquid droplet was elongated slowly and grew up under the action of gravity.

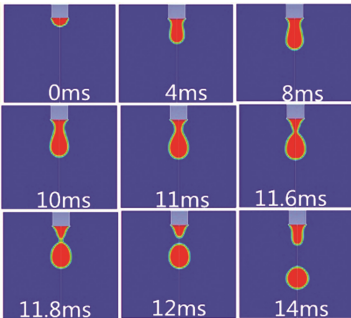
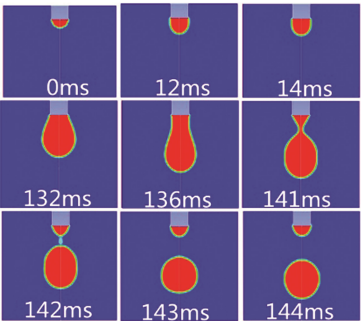


Fig. 2. Process of droplet transfer under 100 A **Fig. 3.** Process of droplet transfer under 280 A

During this period, owing to the arc root angle is smaller, the upward axial electromagnetic force prevented droplet transfer; at the moment of 141 ms, the neck formed as a result of the radial electromagnetic shrinkage force, due to the neck formed fully, the arc root angle became larger, with the increase of arc root angle, the direction of the electromagnetic force change from upward to downward, so the downward axial electromagnetic force and gravity promote the droplet transfer collectively.

On the other hand, the surface tension hamper the droplet transfer, and the radial shrinkage stress increased, those factors lead to the formation of wire tip; because the resultant of vertical downward electromagnetic force and the gravity is greater than the surface tension, so the droplet detached from the end of the wire rapidly.

From 142 ms to 144 ms, owing to the detached metal conducted only by gravity and surface tension, therefore the droplet deforms from approximate long oval to circular;

what's more, the residue liquid metal at the wire tip will rebound and oscillate as a result of surface tension, which can be seen from the last three small picture in the Fig. 2.

Figure 3 is the droplet transfer process when the welding current is 280 A, voltage is 28 V, the type of droplet transfer belongs to projected transfer, the tip of a pencil fully formed, the period of droplet transfer is approximately 14 ms, the cycle became shorter obviously when compared with 100 A, as we can see from Fig. 3, the neck formed fast, the direction of electromagnetic force change from vertical upward into downward, this change will promote metal transfer. According to the calculation formula of the electromagnetic force, due to the current increased, the axial electromagnetic force and the radial electromagnetic force will increase, those will lead to the formation of neck and the tip of pencil rapidly, the period of droplet transfer became shorter. So, we can infer that the type of droplet transfer related to the speed of formation of the neck, when the neck formed rapidly, the type of droplet transfer will vary.

Figure 4 is the cycle of droplet transfer under different welding currents, as it's displayed, with the increase of welding current, the period of droplet transfer becomes shorten, droplet transfer cycle shortened greatly from 100 A to 220 A, droplet transfer cycle shortened slightly from 220 A to 300 A, we regarded the moment of transformation of metal transfer type as the critical transition, so the critical transition current is about 220 A; what's more, we can speculated that the formation of droplet transfer belong to spray transfer when the current is more than 300 A.

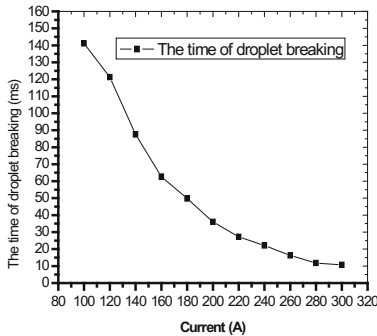


Fig. 4. The time of droplet breaking under different currents

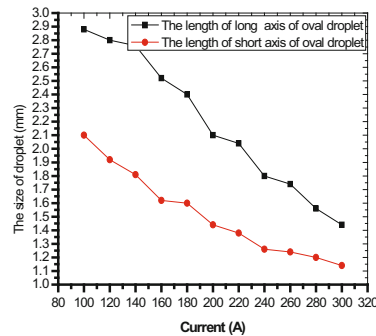


Fig. 5. The size of droplet under different currents

Owing to the shape of detached droplet is similar to a long-oval, Fig. 5 shows the length of long axis and short axis of oval droplet at the detaching time under different currents, the length of short axis is equal to the diameter of droplet, we can see from the graph that the length of long axis and short axis of oval droplet became smaller with the increase of welding current. The length of long axis is greater than the droplet diameter, which may be related to the density of magnesium alloy and the surface tension coefficient, the metal can be elongated easily under the comprehensive action of all kinds of force. According to the distance between long axis and short axis under the condition of the same current in Fig. 5, the ratio of the long axis to short axis is more and more small with the increase of current, then the droplet shape change from a long-oval to

