

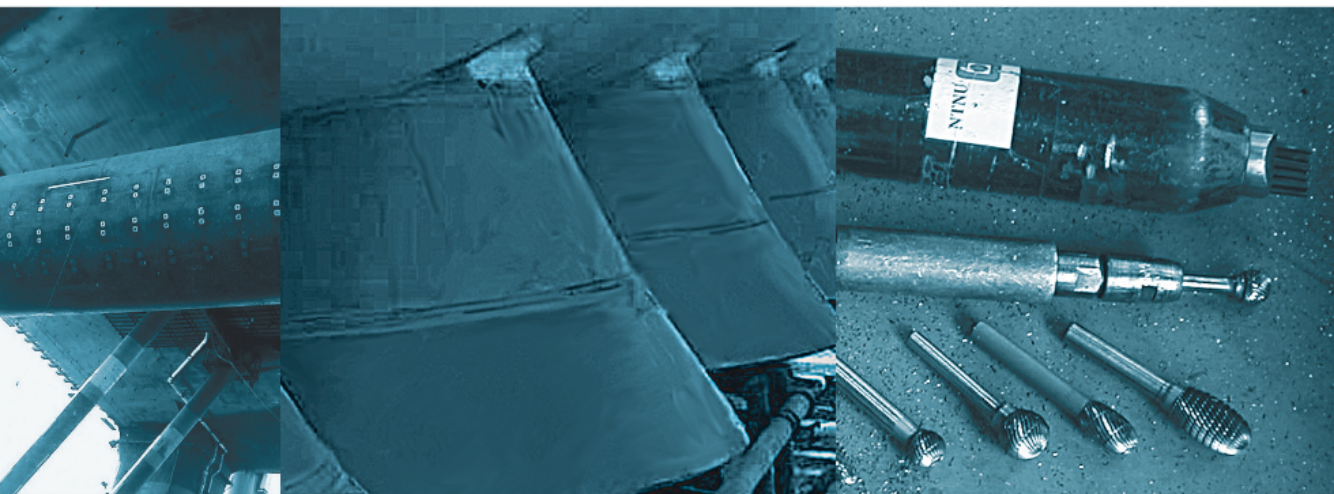


INTERNATIONAL INSTITUTE OF WELDING
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IIW RECOMMENDATIONS ON METHODS FOR IMPROVING THE FATIGUE STRENGTH OF WELDED JOINTS

IIW-2142-10

P. J. Haagensen and S. J. Maddox





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1. INTRODUCTION

Weld toe improvement methods have been widely investigated and have, in most cases, been found to give substantial increases in fatigue strength. However, there are large variations in the actual improvements achieved, and the results obtained by various methods are not always ranked in a consistent manner. One explanation for the observed variations is the lack of standardization of the optimum method of application, but variations in the material, type of loading and type of weld detail may also have influenced the results. The effectiveness of the treatment also depends heavily on the skill of the operator. In order to improve the reproducibility of the methods, and to produce guidance for the degree of improvement that could be expected when using the methods in actual practice, an inter-laboratory round-robin test programme was undertaken by IIW in 1995 (Haagensen, 1995). The participating organizations are listed in Appendix 1. The programme, involving 13 testing laboratories in 10 countries, addressed the 3 commonly used improvement methods: burr grinding, TIG dressing and hammer peening. It has contributed to a better understanding of the reasons for the large scatter that is sometimes observed in fatigue tests of improved welds, and has provided a basis for a higher confidence in the use of the methods.

The recommendations in this document are derived mainly from earlier IIW publications (Maddox, 1993; Haagensen, 1993; Millington, 1973; and Kado *et al.*, 1975), but many publications were consulted, as listed in Appendix 2. They supplement the IIW Recommendations for Fatigue Design of Welded Joints and Components (Hobbacher, 2009), which present S-N curves expressed in terms of applied nominal or hot-spot stress range. These are of the form $\Delta\sigma^m N = \text{constant}$, where $\Delta\sigma$ is the stress range, N is the fatigue life and m is the inverse slope of the $\log \Delta\sigma$ vs $\log N$ curve. The benefits from the use of the improvement techniques are related to those design S-N curves. In addition to specifications for the practical use of the methods, guidance on inspection and quality control is also given. Successful implementation of these methods depends on adequate training of operators as well as inspectors. It is anticipated that publication of the present Recommendations will encourage the production of appropriate training aids and guidance for educating, training and certifying operators and inspectors.

The improvement techniques described in these Recommendations are intended for use under the following circumstances:

- increasing the fatigue strength of new structures;
- repair or upgrading of existing structures.

It should be noted that the use of the higher S-N curves for improved welds given in this document depends critically on adherence to the quality requirements outlined under each improvement technique. Depending on the circumstances, approval from, for example, the purchaser or a certifying authority may be required before an improvement technique is used and an increase in fatigue strength is claimed.

2. SCOPE

2.1 Methods

The weld toe is a primary source of fatigue cracking because of the severity of the stress concentration it produces. Apart from a relatively sharp transition from the plate surface to the weld, dependent on the weld profile, the stress concentration effect is enhanced by the presence of minute crack-like flaws, extending to depths (below any undercut) of a few tenths of a millimetre. Fatigue cracks readily initiate at these flaws.

The weld toe improvement methods described in these Recommendations rely on two main principles:

- (i) *Reduction of the severity of the weld toe stress concentration* – two methods are given: grinding and re-melting by TIG dressing. The primary aim is to remove or reduce the size of the weld toe flaws and thus extend the crack initiation part of the fatigue life. A secondary aim is to reduce the local stress concentration due to the weld profile by achieving a smooth blend at the transition between the plate and the weld face.
- (ii) *Introduction of beneficial compressive residual stress* – this has the effect of 'clamping' the weld toe in compression, with the result that an applied tensile stress must first overcome the residual stress before it becomes damaging. Thus, the applied stress range is less damaging. Two methods are given, hammer and needle peening. In each case, compressive residual stresses are induced by mechanical plastic deformation of the weld toe region. Residual stresses then arise as a result of the constraint imposed by the surrounding elastic material. Similar effects may be achieved with other techniques, such as shot peening and high-frequency (e.g. ultrasonic) peening (e.g. Kudryavtsev *et al.*, 2007; Weich, 2009a and 2009b; and Roy *et al.*, 2003), and they will be addressed in a future up-date of these Recommendations.

An important practical limitation on the use of improvement techniques that rely on the presence of compressive residual stresses is that their fatigue lives are strongly dependent on the applied mean stress of the subsequent fatigue loading. In particular, their beneficial effect decreases as the maximum applied stress approaches tensile yield, disappearing altogether at maximum stresses above yield. Thus, in general the techniques are not suitable for structures operating at applied stress ratios (R) of more than 0.4 or maximum applied tensile stresses above around 80% yield. Similarly, their benefit may be reduced under variable amplitude loading as a result of relaxation of the compressive residual stress by the occasional application of high stresses, in tension or compression.

2.2 Materials

The Recommendations apply to any arc welded steel or aluminium structure that is subjected to fatigue loading. Due to lack of experimental data for extra high strength steels, the fatigue strength (or S-N) curves apply only to structural steel and stainless steel grades up to a maximum specified yield strength of 900 MPa. However, it is reasonable to expect that, in principle, the methods will also improve the fatigue performance of welded higher strength steels. In the absence of relevant published data, it is recommended that such benefit should be quantified by special testing. The present Recommendations are also applicable to aluminium alloys commonly used in welded structures, primarily the 5000 and 6000 series alloys.

2.3 Environment and Loading

The application of improvement techniques is limited to structures operating at temperatures below the creep range. Although some of the improvement methods will increase the fatigue lives of structures operating under freely corroding conditions, no guidance is given on the improvement that can be expected.

The Recommendations for burr grinding and TIG dressing only apply to conditions where the nominal stress range $\Delta\sigma < 2 \times YS$, YS being the specified minimum yield strength of the material.

For peening techniques, special restrictions are imposed regarding applied peak stresses and stress ratios, see Sections 5 and 6. Consistent with the IIW Recommendations for Fatigue Design of Welded Joints (Hobbacher, 2009), the present Recommendations do not apply to low-cycle fatigue conditions. However, there is evidence that the weld toe dressing methods are still effective under strain cycling (Dickerson and Branco, 1997).

2.4 Types of Welded Joints

The current Recommendations apply to the improvement of welded planar joints or welded hollow section connections with plate thickness from 6 to 50 mm for steel, 4 to 20 mm for aluminium, or as specified for each improvement method.

The improvement methods covered in this document are applied to the weld toe. Thus, they are intended to increase the fatigue life of the weld treated from the viewpoint of potential fatigue failure from the weld toe (some examples of relevant weld details are shown in Fig. 2.1). Therefore, the possibility of a failure starting at some other location must always be considered. For instance, if the failure origin is merely shifted from the weld toe to the root, there may be no significant improvement in fatigue life. It is emphasized that fatigue cracking from the root is governed by different design curves so toe treatment cannot be expected to provide any improvement in the general case. Improvement of details with incomplete penetration should be verified by fatigue testing or by analysis (Hobbacher, 2009). Examples of details in which root cracking might occur are shown in Fig. 2.2, but even nominally non-load-carrying welds may fail from the root when the toe has been improved. Consequently, when weld improvement is planned, full penetration welds or welds with extra large throats should be used where possible, particularly for welds at the ends of cover plates or longitudinal stiffeners.

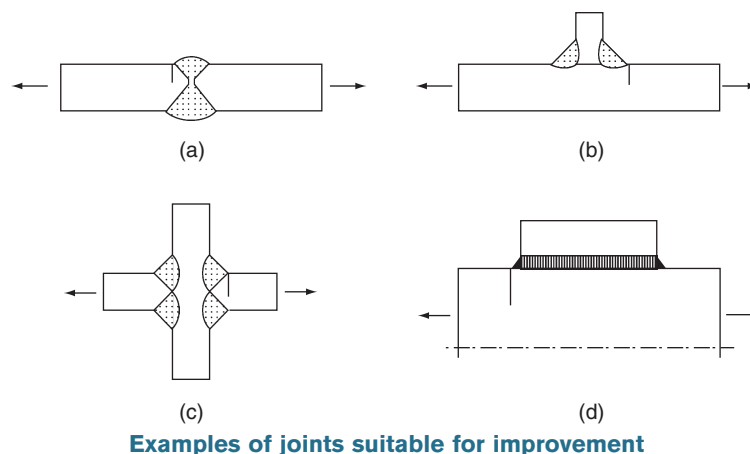
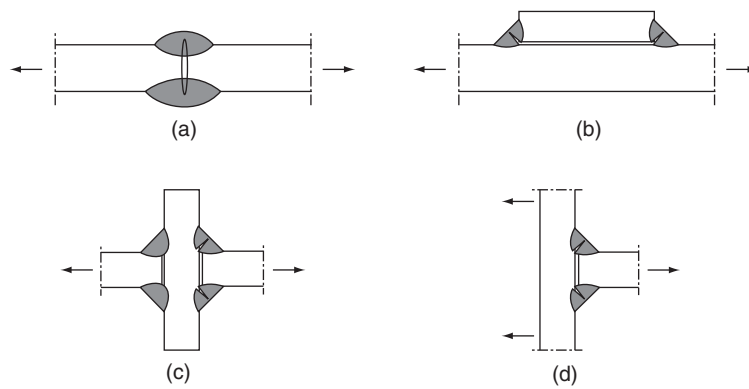


Fig. 2.1



Examples of details for which the improvement in fatigue strength is likely to be limited by the occurrence of root cracking. To ensure that a significant increase in fatigue strength is obtained, full penetration welds should be used in cases (a), (c) and (d), while an extra large weld throat should be used in case (b)

Fig. 2.2

3. BURR GRINDING

3.1 Introduction

The primary aim of grinding is to remove or reduce the size of the weld toe flaws from which fatigue cracks propagate. At the same time, it aims to reduce the local stress concentration effect of the weld profile by smoothly blending the transition between the plate and the weld face.

3.2 Equipment

A high-speed pneumatic, hydraulic or electric grinder with rotational speed from 15000 to 40000 rpm is required. A pressure from 5 to 7 bar for air-driven grinders is recommended. The tool bit is normally a tungsten carbide burr (or rotating file) with a hemispherical end (Fig. 3.1).



Pneumatic grinder and burrs

Fig. 3.1

To avoid a notch effect due to small radius grooves, the burr diameter should be scaled to the plate thickness (t) at the weld toe being ground (see Section 3.5). The diameter should be in the 10 to 25 mm range for application to welded joints with plate thickness from 10 to 50 mm, and the resulting root radius of the groove should be no less than $0.25t$.

3.3 Safety Aspects

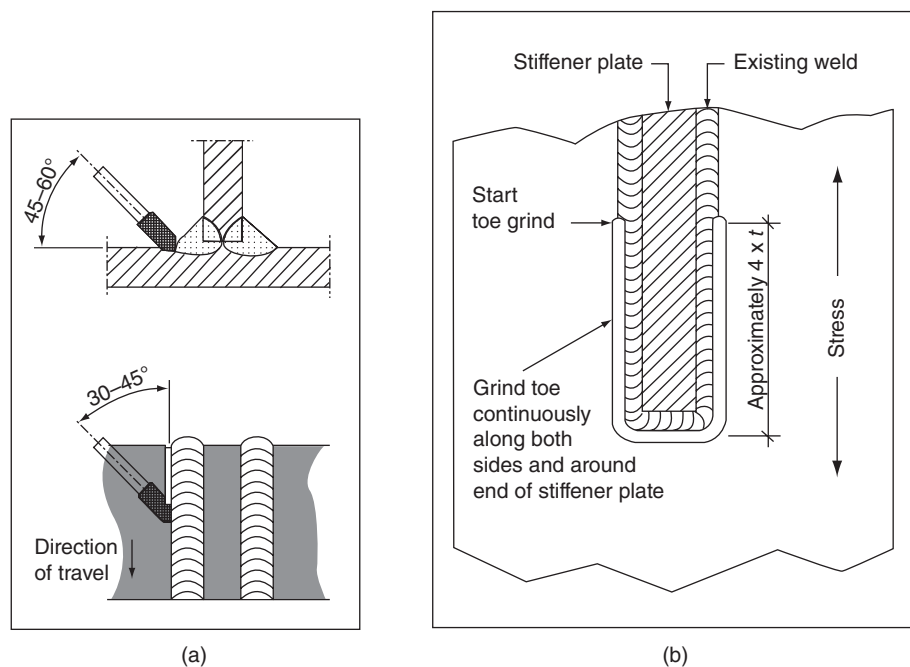
The high-speed grinding tool removes material at a high rate and is therefore capable of inflicting serious injuries to the operator or bystanders. The cutting operation itself produces hot, sharp cuttings and some noise. Therefore, appropriate protective clothing together with leather gloves, safety glasses and ear protection are strongly recommended.

