POST-TREATMENT OF WELDING JOINTS OF HIGH STRENGTH STEELS II.: IMPROVING RESIDUAL STRESS CONDITION – OVERVIEW

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Abstract
High strength steel welding joints fatigue strength could be improved by changing the as weld condition with post-weld treatment. These post-weld treatments are classified to two categories which are the weld geometry and residual stress condition improvement methods. Post-weld treatment methods of high strength steel welding joints by improving weld geometry were overviewed in the first part of our article. The post-weld treatment methods for improving the welding joint residual stress condition are also applicable in high strength steels, but some consideration have to take in place when applying these techniques. The aim of this paper to review the welding joint residual stress condition improvement techniques considers application of these techniques in high strength steels.

Keywords: *high strength steel, post-weld treatment, residual stress condition improvement, fatigue strength improvement*

1. Introduction

Fatigue strength of high-strength steel welding joints is lower than the fatigue strength of relevant base materials (Gáspár, 2016; Dobosy, 2017; Mobark, 2020), it is because of the high residual tensile stresses what occurred by the shrinkage of the weld metal, the limited deformability of the welded structures and the radii of the imperfections in the weld geometry. The priority to improve the fatigue strength of high strength steel welded structures is to design the welding joint in low(er) stressed areas. Due to manufacturing or/and economic considerations, it is required to position welding joint in critical areas of dynamically loaded structures. The fatigue cracking primary sources in these cases is the weld toe because of the stress concentration and high residual tensile stresses of this zone. To improve the fatigue strength of the welding joint during repairing of operating or manufacturing of new structures post-weld treatment methods applied based on two main principles: by reducing the severity of the weld toe stress concentration (in other words weld geometry improvement methods) and by improving the residual stress condition of the welding joint or/and welded structures (in other words residual stress methods). *Figure 1* provides an overview of different post-weld improvement methods on the market today, where green is covered by IIW (International Institute of Welding) recommendations (Haagensen et al., 2013; Hobbacher, 2009), and red is planned and/or in progress (Leitner et al., 2020).

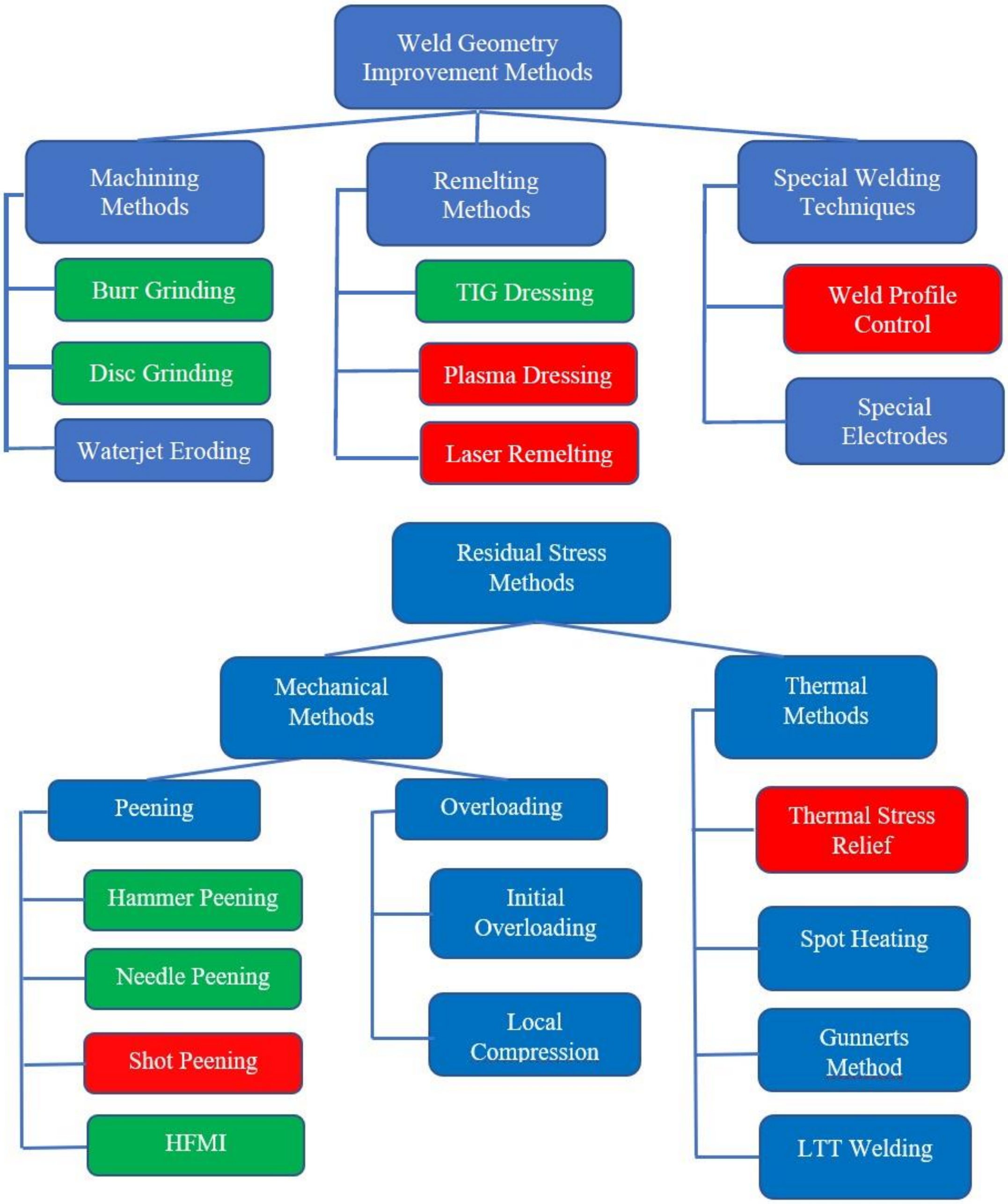


Figure 1. *Overview of different weld improvement techniques – top part: weld geometry improvement methods; bottom part: residual stress methods* (Leitner et al., 2020)