round slowly. During the region of 100 A to 220 A, the droplet diameter is greater than the wire diameter, so the droplet transfer mode belongs to globular transfer, from 220 A to 300 A, the diameter of droplet is smaller than the wire diameter, so the transition from attributed to projected transfer. Figure 6 displayed the maximum length of liquid metal at the end of wire (namely the distance from the bottom of the droplet to wire at the moment of droplet falling soon, such as the moment of 140 ms in Fig. 2 and 11.6 ms in Fig. 3) under different current conditions, as can be seen from the graph, with the increase of welding current, the maximum length became small, which maybe relate to the type of droplet transfer, when globular transfer, droplet is long and large, when projected transfer, droplet is small and thin.

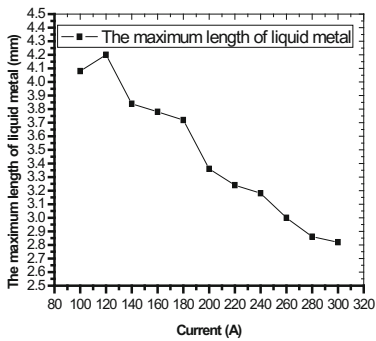


Fig. 6. The maximum length of droplet under the different currents

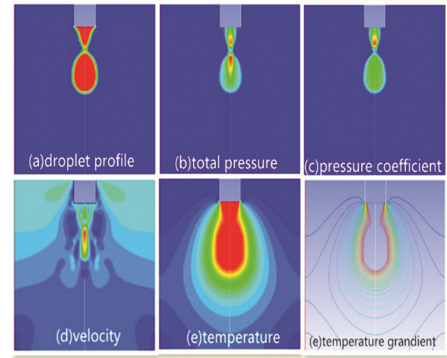


Fig. 7. Distribution of physical property in the droplet ($I = 280$ A, $t = 11.8$ ms)

In order to analyze the droplet transfer process in more detail, we need to monitor the droplet shape, the pressure distribution on the droplet, velocity and testing pressure coefficient and temperature distribution at arbitrary moment. Figure 7 shows the droplet physical parameters distribution at 11.8 ms when the welding current is 280 A, the Fig. 7(a) is the function of volume distribution for the liquid droplet, namely the droplet shape profile, at this moment the liquid bridge formed fully and the curvature of the neck part is larger than other place; what's more, we can see that the maximum total pressure located in the neck part from the Fig. 7(b), it's necessary to pointed out that the red part represent the greater value from Fig. 7(b) to (f); on the contrary, the maximum pressure coefficient not located in the neck part, but behind the neck part; the maximum velocity of liquid metal located in the neck part as show in the Fig. 7(d), the maximum value was approximately 2.9 m/s; Fig. 7(e) is the temperature distribution on the droplet and Fig. 7(f) s the gradient distribution of temperature, the temperature gradient is smaller when it closed to the bottom of the droplet, approaching to the workpiece has a larger temperature gradient, so temperature gradient increased along the axial direction of welding wire; those factors will accelerate the formation of the tip of pencil and promote the droplet transfer.

Given some physical property parameters of AZ31B magnesium alloy in high temperature state are uncertain, this paper ignored the effect of metal vapor pressure to

the droplet transfer, so in the future work we need fully consider the influence of high temperature properties of the liquid metal and the shield gas to make the simulation results more accurate.

4 Conclusions

In this study, it based on the FLUENT software to simulate AZ31B magnesium alloy GMAW droplet transfer process under different welding currents, when the welding current is 100 A, the type of droplet transfer belongs to globular transfer, the type of droplet transfer of 280 A belongs to projected transfer; the critical transition current from globular transfer to projected transfer is about 220 A.

With the increase of welding current, the diameter and length of droplet become small, the ratio of the long axis length to the short axis length is also more and more small, so the droplet shape change from long-oval to round.

