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Material and residual stress improvement in S355 welded structural steel using mechanical and thermal post-weld treatment methods

Welding is by far the most widely used metal joining method. High-Frequency Mechanical Impact (HFMI) treatment and Tungsten Inert Gas (TIG) remelting are two post-weld treatment methods that aim to enhance the strength of the steel. In this paper, the improvement in residual stress and material characteristic obtained with these methods are studied by conducting several experimental investigations such as hole drilling, hardness testing and microscopy. Hole drilling shows that HFMI treatment improves the status of residual stress at the weld toe in the first 1 mm from the surface. Furthermore, Vickers testing shows a remarkable improvement in the hardness values at the weld toe in the first 2 mm. This can be attributed to the reduction in grain size after treatment. Moreover, acicular ferrite and tempered bainite are found to be the main constituents in the fusion and heat-affected zones after TIG-remelting.

Keywords S355; structural steel; High-Frequency Mechanical Impact; Tungsten Inert Gas remelting; residual stress

1 Introduction

Structural steel is a carbon steel category that is widely used for construction and building projects. Different steel components need to be fabricated in order to build the desired geometries. Welding is by far the most prominent fabrication method for joining materials. Metal active gas (MAG) welding is a method of arc welding in a shielded environment. This welding method has a high disposition rate with no slag formation. Moreover, high welding speed can be achieved while still maintaining a high-quality weld. However, welded structures are prone to several forms of material degradation such as cracking, fatigue and corrosion. Therefore, several post-weld treatment methods are proposed to improve the welded area [1]. High-Frequency Mechanical Impact (HFMI) treatment aims to improve the weld toe's vicinity by inducing permanent plastic deformation. Tungsten Inert Gas (TIG) can also be used to enhance the weld toe via fusion.

Several studies have demonstrated the capabilities of HFMI treatment and TIG remelting in enhancing the fatigue strength of welded structures [2, 3]. However, the mechanisms of improvement at the material level need to be further investigated. Moreover, in the literature, there is a scarcity of studies that explore the fatigue life improvement achieved with post-weld treatment by conducting investigations at the material level rather than focusing on fatigue testing alone. Therefore, this paper contributes to studies of the improvement in residual stress status and local hardness by HFMI treatment, TIG remelting and the combination of both in S355 structural steel via several investigations such as Vickers testing, microscopy, and hole drilling. Moreover, it sheds light on the effect of these treatment methods on the local microstructure of the welded area.

2 Manufacturing and investigations

The study is conducted on S355 structural steel plate welded to a transversal attachment via metal-cored weld C6LF. The mechanical proprieties and the chemical composition of both are obtained from [4]. The welding process is MAG welding with a Mison18 gas. The attachment is first chamfered, and then two welding runs (i.e., root and cap welding) are conducted with almost identical welding parameters. The heat input is controlled to be around 1 KJ/mm for both welding runs by regulating the welding speed, voltage and current. The manufactured specimens are then divided into four groups. The first group contains the reference specimens which receive no form of treatment. The remaining three groups comprise the specimens treated by either HFMI treatment, TIG remelting or a combination of both.

The process of TIG remelting is robotized in order to control the heat input during remelting and avoid overheating and subsequent inflammation. Heat input of 1.78 KJ/ mm is selected in accordance with the recommendations [1]. Two HiFIT indentors are used to perform HFMI treatment. The first with a diameter $\varphi = 5$ mm is used to treat the TIG remelted specimens, while $\varphi = 3$ mm is used to treat specimens with no previous remelting.

The status of the residual stresses in different groups is measured by means of the hole drilling method. SINT technology automatic residual stress measurement systems are used. Several holes are drilled at the weld in as-welded and TIG remelting, and close to the edge of the HFMI groove. The maximum depth of penetration of each hole is limited to 1.2 mm from the surface. This is because the accuracy of the measurement decreases as the depth of penetration increases [5]. The specimens are cut in a position perpendicular to the weld line to per-