3.4 Weld Preparation

The weld should be de-slugged and cleaned by wire brushing before burr grinding.

3.5 Procedure

The quality of grinding depends on the skill of the operator, and each operator should experiment to find a technique that gives the desired result. Therefore, only general advice is given below.



The weld toe burr grinding technique

Fig. 3.2

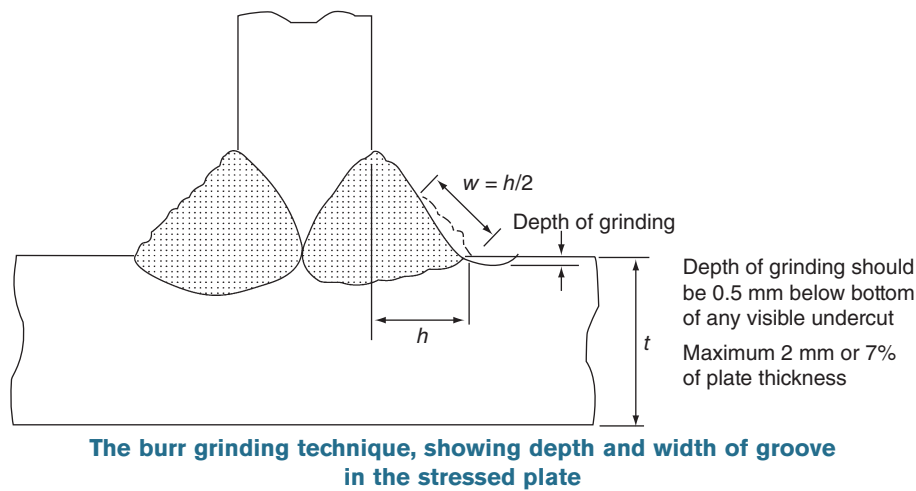


Fig. 3.3

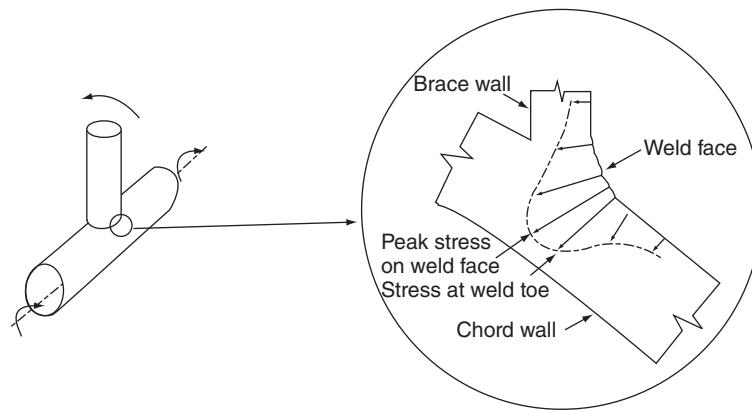
The burr grinding procedure is illustrated in Fig. 3.2. The burr is centred over the weld toe. The axis of the tool should be 45–60° to the main plate, and approximately 45° to the direction of travel. The grinder can be either pushed or pulled along the weld. Usually, the former is more successful at establishing a straight groove of even depth. Grinding has to be extended to areas well outside the highest stress region at the ends of attachments, as indicated for plate thickness t in Fig. 3.2(b).

In general, grinding must extend to a depth of at least 0.5 mm below any visible undercut, see Fig. 3.3. For plates up to 30 mm thick the maximum allowable depth is 7% of the plate thickness, with a limit of 2 mm for thicker members. However, it is clearly preferable to minimize the depth of groove produced and, in general, a maximum of 1 mm should be sufficient.

3.5.1 Large-scale Joints

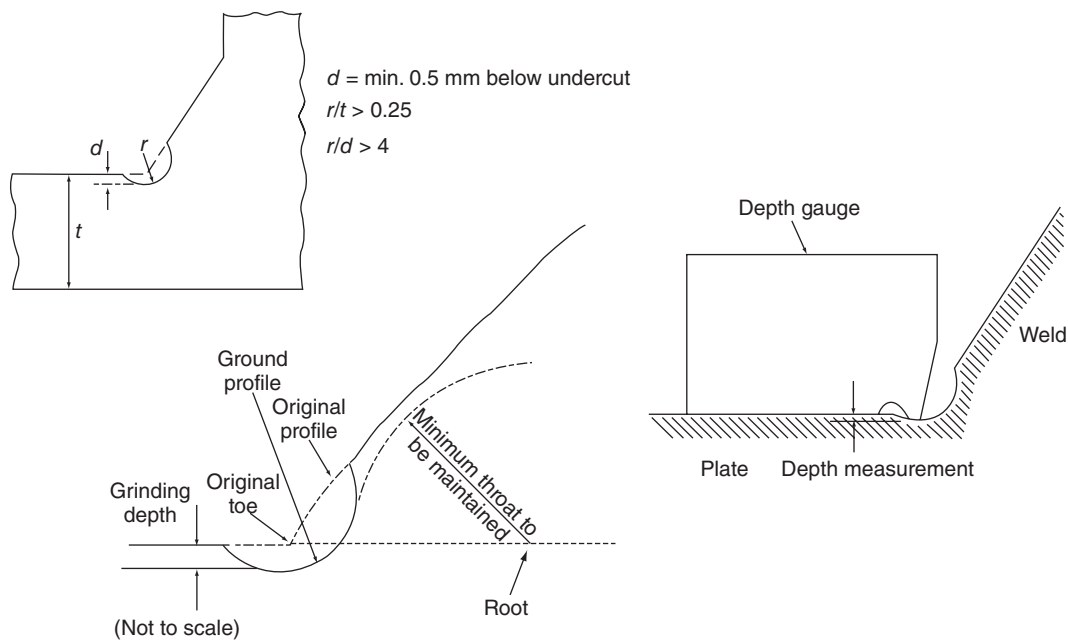
In large-scale planar welded joints with plate thickness in the order of 40 mm and more, the high notch stresses in the toe region extend up on the weld face, and inter-bead toes may also become crack initiation sites. This applies in particular to welds with low weld face angles. Such inter-bead toes should also be ground. As a guide, it should be sufficient to extend the treatment up the weld face by a distance (w) of at least half the leg length h , as illustrated in Fig. 3.3, but more extensive grinding may be prudent in critical cases. In this respect, a particular case where this situation arises is for welds in tubular joints, particularly those with large beta ratios (β = brace diameter/chord diameter), where the maximum stress is likely to be located on the weld face. Thus, as well as both weld toes, it is advisable to grind the whole weld face. The situation is illustrated in Fig. 3.4.

The weld toe geometry to be achieved by burr grinding is illustrated in Fig. 3.5. Note that an adequate throat thickness must be maintained for static strength and to limit the possibility of premature fatigue failure through the weld throat. As mentioned earlier, it is important that the burr radius r is scaled to the plate thickness and to the grinding depth d , otherwise the stress concentration factor will increase with increasing thickness. Unless alternative dimensions can be justified, those in Fig. 3.5 are recommended.



Stress distribution in a tubular joint (schematic), requiring grinding of the entire weld face and the weld toes in the brace and the chord

Fig. 3.4

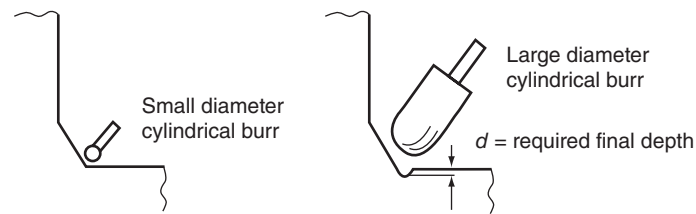


Details of burr ground weld toe geometry

Fig. 3.5

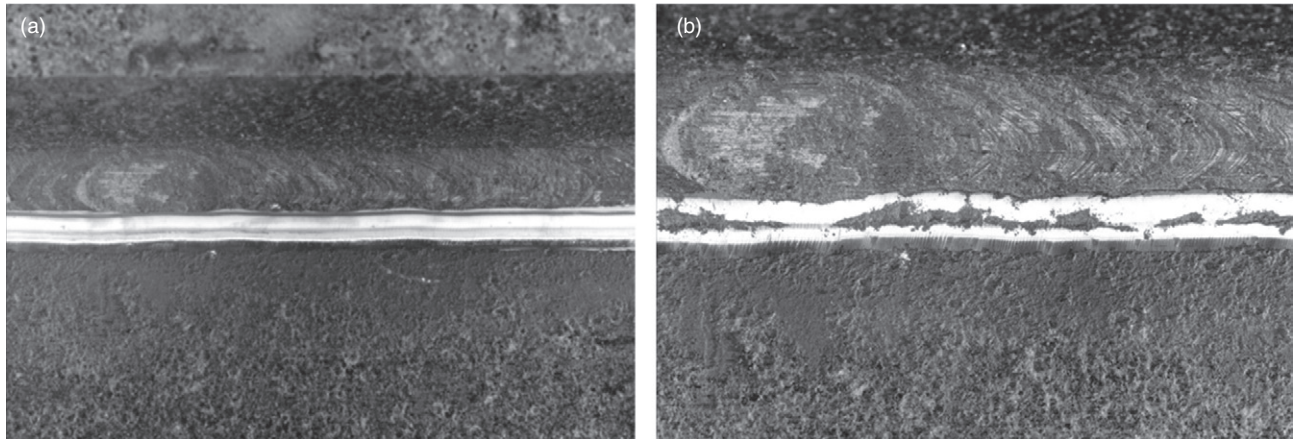
3.5.2 Two-stage Grinding

In the case of a steep weld angle fillet or T butt welds in thick plates, for which large diameter burrs are required, it is often found that the burr has a tendency to 'climb' up the weld face, making it difficult to position it on the weld toe line. In such circumstances, it is recommended that grinding should be carried out in two stages. First, a small spherical tool, e.g. 6 mm diameter, is used to establish a groove of the correct depth and position, see Fig. 3.6. The grinding operation is then completed with the larger diameter burr. In this way, it is easier to obtain the required quality of grinding in less time than when using the large diameter tool alone.



Two-stage grinding of large welds with steep weld angles

Fig. 3.6



Appearance of correctly and incorrectly burr ground fillet weld toes.
(a) Correctly ground weld toe, (b) incorrectly ground weld toe

Fig. 3.7

The grinding rate depends on the weld geometry and the material, but will be typically 50 to 100 mm per minute. The finished ground surface should be as smooth as possible, with no visible evidence of the original weld toe and any grinding marks at right angles to the weld toe line. Examples of the appearance of correctly and incorrectly ground welds are shown in Fig. 3.7 (a) and (b), respectively.

3.6 Corrosion Protection

Corrosion pitting of the ground metal surface virtually eliminates the benefit of burr grinding. Therefore, the ground surface must be adequately protected. The protection may be of a temporary nature, as would be the case for a part of an offshore structure that would eventually be submerged and protected by a cathodic protection system. In other cases, permanent protection must be provided, e.g. paint.

3.7 Operator and Inspector Training

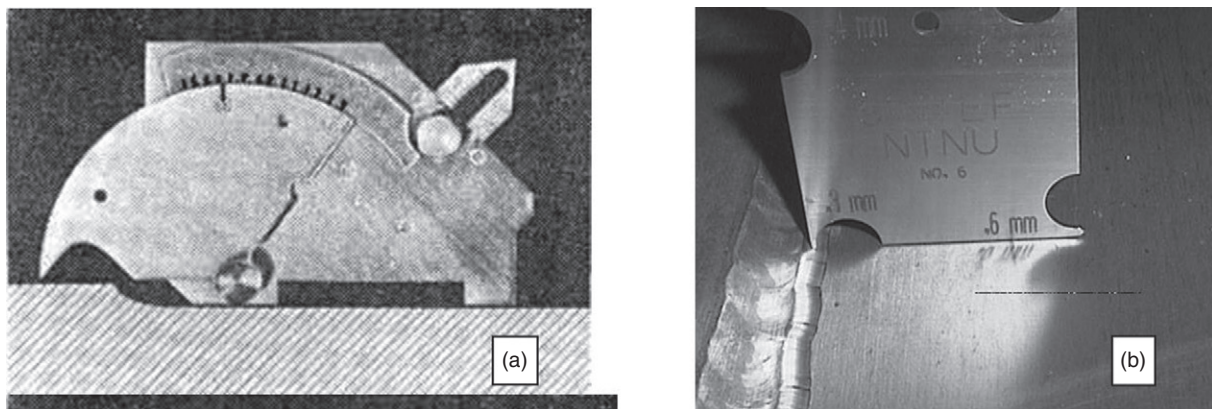
Some skill is required to perform burr grinding according to this specification, and a training programme should be implemented for inexperienced operators. This should include a demonstration of the appearance of an adequately ground weld as well as a demonstration of unacceptable welds, and an explanation of the factors that influence the result. Actual grinding of at least 2 metres of weld, combined with periodic inspection and evaluation, is recommended.

3.8 Inspection, Quality Control and Documentation

The inspection procedure must include a check on the weld toe radius, the depth of grinding and confirmation that the weld toe has been removed completely. A depth gauge similar to the one used for measuring weld toe undercut (see Fig. 3.8(a)) may be used, although the accuracy is low. Alternatively, a 'go-no go' type of gauge, such as shown in Fig. 3.8(b), may be more suitable. Visual examination under a bright light should be made to ensure that all traces of the original weld toe have disappeared. The ground surface of the groove should be inspected to make sure there are no deep scratches along the weld toe. A low-power (approximately x5) magnifying glass is suitable.

A cast of the weld made using a silicone rubber of the type used by dentists is useful for documentation and for measuring the local geometry at the weld toe.

Data pertaining to the procedure should be recorded for the purpose of quality control and quality assurance. The data are also useful for correlating fatigue performance with burr grinding conditions when fatigue testing is performed. Examples of suitable data sheets, similar to those used for welding procedure specification, are reproduced in Appendix 3.