The post-treatment of welding joint is close correlation with the structural integrity (Koncsik, 2019; Koncsik, 2021) of both the welding joint and the welded structural element or structure. Furthermore, the post-treatment techniques can be inserted in the digitized production philosophy (Skriko et al., 2022), under digitized fabrication.

Weld geometry improvement methods of welding joints of high strength steels were reviewed in first part of our article (Sas et al., 2022). This paper, the second part, is overviewing the residual stress methods applied in welding joints of high strength steels.

2. Residual stress methods

After welding of high strength steels, it is obvious that high tensile welding residual stresses exist in the region of the weld. Improvement of fatigue strength of welded joint can be obtained if these tensile residual stresses are reduced or induced compressive residual stress condition in weld toe zone. Residual stress condition of welding joint could be modified by mechanical processing of the weld toe and thermal methods could be also applied to reduce or transform residual stresses.

Based on IIW recommendation (Hobbacher, 2009; Haagensen et al.; 2013, Marquis et al., 2016) these post-weld treatment methods recommendation is apply to all arc welded steel or aluminium components subjected to cyclic stresses, and designed based on a fatigue limit state criterion. These recommendations are limited to structural steels with specified yield strength up to 900 MPa.

2.1. Mechanical methods

Several mechanical methods can be applied to reduce welding residual tensile stress and/or induce compressive residual stress in the weld toe and weld interpass notches shown in *Figure 1* (bottom part). The aim of these mechanical methods is to induce compressive residual welding stress in weld to and weld interpass notches. The mechanical methods were classified into two main groups (Leitner et al., 2020) as peening and overloading processes (see bottom part of *Figure 1*). A classification of peening methods into conventional and modern categories can be seen in *Figure 2* (Dhakal et al., 2018), where green marked techniques meet the scope of our review, but red marked techniques not.

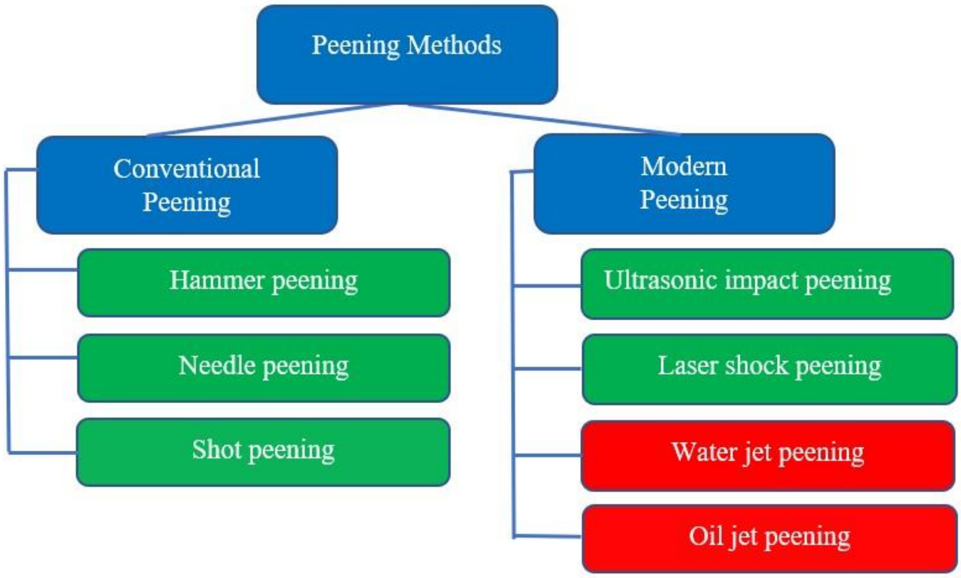


Figure 2. *Classification of peening methods* (Dhakal et al., 2018)

2.1.1. Hammer peening

During hammer peening, compressive residual stresses are induced as result of plastic deformation produced by repeatedly hammering the weld toe region with a blunt-nosed chisel. The benefit of hammer peening depends on to large extent on whether the weld toe to be peened is under tensile or compressive loading during the peening operation.

Pneumatic and hydraulic tools are also used for hammer peening. Pneumatic hammer gun has a 15–30 mm diameter piston, operates at 5–7 bar, and deliver 25–100 impacts per second. Impact energy is typically in the range of 5–15 J. Most research investigations of hammer peening has made use of the above detailed types of hammer guns, both of which are primarily intended for as chipping hammers. However, riveting guns have also been found to be suitable for peening because they are lighter and have better vibration damping. Riveting guns used successfully for hammer peening are shown in *Figure 3* (Haagensen et al., 2013).

The weld face and the adjacent base material should be fully deslagged and wire brushed or ground removing 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 *Figure 4*.

