POST-TREATMENT OF WELDING JOINTS OF HIGH STRENGTH STEELS I.: IMPROVING WELD GEOMETRY – OVERVIEW

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Abstract
The International Institute of Welding (IIW) published a recommendation on methods for improving the fatigue strength of welded joints in 2013, valid for maximum specified yield strength of 900 MPa. In this time was consider that by using these methods is reasonable to expect that fatigue performance of welded higher strength will also improve. Since the publication several studies investigate different improvement techniques effects on high strength steels fatigue strength. The aim of this paper is to review post treatment techniques by improving the weld geometry consider the application of these techniques in high-strength steels. The post treatment techniques by residual stress methods will be reviewed in the second part of our article.

Keywords: *high strength steels, post weld treatment, weld geometry improvement, fatigue strength improvement*

1. INTRODUCTION

Nowadays, high-strength steels, based on economic and environmental considerations, are becoming more and more widespread in welded structures (Gáspár, 2016; Dobosy, 2017; Mobark, 2020; Sisodia, 2021). In the manufacture of welded structures made of high-strength steels, such as mobile cranes, material handling machines and mining equipment, welding technology can significantly affect to the life time of the structure. Given the functions of these engineering structures, the condition of their safe operation is the appropriate life time of the welding joints, based on both design and manufacturing considerations. In the case of high-strength steels, the life time is significantly affected by lower deformation capability, by increased cold cracking sensitivity, by welding residual stresses and by the geometry of the welding joints. The sensitivity of cold cracking can be well controlled by selection appropriate welding parameters; however, the welding residual stresses and the welding joints geometry – even with a proper welding technology – play significant role in the life time of the welded structures.

Critical parts of the welding joints geometry are the welding toes, the junction lines of the base material and the welding seam, and in case of multi-pass welding the junction lines between the welding layers too. In critical cases, these lines can behave as notches and cause cracks in the welding joint due to the tensile welding residual stresses. During the operation of the welded structures the cracks can be growth further and, due to the lower deformation capability of the high strength steels, can be led to failure of the structure (even suddenly too). The aim of the post-treatment of the welded joints is to improve the fatigue properties or resistance of these areas.

The post-treatment possibilities of welded joints can be divided into two main groups, based on the affected area, so that we can distinguish between methods aimed reducing or transforming the welding residual stresses or/and improving the welding joint geometry. Even though there are numerous techniques for the post-treatment of welded joints, these methods have limited applicability to high strength steels for microstructural and economic reasons.

2. WELDING IMPERFECTIONS

First of all to understand how the fatigue strength of welding joint can be modified by post treatment we have to understand how the welding joint fatigue resistance with imperfections effected.

The worldwide accepted standard ISO 5817 (ISO, 2014) classified different categories of imperfection and allowable extent of each type of imperfection is tabulated for the different quality levels B, C and D. This standard was not applied directly to fatigue problems however most codes specify general quality level according ISO 5817 and give additional regulations. IIW recommendations (Haagensen et al., 2013) have extended the scope of usual fatigue design codes by describing the fatigue properties of joints containing weld imperfections on a scientific basis. Users or writers of specific application codes may use it in order to establish adequate regulations for their specific purpose (Hobbacher, 2009).

The first step – based on known weld imperfection – of the assessment procedure is to determine the type and the effect of the imperfection categorization as given in *Table 1*.

Table 1. *Categorization and assessment procedure for weld imperfections* (Hobbacher, 2009)

Effect of imperfection	**Type of imperfection**	**Assessment**
Rise of general stress level	Misalignment	Formulae for effective stress concentration
Local notch effect Additive Competitive	 Weld shape imperfections, undercuts Porosity and inclusions not near surface	 Tables given Tables given
Cracklike imperfections	Cracks, lack of fusion and penetration All types of imperfections other than given here	Fracture mechanics

Three effects of geometrical imperfections can be distinguished, as summarized in *Table 1*.

- **Increase of general stress level.** This is the effect of all types of misalignment due to secondary bending. The additional stress magnification factor can be calculated by appropriate formulae. The fatigue resistance of the structural detail under consideration is to be lowered by division by this factor.
- **Local notch effect.** Here, interaction with other notches present in the welded joint is decisive. Two cases are to be distinguished, as follows.
- **Additive notch effect.** If the location of the notch due to the weld imperfection coincides with a structural discontinuity associated with the geometry of the weld shape (e.g. weld toe), then the

fatigue resistance of the welded joint is decreased by the additive notch effect. This may be the case at weld shape imperfections.

