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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

To analyse the microstructure and mechanical properties of GTAW/ TIG and laser welded joints of specific Fe-Mn-Al-C lightweight steel.

TESI DI LAUREA MAGISTRALE IN
MECHANICAL ENGINEERING-INGEGNERIA MECCANICA

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1. State of the Art

The automotive industry endeavors to enhance fuel efficiency, reduce emissions, and achieve sustainability objectives through the utilisation of lighter components[1], [2] Various lightweight materials are currently under investigation for this specific application. These materials include carbon fibre composites, magnesium and aluminium alloys, as well as magnesium and aluminium composites [2], [3]. Notwithstanding, these materials exhibit certain limitations, including challenges in shaping, susceptibility to rust, and high cost [4]. Fe-Mn-Al-C alloy, a type of lightweight steel, presents a viable solution to the challenges. This material boasts high strength and durability while simultaneously reducing weight [4]– [6]. The Fe-Mn-Al-C steels have been found to possess exceptional mechanical properties, fatigue strength, low-temperature toughness, and corrosion resistance [5], [7]– [9]. The utilisation of these materials in the automotive sector can make a substantial impact on decreasing weight, enhancing fuel efficiency, and minimising emissions [1], [10], [11]. The implementation of lightweight materials may help in the extension of the electric vehicle range by decreasing the weight of the battery [12]–[14]. Further research is needed to address challenges related to weldability and optimisation of compositions and manufacturing processes [5], [15]. The automotive industry has the potential to be revolutionised by lightweight steel, which can contribute to a more sustainable future. However, continuous development is required.

2. Experimental Procedure

The objective of this study is to analyse the microstructure and mechanical properties of laser and GTAW welded joints of a particular Fe-Mn-Al-C lightweight steel. An optical emission spectroscopy technique was employed to analyse the elemental composition of a plate that was 5 mm in thickness. The alloy's chemical composition was anticipated to cause modifications in particle size, carbide precipitation, and consequent mechanical characteristics. The study involved the application of two distinct heat treatment conditions, namely hot rolling and solubilisation, followed by the use of GTAW and laser welding techniques. Welding current modes were employed in the Gas Tungsten Arc Welding (GTAW) process. It was expected that every sample would display distinct microstructures and mechanical properties.

2.1. Thermo-mechanical Treatments:

Thermal treatment is a metallurgical process that is employed to modify the microstructure of the steel and enhance its mechanical characteristics. The hot rolling process entails heating the steel material to a temperature that exceeds its recrystallisation point. The material is then subjected to rolling mills, which compress it to reduce its thickness. The aforementioned procedure improves the grain structure, enhances mechanical characteristics, and eradicates internal tensions. Solubilisation is a heat treatment technique that involves heating steel above its austenitising temperature. This process dissolves alloying elements into the matrix, resulting in a homogeneous solid solution. The duration of the treatment is a factor that affects the dimensions of the austenite grains. Thermal treatments are essential for enhancing the characteristics of lightweight steels.

2.2. Tests and Analyses

The steel sample preparation procedure comprised of the following stages, namely mounting, grinding, polishing and etching. The process of grinding was executed by utilising rotating plates that were lubricated with water and abrasive material. This gradually decreased the size of the particles. The process of polishing was performed by utilising lubricated-rotating cloths that were coated with diamond suspension. This method resulted in a surface that was smooth and had a maximum roughness of 1 μm. Cleaning was performed subsequent to every polishing procedure. The analysis of the microstructure of the samples was performed utilising an optical microscope that was equipped with imaging software and a camera. The ASTM E112-13 standard was followed to conduct the experiment, which involved utilising various magnifications ranging from 25x to 500x.

To conduct a thorough analysis, the morphology and microstructure of the materials were investigated utilising a Zeiss Sigma500 field emission microscope via Scanning Electron Microscopy (SEM). The investigation of secondary phases and carbide precipitation was carried out using magnifications of 1000x, 5000x, and 10000x. The qualitative phase identification was carried out using Energy-Dispersive X-ray Spectroscopy (EDS). Additionally, the examination of grain misorientation and crystallographic characteristics was made possible through the use of Electron Backscatter Diffraction (EBSD) analysis.