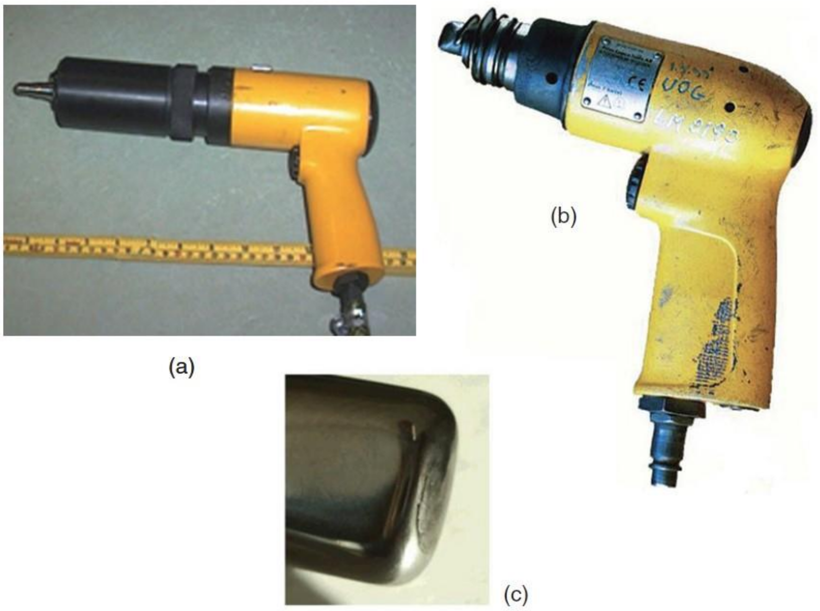


Figure 3. *Pneumatic riveting guns for hammer peening with (a) hemispherical tip, (b) elongated tip, (c) worn and cracked tip* (Haagensen et al., 2013)

The resulting fatigue performance of the welded joint may 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 (Haagensen et al., 2013).

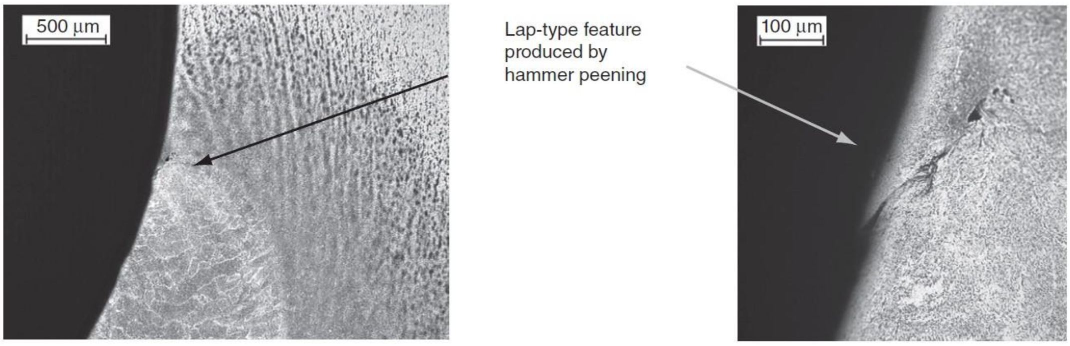


Figure 4. *Lap-type defect in hammer peened weld* (Haagensen et al., 2013)

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 base 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, as shown in *Figure 5* (Haagensen et al., 2013).

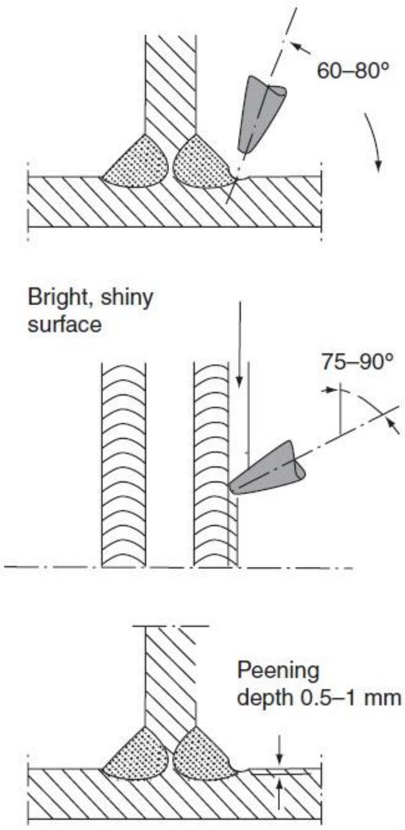
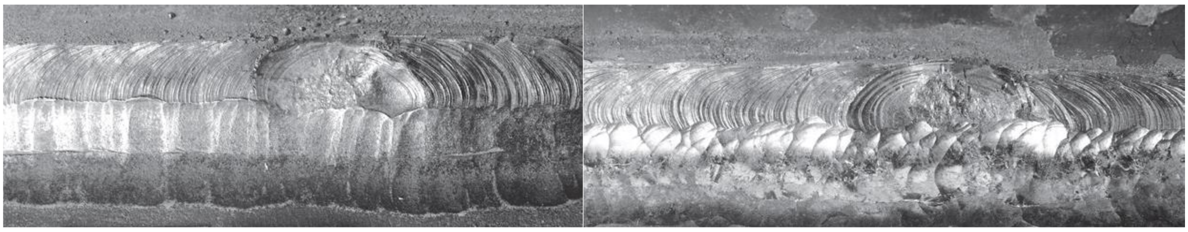


Figure 5. *Hammer peening operation* (Haagensen et al., 2013)

The resulting groove must be smooth and free from obvious individual indentations, as illustrated in *Figure 6 (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 is like 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 (Haagensen et al., 2013).