The neck part produces the maximum pressure, maximum pressure coefficient, maximum droplet velocity; the temperature gradient increases along the axial direction; those factors will accelerate the formation of the tip of pencil and promote the droplet transfer.

Acknowledgement. The research is supported by the National Natural Science Foundation of China (51665037, 61165008).

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Research of Maintenance Manipulator in Remote Handling System for Small Openings

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Abstract. Remote handling maintenance system, especially in the cavity with small openings and complex inner geometry, has been regarded as the key issue on the maintenance for the Magnetic Confinement Fusion (MCF). The maintenance system presented here is specially researched for Tokamak of ITER that need to be monitored to guarantee working well and safely. Due to neutron activation, the repair, inspection or maintenance of in-vessel components of Tokamak has to be carried out remotely. With the increasing demand of communication bandwidth, response speed and real-time of open control system for multi-DOFs manipulator and considering the current system's shortage in real-time and stability, this paper presents the control system of 12-DOFs maintenance manipulator in remote handling system. The system based on the EtherCAT network performances well in real time with sufficient stability.

Keywords: ITER · Real-time Ethernet · EtherCAT · Remote handling

1 Introduction

ITER machine, the full superconducting tokamak with doughnut-shape chamber and no-circle cross-section, which will be built at Cadarache in the South of France, aims to verifying that the whole system function works properly and is ready for the operation. Remote Handling maintenance system, especially in the Tokamak with small openings and complex inner geometry, has been regarded as the key issue to the maintenance for the Magnetic Confinement Fusion (MCF) [1] and are engaged in the maintenance process (viewing, dust deposition, fault detection, fault diagnosis, maintenance) of MCF [2, 3]. The maintenance system of the Magnetic Confinement Fusion (MCF) need to be monitored to guarantee working well and safely. Meanwhile the repair, inspection and maintenance of it has to be carried out remotely due to neutron activation [4]. In order to complete the maintenance task, such as fixing a loose screw mounted on the inner cavity surface, the mechanical system design of multi-DOFs manipulator, control system design, remote handling, motion control and other technology should be taken into account. Many remote handling researches have been done in the past regarding inspection and maintenance tasks of tokamak vacuum vessel, such as the vehicle-manipulator system for blanket maintenance [5], the dexterous water hydraulic manipulator [6], the flexible in-vessel inspection

system for the plasma facing components (PFCs) [7] and an 8-m long multilink articulated inspection arm robot [8], etc. Although lots of researches on the remote handling system, such as blanket handling system, diverter handling system, close inspection of PFCs system, have been carried out, there is no one system focusing on sophisticated tasks, such as mounting an screw on the inner wall of cavity. Without any doubts such complex system may bring into some disastrous defects because of its complexity and the lacking experience of researchers and the system itself should have a better performance of communication bandwidth, response speed and real-time because of the high-precision in motion controlling. In recent years, more and more fieldbus apply to the open control system of multi-DOFs manipulators, especially for the sophisticated system. However, the control system transmitted by conventional bus will be faced with severer problems of real-time and coordination especially while controlling more axes and joints and cannot meet the demands gradually.

Real-time EtherCAT can achieve high performance of anti-interference and robustness in process, especially for high-speed, high-reliability and high real-time data transfer applications. It overcomes the bottleneck of high performance of data transmission in complex remote handling system. In this paper, we present the complex remote handling system including the mechanical design of manipulator and the control system architecture. In detail, the paper is organized as follows. In Sect. 2, a brief description of EtherCAT is presented and the remote handling system and the mechanical design of manipulator is proposed in Sect. 3. The details of control system architecture and some insights on system behavior and performance based on EtherCAT networks are presented in Sect. 4. Finally, Sect. 5 draws the corresponding conclusion.

2 EtherCAT

EtherCAT (Ethernet for Control Automation Technology) is real-time Ethernet network that achieves high communication efficiency that reaches cycle times well below 1 ms. EtherCAT protocol is a kind of industrial communication protocol that makes full usage of Ethernet full-duplex features. EtherCAT overcomes the traditional field-bus and industrial Ethernet bottlenecks, making real-time performance higher. Therefore, EtherCAT has obvious advantages of precious position control of serial robots.