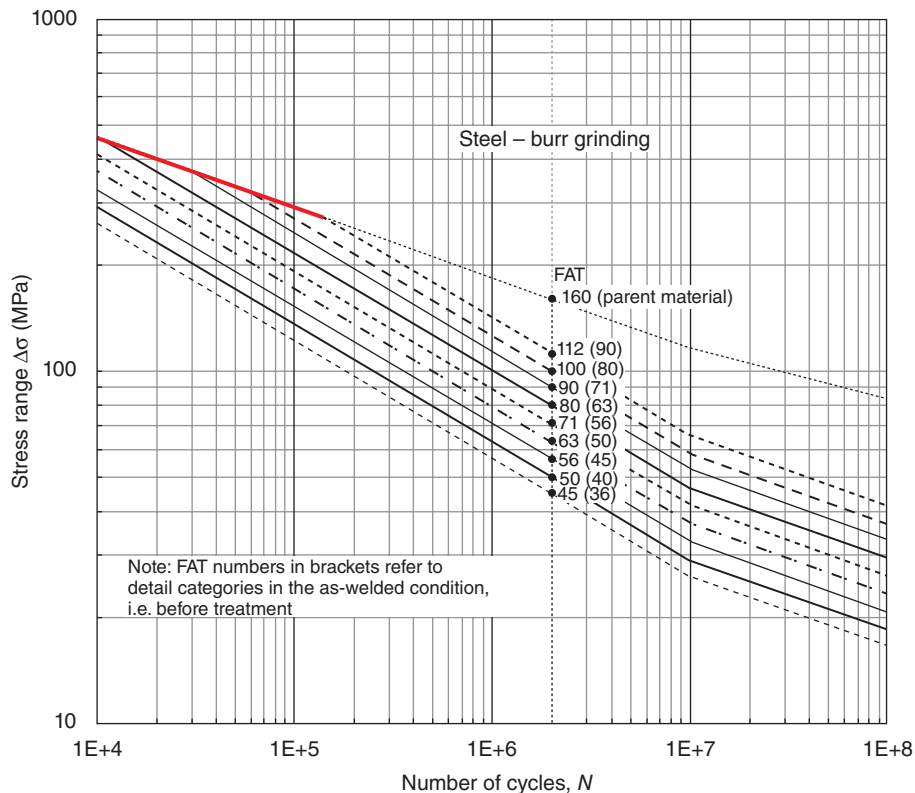
Gauges for checking depth of groove

Fig. 3.8

3.9 Fatigue Strength of Joints Improved by Burr Grinding

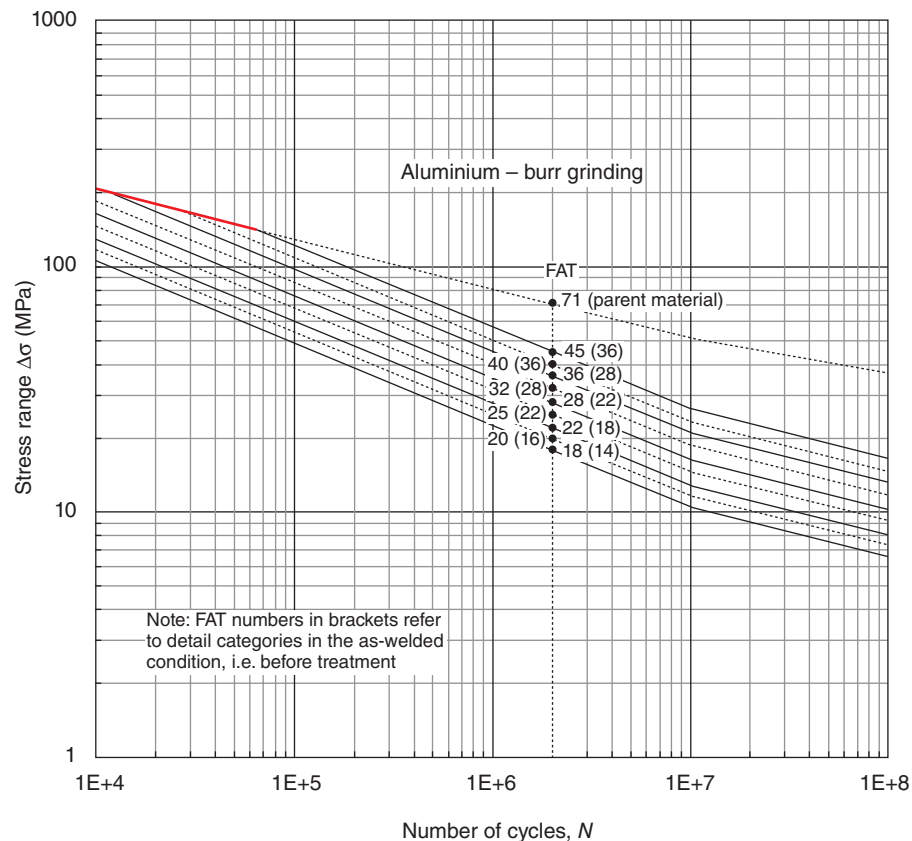
The benefit of weld toe burr grinding for steel can be claimed only for details in FAT 90 Class or lower in the IIW notation for S-N curves. This limitation is due to the fact that the higher classes include non-welded details, details whose lives are not governed by weld toe failure or welds that have already been improved, e.g. by grinding a butt weld flush with the surface.

For IIW FAT 90 or lower class details, the benefit of burr grinding corresponds to an increase in allowable stress range by a factor of 1.3, corresponding to a factor of 2.2 on life (for $m = 3$, the appropriate value for FAT 90 and lower). However, the maximum class that can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.3. For ease of computation, this corresponds to a two fatigue class increase. For example, when a weld detail that, in the as-welded condition, would be classified as FAT 63 is burr ground, the new FAT value is FAT 80. In Fig. 3.9, this S-N curve is denoted as 80 (63). The highest S-N curve that can be claimed following improvement is FAT 112, as shown in Fig. 3.9. The slopes of the S-N curves follow the IIW Recommendations for Fatigue Design (Hobbacher, 2009). For variable amplitude loading, the slope is changed from $m = 3$ to $m = 5$ at $N = 10^7$ cycles for FAT 112 details and lower. For constant amplitude loading there is either a change to a horizontal line (fatigue limit) at 10^7 cycles or, under special conditions, the slope parameter m is changed to 22 at 10^7 cycles, see Section 3.2 of Hobbacher (2009).



Design S-N curves for details improved by weld toe burr grinding in steel structures, variable amplitude loading

Fig. 3.9



Design S-N curves for details improved by weld toe burr grinding in aluminium structures, variable amplitude loading

Fig. 3.10

As shown in Fig. 3.9, all S-N curves in the low endurance region are limited by the parent material curve, i.e. the FAT 160 curve with a slope parameter of $m = 5$ (Hobbacher, 2009).

For welds improved by grinding in aluminium alloys, the benefit of burr grinding corresponds to an increase in allowable stress range by a factor of 1.3, corresponding to a factor of 2.2 on life (for $m = 3$). However, the maximum class that can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.3. For ease of computation, this corresponds to a two fatigue class increase. For example, when an aluminium weld detail that, in the as-welded condition, would be classified as FAT 22 is burr ground, the new FAT value is FAT 28. In Fig. 3.10, this S-N curve is denoted as 28 (22). The highest detail class for which an improvement can be claimed is FAT 36. The design class FAT 12 curve does not appear in Fig. 3.10 because it represents fatigue failure from the weld root, which is not influenced by burr grinding. The highest S-N curve that can be claimed following improvement is FAT 45, as shown in Fig. 3.10. The slopes of the S-N curves follow the IIW Recommendations for Fatigue Design. For variable amplitude loading, the slope is changed from $m = 3$ to $m = 5$ at $N = 10^7$ cycles for FAT 50 details and lower. For constant amplitude loading, m is changed to 22 at $N = 10^7$ cycles, see Section 3.2 of Hobbacher (2009).

As for steel, and as shown in Fig. 3.10, all S-N curves in the low endurance region are limited by the parent material design curve, i.e. the FAT 71 curve with a slope parameter of $m = 5$.

3.10 Thickness Effect for Joints Improved by Burr Grinding

Weld toe grinding reduces the stress concentration factor, and in accordance with Section 3.5.2 of Hobbacher (2009), the thickness correction factor $f(t)$ for toe ground joints is:

$$f(t) = \left(\frac{25}{t_{eff}} \right)^{0.20} \quad [3.1]$$

where $t_{eff} = L/2$ for $L/t < 2$ and $t_{eff} = t$ for $L/t \geq 2$; L is the sum of the thickness or length of the attachment and the weld leg lengths as shown in Fig. 3.11 (Hobbacher 2009).

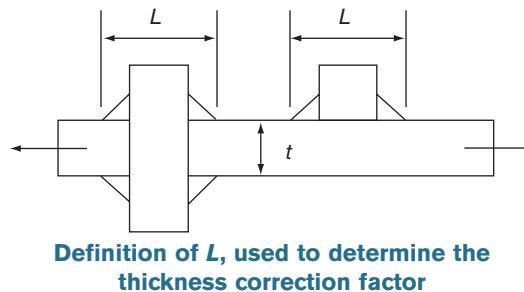


Fig. 3.11

4. TUNGSTEN INERT GAS (TIG) DRESSING

4.1 Introduction

The objective of TIG dressing is to remove the weld toe flaws by re-melting the material at the weld toe. It also aims to reduce the local stress concentration effect of the local weld toe profile by providing a smooth transition between the plate and the weld face.

The present Recommendations are applicable only to connections with main plate thicknesses of at least 4 mm for aluminium and 6 mm for steel.

4.2 Equipment

A standard TIG welding machine is used, normally with argon as shielding gas. The addition of helium is beneficial since this gives a larger pool of melted metal due to a higher heat input. Typical conditions and range of dressing parameters used in reported tests are shown in Table 4.1, while Fig. 4.1 shows manual TIG dressing of a weld toe.

Table 4.1 Typical TIG dressing conditions for steel

Shielding gas	Argon or argon + helium ^a
Gas flow rate	7–12 litre/min
Nozzle diameter	10–14 mm
Preheat	50–200°C
Electrode diameter	3 to 4 mm
Voltage (V)	12–17 volts
Current (A)	160–250 amperes
Dressing speed (S)	80–160 mm/min
Heat input (Q) ^b	1.0–2.5 kJ/mm

^aDependent on steel type and plate thickness.

^bHeat input is calculated from $Q = \frac{60 \times V \times A}{1000 \times S}$ (kJ/mm).



**TIG dressing equipment and
a partially dressed weld**

Fig. 4.1

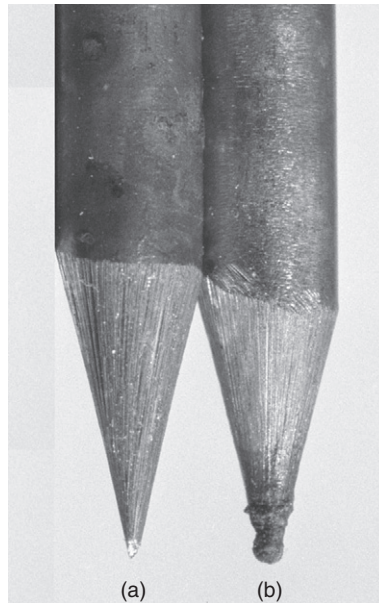
4.3 Weld Preparation

TIG dressing is sensitive to most types of common plate and weld surface contaminants, such as mill scale, rust, oil and paint. The weld and adjacent plate should be thoroughly de-slagged and wire brushed. If necessary, light grinding should be used to obtain a clean surface. Insufficient cleaning tends to result in the formation of gas pores that can have a strongly detrimental effect on fatigue performance. The problem of porosity is particularly important in TIG dressed aluminium welds.

4.4 Dressing Conditions and Procedure

4.4.1 Tungsten Electrode

The shape of the arc depends on the shape and condition of the electrode tip. If the tip is contaminated, or rounded by wear (oxidation), the arc becomes concentrated, with the result that the re-melted zone narrows with an unfavourable effect on the bead shape. It is also difficult to start the arc and to keep it stable. These problems can be avoided by re-grinding the tip or replacing the electrode. Acceptable and unacceptable electrode tips are shown in Fig. 4.2 (a) and (b) respectively.



Electrodes for TIG torch: (a) unused tip, (b) contaminated electrode used on oxidized plate (after Millington, 1973)

Fig. 4.2

4.4.2 Shielding Gas

If the gas flow rate is low, or strong draughts disturb the gas shield, the arc becomes unstable and defects such as surface pores are formed, or the electrode and bead oxidize. An adequate gas supply rate depends on many factors, including gas shroud (cup) size, welding conditions and welding location (presence of draughts). An optimum flow rate should therefore be determined by trial dressing. For TIG dressing of duplex stainless steels, it is advisable to add 1% to 2% nitrogen to the shielding gas to avoid unfavourable changes to the austenite–ferrite balance.

4.4.3 Pre-heat (Steel Only)

The heat input during TIG dressing is normally less than that used for welding the joint. Therefore, as a general rule, the minimum pre-heat temperature used should be equal to that specified in the welding procedure. The exception to this is welds produced by the flux-cored arc welding (FCAW) process on account of their high hydrogen content. If TIG dressing is carried out just after welding, a pre-heat of approximately 150°C for a minimum of 20 minutes must then be chosen to avoid cracking of the weld metal. However, some time after welding is completed, the hydrogen content is less and the risk of weld metal cracking is reduced, with the result that the pre-heat temperature can be reduced. In this case, therefore, the pre-heat temperature for TIG dressing of FCAW joints may be chosen on the basis of the pre-heat temperature that would be used for MMA welding. For steels with a carbon content in excess of 0.12% weight, the possible formation of hard zones in the heat-affected zone (HAZ) should be considered. In such cases, a second tempering TIG pass on the weld metal should be considered (Haagensen, 1978).

4.4.4 Dressing Parameters

The objective of TIG dressing is to obtain a smooth transition from the plate to the weld bead. Dressing conditions may vary with welding position, but, as a general rule, a high heat input should be used since this normally gives a low hardness in the HAZ as well as allowing higher dressing speeds. However, care is needed since excessive heat input caused by a combination of high current and a low travel speed usually produces undercut or a poor bead profile. Suitable dressing conditions for the horizontal-vertical position are shown in Fig. 4.3.