(a) (b)

Figure 6. *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 insufficient coverage* (Haagensen et al., 2013)

Based on research studies (Fueki et al., 2019; Lefebvre et al., 2015; Tai et al., 2014), hammer peening is also applicable for high strength steel welding joints fatigue strength improvement, however practical experiences show that weld geometry improvement methods is more often requested on manufacturing drawing. Advantages of the hammer peening process that chipping hammer is often available in high strength steel structure manufacturers; therefore welded structures can be treated easily. Hammer peening can be considered as process during installation or operation detected welding toe imperfection post-weld treatment. With hammer peening significant improvement could be achieved on fatigue strength what can replace the higher costly repairing of welding joint.

2.1.2. Needle peening

During needle peening, compressive residual stresses are induced as 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 more suitable when large areas need to be treated (e.g., welds of tubular joints). A standard needle gun of the type used for removing slag and scale is suitable for needle peening as shown in *Figure 7* (Haagensen et al., 2013).

The aim of needle peening is to deform the material plastically at the weld toe inducing advantageous 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 base plate) is deformed. If required, needle peening can be performed immediately after welding, while the weld is still hot. 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 N = 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. Regarding 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 (Haagensen et al., 2013).

Figure 7. *Needle peening equipment and operation* (Haagensen et al., 2013)

Needle peening is applied for high strength steel multi-layer welding joints improving fatigue strength (Fueki et al., 2019). Main advantages of the process like in the hammer peening that the slag removing needle gun is available in high strength steel structure manufacturers, therefore welded structure can be treated easily without further investment needs and in case of large areas like thick plates multi-layer welding joint (see *Figure 8*) welding toe and welding notches between the runs.

Figure 8. *High strength steel multi-layer welding joint suitable for needle peening*

2.1.3. Shot peening

Shot peening process is like sand blasting with the sand replaced by small cast iron or steel particles. Shot is propelled against the surface by high-velocity air stream and causes yielding of the surface layer which builds up compressive residual stresses. The effectiveness of the shot peeing is affected by many variables, the control of which are cumbersome and impractical therefore only two parameters are used to specify the process. These parameters are the Almen intensity and the coverage. The intensity of peening which is related the depth of plastic deformation is measured by Almen strips which are attached to the surface and exposed to the same peeing intensity. Almen strips, strip-holder gauge and measurement device can be seen in *Figure 9* (Eder Strahltechnik, 2022). The Almen strips develop curvature due to the surface deformation on the exposed side and the curvature of the strips of given material and thickness defines the Almen intensity (Kirkhope et al., 1999).

The coverage is related to the areas covered by dimples produced by shot on the surface. A hundred percent coverage is obtained when visual examination at N = 10× magnification of the surface reveals that all dimples just overlap. To produce 200% coverage the time required to produce 100% coverage is doubled.

The major advantage of shot peening is that it covers large areas at low cost, however, care must be taken to ensure that the shot size is small enough to reach the bottom of all undercuts and weld interpass notches. Typical shot size is in the range of 0.2–1.0 mm, and the velocities of projection are the range of 40–60 m/s (Kirkhope et al., 1999).

Figure 9. *Almen strip set* (Eder Strahltechnik, 2022)

Shot peening process is also applicable to improve fatigue strength of high strength steels welding joints however some important consideration takes in place. First of all, suitable steel grade Almen strips must use to verify and control the shot peening process. Fatigue strength improvement of high strength steel welding joints linked to the achieved Almen intensity and coverage therefore prior the manufacturing application the suitable parameters of shot peening process must investigate and verify. Almen intensity and coverages is also depend on the stability of shot peening process therefore in case of manual process the result could be variate widely what could be improved by extending the inspection of Almen intensity and coverage or apply automatized processes. Obvious that extending inspection increase the production cost and not achieve stabile process result therefore automatized shot peening process is recommended.

2.1.4. High frequency mechanical impact (HFMI)

In 2010 IIW Commission XIII introduced the term high frequency mechanical impact (HFMI) as a generic term to describe several related technologies for improving the fatigue strength of welded structures by locally modifying the residual stress state using ultrasonic, pneumatic, or other technologies. HFMI makes use of cylindrical indenters which are accelerated against a component or structure with high frequency (f > 90 Hz). The impacted material is highly plastically deformed causing changes in the local weld toe geometry as well as modifying the residual stress state in the region of impact. The indenters are high strength steel cylinders and manufacturers have customized the effectiveness of their own tools by using indenters with different diameters, tip geometries or multiple indenter configurations (see in *Figure 10*).