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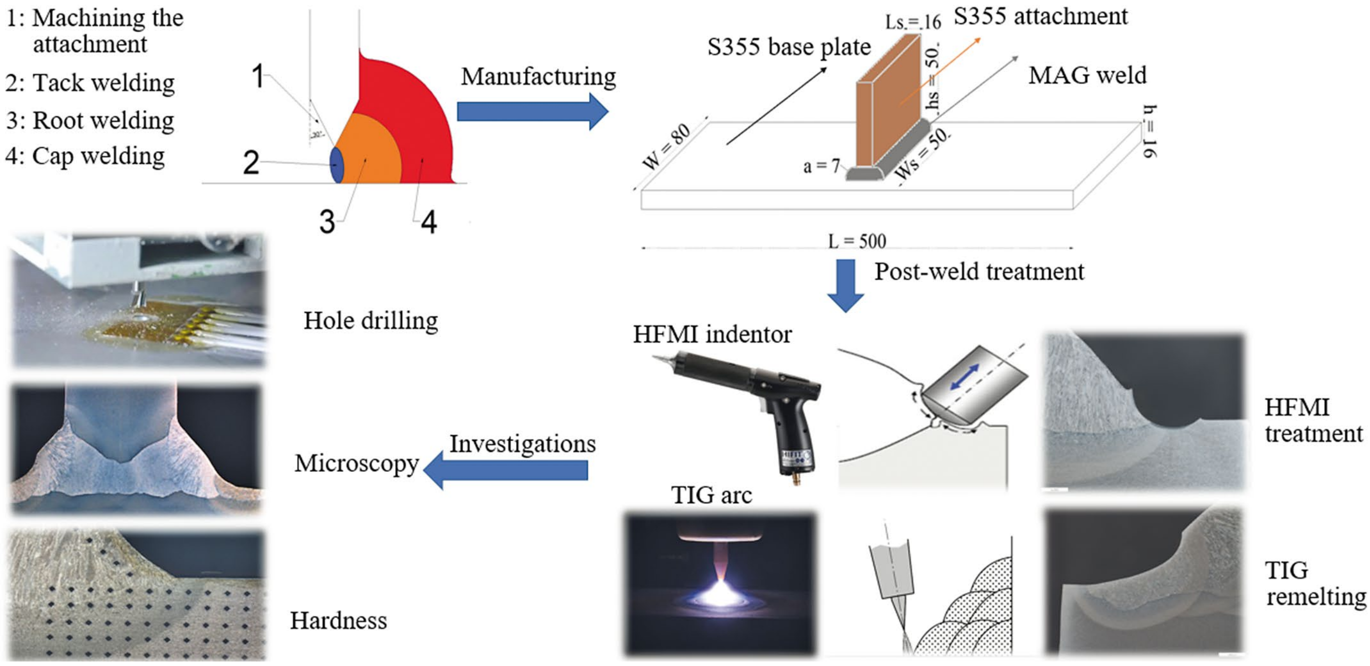

Fig. 1 Manufacturing process, treatment and investigations

form microscopic analysis using a Leica laser microscope. After cutting, the surfaces are ground and processed by etching with 2 % V/v Nital solution. Then a Vicker tester is used to quantify the improvement in material hardness after treatment. A 3 kg test load is applied, and the generated indents are spaced 0.5 mm apart horizontally and vertically. The manufacturing process and investigations are summarized in Fig. 1.

3 Results and discussions

The hole drilling test results for as-welded (i.e. untreated) and treated specimens are given in Fig. 2. Noticeably, compressive residual stress dominates at the weld toe even in as-welded condition. This might be traced back to the expansion of volume due to martensite transformation at the lower temperature [6]. However, the compressive stress is very superficial and will vanish upon fatigue or corrosion when this thin layer is removed. TIG remelting induces more compression at the surface by replacing the heat-affected zone in as-welded condition (which is dominated by bainite) with a new fusion zone (which is dominated by acicular ferrite with islands of Widmanstatten ferrite). The investigated micro-structure in the fusion and the heat-affected zones before and after TIG remelting are shown in Fig. 3.

HFMI treatment induces significant compressive residual stress at the weld toe as shown in Fig. 2. In all the HFMI and HFMI-TIG treated specimens, the maximum compression is obtained at a depth of 0.15–0.30 mm which corresponds to the penetration depth of the HFMI indentors. Moreover, the induced compression after HFMI treatment can exceed 1 mm, which implies that these beneficial stresses do not vanish when the crack starts or if the weld gets corroded. In addition to residual stress improvement, HFMI treatment also helps to harden the weld toe's vicinity because of the steel cold working, see Fig. 4. The increase in hardness after TIG remelting can be attributed to the interlocking structure of ferrite which dominates the weld toe after remelting. Furthermore, deeper beneficial hardness and compressive residual stresses are induced when TIG remelting and HFMI treatment are combined.