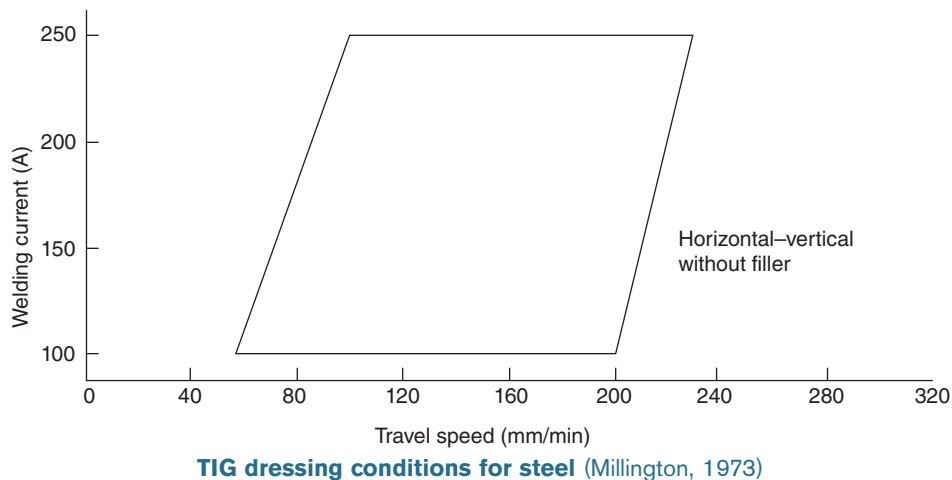


Fig. 4.3

4.4.5 Position of TIG Torch and Dressing Zone

For an optimum result, the re-melted zone has to be positioned carefully with respect to the original weld toe. Normally, the best result is obtained when the arc centre is located a small distance p away from the weld toe, as indicated in Fig. 4.4(a). Also shown in Fig. 4.4(a) is a slight sideways tilt of the torch from the perpendicular position to obtain a favourable bead profile. In addition, the small backward tilt shown in Fig. 4.4(b) may help to maintain an adequate gas shield.

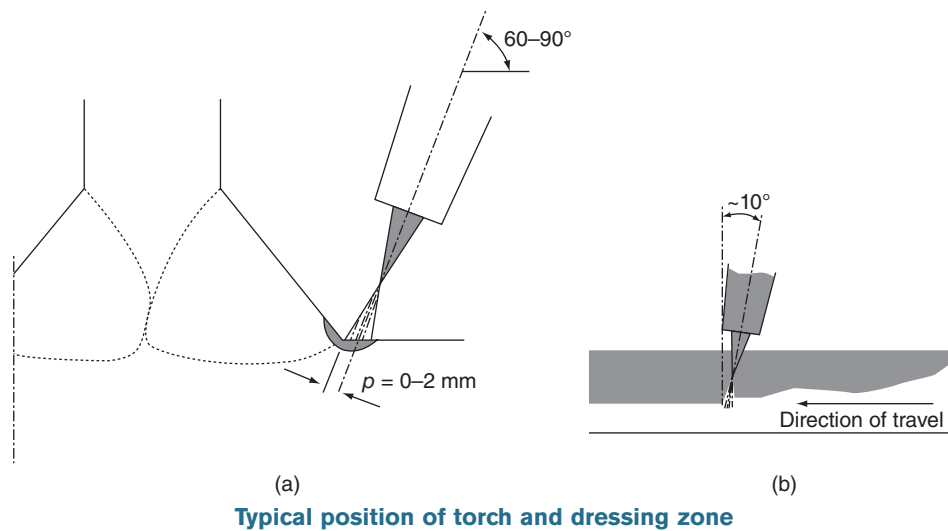
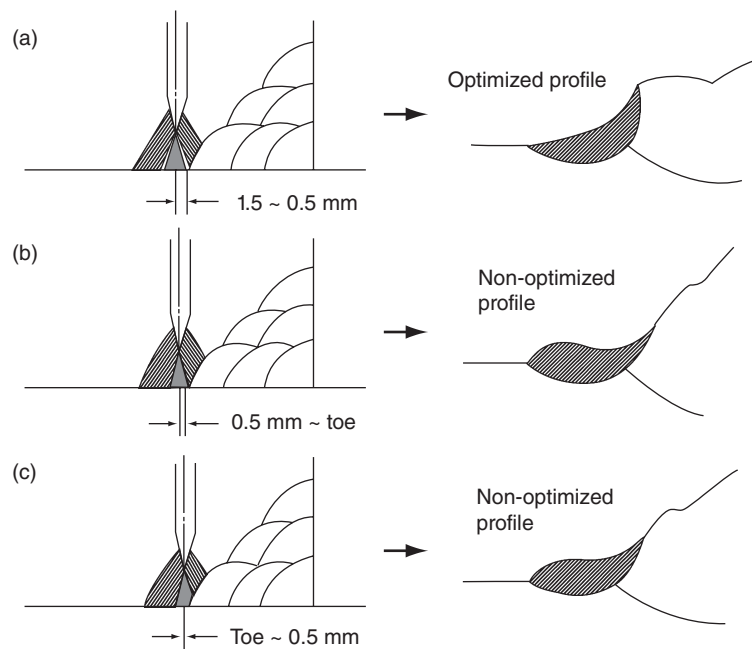


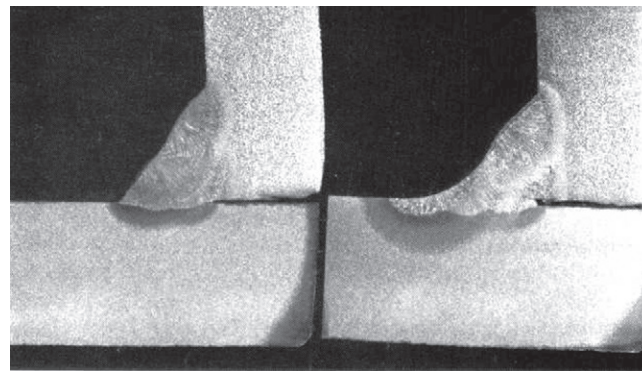
Fig. 4.4

If the arc is positioned too close to the weld bead, it may result in the formation of a new toe as shown in Fig. 4.5(b) and (c). In general, the electrode should be directed more towards the parent plate for steeper weld profiles, whereas for flatter beads, the electrode should be positioned closer to the weld toe. If bead shapes similar to those shown in Fig. 4.5(b) and (c) are obtained, remedial treatment should be considered, see Section 4.6. A re-melted weld toe as shown in Fig. 4.5(a) represents an optimum shape with respect to fatigue. An example of a satisfactorily treated weld profile is shown in Fig. 4.6. Care is also needed to ensure that the original weld toe is, in fact, re-melted. Experience indicates that the fatigue life of a region where TIG dressing has missed the toe is the same as that of the as-welded joint.



Position of TIG torch tip in relation to weld toe, and resulting profiles: (a) over plate, 0.5 to 1 mm from toe; (b) over plate, less than 0.5 mm from toe; (c) over weld, up to 0.5 mm from toe
(Kato *et al.* 1975)

Fig. 4.5

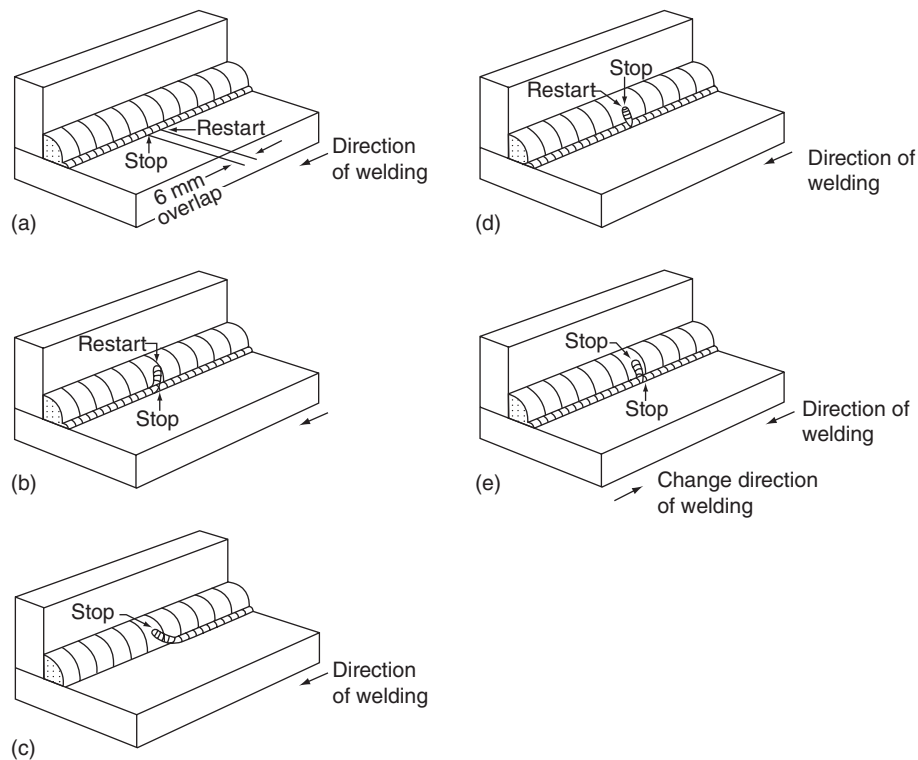


(a) (b)
**Fillet weld (a) before and (b) after TIG dressing
 (x2 magnification)**

Fig. 4.6

4.4.6 Arc Stopping and Restarting

Arc stopping and starting may create craters or unfavourable bead profiles. This can be avoided by restarting the arc about 6 mm behind a stop position, as indicated in Fig. 4.7(a). Alternatively, the arc may be started on the bead and moved to the toe, Fig. 4.7(b). The stop can also be made on the bead, Fig. 4.7(c). The methods illustrated in Fig. 4.7(a) to (c) may be combined, as shown in Fig. 4.7(d). Craters may also be avoided by changing the direction of arc movement, see Fig. 4.7(e). The operator should try various stop/restart techniques and choose one that gives a favourable bead shape.



TIG dressing stop and restart techniques (after Millington, 1973)

Fig. 4.7

4.5 Operator and Inspector Training

The quality of TIG dressing depends on an optimum combination of dressing parameters and the manual skills of the operator. The optimum dressing conditions are related to the individual characteristics of the welding equipment. The optimum shape of the dressed profile also depends to some extent on the shape of the initial bead profile. For this reason it is recommended that a trial programme be set up to familiarize the welder with the technique and develop optimum dressing conditions. The trials should include dressing with different heat inputs and torch positions. Arc starting and stopping techniques should also be practised, see Section 4.4.6. After completing the training, the operator should treat at least 1 metre of similar weld before starting production treatment.

4.6 Remedial Dressing

If the TIG-dressed weld does not satisfy the inspection criterion with respect to weld shape (see Section 4.8), a new dressing run may be performed. If necessary, a weaving technique may be tried or filler material could be added. The ease of repeating TIG dressing is one of the advantages of this method.

4.7 Corrosion Protection

The benefit of TIG dressing is reduced if the surface is degraded by corrosion. Therefore, for maximum benefit, the TIG-dressed surface must be adequately protected against possible corrosion. The protection may be of a temporary nature, as would be the case for a part of an offshore structure that would eventually be submerged and protected by a cathodic protection system. In other cases, permanent protection must be provided by other means, e.g. paint.

4.8 Inspection, Quality Control and Documentation

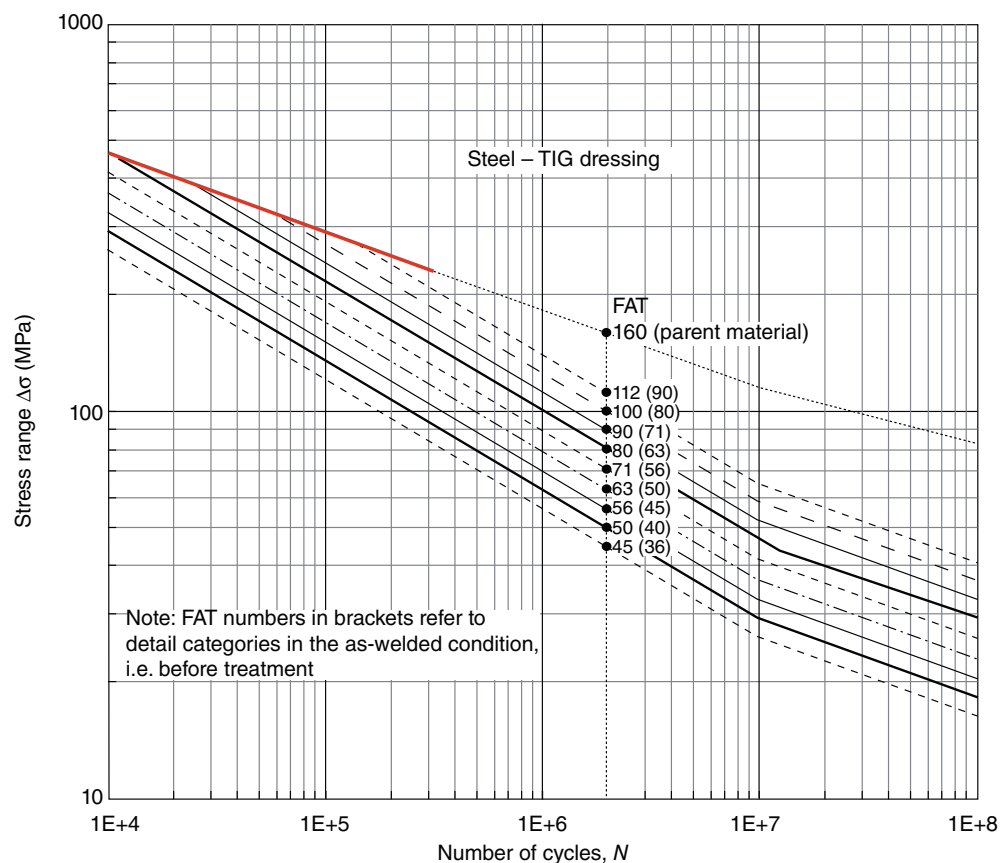
The dressed weld should have a smooth transition from the plate to the weld face, in accordance with Figs 4.5 and 4.6. The minimum toe radius at this transition region is 3 mm, but larger radii are allowable and may permit easier inspection. The weld should be checked for complete treatment along the entire length of the part treated. If any part of the weld toe has been missed by the TIG dressing, it should be treated again.