- **Competitive notch effect.** If the location of the notch due to the weld imperfection does not coincide with a structural geometry associated with the shape geometry of the weld, the notches are in competition. Both notches are assessed separately. The notch giving the lowest fatigue resistance is governing.
- **Crack-like imperfections.** Planar discontinuities, such as cracks or cracklike imperfections, which require only a short period for crack initiation, are assessed using fracture mechanics on the basis that their fatigue lives consist entirely of crack propagation (Hobbacher, 2009).

Based on known welding imperfection detected by appropriate non-destructive testing and inspection- fatigue resistance can be assessed according IIW recommendations (Hobbacher, 2009). In case of welded joints of high strength steel welded by 135 GMAW process obvious that significant higher risk existing due the raw material higher sensitivity for cold cracking therefore using adequate welding technology and non-destructive testing of welded structures is necessary. Some example for crack of welding joints of high strength steels are shown in *Figure 1*. Based on practical experiences, these kinds of welding imperfections have to be repaired by removing the crack and rewelding of the welding joint.

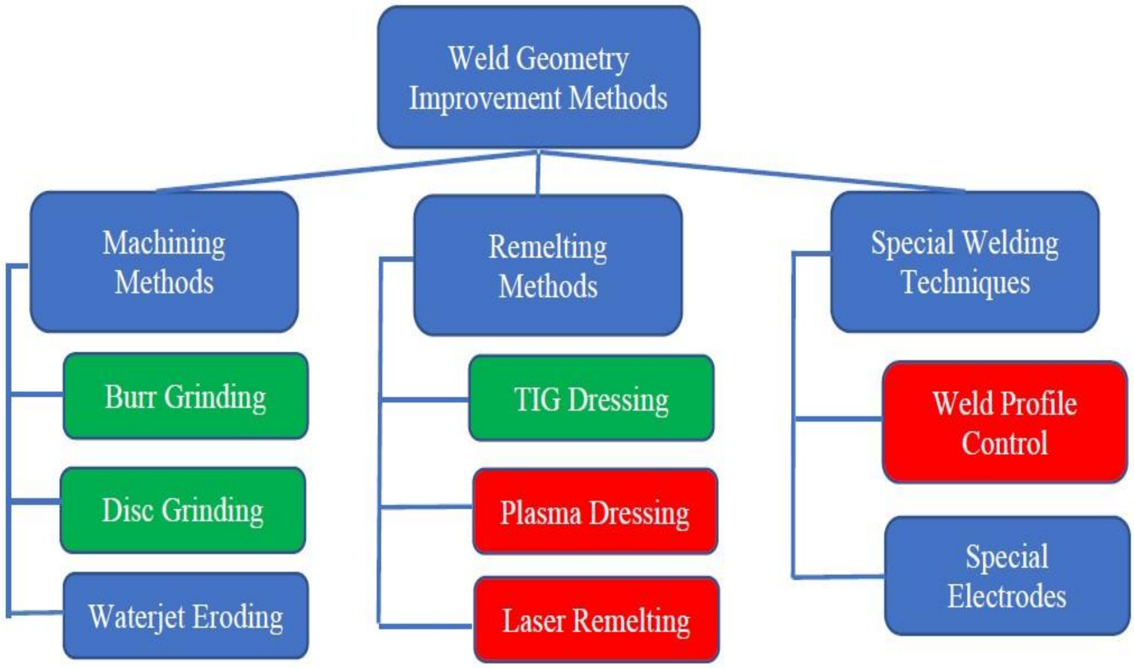
Figure 1. *Cracks in welding joints of high strength steel structures*

Weld toe and weld shape imperfections *(Figure 2)* can consider during fatigue assessment but also possible to apply post weld treatment to improve fatigue resistance of welding joint.

Figure 2. *Undercuts and weld shape imperfection in welding joints*

3. POST WELD TREATMENT TECHNIQUES

Weld toe improvement methods have been widely investigated and have in most cases been found to give substantial increases in fatigue strength. In some cases, the degree of improvement is limited by alternate failure modes; the material strength and type of loading also influence the observed fatigue crack behaviour (Marquis, 2010). However, there are large variations in the actual improvements achieved and clear dependency of the base material yield strength (f_y). According to the IIW recommendation (Hobbacher, 2009), the fatigue strength of welded steel joints is generally independent of the base material yield strength in the as-welded condition. Furthermore, when post weld improvement techniques are used with the target of enhancing the fatigue strength, there is a clear observation of that an increase in yield strength of the base material will render an increase of the fatigue strength for some post-weld improvement techniques investigated. This has been addressed in the IIW recommendations on improvement techniques (Haagensen et al., 2013) for selected methods such as burr grinding (Hansen et al., 2007), TIG dressing (Dahle, 1998; Yildirim, 2015), hammer peening (Tai et al., 2014) and needle peening (Fueki et al., 2019). These improvement techniques could be divided into two different groups, mainly depending on the type of improvement: residual stress modification (e.g. hammer and needle peening) or geometrical modification (e.g. burr grinding and TIG dressing). *Figure 3* provides an overview of different improvement techniques on the market today, where green is covered by IIW recommendations (Haagensen et al., 2013; Hobbacher, 2009), and red is planned and/or in progress (Leitner et al., 2020).