EtherCAT relies on a master/slave medium access control policy where a single master sends commands to the slave devices to read and write values [9]. The master has to process, send and receive Ethernet frames for slave nodes during each network cycle. Usually all nodes communication are completed within one or two frames each cycle. EtherCAT does not require a dedicated master card: any standard Ethernet Controller is suitable, since the master protocol is implemented in software on the host CPU that runs the application program as well [10]. EtherCAT slave device must have EtherCAT slave controller while no need of a microcontroller at all. Simple devices that get by with an I/O interface can be implemented only with the ESC and the underlying PHY, magnetics and the RJ45 connector.

3 Remote Handling System and Mechanical Design

At the beginning of the system design study, it is necessary to make an analysis of the requirements and constraints for the remote handling system. Firstly the geometrical requirements are the ITER Tokamak parameters ($R = 6.25$ m, $a = 4.5$ m), the remote handling equatorial port ($W \times H$, $2 \text{ m} \times 2.5 \text{ m}$) and the limited small openings in the Tokamak. Here, the design and system verification in details should be done according to the model proportion of 1:10. Secondly the workspace should be able to reach the overall volume of the Tokamak and the accuracy is within 1 mm. Thirdly, the system should ensure not damage or collide the normal operation area of MFC during fault diagnosis and maintenance. The last one is that the operation should be controlled remotely.

Considering the actual geometric requirements and the intensity of the Tokamak equatorial port distribution, it seems that the system with multi-DOFs manipulator (macro-micro structure) is a good choice for executing detecting and maintaining tasks. The task can be naturally divided into three subtasks: transfer the manipulator folded in cassette mover to reach the vessel and lock with the maintenance port of the vessel, push the 12-DOFs manipulator to slide into the vessel and execute the detecting and maintenance task in the vessel. A long distance multi-DOFs manipulator is distinguished by its larger doughnut-shape workspace, narrow cross-section corresponding to the small openings and lightweight design. Unfortunately, increasing the joints' numbers and decreasing its mass enhance obviously structure compliance [11, 12]. Usually, two sets of remote handling maintenance systems are typically used to achieve some collaborative maintenance. The 3D model view of the remote handling maintenance with Tokamak and its non-circular cross-section is shown in Fig. 1.

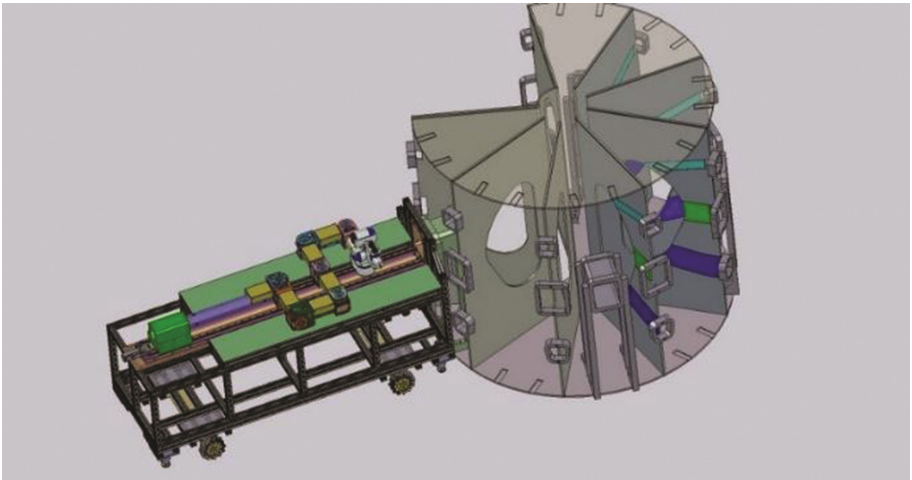


Fig. 1. 3D model of the ITER Tokamak

The architecture of the remote handling system is a modular subsystem design that consists of a long distance multi-DOFs manipulator with 12 degrees of freedom (DOF) including a 6-DOFs macro arm and another 6-DOFs teleoperation manipulator also known as micro arm. Furthermore, a designated multipurpose transport cask (MTC) provides one DOF for pushing the 12-DOFs manipulator to slide into the Tokamak vessel. The function of the MTC, which has four omnidirectional mobile wheels and a high-precision translational guide rail, is to store the 12-DOFs manipulator and transmitting the manipulator into the vessel. The macro arm, which has six modular rotary axes, is used to carry and transmit the micro arm into the Tokamak in the range of 180° along the horizontal direction as shown in Fig. 2. All the joints of the manipulator are driven by the actuator with harmonic gear and have a planet or spur gear mechanism for all revolute joints.