Figure 10. *Indenters for HFMI treatment* (Barsoum, 2017)

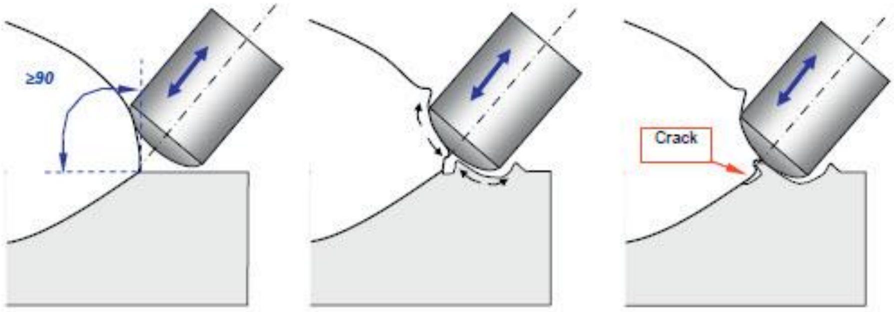
Devices and/or technologies are known by many names: ultrasonic impact treatment (UIT), ultrasonic peening (UP), ultrasonic peening treatment (UPT), high frequency impact treatment (HiFiT), pneumatic impact treatment (PIT) and ultrasonic needle peening (UNP) (Marquis et al., 2013). HiFiT gun for HFMI treatment can be seen in *Figure 11*.

Improvement techniques defined by the IIW are intended to be used both for increasing the fatigue strength of new structures and repair or upgrading of existing structures. The IIW has consistently emphasized that, especially with respect to new structures, weld improvement techniques should never be implemented to compensate for poor design and/or inadequate fabrication practices. Quite the opposite, improvement measures should be implemented as a means of providing additional strength after other measures have been taken. Because HFMI is normally specified as a fatigue strength improvement technology for new structures or during repair and retrofitting operations, it is always essential to consult fatigue experts to ensure that all critical regions in a structure identified and properly treated. Most fatigue loaded structures will normally have only a limited number of locations that are critical from a fatigue point of view. Proper identification of these regions is also important to avoid extra costs and treatment of regions which are not fatigue critical. Additionally, the possibility of a failure starting at some other location must always be considered. For example, if the failure origin is merely shifted from the weld toe to the root there may be no significant improvement in fatigue life (Marquis et al., 2013).

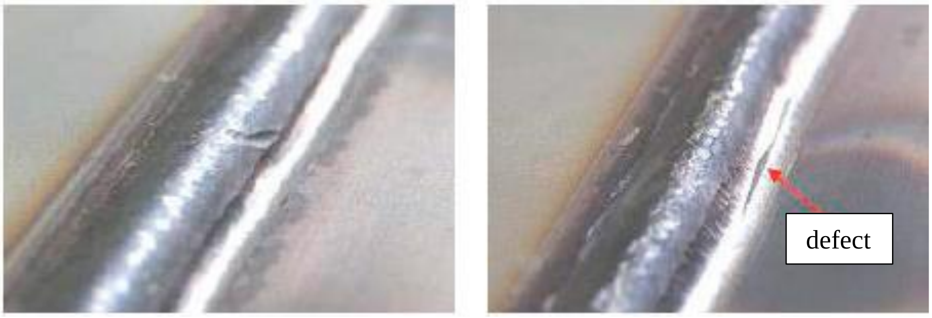
Figure 11. *HiFiT gun for HFMI treatment* (HiFiT, 2022)

Prior to HFMI treatment the weld face and adjacent base material shall be fully deslagged and wire brushed or ground removing all traces of oxide, scale, spatter, and other foreign material. HFMI treatment of a convex weld profile or of a weld with a large weld angle 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. The weld bead profile should meet the acceptance limits for weld profile quality level B in ISO 5817 (ISO, 2014). This requirement does not imply that the weld must fulfil all quality level B criteria in ISO 5817 (ISO, 2014). However, weld profile-related quality criteria in ISO 5817 (ISO, 2014) need to be evaluated. These include undercuts (imperfection 1.7), excessive overfill (imperfection 1.19), excessive concavity (imperfection 1.10) and overlaps (imperfection 1.13). If the weld profile does not comply with these acceptance limits, light grinding before the treatment may be desired. It should be noted, that HFMI treatment is most effective when the weld toe region itself is treated. Thus, grinding operations which make it difficult for the HFMI operator to distinguish the exact location of the weld toe should be avoided. Decisions on the need for weld grinding and the proper grinding procedure should be agreed on with an experienced HFMI operator (Marquis et al., 2013).

The need for proper weld profile before HFMI is illustrated in *Figure 12 (a)* which illustrates the formation of a crack like defect due to improper contact between the indenter and weld toe. Surface inspection of such a defect reveals a dark crack-like line in the middle of the otherwise smooth and shiny HFMI groove as seen in *Figure 12 (b)*. *Figure 12 (c)* shows section micrographs of these defects. The resulting fatigue performance of a welded joint with such defects may be less than that of the original as-welded joint. The same type of flaw has been observed in welds with adequate profiles but with improper indenter selection or too severe treatment, i.e., too many passes over the same region. For specific applications it may be needed to consult with the HFMI tool manufacturer to select the proper treatment procedures and optimal indenter configuration to avoid crack-like defects. Depending on the yield strength of the steel and the size of the indenters, typically the optimum HFMI groove will be 0.2–0.6 mm in depth and 2–5 mm in width, as can be seen in *Figure 13* (Marquis et al., 2013).