Micro-hardness tests were performed on the material using a Vickers micro-hardness tester to evaluate its hardness distribution and microscopic variations. The process of tensile testing complied with established standards, with the measurement of parameters including ultimate tensile strength, yield strength, elongation, and area reduction. The SEM and optical microscopy techniques were utilised to examine the microstructure of the material. Fracture surface analysis was conducted to investigate the fracture behaviour of the material. Vickers microhardness testing was performed to determine the hardness of the material. Tensile testing was carried out to evaluate the mechanical properties of the material. The combination of these techniques provided a thorough understanding of the microstructural characteristics, mechanical properties, and fracture surface.

3. Results

3.1. Microstructure Evaluation

Hot-rolled Condition

The Fe-30Mn-9Al-1C alloy exhibits equiaxed and randomly oriented austenitic grains, suggesting the absence of any favoured crystallographic orientation. The presence of twin boundaries and deformation micro-bands indicates the potential influence of mechanisms such as Twinning Induced Plasticity (TWIP) and Microband Induced Plasticity (MBIP). The hot-rolled state exhibits a finer grain structure as a result of dynamic recrystallisation when compared to the solubilised state.

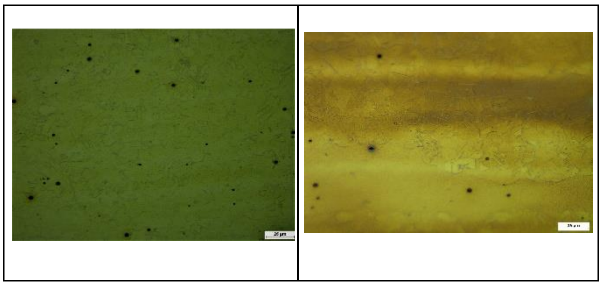

Figure 1 Micrographs of the hot-rolled solubilised condition samples

Solubilised Condition

The optical micrographs indicate that the sample displays austenitic grains that are equiaxial and randomly oriented. Twin boundaries are present in a significant amount. The phenomenon can arise as a result of plastic deformation or due to particular crystallographic orientations present in the material. The analysis indicates that the grain size is coarse. Figure 1 shows the micrographs of both hot-rolled and solubilised condition samples.

TIG Cladded Plate

The microstructural changes in a cladded joint, which includes the fusion zone, heat-affected zone (HAZ), and base zone, are essential for evaluating the mechanical properties and joint integrity. The utilisation of optical microscopy enables the observation of dendritic structures present in the welded zone, which serves as an indication of the solidification front. The Heat Affected Zone (HAZ) may exhibit changes in grain size, precipitation of secondary phases, and hardness. The microstructural analysis is a technique that enables an assessment of the strength, toughness, and corrosion resistance of a material. The use of AC cladding results in a weld pool that is shallower in comparison to DC cladding. DC cladding leads to deeper penetration as a result of the concentration of heat. Direct current (DC) welding results in a greater heat-affected zone (HAZ) due to the high level of heat input. The phenomenon of twinning has been detected in both the heat-affected zone (HAZ) and the base material. The base material displays elongated dendrites, small equiaxial grains, and finer grain size in contrast to the Heat Affected Zone (HAZ).