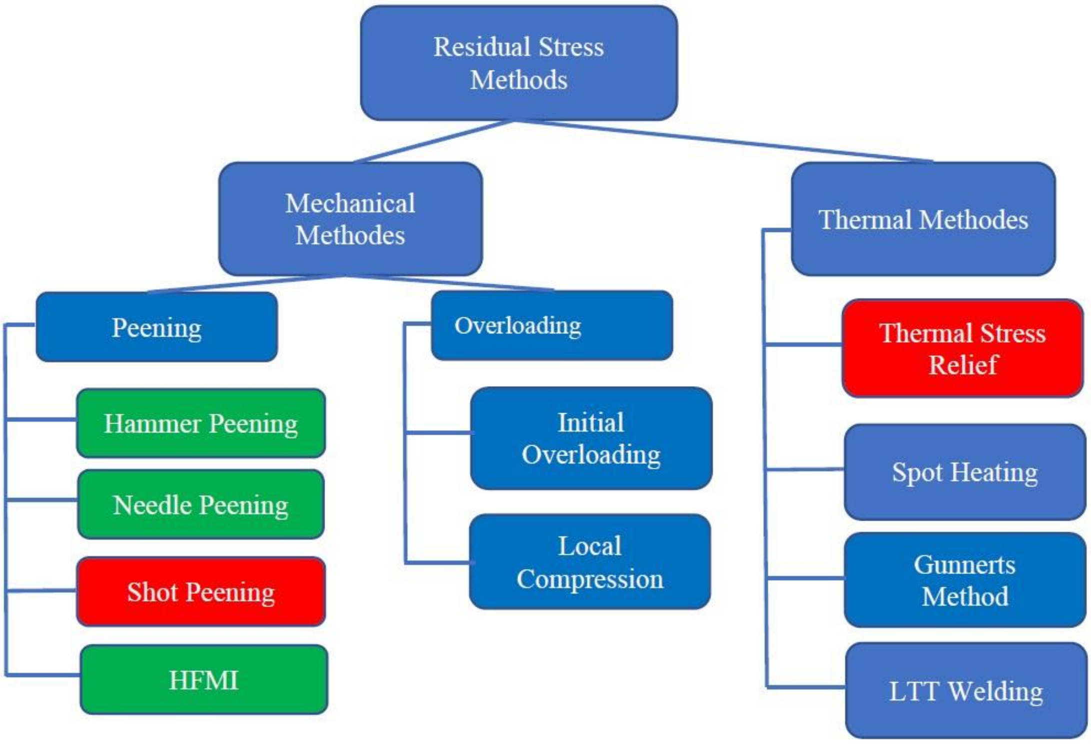


Figure 3. *Overview of different weld improvement techniques – top part: weld geometry improvement methods; upper part: residual stress methods* (Leitner et al., 2020)

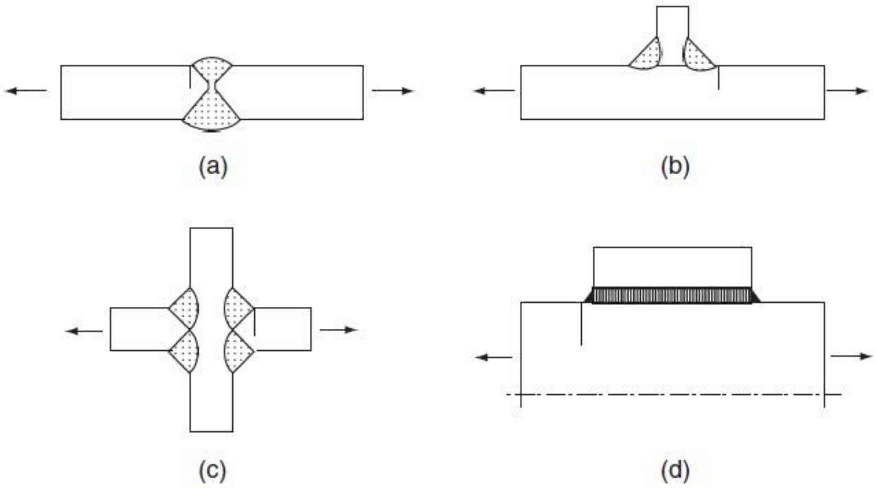


Figure 4. *Examples of joints suitable for improvement* (Hobbacher, 2009)

Some of welding joints where root cracking might occur are shown in *Figure 5*. In these cases significant improvement of fatigue strength is obtained if full penetration weld or extra-large throats should be used where possible. Improvement of incomplete root penetration should be verified by fatigue testing or by analysis (Hobbacher, 2009).