(a)



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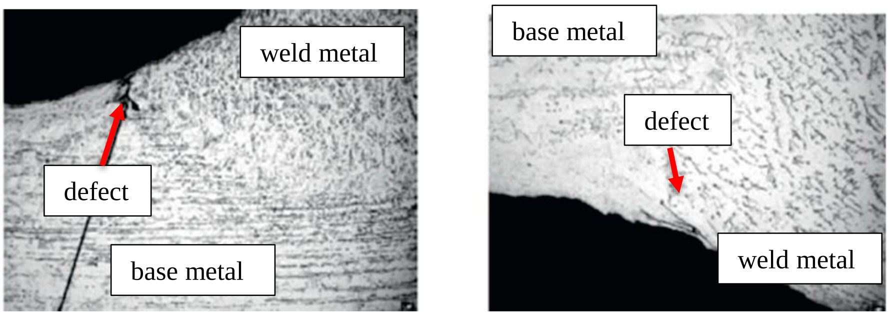

(c)

Figure 12. *(a) Potential introduction of crack-like defect due to HFMI treatment of a weld with a steep angle or with too large of an indenter; (b) resulting groove for properly treated (left) and improperly treated weld toe (right); (c) micrographs of the induced crack-like defects due to improper HFMI treatments* (Marquis et al., 2013)

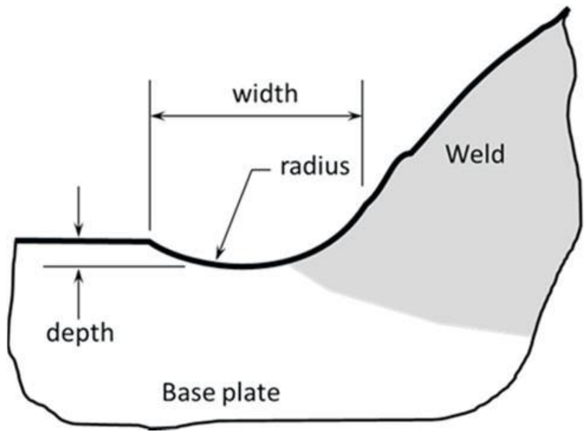

Figure 13. *Characteristics of the HFMI indentation after treatment: depth 0.2–0.6 mm, width 2–5 mm* (Marquis et al., 2013)

Many research studies reported fatigue strength improvement on HFMI post-weld treated high strength steels welding joint (Marquis, 2010; Marquis et al., 2013; Aldén et al., 2020; Harati et al., 2020) with significant result. However, in 2016 IIW also published recommendation (Marquis et al., 2016) for HFMI treatment for improving fatigue strength practical manufacturing experiences show in heavy, high strength steel structure HFMI treatment limitedly applied. Research study observes an increase in fatigue life regardless of the as-welded weld quality level according to ISO 5817 (ISO, 2014). According to IIW recommendation (Marquis et al., 2016) for steel grade of 700 MPa the fatigue strength recommendation is FAT 160 (m = 5) for transverse stiffener-welded joints with as-welded quality B according to ISO 5817 (ISO, 2014). It can be observed that fatigue tested HFMI treated welded joints, welded with weld quality D, are in good agreement with the IIW recommendation (Aldén et al., 2020).

High strength steels produced by innovative processes, like thermomechanical rolling are increasingly applied in different engineering structures. The application of these metal grades enables longer life time, improved performance and thinner wall thickness, which require less welding activities (Dobosy et al., 2018). Besides these advantageous properties, these steel grades can contain material discontinuities, for example cracks, in their microstructure (Koncsik, 2019). In this regard the identification of the fatigue crack initiation site of high-frequency mechanical impact (HFMI)-treated high-strength steel welded joints has both theoretical and practical importance (Ono et al., 2022).

2.1.5. Laser shock peening (LSP)

A sub-type of modern peening process used to introduce compressive residual stress at near surface of the welding joints by using high energy laser beam is called Laser Shock Peening (LSP). The deep (of the order of mm) and large compressive residual stresses (several hundreds of MPa) induced by laser shock peening increase the resistance of the weld toe surface failures by delaying the crack initiation time and its propagation. The schematic diagram of laser shock peening process is shown in *Figure 14* (Dhakal et al., 2018).

When the laser is triggered, it passes through the transparent overlay (confining medium) and reaches to the surface to be peened, covered by opaque layer or sacrificial layer. The continued delivery of laser pulses rapidly heats and ionizes the vaporized material, converting into rapidly expanding plasma. Meanwhile the pressure exerted by expanding plasma in between confining medium and target surface, enters the target surface as a high amplitude shock wave. If the amplitude of the shock wave is above the Hugoniot Elastic Limit (HEL) of the target, the material deforms plastically during the passage of shock waves and results in generation of compressive residual stresses below the target surface. The magnitude of compressive residual stress is highest at or immediate below the surface and varies as a function of depth (Dhakal et al., 2018).

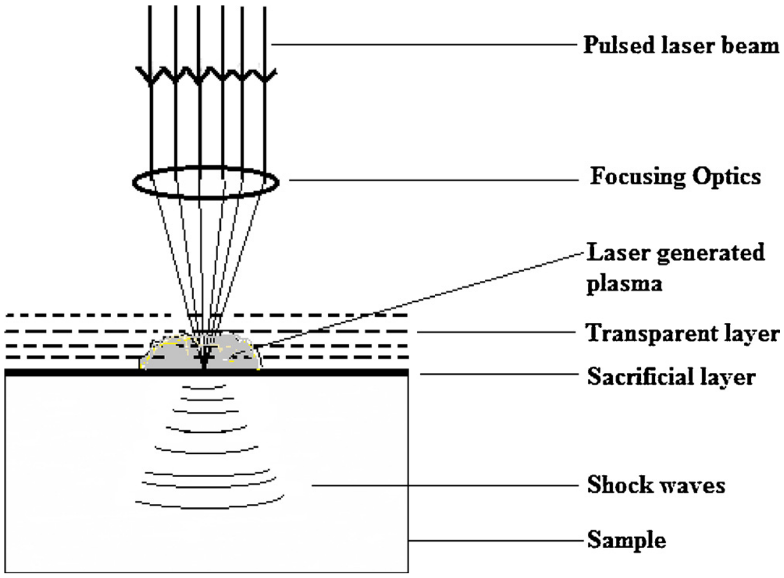

Figure 14. *Schematic diagram of LSP* (Dhakal et al., 2018)