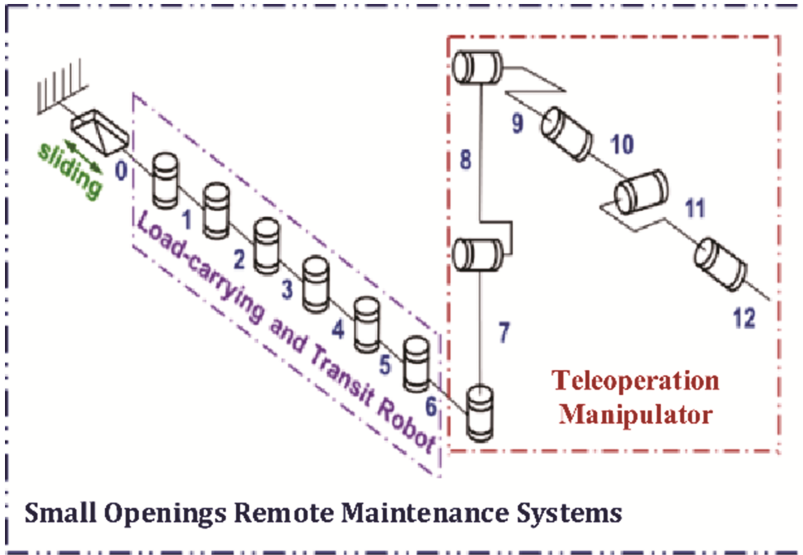


Fig. 2. The configuration of the 12-DOFs manipulator

4 Remote Handling System Architecture

The remote handling system is one of the numerous ITER Plant systems that are closely based on the hierarchical structure of the ITER CODAC system [13, 14]. The control system presented in this paper is especially suitable for remote handling system that is designed for performing maintenance tasks in the Tokamak. The remote handling system mechanical structure is shown in Fig. 3. Taking into account the complexity of inner geometry features of Tokamak, working randomness and uncertainty, we should ensure high response speed of motion control, multi-axis synchronous operation and higher motion accuracy of the system.

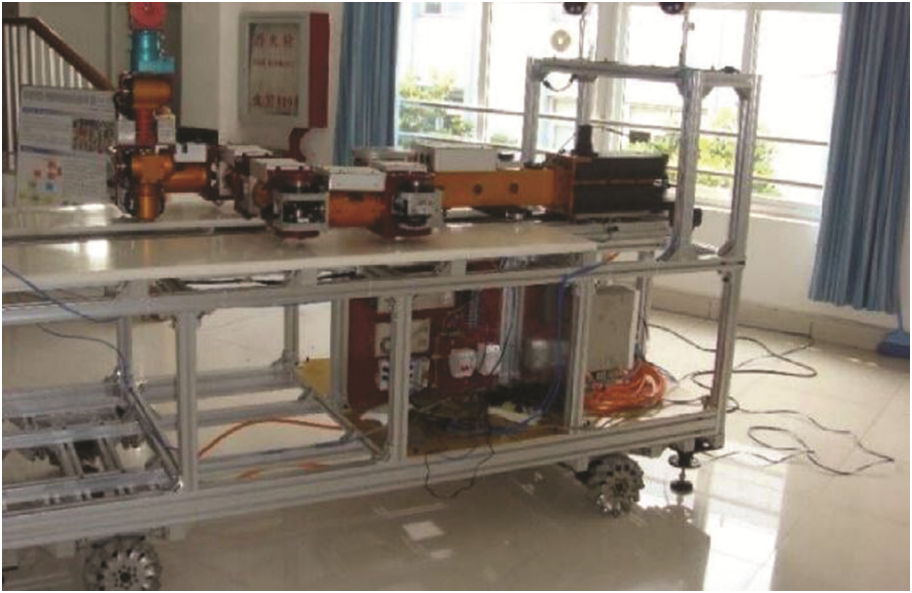


Fig. 3. The real photo of the remote handling system

The remote handling system based on EtherCAT network takes a master/slave control approach. The master is industrial computer while slave devices are servo drivers in favor of EtherCAT protocol, sensors, EK1100 and EL6752 terminal boxes developed by Beckhoff, etc. We adopt the simple line structure as shown in Fig. 4 considering that the wiring length of mechanism has a great impact on the robot movement and that the performance of bus coupler influences the network cycle.