Data pertaining to the procedure should be recorded for the purpose of quality control and quality assurance. The data are also useful for correlating fatigue performance with TIG dressing conditions when fatigue testing is performed. An example of a data sheet for TIG dressing, similar to that used for welding procedure specification, is reproduced in Appendix 3.

4.9 Fatigue Strength of Joints Improved by TIG Dressing

The benefit of TIG dressing for steel can be claimed only for details in FAT 90 Class or lower in the IIW notation for S-N curves. This limitation is due to the fact that the higher classes include non-welded details, details whose lives are not governed by weld toe failure or welds that have already been improved, e.g. by grinding a butt weld flush with the surface.

For IIW FAT 90 or lower class details, the benefit of TIG dressing corresponds to an increase in allowable stress range by a factor of 1.3, corresponding to a factor of 2.2 on life (for $m = 3$, the appropriate value for FAT 90 and lower). However, the maximum class that can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.3. For ease of computation, this corresponds to a two fatigue class increase. For example, when a weld detail that, in the as-welded condition, would be classified as FAT 63 is improved by TIG dressing, the new FAT value is FAT 80. In Fig. 4.8, this S-N curve is denoted as 80 (63). The highest S-N curve that can be claimed following improvement is FAT 112, as shown in Fig. 4.8. The slopes of the S-N curves follow the IIW Recommendations for Fatigue Design (Hobbacher, 2009). For variable amplitude loading, the slope is changed from $m = 3$ to $m = 5$ at $N = 10^7$ cycles for FAT 112 details and lower. For constant amplitude loading there is either a change to a horizontal line (fatigue limit) at $N = 10^7$ cycles or, under special conditions, the slope parameter m is changed to 22 at 10^7 cycles, see Section 3.2 of Hobbacher (2009).



Design S-N curves for details improved by weld toe TIG dressing in steel structures, variable amplitude loading

Fig. 4.8

As shown in Fig. 4.8, all S-N curves in the low endurance region are limited by the parent material curve, i.e. the FAT 160 curve with a slope parameter of $m = 5$ (Hobbacher, 2009).

For welds improved by TIG dressing in aluminium alloys, the benefit corresponds to an increase in allowable stress range by a factor of 1.3, corresponding to a factor of 2.2 on life (for $m = 3$). However, the maximum class that can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.3. For ease of computation, this corresponds to a two fatigue class increase. For example, when an aluminium weld detail that, in the as-welded condition, would be classified as FAT 22 is TIG dressed, the new FAT value is FAT 28. In Fig. 4.9, this S-N curve is denoted as 28 (22). The highest detail class for which an improvement can be claimed is FAT 36. The design class FAT 12 curve does not appear in Fig. 4.9 because it represents fatigue failure from the weld root, which is not influenced by TIG dressing. The highest S-N curve that can be claimed following improvement is FAT 45, as shown in Fig. 4.9. The slopes of the S-N curves follow the IIW Recommendations for Fatigue Design. For variable amplitude loading, the slope is changed from $m = 3$ to $m = 5$ at $N = 10^7$ cycles for FAT 50 details and lower. For constant amplitude loading, m is changed to 22 at 10^7 cycles, see Section 3.2 of Hobbacher (2009).

As for steel, and as shown in Fig. 4.9, all S-N curves in the low endurance region are limited by the parent material design curve, i.e. the FAT 71 curve with a slope parameter of $m = 5$.

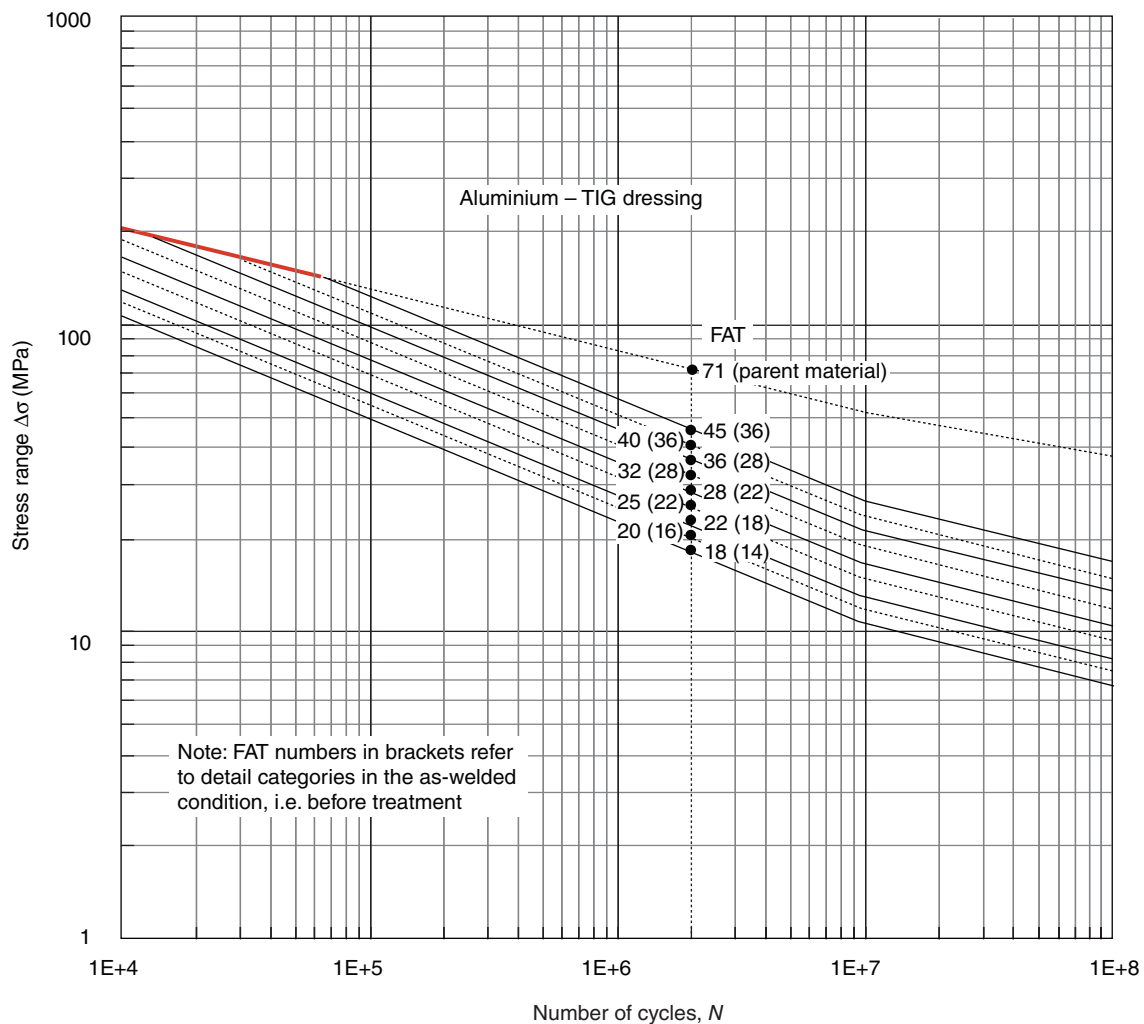


Fig. 4.9

4.10 Thickness Effect for Joints Improved by TIG Dressing

The thickness effect of joints improved by TIG dressing is the same as the thickness effect of joints improved by burr grinding and is described in Section 3.10 of this Recommendation.

5. HAMMER PEENING

5.1 Introduction

In hammer peening, compressive residual stresses are induced as a result of plastic deformation produced by repeatedly hammering the weld toe region with a blunt-nosed chisel. The following specification is applicable only to connections with main plate thickness of at least 4 mm for steel and 8 mm for aluminium.

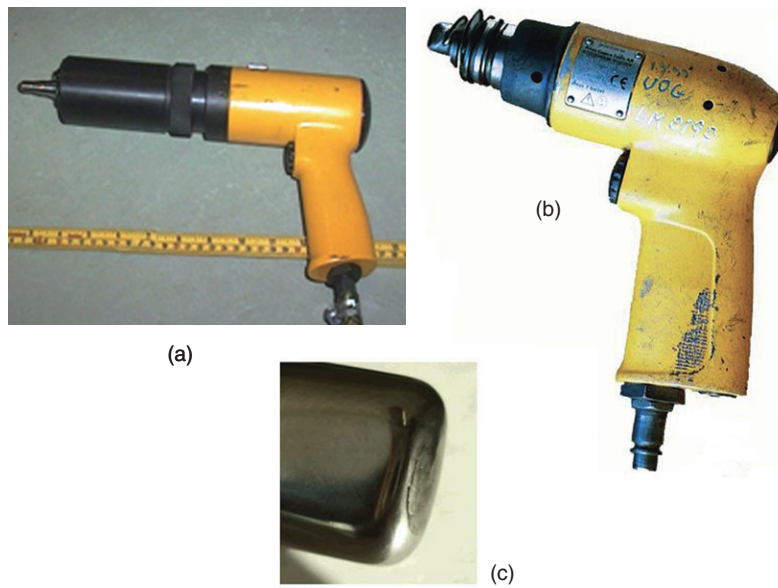
The benefit of hammer peening depends to a large extent on whether the weld to be peened is under tensile or compressive loading during the peening operation. A better result can be expected if the component is loaded during peening in such a way as to give *tensile* stress in the region to be peened (Fisher *et al.*, 1974). Conversely, an applied *compressive* stress during peening will reduce the effectiveness of the treatment and therefore it is advisable to verify the degree of improvement by fatigue testing.

5.2 Equipment

A pneumatic or hydraulic hammer is commonly used. A suitable pneumatic hammer gun has a 15 to 30 mm diameter piston, operates at an air pressure of 5 to 7 bar and delivers 25 to 100 impacts per second. Impact energy is typically in the range 5 to 15 joules. The weight of the gun is typically 1 to 3.5 kg. Most research investigations of hammer peening have made use of the above types of hammer guns, both of which are primarily intended for use as chipping hammers. However, riveting guns have also been found to be suitable for peening because they are lighter and have better vibration damping. These features will increase operator comfort and ease of use, which in turn should improve control over the peening operation and hence consistency and reliability of the resulting treatment. Riveting guns used successfully for hammer peening are shown in Fig. 5.1.

Hardened steel tool bits with hemispherical tips and radii between 3 and 9 mm (Fig. 5.1(a)), or elongated tips to follow the weld toe (Fig. 5.1(b)), are used. Such tools are not generally available as standard equipment, but they can be produced relatively simply by grinding and polishing the tips of standard chisels. In the case of tools with elongated tips, it may be necessary to restrict their rotation in the hammer gun chuck.

The tip of the tool will wear, causing flattening and surface roughening, and therefore it should be checked regularly with a gauge and, if necessary, ground and polished to a mirror finish. After extensive use, fatigue cracking may occur at the tip of the tool, see Fig. 5.1(c).



**Pneumatic riveting guns used for hammer peening with:
(a) hemispherical tip, (b) elongated tip, (c) worn and cracked tip**

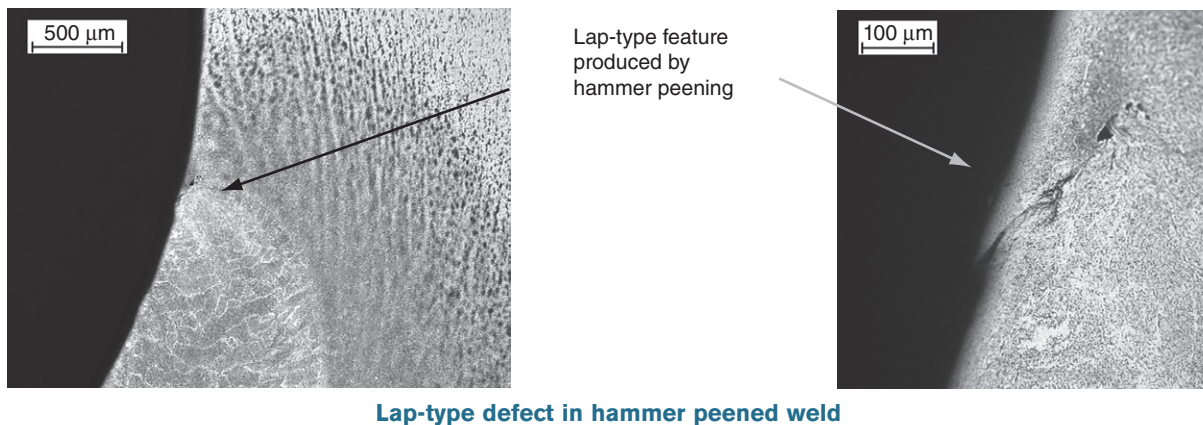
Fig. 5.1

5.3 Operator and Inspector Training

Hammer peening is carried out manually. Some skill is required: therefore, the operator should receive appropriate training, including a demonstration of successfully treated welds as well as unacceptable treatment. A Production Data Sheet (see Appendix 3), similar to a welding procedure specification, should be written. Some trial treatments, over at least 1 metre of weld, should be carried out before attempting to treat the actual component.

5.4 Weld Preparation

The weld cap and adjacent parent material should be fully de-slugged and wire brushed or ground to remove all traces of oxide, scale, spatter and other foreign material. Peening of the toe, especially of a peaky or severely convex weld profile, can cause the plastically deformed metal to fold over the original weld toe and leave a crack-like lap feature that resembles a cold lap, as illustrated in Fig. 5.2. The resulting fatigue performance of the welded joint may actually be less than that of the original as-welded joint. Therefore, it is advisable to grind the weld lightly to improve its shape and create a groove that facilitates a steady movement of the hammer tool. The same type of flaw has been observed in welds with adequate profiles but in which the material was relatively soft, such that the required depth of peening could be achieved in just one or two passes. However, again light grinding to improve the weld profile should eliminate the problem.



Lap-type defect in hammer peened weld

Fig. 5.2

5.5 Safety Aspects

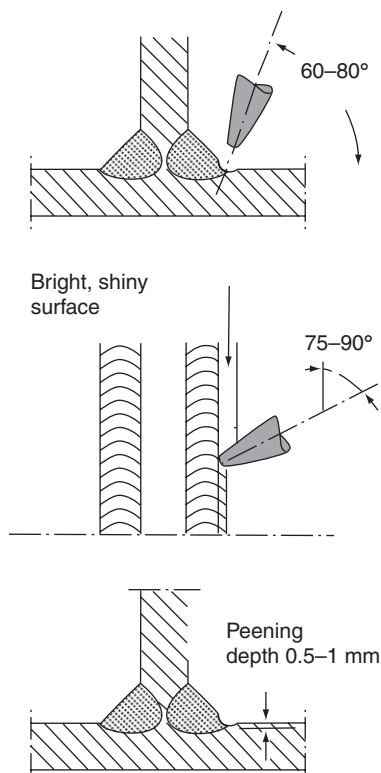
Hammer peening, even using modern silenced hammers, is a noisy operation and it is essential that the operator and others working in the vicinity should use ear protection. Normal protective clothing for working in a fabrication shop is adequate, but it should include a face-mask or goggles. Vibration from peening equipment may cause physical discomfort or harm, and the operator should not perform the operation for extended periods of time. Vibration damping gloves may help to mitigate this problem.