HFMI treatment causes a reduction in the average grain size at the weld toe from 30 µm to 4 µm which contributes to increased hardness close to the weld toe. However, this effect diminishes at 2 mm from the weld toe. The grain size is defined as the diameter of a circle which has an area equal to the grain area. Furthermore, Revilla-Gomez et.al found that the dislocation density increases in the first 250 µm below the surface [7]. Although the HFMI treatment does not affect the microstructure of the heat-affected zone significantly, the width of this zone decreases at the surface as a result of the flow of material from the base metal toward the weld, see Fig. 4.

TIG remelting can contribute to either softening or hardening at the weld toe. For the studied specimens, the hardness value increases after TIG remelting down to 2.5 mm from the weld toe as shown in Fig. 5. Moreover, the combined effect of TIG remelting followed by HFMI treatment causes a remarkable increase in the hardness value compared with both individual treatments as shown in the same figure.

Both TIG remelting and HFMI treatment can be applied to structures containing cracks [8]. TIG remelting causes complete removal of the cracks in the fusion zone. However, it might contribute to crack opening in the subsequent layer (e.g. heat-affected zone). This might be attributed to the tensile residual stresses dominating this layer.

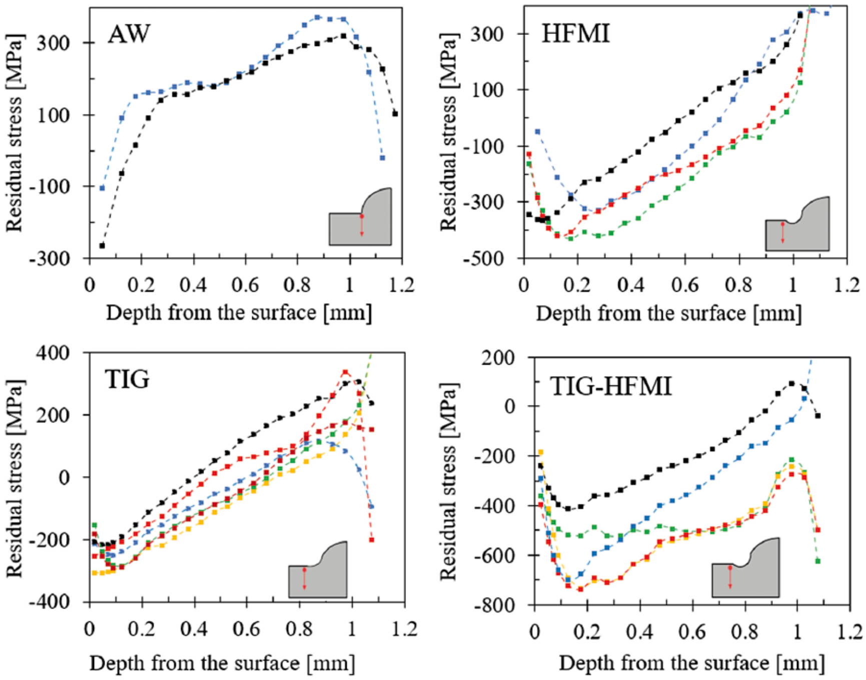

Fig. 2 Residual stress measurements for specimens in different status

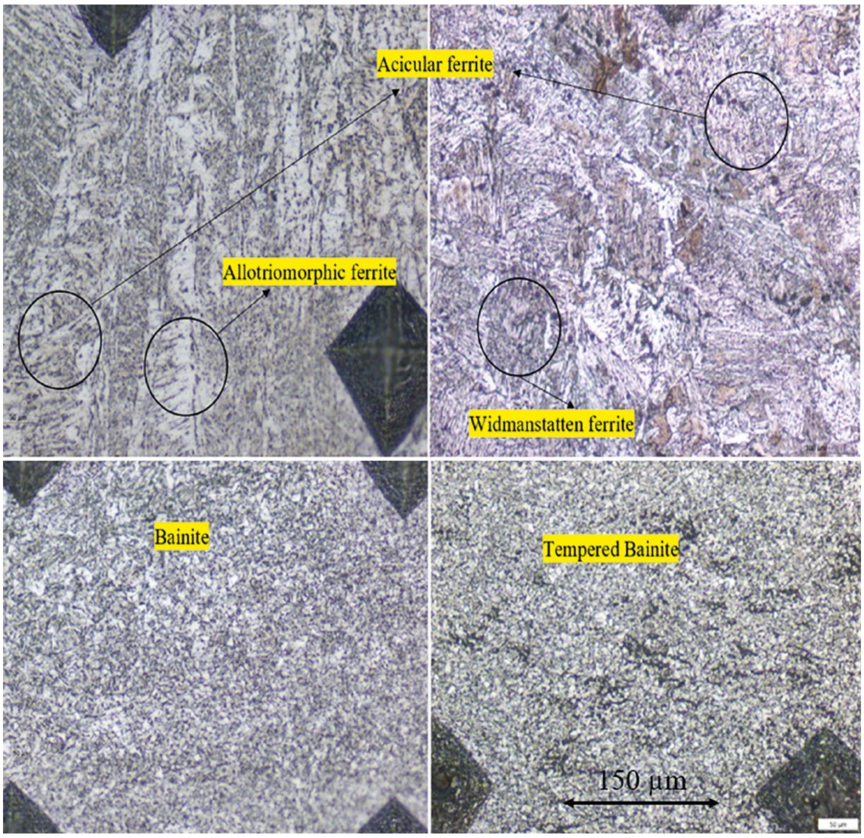

Fig. 3 Fusion zone (top) and heat-affected zone (bottom) before and after TIG-remelting

In contrast, HFMI treatment does not remove the crack, but it causes crack closure because of the material flow toward the crack due to cold working.

4 Conclusion

This paper investigates the improvement in local residual stresses and hardness in S355 welded structural steel by means of two post-weld treatment methods: HFMI treatment and TIG remelting. Hole drilling shows an increase in the compressive residual stress following all treatment methods. Vickers hardness increase is also measured in the top 2 mm from the surface. This is explained by the reduction in the grain size after HFMI treatment and the acicular ferrite formation in the new fusion zone after TIG remelting. The combined effect of TIG remelting followed by HFMI treatment yields high-

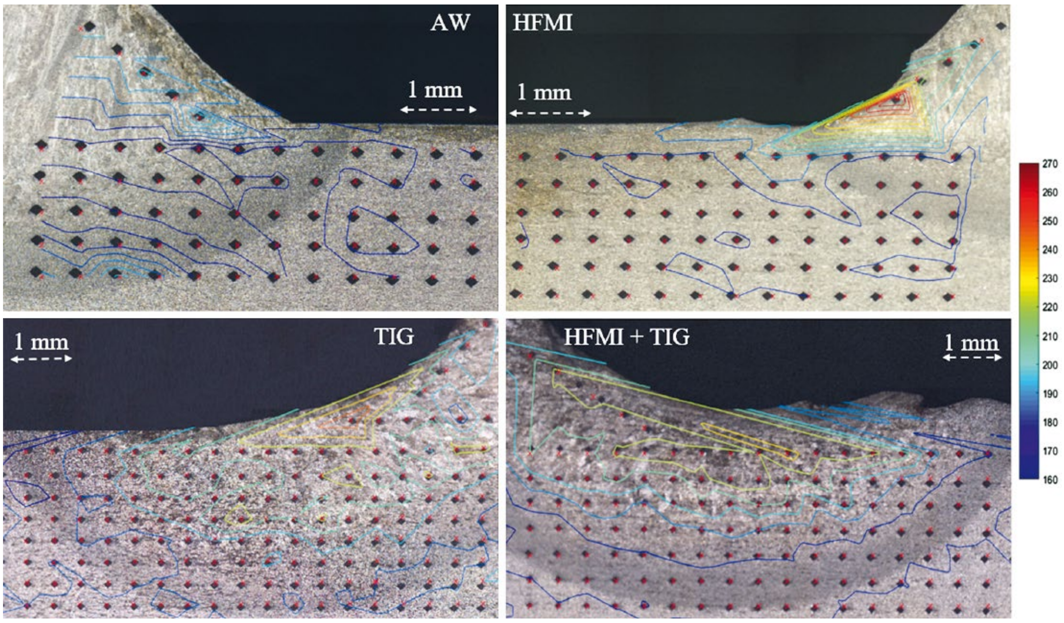

Fig. 4 Vickers hardness distribution before and after treatment

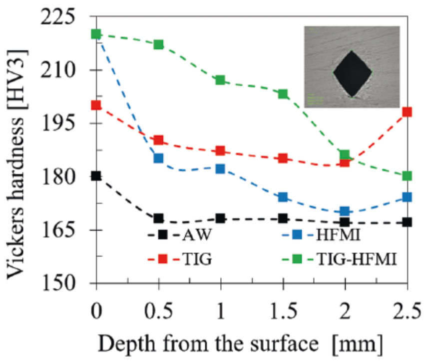

Fig. 5 Vickers hardness distribution below the weld toe, for as-welded and treated specimens

er compressive residual stress and better improvement in local hardness.

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