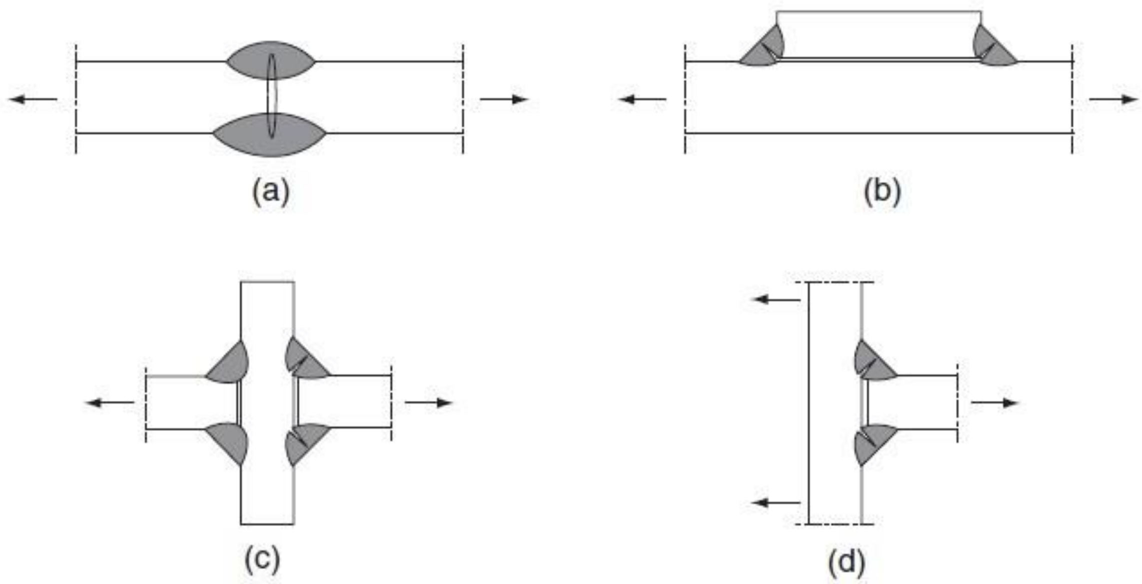


Figure 5. *Examples of joints improvement of fatigue strength limited by occurrence of the root cracking* (Hobbacher, 2009)

4. WELD GEOMETRY IMPROVEMENT METHODS

4.1. Machining methods

There are numerous techniques for machining methods; the background of these methods contain the measuring and evaluating of the weld toe geometry using both conventional and up-to-date technics (Martins Ferreira et al., 1989; Hou, 2007), both before and after the treatment. The aims of these techniques are to improve the weld toe, weld shape geometry to reduce the additive notch effect by removing material from the weld toe or weld shape imperfection *(Figure 6)*. During grinding methods special attention is required for the material removing. As shown in the Figure 6, the depth of grinding has to be enough to completely remove the surface imperfections but not allowed to grind deeper than 7% of the plate thickness (t) but maximum 2 mm (Haagensen et al., 2013). Some cases there is more strict requirement for the dept of material removing when the plate thickness after grinding have to be within the EN 10029 (EN, 2010) standard given thickness tolerance.

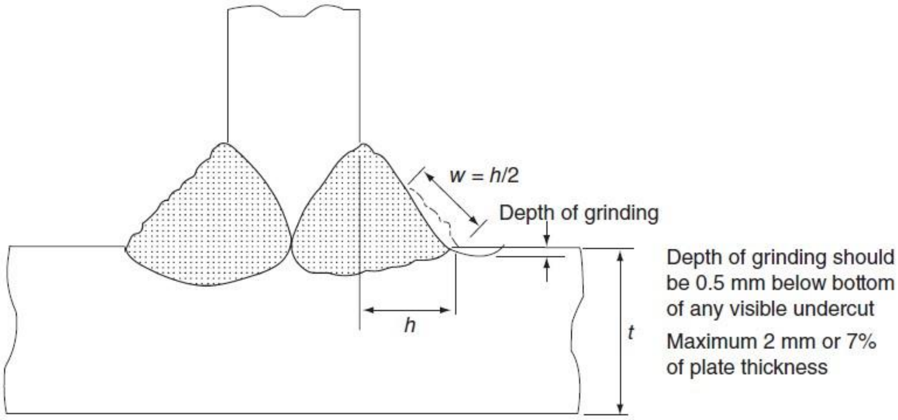


Figure 6. *Grinding technique showing depth and width of grove in stressed plate*
(Haagensen et al., 2013)

In the *Figure 7 (a)* correctly and *(b)* incorrectly grounded weld toes are presented (Haagensen et al., 2013). In case of incorrectly grounded weld toe it is visible the original welding shape imperfection was not removed completely therefore the additive notch effect is still existing.