5.6 Procedure

The aim in hammer peening is to plastically deform the material at the weld toe to introduce beneficial compressive residual stresses.

Effective treatment requires reasonably accurate positioning of the tip of the tool over the weld toe, which is facilitated by prior grinding so that metal on each side (both weld metal and parent plate) is deformed. This will normally be achieved by supporting the hammer firmly and keeping the peening tool tip in close contact with the weld toe as it is moved along the weld. The hammer peening tool should be held at a suitable angle for producing reasonably uniform deformation either side of the weld toe, typically between 45 and 80 degrees to the plate surface, and approximately perpendicular (75 to 90 degrees) to the direction of travel, as shown in Fig. 5.3.

The resulting groove must be smooth and free from obvious individual indentations, as illustrated in Fig. 5.4(a). The travel speed will depend to some extent on access and hammer peening position, but also on the equipment used. In the case of a heavy hammer gun, vibrations will cause the tool to jump along the weld, missing some areas. Repeated peening, but rarely more than four passes, is then needed to achieve full coverage and a smooth surface. Lighter, vibration-damped hammer guns facilitate slower travel speeds, and hence more thorough treatment per pass. A travel speed of 50 to 100 mm/min per pass, similar to typical welding speeds, is normally sufficient to achieve the required depth in one pass, although a lower speed might be necessary for higher strength steels.

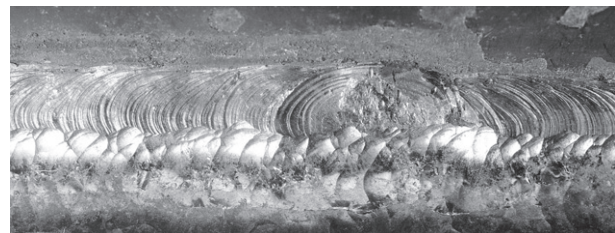


Hammer peening operation

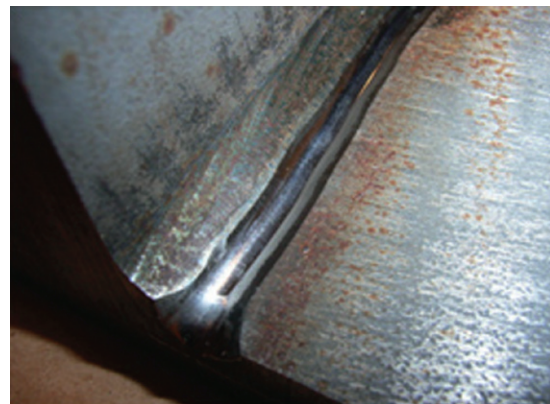
Fig. 5.3



(a)



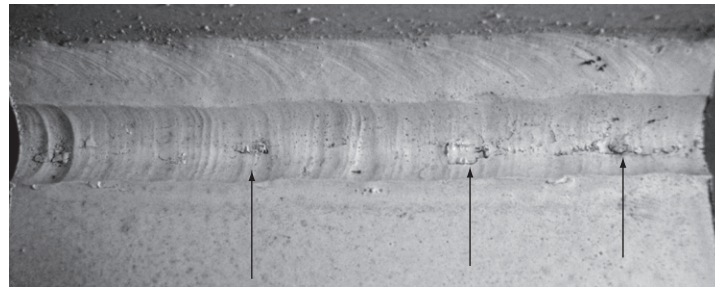
(b)



(c)

Examples of hammer peened weld toes in steel: (a) acceptable, with sufficient coverage to leave a smooth surface; (b) unacceptable, with individual indentations visible due to insufficient coverage; (c) fatigue test specimen peened with the tool in Fig. 5.1(b)

Fig. 5.4



Weld toe lap-type flaws produced by hammer peening revealed by magnetic particle inspection (arrowed)

Fig. 5.5

The diameter of the tool tip influences the resulting appearance of the hammer peened surface. In general, the smaller the diameter, the greater the likelihood that the actual weld toe itself will be peened and eventually disappear. Peening with a large diameter tool (greater than 12 mm) does not usually reach the weld toe but instead deforms material either side of it. Although, in general, the desired effect will be achieved with fewer passes using a large diameter tool, the presence of the original weld toe is a disadvantage from the viewpoint of inspection. In particular, it is not obvious that the toe has been correctly treated (i.e. left in a state of compressive residual stress) and remnant traces of weld toe confuse in-service inspection, since it is difficult to distinguish between them and fatigue cracks. Thus, the use of a small diameter tool, or a combination of small and large diameter tools, with the aim of deforming the actual weld toe offers the best compromise. Inspection would then ensure that all traces of the original weld toe had disappeared. The smoother surface obtained with the elongated tool tip in Fig. 5.1(b) makes it easier to find lap defects such as those shown in Figs 5.2 and 5.5.

In circumstances in which the treated weld will be subjected to a high-tensile mean stress in service, hammer peening will offer little or no benefit. When practicable, this problem can be mitigated by performing the peening operation while the weld is under tensile stress. For maximum benefit, this should be at least as high as the minimum stress to be experienced in service.

5.7 Inspection, Quality Control and Documentation

In general, it is not possible to verify that hammer peening has been performed correctly by visual inspection alone. Important features such as coverage and surface finish can only be described qualitatively, while the extent of plastic deformation, which reflects the level of compressive residual stress induced, is too small for reliable measurement in most practical circumstances. An important step is therefore to establish an acceptable hammer peening procedure and then to ensure that it is followed. The hammer peening procedure should be established by performing trials on the material to be treated, preferably containing a representative weld, in the same position as the welded joint to be treated. The toe should be peened and examined after each pass. The treatment can be assumed to be complete when there is a uniform indentation along the weld toe with a smooth surface finish, and all traces of the original weld toe have disappeared. As a guide, but not a requirement, the indentation depth below the original plate surface is likely to be of the order of 0.5 mm. The minimum depth is 0.15 mm. The indentation depth will not normally exceed 1 mm. If it is suspected that lap-type flaws of the kind shown in Fig. 5.5 have been produced, the treated area should be inspected carefully. Visual inspection will require a bright light and magnifying glass. Some success at detecting the flaws in ferritic steel has been achieved using magnetic particle inspection (Fig. 5.5). Treatment of

the actual weld detail should be verified by visual inspection. This will check hammer peening position, coverage and general uniformity by comparing the hammer peened area with a reference sample or photograph.

Data pertaining to the procedure should be recorded for the purpose of quality control and quality assurance. The data are also useful for correlating fatigue performance with hammer peening conditions when fatigue testing is performed. An example of a production data sheet, similar to those used for welding procedure specification, is reproduced in Appendix 3. Test pieces used in trials should be retained for later review.

5.8 Fatigue Strength of Joints Improved by Hammer Peening

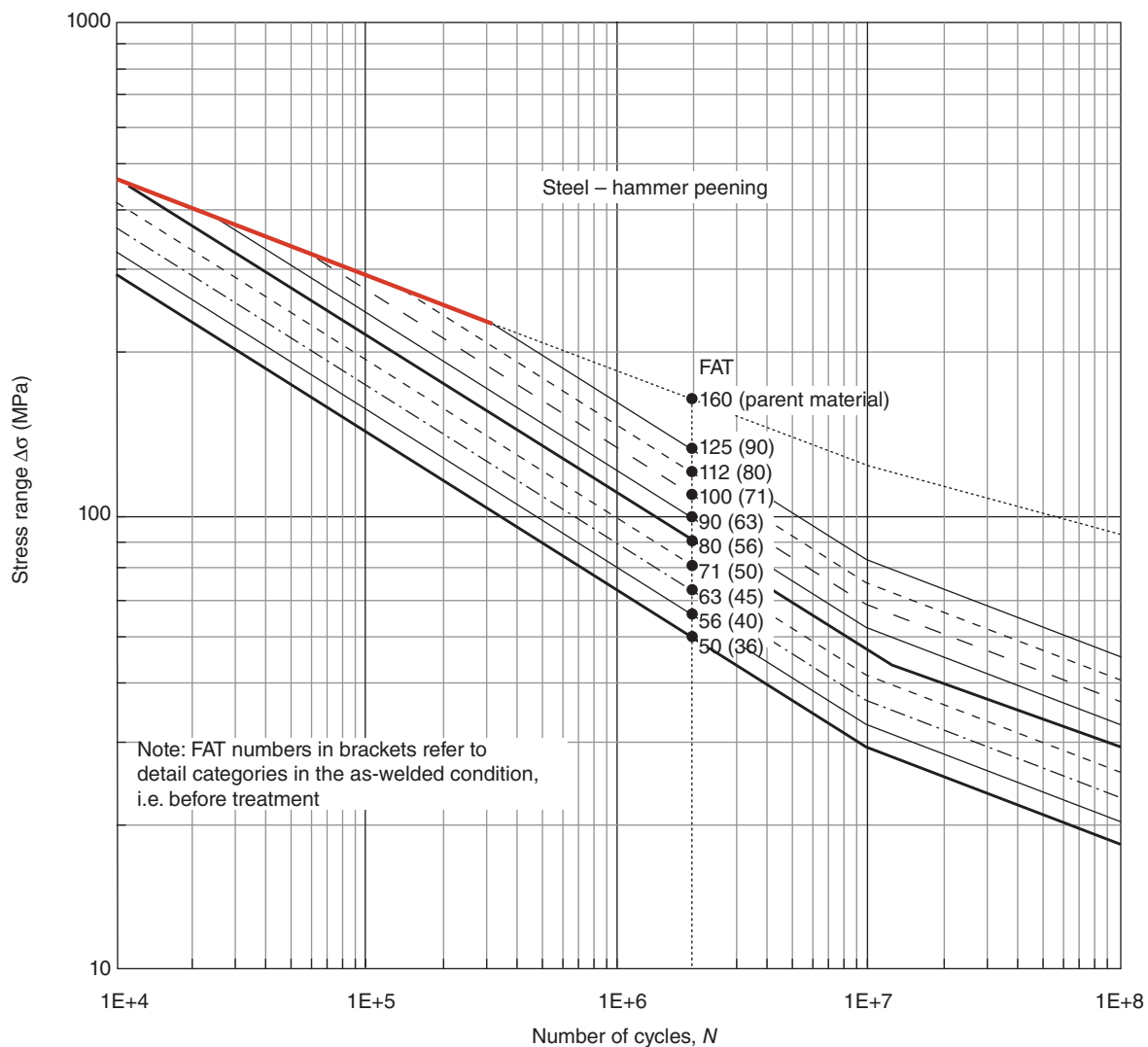
The benefit of weld toe hammer peening for steel can be claimed only for details in design Class FAT 90 or lower in the IIW notation for S-N curves, as shown in Fig. 5.6. This limitation is due to the fact that the higher classes include non-welded details, details whose lives are not governed by weld toe failure or welds that have already been improved, e.g. by grinding a butt weld flush with the surface.

For IIW FAT 90 or lower class details in steels with specified yield stress higher than 350 MPa, the benefit consists of an increase in allowable stress range by a factor of 1.5, corresponding to a factor of 3.375 on life (for $m = 3$, the appropriate value for FAT 90 and lower). However, the maximum class that can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.5. For ease of computation, this corresponds to a three fatigue class increase. For example, when a weld detail that, in the as-welded condition, would be classified as FAT 63 is hammer peened, the new FAT value is FAT 90. In Fig. 5.6 this S-N curve is denoted as 90 (63). The highest S-N curve that can be claimed following improvement is FAT 125, as shown in Fig. 5.6. The slopes of the S-N curves follow the IIW Recommendations for Fatigue Design (Hobbacher, 2009). For variable amplitude loading, the slope is changed from $m = 3$ to $m = 5$ at $N = 10^7$ cycles for FAT 125 details and lower. For constant amplitude loading there is either a change to a horizontal line (fatigue limit) at 10^7 cycles or, under special conditions, the slope parameter m is changed to 22 at 10^7 cycles, see Section 3.2 of Hobbacher (2009).

As shown in Fig. 5.6, all S-N curves in the low endurance region are limited by the parent material curve, i.e. the FAT 160 curve with a slope parameter of $m = 5$ (Hobbacher, 2009).

Fatigue tests on large-scale structures indicate lower benefit from hammer peening than for small-scale specimens. However, the main basis for the above recommendations is data obtained from small-scale welded specimens. Therefore, it is recommended that for steel structures with plate thickness greater than 20 mm, the benefit for hammer peening is assumed to be the same as for burr grinding and TIG dressing, i.e. a fatigue class increase of two limited to a maximum design Class of FAT 112. Also, there is only limited experimental support for the above recommendations for mild steels ($YS < 350$ MPa) and stainless steels. Therefore, again the benefit for hammer peening is assumed to be the same as for burr grinding and TIG dressing, i.e. a fatigue class increase of two limited to a maximum design Class of FAT 112 for any plate thickness.