Laser shock peening of laser welded Incoloy 800 H joint were performed and the microstructure of the specimen with optical microscopy and TEM analysis were studied (Chen et al., 2014). The results show the significant grain refinement in the weld zone after laser shock peening. The grains before peening were more columnar with very few equiaxed grains at weld zone due to the high heat input during the welding. After laser shock peening the pattern was changed to large volume fraction of equiaxed grains by the virtue of twinning at high strain rate plastic deformation. High strain rate plastic deformation causes dislocation generation, motion (slip) and pile-up which results to accumulation of dislocations at surface and sub surface layer of peened specimen. On the other hand, high strain plastic deformation breaks the original grain boundaries to some extent and induces dislocation initiation and propagation that leads to the formation of mechanical twinning in the matrix which subdivides the coarse grains and forms sub-grains boundaries. As the shock wave continues, these small sub-grains are shredded to equiaxed grains with smaller sizes (Chen et al., 2014).

Apart from the conventional method of post-weld treatment are full of limitations like high surface roughness, less effective depth of induced compressive residual stresses and work hardened layer and inaccessibility of areas like joints, notches, and filets. So, in this circumstance new approach is essential with promising technique to deal with those limitations and laser shock peening is the one which can possibly fit, the capability of laser shock peening in notably improving the overall mechanical and microstructural properties of weldments (Dhakal et al., 2018).

Based on significant compressive residual stress induced and microstructural improvements by laser shock peening, it can be concluded that laser shock peening also applicable in high strength steel welding joints. Also, important to highlight the laser shock peening process caused grain refinement in weld and heat effected zone what can also be advantageous in case of post-weld treatment of high strength steel welding joints. Consider the development of the laser welding power sources and spreading in the industrial use in recent years it is possible that laser shock peening will be deeply investigated and based on the result spreading in industrial use in high strength steels welding joints post-weld treatment.

2.1.6. Overloading treatments

Overloading treatments are introducing the compressive residual stresses in the weld toe by overloading the joint and/or the structure. Based on the overloading process these treatments are categorized into two groups as follows.

- **Prior static overloading.** This treatment is relying on the introduction of compressive residual stress at the weld toe as result of local yielding. The positive effect of prior static overloading has been observed in joint with both mild and severe stress concentration. It should be noted that the regular periodic tensile overloading of the structure throughout its life may also be advantageous, but the fatigue damage caused by these overloads' cycles must also be considered in the life calculation.
- **Local compression.** In these techniques a small part of the structure is forced to yield locally by compression between circular dies. After the load is removed the plastic deformation of material will cause residual compressive stresses to be induced around the indentation. The main disadvantage of this local compression method is the high loads that must be applied at the dies and the need for access to both sides of the plate (Kirkhope et al, 1999).

Overloading treatments of high strength steels are not considered practicable due the high strength material require high loads to reach local yielding and the low elongation of the base material is also considered as risk of negative effect on the lifetime of the structures.

2.2. Thermal methods

Thermal methods are also applied to reduce welding residual tensile stress globally in the welded structure and/or induce compressive residual stress in the weld toe and weld interpass notches (see bottom part of *Figure 1*). Low Transformation Temperature (LTT) welding is also categorized as thermal residual stress reduction post-weld treatment (PWHT) method; however this method is post-weld treatment method due that special welding wire is applied but special wire effect the residual stress reduction.

2.2.1. Thermal stress relief

Thermal stress relief also known as post-weld heat treatment (PWHT), relies on the removal of welding residual stresses in all welded structure rather than to introduction of compressive stresses. Schematic diagram of thermal stress relief is shown in *Figure 15*.

Performing thermal stress relief is limited by the dimensions of the furnace, therefore over the furnace limited dimension other method must consider like vibration stress relief.

Thermal stress relief of complete high strength steel welded structures practically not used rather than the hydrogen reduction post-weld heat treatment what is applied immediately after welding the joint and approximately 200 mm area heat up to 200–300 °C and hold the joint temperature in this range till 2 h than let the joint to cool slowly under covered condition. Hydrogen reduction post-weld heat treatment is applied in thick throat size over 30 mm (fillet welds).