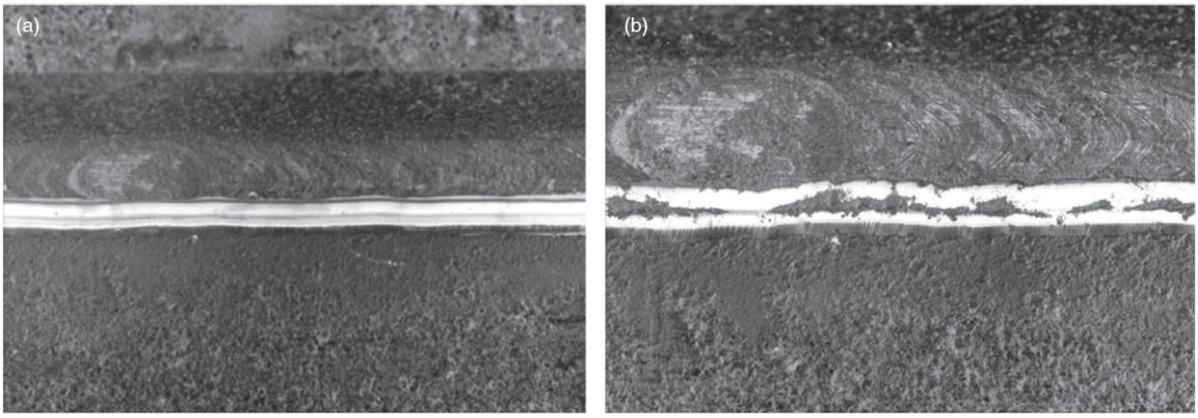


Figure 7. *Appearance of a) correctly and b) incorrectly burr ground fillet weld toes*
(Haagensen et al., 2013)

In case of welded construction made of high strength steels, these methods are also applied for repairing and in some cases already required for manufacturing in critical areas to machine the whole surface of the welding shape to notch free by grinding. As shown in *Figure 8*, the critical areas of welded component were grinded smoothly after welding, based on design requirement. These areas usually required to inspect with sufficient non-destructive inspection as visual and magnetic particle inspection with the scope of inspection mainly 100%.

Figure 8. *Grinding of critical areas of high strength steel structures*

If we review the industrial practice, the most well-known grinding techniques are the burr grinding, disc grinding and water jet eroding. Industrial experiences in high strength steel welding joint weld geometry improvement with waterjet eroding is not well known, however the material removal could be faster but require more experienced operator and special equipment therefore this process is not presented in this paper.

4.1.1. Burr grinding

Weld toe burr grinding was performed by using high speed pneumatic, hydraulic or electric grinder with rotation speed range between 15,000 and 40,000 rpm using rotary tool bit with hemispherical, conic or cylindrical rounded shape. The tool bits are also available with different diameters to select to most sufficient size for removing weld shape imperfection.

Figure 9. *Pneumatic grinder and burrs* (Haagensen et al., 2013)

Based on IIW recommendation (Haagensen et al., 2013), the size of the grinding tool can be selected based on the thickness of the plate and the size of the weld shape imperfection, as shown in *Figure 10*.