For aluminium welded components improved by hammer peening, an improvement factor of 1.5 on stress range applies to joints corresponding to FAT 36 and lower. However, the maximum class that can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.5. For ease of computation, this corresponds to a three fatigue class increase. For example, when an aluminium weld detail that, in the as-welded condition, would be classified as FAT 22 is improved by hammer peening, the new FAT value is FAT 32. In Fig. 5.7, this S-N curve is denoted as 32 (22). The highest S-N curve that can be claimed following improvement is FAT 50, as shown in Fig. 5.7. The slopes of the S-N curves follow the IIW Recommendations for Fatigue Design (Hobbacher, 2009). For variable amplitude loading, the slope is changed from $m = 3$ to $m = 5$ at $N = 10^7$ cycles for FAT 50



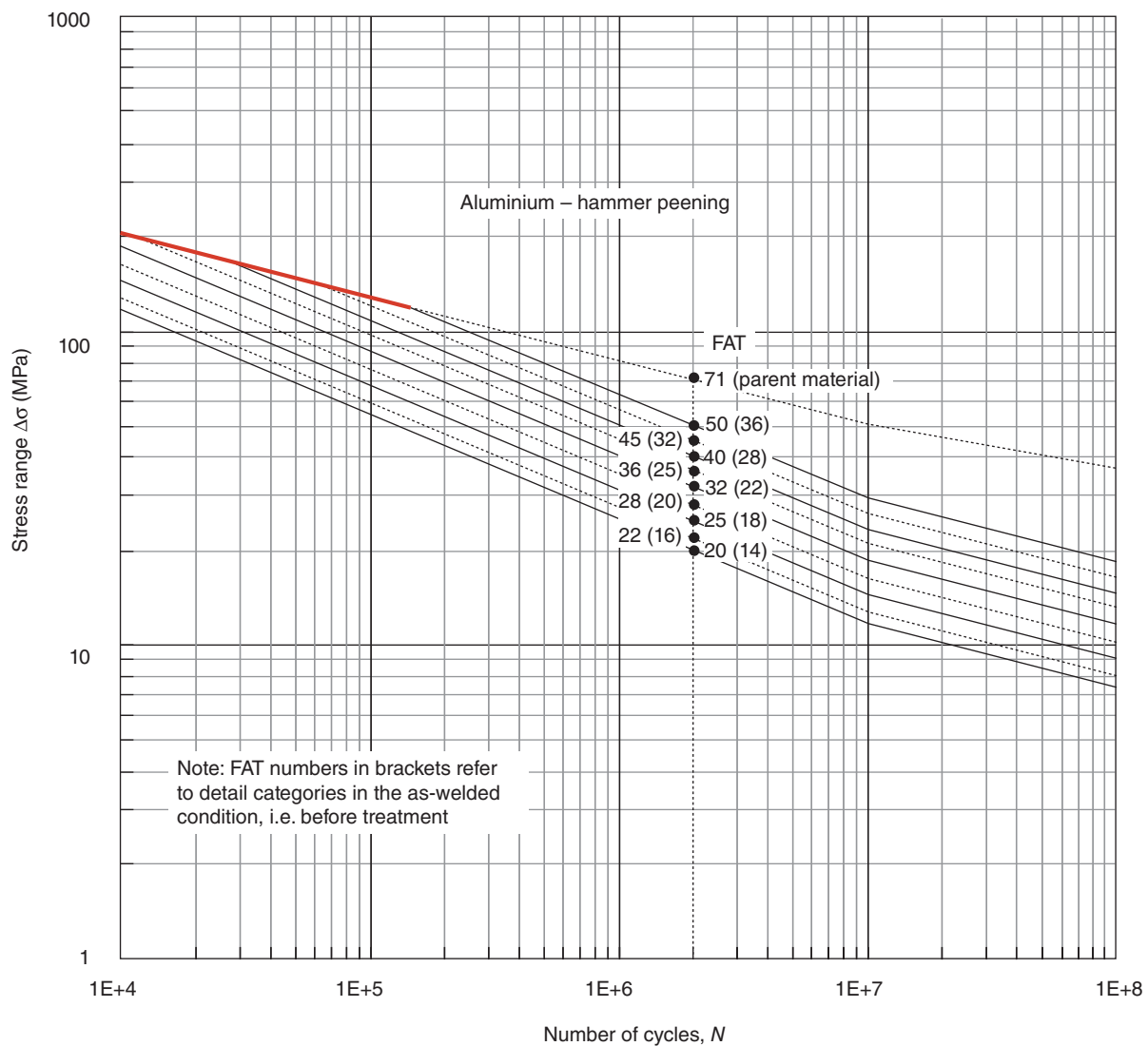
Design S-N curves for hammer peened welds in steel

Fig. 5.6

details and lower. For constant amplitude loading, m is changed to 22 at 10^7 cycles, see Section 3.2 of Hobbacher (2009).

As shown in Fig. 5.7, all S-N curves in the low endurance region are limited by the parent material design curve, i.e. the FAT 71 curve with a slope parameter of $m = 5$.

Fatigue tests on large-scale structures indicate lower benefit from hammer peening than for small-scale specimens. However, the main basis for the above recommendations is data obtained from small-scale welded specimens. Therefore, it is recommended that for structures with plate thickness greater than 20 mm, the benefit for hammer peening is assumed to be the same as for burr grinding and TIG dressing, i.e. a fatigue class increase of two, limited to a maximum design Class of FAT 45.



Design S-N curves for hammer peened welds in aluminium structures, variable amplitude loading

Fig. 5.7

5.9 Stress Ratio Effects for Joints Improved by Hammer Peening

The fatigue strength improvement benefit of hammer peening is sensitive to the applied stress ratio. As a result, the recommended benefits in Section 5.8 are valid only for $R \leq 0.15$. For higher values, $R > 0.4$, no fatigue strength improvement can be claimed without verification by fatigue testing. For $0.15 < R \leq 0.28$, the benefit for hammer peening is assumed to be the same as for grinding or TIG dressing, i.e. a fatigue class increase of two, limited to a maximum design Class of FAT 112 for steel and FAT 45 for aluminium. For $0.28 < R \leq 0.4$, the benefit for hammer peening is one fatigue class increase for details with design Class 90 or less for steel and Class 36 or less for aluminium. This is summarized in Table 5.1.

Table 5.1 Summary of stress ratio effects on fatigue improvement by hammer peening

Stress ratio	Improvement
$R \leq 0.15$	Up to 3 fatigue classes as outlined in Section 5.8
$0.15 < R \leq 0.28$	Up to 2 fatigue classes: the same as for burr grinding or TIG dressing
$0.28 < R \leq 0.4$	One fatigue class for details with design Class 90 and less for steel and Class 36 or less for aluminium
$R > 0.4$	No claimed improvement or fatigue testing required

5.10 Thickness Effect for Joints Improved by Hammer Peening

The thickness effect for welded joints improved by hammer peening is the same as that for burr ground welds, as described in Section 3.10 of this Recommendation.

6. NEEDLE PEENING

6.1 Introduction

In needle peening, compressive residual stresses are induced as a result of plastic deformation produced by repeatedly hammering the weld toe region with a bundle of round-tipped rods. Compared with hammer peening, it is generally more suitable when large areas need to be treated, e.g. welds in tubular joints. As in the case of hammer peening, the following specification is restricted to plate thicknesses of at least 4 mm for steel and 8 mm for aluminium.

The benefit of needle peening depends to a large extent on whether the weld to be peened is under tensile or compressive loading during the peening operation. A better result can be expected if the peened component can be loaded in such a way as to give *tensile* stress in the region to be peened. Conversely, an applied *compressive* stress will reduce the effectiveness of the peening treatment and therefore it is advisable to verify the degree of improvement by fatigue testing.

6.2 Equipment

A standard needle gun of the type used for removing slag and scale is suitable for needle peening, Fig. 6.1(a). However, where necessary, it is advisable to modify the chuck, as shown in Fig. 6.1(b), to align the steel rods in a rectangular pattern rather than a circular one; this will facilitate the treatment of weld toes. Additionally the ends of the rods should be rounded, see Fig 6.1(b).



Needle peening equipment and operation

Fig. 6.1

6.3 Operator Training

Some skill is required to perform needle peening and a training programme should be implemented for inexperienced operators. This should include a demonstration of the appearance of an adequately treated weld, as well as a demonstration of unacceptable welds, and an explanation of the factors that influence the result. If available, reference samples that have been needle peened correctly should be used for comparison. The training programme should include actual peening of at least 1 metre of weld, combined with periodic inspection and evaluation. Inspectors should be similarly trained to understand the requirements for correctly treated welds.

6.4 Weld Preparation

The weld should be prepared in the same way as for hammer peening, as detailed in Section 5.4 of this Recommendation.

6.5 Safety Aspects

Needle peening, even using modern silenced hammers, is a noisy operation and it is essential that the operator and others working in the vicinity should use ear protection. Normal protective clothing for working in a fabrication shop is adequate, but it should include a face-mask or goggles. Vibration from peening equipment may cause physical discomfort or harm, and the operator should not perform peening for extended periods of time. Vibration damping gloves may help alleviate this problem.

6.6 Procedure

The aim in needle peening is to deform the material plastically at the weld toe to induce beneficial compressive residual stresses. Effective treatment requires reasonably accurate positioning of the needles over the weld toe so that metal on each side (weld metal and parent plate) is deformed. If required, needle peening can be performed immediately after welding, while the weld is still hot.

The operation is carried out with the tool held at approximately 45° to the plate surface, with the ends of the needles in contact with the weld toe, as illustrated in Fig. 6.1(c). Sufficient force should be applied to the tool to prevent unsteady movement and to ensure even treatment. It is not necessary for the operator to exert undue force in this operation, particularly when using a lightweight gun, and therefore operation in the overhead position can be carried out with relative ease. The rate of treatment is approximately 800 mm per minute.

It is important to achieve full coverage of the surface to be treated. To this end, peening should be continued until the area is free of untreated spots, typically in up to four passes. The resulting surface should be bright in appearance and contain a uniform distribution of small indentations. The time taken to achieve this should be noted. It is recommended that 100% coverage is then checked visually, using a $\times 5$ – 10 power magnifying glass. When 100% coverage has been achieved, the area is treated again for the same length of time, to achieve what is termed 200% coverage.

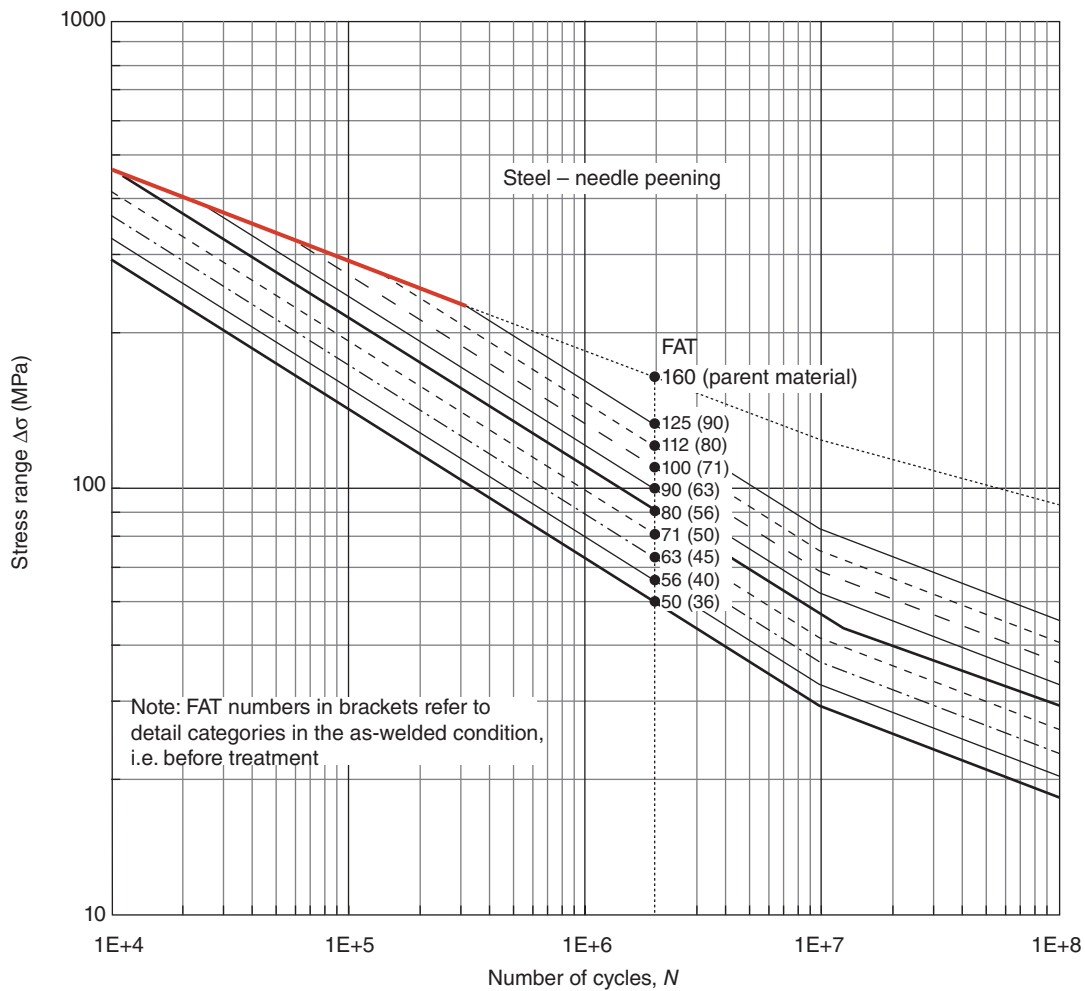
With regard to inspection, a useful contrast between the needle peened surface and the surrounding untreated surfaces can be achieved if the area is first stained with toolmakers blue, the dye being removed by the needle peening operation. Light grinding of the weld toe region before needle peening, to obtain a dull surface finish, will also facilitate visual examination of peened areas.

6.7 Inspection, Quality Control and Documentation

Photographs taken at intervals along the peened area, which should include appropriate identification markers, provide a suitable record of the needle peening treatment. Care is needed to arrange the lighting source in such a way that the photographs show any areas that inadvertently may not have been treated. After prolonged use, the tips of the needles will revert back from the rounded shape introduced by grinding to being flat ended. Such tips should be reground to produce a rounded shape.

6.8 Fatigue Strength of Joints Improved by Needle Peening

The benefit of weld toe needle peening for steel can be claimed only for details in design Class FAT 90 or lower in the IIW notation for S-N curves, as shown in Fig. 6.2. This limitation is due to the fact that the higher classes include non-welded details, details whose lives are not governed by weld toe failure or welds that have already been improved, e.g. by grinding a butt weld flush with the surface.