In order to ensure the maintenance tasks successfully completed in the cavity, some sensors have access to the network such as force sensors, laser sensors and cameras. The force sensor based on DeviceNet is accessed to the network by EL6752 DeviceNet master terminal from Beckhoff for force feedback of the manipulator end. The laser based on RS232 interface is used for the location of manipulator end in the cavity and has direct access to the master. The camera is applied to the real-time feedback of working condition through wireless transmission. Servo drivers connected to the EtherCAT networking are available in a variety of feedback selections such as incremental encoder and digital hall and I/O configuration possibilities.

As to the software, we adopt the TwinCAT (The Windows Control and Automation Technology) as communication application. The Ethernet card integrated on PC motherboard is used as communication module instead of dedicated PCI card, which simplifies the complexity of system but increases the stability. It turns almost any compatible PC into a real-time controller with a multi-PLC system and replaces conventional PLC controllers. Therefore, the PC acts as the EtherCAT master. TwinCAT software architecture can be divided into three layers: user interface layer, intermediate layer and motion control layer. The user interface layer is to realize human-robot interaction via HMI (Human Machine Interface). Intermediate layer mainly made up of run-time system

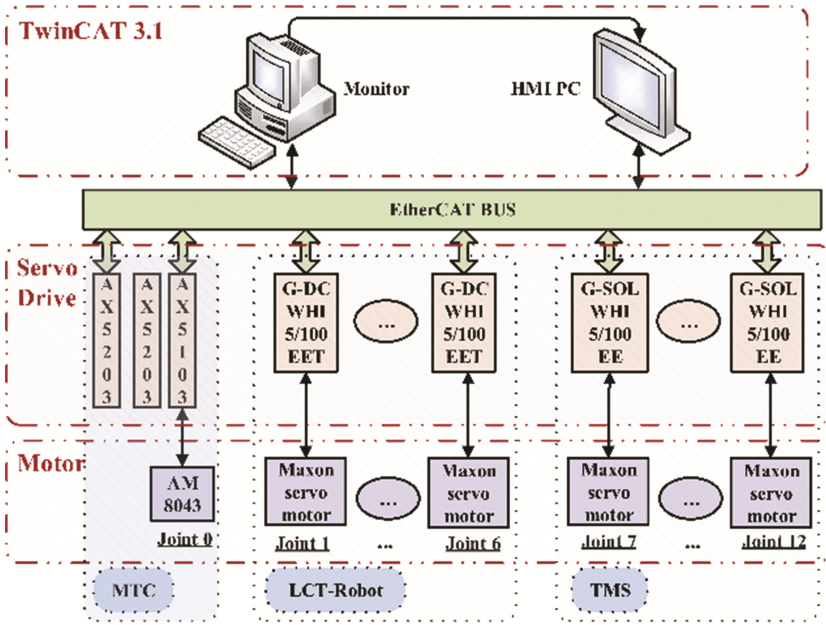


Fig. 4. System hardware components

is applied to realize the interaction between user interface layer and motion control layer via configuring different task information, I/O information and NC axis variables information. Motion control layer includes PLC control unit and servo control unit.

This paper takes the 12-DOFs manipulator as test platform and do some basic analysis of real-time parameters of EtherCAT network such as communication cycle time and propagation delay time. The propagation delay consists of a time component for forwarding a frame and the medium delay [15]. The cycle time is basically stable at 1 ms when we set the cycle time to 1 ms. In addition, there is nearly no change between the different slave nodes when the nodes are no more than 30. To a conclusion the system based on EtherCAT network achieves a good performance of real-time and stability. Although the presence of jitter in the communication process, the rate is small and the jitter substantially has no effect on the cycle. Additionally, propagation delay will increase as slave nodes increase. Nevertheless, sub-microsecond rise time almost has no influence on the real-time.

5 Conclusion

The remote handling system is under design and manufacture for the purpose of remote flexible inspection and maintenance of the surface of ITER Tokamak, helping to understand what would happen in the Tokamak and how to handle some special breakdown during operation. We present the detailed design of remote handling system that has the benefit of easy passing each equatorial port and the potential to be developed into a

components replacement remote handling system. Some elementary analysis work, such as mechanical design and the control system architecture, was fulfilled.

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