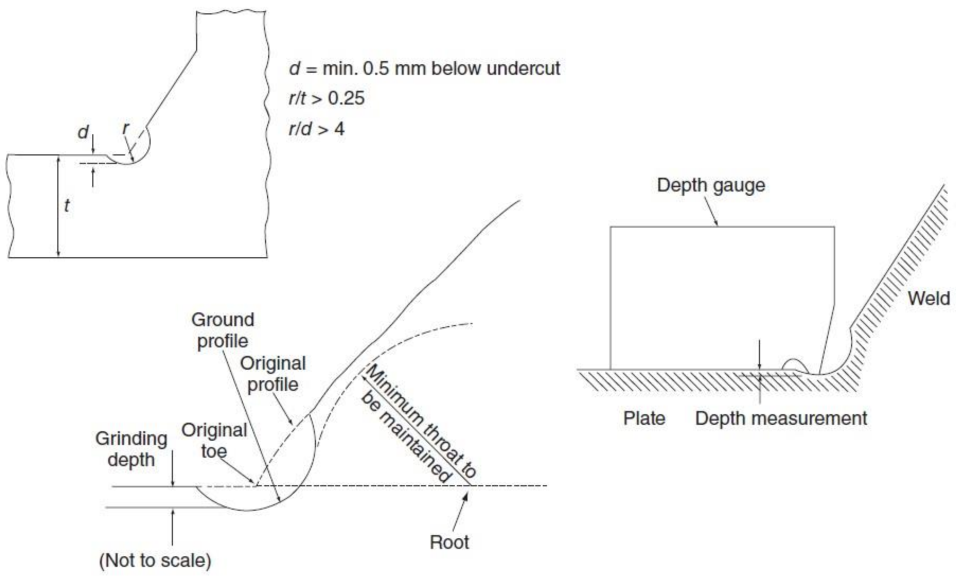


Figure 10. *Details of burr ground weld toe geometry* (Haagensen et al., 2013)

The result of the burr grinding process is also influenced by the skill of the operator. The life cycle of the tool bit depends on tool and raw material of the welded joint. Typically, the tool bits should be changed due the end radius is damaged rather than the tool is worn out. During the process small chips were removed what require sufficient protective equipment (safety glasses, gloves and closed work clothes). After the finishing the process and before the inspection, all chips should be removed from the surface to avoid injuries. During inspection the correct removing of the shape imperfection should be controlled, as well as the weld toe radius and the depth of the grinding.

In case of thick plates and large weld throats, during the burr grinding process the bigger diameter tool it is possible that climb up to the weld face what makes the positioning difficult and the result is that weld toe cannot remove correctly therefore in such cases two-stage grinding has to apply *(Figure 11)*. As first step with smaller diameter tool the weld toe has to grind in correct depth than finish the post treatment by bigger diameter tool.

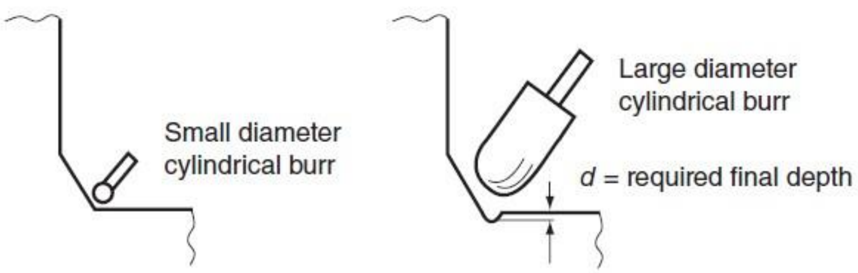


Figure 11. *Two-stage grinding of large weld throat* (Haagensen et al., 2013)

In case of high strength steels, typically undercuts and weld toe imperfections and in case of multilayer welding the weld shape imperfections between welding layers are commonly repaired by burr grinding processes *(Figure 12)*.

Figure 12. *Weld toe imperfections in corner*

4.1.2. Disc grinding

Disc grinder is also suitable for post treatment of weld shape imperfection mainly used to remove slag, undercuts or modify the weld shape geometry. Material removal in case of disc grinding is much higher compared with burr grinding, therefore the process require less time but also required experienced operator because may too much material could remove. Other disadvantage of the process that grinding marks which are normal to the stress direction in transversely loaded weld process could serve as initiation for fatigue cracks (Kirkhope et al., 1999a). These grinding marks can be removed coldly, by additional surface burr grinding with cylinder grinding burrs. Disc grinding process is commonly applied in case of notch free a flat grinding requirement of welding joint like already shown in *Figure 8*.

Figure 13. *Disc grinding*

For the applicability and the efficiency assessment of the grinding-type post-weld treatment methods, in other words for the fatigue lifetime increasing, both experimental and numerical research methods or programs can be applied (Kirkhope et al., 1999b; Mecséri et al., 2020).

4.2. Remelting methods

Using these techniques the weld to region is remelted to a shallow depth which result in a welding joint with a substantially increased fatigue strength. This increase result from an improved weld toe shape with reduced stress concentration factor providing by a smooth transition between plate and weld face. The remelting of weld toe process is carried out using Tungsten Inert Gas (TIG), Plasma or Laser welding equipment (Kirkhope et al., 1999a; Gerritsen et al., 2013).

Main different between the mentioned remelting process is the heat input compared the TIG and plasma process in case of the plasma process about twice higher heat input used than TIG process (Kirkhope et al., 1999a). Laser remelting process is started to apply in recent years when new hand-held laser welding systems are take in industrial use.

These remelting processes are sensitive to the weld surface contamination such as mill scale, rust, oil, and welding slag, therefore, before the remelting process the welding joint surface have to clean. In case of insufficient cleaning may result gas pores what decrease the fatigue strength of the treated welding joint (Haagensen et al., 2013).