Design S-N curves for needle peened welds in steel structures

Fig. 6.2

For IIW FAT 90 or lower class details, in steels with specified yield stress higher than 350 MPa, the benefit consists of an increase in allowable stress range by a factor of 1.5, corresponding to a factor of 3.375 on life (for $m = 3$, the appropriate value for FAT 90 and lower). However, the maximum class that can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.5. For ease of computation, this corresponds to a three fatigue class increase. For example, when a weld detail that, in the as-welded condition, would be classified as FAT 63 is needle peened, the new FAT value is FAT 90. In Fig. 6.2, this S-N curve is denoted as 90 (63). The highest S-N curve that can be claimed following improvement is FAT 125, as shown in Fig. 6.2. The slopes of the S-N curves follow the IIW Recommendations for Fatigue Design (Hobbacher, 2009). For variable amplitude loading, the slope is changed from $m = 3$ to $m = 5$ at $N = 10^7$ cycles for FAT 125 details and lower. For constant amplitude loading, there is either a change to a horizontal line (fatigue limit) at 10^7 cycles or, under special conditions, the slope parameter m is changed to 22 at 10^7 cycles, see Section 3.2 of Hobbacher (2009).

As shown in Fig. 6.2, all S-N curves in the low endurance region are limited by the parent material curve, i.e. the FAT 160 curve with a slope parameter of $m = 5$ (Hobbacher, 2009).

Fatigue tests on large-scale structures indicate lower benefit from needle peening than for small-scale specimens. However, the main basis for the above recommendations is data obtained from small-scale welded specimens. Therefore, it is recommended that for steel structures with plate thickness greater than 20 mm, the benefit for needle

peening is assumed to be the same as for burr grinding and TIG dressing, i.e. a fatigue class increase of two limited to a maximum design Class of FAT 112. Also, there is only limited experimental support for the above Recommendations for mild steels ($YS < 350$ MPa) and stainless steels. Therefore, again the benefit for needle peening is assumed to be the same as for burr grinding and TIG dressing, i.e. a fatigue class increase of two limited to a maximum design Class of FAT 112 for any plate thickness. The thickness correction (see Section 3.10) still applies in both cases.

For aluminium welded components improved by needle peening, an improvement factor of 1.5 on stress range applies to joints corresponding to FAT 36 and lower. However, the maximum class that can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.5. For ease of computation, this corresponds to a three fatigue class increase. For example, when an aluminium weld detail that, in the as-welded condition, would be classified as FAT 22 is improved by needle peening, the new class is FAT 32. In Fig. 6.3, this S-N curve is denoted as 32 (22). The highest S-N curve that can be claimed following improvement is FAT 50, as shown in Fig. 6.3. The slopes of the S-N curves follow the IIW Recommendations for Fatigue Design (Hobbacher, 2009). For variable amplitude loading, the slope is changed from $m = 3$ to $m = 5$ at $N = 10^7$ cycles for FAT 50 details and lower. For constant amplitude loading, m is changed to 22 at 10^7 cycles, see Section 3.2 of Hobbacher (2009).

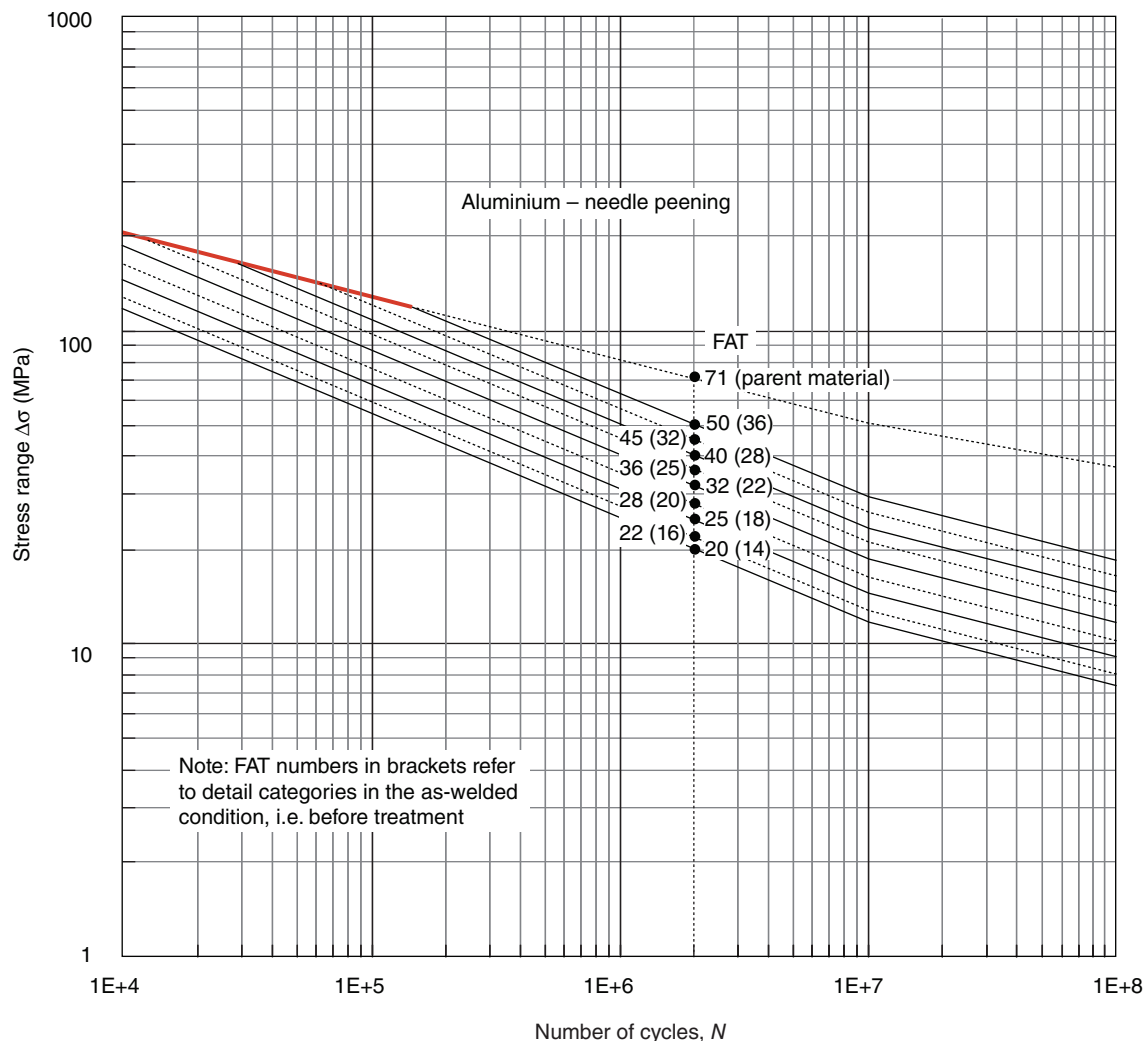


Fig. 6.3

As shown in Fig. 6.3, all S-N curves in the low endurance region are limited by the parent material design curve, i.e. the FAT 71 curve with a slope parameter of $m = 5$.

Fatigue tests on large-scale structures indicate lower benefit from needle peening than for small-scale specimens. However, the main basis for the above recommendations is data obtained from small-scale welded specimens. Therefore, it is recommended that for structures with plate thickness greater than 20 mm the benefit for needle peening is assumed to be the same as for grinding and TIG dressing, i.e. a fatigue class increase of two limited to a maximum design Class of FAT 45.

6.9 Stress Ratio Effects for Joints Improved by Needle Peening

The fatigue strength improvement benefit of needle peening is sensitive to the applied stress ratio. The recommended benefits in Section 6.8 are valid only for $R \leq 0.15$. For high values, $R > 0.4$, no fatigue strength improvement can be claimed without verification by fatigue testing. For $0.15 < R \leq 0.28$ the benefit for needle peening is assumed to be the same as for grinding or TIG dressing, i.e. a fatigue class increase of two, limited to a maximum design Class of FAT 112 for steel and FAT 45 for aluminium. For $0.28 < R \leq 0.4$, the benefit is one fatigue class increase for details with design Class 90 or less for steel and Class 36 or less for aluminium. This is summarized in Table 6.1.

Table 6.1 Summary of stress ratio effects on fatigue improvement by needle peening

Stress ratio	Improvement
$R \leq 0.15$	Up to 3 fatigue classes as outlined in Section 6.8
$0.15 < R \leq 0.28$	Up to 2 fatigue classes: the same as for burr grinding or TIG dressing
$0.28 < R \leq 0.4$	One fatigue class for details with design Class 90 and less for steel and Class 36 or less for aluminium
$R > 0.4$	No claimed improvement or fatigue testing required

6.10 Thickness Effect for Joints Improved by Needle Peening

The thickness effect for welded joints improved by needle peening is the same as that for burr ground welds, as described in Section 3.10 of this Recommendation.

7. RECOMMENDATIONS RELATED TO STRUCTURAL HOT-SPOT STRESS

All the benefits due to the use of an improvement technique discussed so far have referred to S-N curves expressed in terms of nominal applied stress range. This is the most commonly used fatigue design approach for assessing welded structures and is the basic method in the IIW Recommendations (Hobbacher, 2009). However, in the context

of potential fatigue failure from a weld toe or end, there is growing interest in an approach based on the structural hot-spot stress. Thus, there will also be an interest in expressing the fatigue performance of improved welds in the same terms. Little direct research has addressed this issue, apart from the case of tubular joints. In this case, notably in the context of offshore structures (ISO, 2007), fatigue design rules already use the hot-spot stress and indeed include design data for toe ground welds. The approach is the same as that recommended in Sections 3.9, 4.9, 5.8 and 6.8 of the present document, namely allowing increased fatigue classes in comparison to welded joints in the as-welded condition. In the absence of relevant data, the same approach is recommended for all the improvement techniques covered by the present document.

The IIW has recently published fatigue design recommendations based on the use of the hot-spot stress which include proposals for design S-N curves expressed in terms of the hot-spot stress range (Niemi *et al*, 2006). The enhancement factors in the present document are applied to those curves.

In the case of welded steel, two design curves are proposed for as-welded fillet welds, namely FAT 90 for load-carrying or FAT 100 for non-load-carrying welds. The corresponding classes for aluminium alloys are FAT 36 and FAT 40 respectively. Thus, the corresponding S-N curves for welds improved using any of the methods are given in Tables 7.1 and 7.2. It will be noted that, in view of the lack of relevant experimental data, the recommendations for peened welds are limited to the range of plate thicknesses indicated. Thus, the reduction in benefit for hammer or needle peened welds in plate thicknesses >20 mm is not applicable. It should also be noted that the increased classes refer only to potential weld toe failure. There is still the risk of premature failure from the weld root, especially in load-carrying joints. Therefore, that potential failure mode should also be checked on the basis of the relevant design curve (e.g. FAT 36 for steel or FAT 12 for aluminium alloys based on the nominal stress range on the weld throat).

Table 7.1 Structural hot-spot classes for joints improved by grinding or TIG dressing

Material	Load-carrying fillet welds	Non-load-carrying fillet welds
Mild steel, $YS^* < 350$ MPa	FAT 112	FAT 125
Higher strength steels, $YS^* > 350$ MPa	FAT 112	FAT 125
Aluminium alloys	FAT 45	FAT 50

Table 7.2 Structural hot-spot classes for joints improved by hammer or needle peening, thickness 4 to 20 mm (steel) and 8 to 15 mm (aluminium)

Material	Load-carrying fillet welds	Non-load-carrying fillet welds
Mild steel, $YS^* < 350$ MPa	FAT 112	FAT 125
Higher strength steels, $YS^* > 350$ MPa	FAT 125	FAT 140
Aluminium alloys	FAT 50	FAT 56

* YS = specified minimum yield strength.

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APPENDICES

Appendix 1: Participants in IIW Inter-laboratory Test Programme

Lab. ID	Organization		Country
	Short name	Full name	
Lab 1	CETIM/ IRSID	Centre Technique des Industries Mecaniques/ Institut de Recherche de la Siderurgie (two labs shared testing)	France
Lab 2	SSAB	Swedish Steel AB	Sweden
Lab 3	NTNU	The Norwegian University of Science and Technology	Norway
Lab 4	TIT	Tokyo Institute of Technology	Japan
Lab 5	TWI	TWI (formerly The Welding Institute)	UK
Lab 6	CEMUL	Instituto Superior Technico, Lisbon	Portugal
Lab 7	LUT	Lappeenranta University of Technology	Finland
Lab 8	BAM	Bundesanstalt für Materialforschung und -prüfung	Germany
Lab 9	TUD	University of Delft	The Netherlands
Lab 10	TUB	Technical University of Braunschweig	Germany
Lab 11	PWI	Paton Welding Institute	Ukraine
Lab 12	IS	Institut de Soudure	France

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Appendix 3: Production Data Sheets

PRODUCTION DATA SHEET for WELD TOE IMPROVEMENT by BURR GRINDING		 International Institute of Welding Commission XIII
WELDING SPECIFICATION Base material: _____ Filler material: _____ Welding procedure No: _____		COMPONENT Type: _____ Identification: _____
EQUIPMENT Make and model: _____ Power: _____ Tip diameter: _____ Weight (with tool tip): _____ Rotation speed: _____		SKETCH OF COMPONENT
TREATMENT DATA Position: _____ Work angle, sideways: _____ Work angle, weld direction: _____ Travel speed: _____ Number of passes: _____ Length of treatment: _____ Time of treatment: _____		
INSPECTION ☐ Visual ☐ Photo ☐ Geometry measurements Equipment: _____ TOE GEOMETRY MEASUREMENTS Spacing of measurement points (mm): _____ Max. Min. Mean Toe radius (mm): _____ Groove depth (mm): _____ Measurements report: _____		REMARKS
OPERATOR Experience: a). Hours: _____ b). Length of weld treated: _____ Operator's name: _____		
		Date: _____

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PRODUCTION DATA SHEET for SURFACE IMPROVEMENT by HAMMER PEENING		 International Institute of Welding Commission XIII
WELDING SPECIFICATION Base material: _____ Filler material: _____ Welding procedure No: _____		COMPONENT Type: _____ Identification: _____
EQUIPMENT Make and model: _____ Power capacity: _____ Tip, geometry & radius: _____ Tool weight: _____ Impact frequency: _____		SKETCH OR PHOTO
TREATMENT DATA Position (1G, 2G) etc: _____ Preheat temperature: _____ Work angle, sideways: _____ Work angle, weld direction: _____ Travel speed (S): _____ Number of passes: _____ Change of tool tip: _____ Reason for change: _____		
INSPECTION ☐ Visual ☐ Photo ☐ Geometry measurements Equipment: _____		REMARKS
TOE GEOMETRY MEASUREMENTS Spacing of measurement points (mm): _____ Max. Min. Mean Toe radius (mm): _____ Groove depth (mm): _____ Measurements report: _____		
OPERATOR Experience: a). Hours: _____ b). Length of weld treated: _____ Operator's name: _____		Date: _____

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