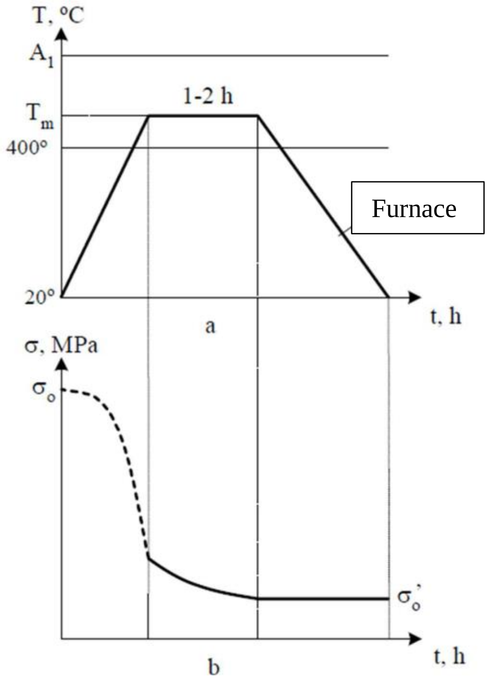

Figure 15. *(a) Schematic diagram of post-weld heat treatment PWHT; (b) residual stress reduction during PWHT* (Balogh et al.,2003)

2.2.2. Spot heating

Fatigue improvement by spot heating involves the local heating of a structure usually by oxyacetylene torch to produce local yielding. Residual stresses are thus formed by similar mechanisms which produce residual stresses during welding process. This local area becomes an area of residual tensile stress and because the internal stress distribution must be self-balancing, compressive residual stresses will exist some distance from the heated spot. The definition of optimum parameters for the application of spot heating requires experiments, however a procedure has indicated for treating steel components (Booth, 1991; Kirkhope et al., 1999).

Spot heating process for improvement of fatigue strength of high strength steel welding joint is practically not applied. The high strength steel spot heating has influence on the microstructure and crack propagation of the welding joints. Researchers (Gyura et al., 2021) found that in high strength steels intentional or accidental heating in the intercritical A_1-A_3 results in significant damage to the original structure of the smoothed steel and martensite-austenite (M-A) islands causes a significant decrease of toughness, due to the mixed structure formed. The results of the instrumented impact tests have shown that in such case, due to the mixed fabric formed, the crack propagation energy is drastically reduced with nearly unchanged crack initiation energy (Gyura, 2021).

2.2.3. Gunnert's method

Gunnert's method, as a technique of fatigue life improvement also involves local heating but eliminates the need for exact positioning of the spot. In this procedure the actual weld toe is heated to a temperature sufficient to cause plastic deformation and surface is rapidly quenched by spraying with a jet of water.

Differential cooling results compressive residual stresses in the surface layers (Booth, 1991; Kirkhope et al., 1999).

High strength steels straightening process were analysed and found immediate water cooling of heated material parts is not recommended due to local hardness increase and critical toughness loss. Water cooling is even more dangerous as the higher the strength group. Based on practical investigations, Gunnert's method is not recommended as high strength steels fatigue strength improvement process (Gyura et al., 2021).

2.2.4. Low Transformation Temperature (LTT) welding

The local weld toe geometry can be improved by different post-weld treatment methods including TIG dressing, laser remelting, burr grinding [see the first part of our article (Sas et al., 2022)]. The residual welding stresses can be reduced or modify into advantageous compressive residual stresses by using peening processes. But being a post-weld treatment, it is only disadvantages as it will increase the production cost of the component. Significant reduction in the residual tensile welding stresses can also achieved by using Low Transformation Temperature (LTT) welding wires instead of the conventional ones.

Phase transformation plays a prominent part in the formation of welding residual stresses in high strength steels. During welding, phase transformation is affected by the chemical composition and the cooling rate in regions that are being austenized during the heat cycle. Depending on these two variables different transformation temperatures are yielded. The characteristic of LTT filler material is that it undergoes austenite to martensite phase transformation at temperature close to room temperature which will reduce the tensile residual stresses in the weld and in some cases result in compressive residual stresses (Bhatti et al., 2013).

Several publications have reported the significant reduction in tensile welding residual stresses and improvement of fatigue strength by using LTT filler material as compared to the joint welded with conventional welding wires (Ohta et al., 2002; Kromm et al., 2011; Shiga et al., 2007).

Experimental result using 1.2 mm diameter iron-based chromium-nickel alloyed and chromium-manganese alloyed metal cored wire for welding of 700 MPa and 960 MPa high strength steel were reported (Bhatti et al., 2013). Concluded the reduction of the tensile residual stresses near the weld toe area of the longitudinal stiffener joint is achieved when welded with LTT filler wire. An increase of fatigue strength is observed for LTT welded specimens when compared whit the specimens welded with conventional filler wire.

3. Conclusions

This paper reviewed post-treatment techniques of high strength steel welding joints to improve the fatigue strength of welded joint by improving the residual stress condition of the welding joint. The aims of these techniques are reducing the residual welding tensile stresses in weld zone and inducing compressive residual stresses in weld toe by mechanical or thermal processes.

Based on the overview, it can be drawn that the peening processes can be applied without restriction and as the reviewed studies result shows significant effect can be achieved by different peening process in the fatigue strength of high strength steel welding joints. The overloading post treatment processes is practically not in used in high strength steels and the thermal post-weld treatments has also some restrictions. Only the Low Transformation Temperature welding process – as thermal residual stress method – based on reviewed studies results shows significant improvements in the fatigue strength and reduction of tensile residual stresses.

Based on overview – consider also the first part of our article the weld geometry improvement methods – it is also found that weld geometry post-weld treatments are more well-known and applied for high strength steel welding joints fatigue strength improvement in practice. This is found based on the high strength steel's structure design requirement reviews and welding experiences in manufacturing sites. Peening process is not so widely spread out in high strength steel welding structures design and manufacturing therefore it is interesting future areas to investigate and compare weld geometry and residual stress condition (peening) improvement methods and also extend the investigation to compare fatigue strength improvement result of mild steels with high strength steels.

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