Positioning of the torch (even in case of TIG plasma or laser torch) respect the original weld toe is important to achieve optimal result of the remelted zone. Normally, in case of TIG dressing the best result is obtained when the arc centre is located a small distance away from the weld toe as shown in *Figure 14* (Haagensen et al., 2013).

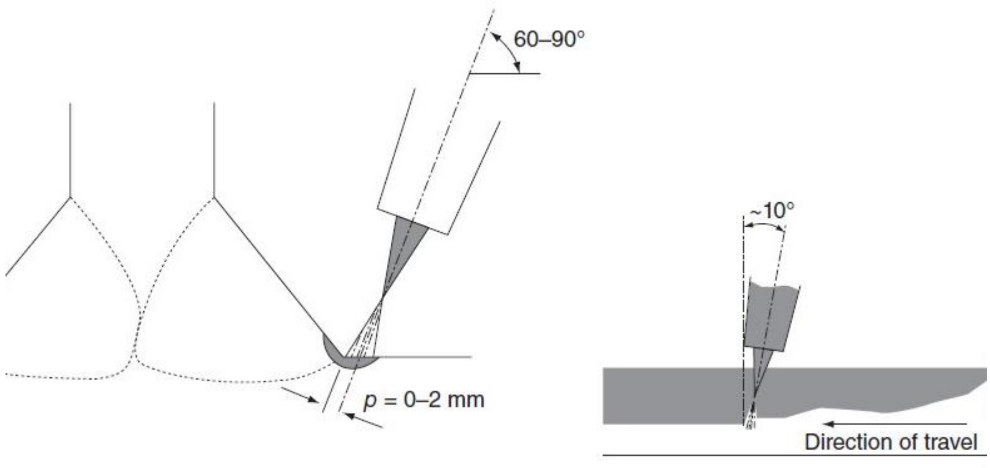


Figure 14. *TIG dressing of weld toe* (Haagensen et al., 2013)

If the arc is positioned too close to the weld toe it may result in the formation of a new toe as shown in *Figure 15 (b)* and *(c)* what require remedial treatment to improve fatigue strength (Haagensen et al., 2013).

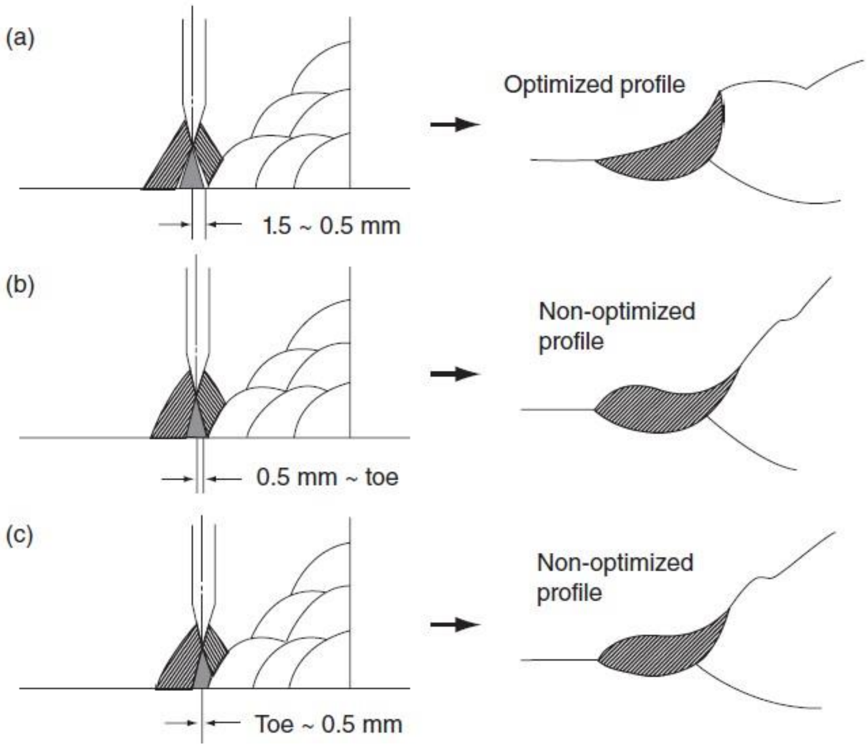


Figure 15. *Positioning of TIG torch tip in relation to weld toe and resulting profiles* (Haagensen et al., 2013)

Figure 16 shows real laser re-melted welded joints sections with different spot sizes, re-melting locations and re-melted sizes (Gerritsen et al., 2013).