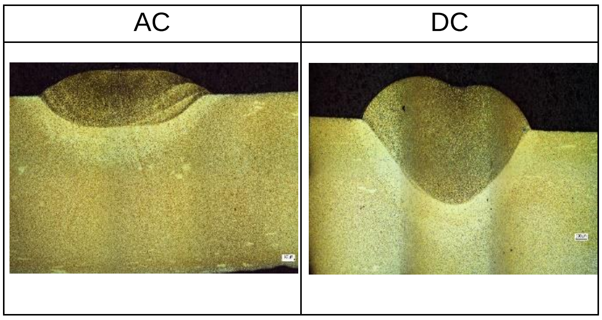

Figure 2 Optical micrograph of TIG cladded plate

Laser Beam on Plate

Distinct zones with unique properties can be observed on the plate during the laser beam. Epitaxial grain growth is a phenomenon that occurs due to rapid heating and cooling rates in the fusion zone. This zone experiences local melting and solidification. The Heat-Affected Zone (HAZ) undergoes increased temperatures without undergoing complete melting, resulting in larger and coarser grain sizes when compared to the base material and fusion zone. The characteristics in question are influenced by grain growth and recrystallisation. The base material possesses a smaller grain size and may display twinning, leading to an impact on mechanical characteristics and deformation. Comprehending the microstructural characteristics is essential in assessing the suitability of laser beams and guaranteeing the best possible performance of the component.

TIG Welding

The welded joint is comprised of three distinct sections, namely the fusion zone (FZ), heat-affected zone (HAZ), and base material (BM). The process of welding causes rapid solidification in the fusion zone, leading to the formation of a microstructure that is fine-grained. The optical microscope enables the visualisation of dendritic structures that form from the solidification front. The Heat Affected Zone (HAZ) is characterised by the absence of melting, resulting in the growth of larger grains due to a slower cooling rate. Microsegregation is a phenomenon that can be observed in the FZ (fusion zone) and HAZ (heat-affected zone) due to chemical inhomogeneity or different microstructures. The solidification behaviour can be influenced by microsegregation, which can also contribute to the development of dendritic structures and fine grains.

Laser welding

The welded joint comprises three distinct sections, namely the fusion zone (FZ), heat-affected zone (HAZ), and base material (BM). The process of welding leads to rapid solidification in the fusion zone, which subsequently results in the formation of a microstructure that is fine-grained. The optical microscope allows for the observation of dendritic structures that form from the solidification front. Within the Heat Affected Zone (HAZ), where there was no melting, the reduced cooling rate results in the development of larger grains.

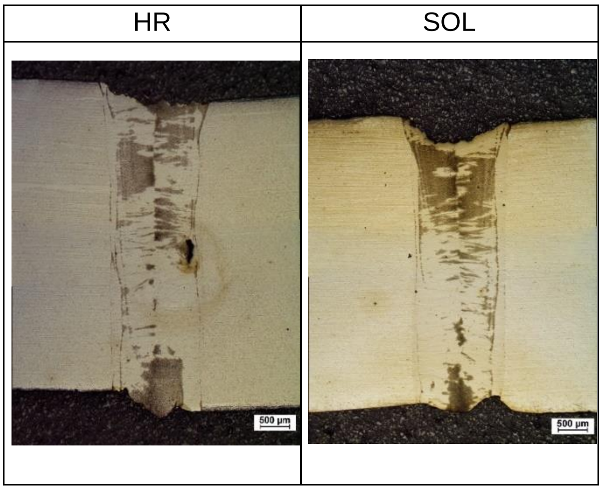

Figure 3 Optical micrograph of laser welded plate

3.2. Microhardness Test

The investigation involved the carrying out of microhardness assessments on multiple specimens before the process of welding or cladding. The results of the analysis indicated that the hot-rolled samples exhibited greater hardness than the solubilised samples before the welding process. Comparable outcomes were achieved through microhardness examination of specimens while they underwent the welding or cladding procedure. The specimens were categorised into three separate regions, namely the welded region, the heat-affected zone (HAZ), and the base region. The base region had the highest hardness in all welding and cladding situations. The observed phenomenon can be explained by various factors, including the material's composition, prior thermal processing, and distinct microstructural features.