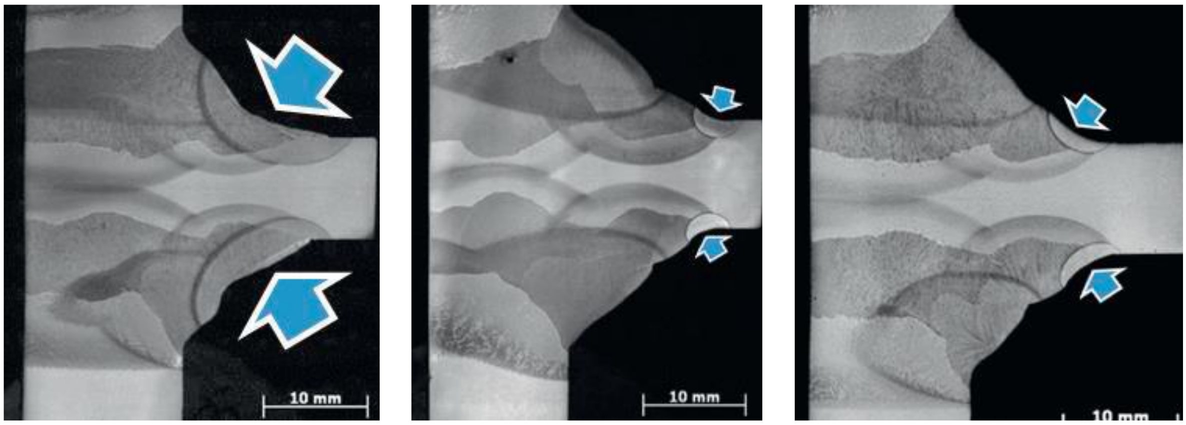


Figure 16. *Macro-sections of laser re-melted welded fatigue samples using different spot sizes, where re-molten zones are indicated by the arrows on the cross-sections* (Gerritsen et al., 2013)

The heat input of the remelting processes normally less or equal than that used for welding the joint. Therefore, as general rule, the minimum pe-heat temperature used should be equal to that specified in the welding procedure (Haagensen et al., 2013). High strength steels are more sensitive for cold cracking than mild steels; therefore, based on the preliminary defined remelting process parameters, preheating temperature has to calculate to reach minimum required $t_{8/5}$ cooling time during the remelting process. In case of high strength steel, TIG remelting process has to consider also the maximum $t_{8/5}$ cooling time to avoid reduction of joint toughness. Obvious if to high heat input is used the toughness of remelted zone has drop what could effect for the complete welding joint toughness in case of thin plates (Skirko et al., 2017). For thick plates and large weld throat the toughness reduction is not critical but maximum $t_{8/5}$ cooling time has to consider.

Some cases in large weld throat welded with multi-layer welding technique required remelting of the complete weld geometry to improve the fatigue strength.

4.3. Complex methods or investigations

Deep rolling is an industrially widely applied mechanical surface treatment process for the modification of roughness, residual stress state, and fatigue resistance, basically in case of non-welded elements. Because the potential of this method is known, the effect of deep rolling (hydrostatic mounted tool) and diamond burnishing (mechanical mounted tool) to increase the fatigue strength of butt joints was investigated on an aluminium alloy. Significant and approximately similar fatigue life improvement was determined for both processes (Schubnell et al., 2020).

The effect of Gas Tungsten Arc Welding (GTAW) repairs on the axial fatigue strength of a hot-rolled aeronautic steel welded joint used in airframe critical to the flight-safety was investigated. The fatigue strength decreased with the number of GTAW repairs, and was related to microstructural and micro-hardness changes, as well as residual stress field and weld profile geometry factors, which gave origin to high stress concentration at the weld toe (Nascimento et al., 2011).

Both the weld geometry and the residual stresses on fatigue life and/or their influence on fatigue improvement were studied using mathematical modelling (Ninh et al., 1995; Teng et al., 2002). The models open the door to welding parameter studies and choosing technological process parameters.

5. CONCLUSIONS

This paper reviewed post-treatment techniques of welding joints of high strength steels to improve the fatigue strength of welded joint by modifying the weld geometry. The aims of these techniques are to improve the weld profile by reformation of welding imperfections in the weld toe zone. Several research studies investigate how effected the fatigue strength of the welding joint by different post treatment techniques and compare the results with the IIW recommendations. A summary of weld geometry improvement methods, the specifications of their advantages and disadvantages can be found in the literature (Kirkhope et al., 1999a). Unfortunately, only the conventional methods were analysed, in consideration of the year of the cited publication.

Based on the result of these studies and the IIW recommendations, it can be concluded that these post treatment techniques are suitable to improve also the high strength steels welding joints fatigue strength, too. However in case of remelting techniques the heat input, the preheating and the $t_{8/5}$ cooling time have to consider to keep the mechanical properties like hardness and toughness of the high strength steels.

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