Upon comparison of the fusion region and the heat-affected zone (HAZ), it was observed that the fusion region consistently exhibited greater hardness. The trend was noted across all occurrences of welding and cladding. The region that was cladded exhibited a rise in hardness as a result of rapid solidification, which promotes the formation of refined grains. The improvement of hardness is facilitated by the incorporation of a distinct material during the cladding process and the subsequent reduction in the concentration of the base material. In contrast, the heat-affected zone (HAZ) consistently displayed lower hardness levels when compared to the fusion region. The observed phenomenon can be attributed to the slower cooling rates and thermal cycling that the heat-affected zone (HAZ) undergoes during welding or cladding. These conditions result in the formation of larger grains and changes in the microstructure.

Upon comparing the hardness results of Tungsten Inert Gas (TIG) cladding, it can be observed that the hardness trends across all material sections are similar for both Alternating Current (AC) and Direct Current (DC) cladding. The influence of current modes on the hardness is observed to be negligible.

3.3. Tensile Test

The strength properties of hot-rolled Tungsten Inert Gas (TIG) welded specimens are higher in comparison to solubilised specimens. The hot rolling procedure results in a more sophisticated and aligned grain configuration, thereby improving the material's strength and other mechanical properties. The process of microstructural refinement is essential for achieving these improvements. The microstructure of the material being welded can be affected by TIG welding, irrespective of the welding technology employed. The aforementioned process can lead to the refinement of grains and the activation of strengthening mechanisms such as precipitation hardening. In comparison to hot-rolled specimens, solubilised specimens demonstrate reduced tensile strength but increased elongation at fracture. The process of solubilisation results in modifications in microstructural properties, particularly the formation of enlarged grains. Increased grain size enhances the ductility and elongation characteristics of the material by enabling more extensive plastic deformation before fracture. The improved ductility is advantageous for situations that involve substantial deformation or exceptional formability. Solubilised specimens with larger grain sizes can have a detrimental impact on tensile strength. This is because larger grain sizes can lead to increased dislocation movement, which causes localised plastic deformation and an overall decrease in tensile strength. From Table 1 number system is used to symbolise the conditions: 1 signifies TIG_DC_HR; 2 signifies TIG_DC_SOL; 3 signifies TIG_AC_HR; 4 signifies TIG_AC_SOL; 5 signifies LW_HR; 6 signifies LW_SOL.

	1	2	3	4	5	6
σ_y	679	498	664	500	558	458
σ_{UTS}	993	842	816	869	760	782
σ_{fract}	877	479	549	664	708	760
ε_{fract}	38.2	53.8	11.1	46.2	9.4	33.4

Table 1 Tensile properties of Fe-Mn-Al-C steel samples after welding

4. Discussion

The analysis of the microstructure of heat-treated samples before welding can be conducted by dividing them into two categories, namely solubilised and hot-rolled samples. The division promotes the analysis of microstructural changes in both situations, providing significant insights into the original condition of the samples and their welding performance. The Fe-30Mn-9Al-1C alloy exhibits equiaxed and randomly oriented austenitic grains in both hot-rolled and solubilised samples. However, there are differences in grain size and the occurrence of twin boundaries. The elevated temperature plastic deformation process causes dynamic recrystallisation in hot-rolled samples, resulting in finer grain sizes. Solubilised samples exhibit increased grain sizes as a result of the lack of dynamic recrystallisation and a fusion of grains. Twin boundaries are a result of plastic deformation or specific crystallographic orientations. These boundaries are indicative of the presence of Twinning Induced Plasticity (TWIP) and Microband Induced Plasticity (MBIP), which serve to improve plastic deformation and prevent fracture.

The cladded material in GTAW (Gas Tungsten Arc Welding) can be categorised into three distinct zones, namely the fusion zone, heat-affected zone (HAZ), and base zone. The utilisation of the AC cladding technique yields a weld pool that is comparatively shallow, whereas the DC cladding technique results in a more profound weld penetration and a larger Heat Affected Zone (HAZ). Twinning may manifest in both the heat-affected zone (HAZ) and the base material as a result of stress and strain experienced during the cladding procedure. The region of the base material displays equiaxed grains and a random orientation, which is typically smaller in size than those observed in the heat-affected zone (HAZ). Laser beam cladding, much like Tungsten Inert Gas (TIG) cladding, exhibits three distinct regions: the fusion zone, heat-affected zone (HAZ), and base material. The region of fusion displays swift solidification with the microstructure of fine grains, whereas the heat-affected zone (HAZ) showcases grains of larger size owing to fluctuations in temperature. The base material exhibits a smaller grain size and may exhibit twinning.

The assessment of mechanical properties, weld integrity, and optimisation of welding parameters is dependent on the comprehension of microstructural characteristics in each zone. The rapid solidification process in both GTAW and laser welding results in the formation of fine grains in the fusion zone. On the other hand, the heat-affected zone (HAZ) exhibits coarser grains. The region of the base material is characterised by smaller grain size and negligible microstructural alterations. These findings contribute to the identification of suitable welding parameters and the achievement of desired welding results. The compositional maps generated by Energy-Dispersive X-ray Spectroscopy (EDS) provide valuable information regarding the distribution of elements within microstructures. Manganese (Mn), aluminium, and iron distributions in Tungsten Inert Gas Direct Current (TIG-DC) cladded microstructures exhibit variations, which may be attributed to welding parameters, cooling rates, or impurities. The fusion zone is characterised by the presence of long dendritic structures, which provide insights into the solidification process. The process of analysing EDS maps and microstructural features enables the comprehension of material properties, evaluation of cladding quality, and enhancement of welding parameters. The understanding of this information is essential in acquiring data regarding the distribution of elements, and solidification patterns within TIG-DC cladded microstructures.

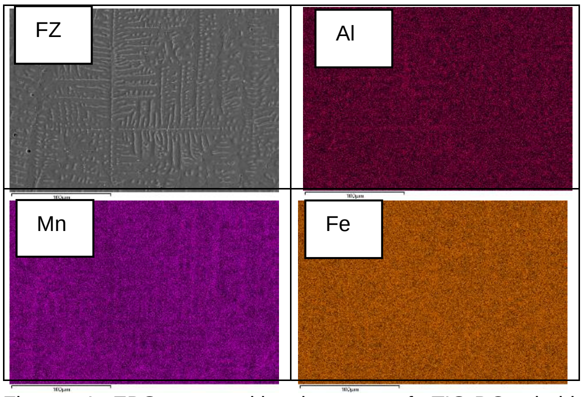

Figure 4 EDS compositional maps of TIG-DC cladded microstructure

In the beginning, the investigation included the utilisation of microhardness testing to evaluate the hardness of samples prior to welding or cladding. The hardness of hot-rolled samples was found to be higher than that of solubilised samples. In welding and cladding scenarios, the base region consistently exhibited the highest level of hardness. The average hardness of the fusion region was observed to be generally higher than that of the heat-affected zone (HAZ). The process of cladding led to a rise in hardness as a result of a high thermal gradient which leads to fine grains. Conversely, the heat-affected zone (HAZ) showed a decrease in hardness due to coarse

grains. The hardness values obtained from Tungsten Inert Gas (TIG) welding were found to be greater than those obtained from cladding. Furthermore, Laser welding demonstrated even greater hardness values. The variation in hardness has been attributed to factors such as heat input, modifications in microstructure, and variations in the process.
The experimental findings indicate that Tungsten Inert Gas (TIG) welded specimens that were hot-rolled exhibit higher strength, stress at fracture, and ultimate tensile strength (yield strength = 679 MPa, ultimate tensile strength = 993 MPa) when compared to solubilised specimens. The process of hot rolling enhances the grain structure of the material, thereby improving its resistance to deformation and fracture. The microstructure is impacted by the welding process, leading to grain refinement and strengthening mechanisms. Specimens that have been solubilised demonstrate increased elongation at fracture but decreased tensile strength as a result of having larger grain sizes. The refined grain structure of hot-rolled Tungsten Inert Gas (TIG) welded specimens results in superior mechanical properties such as hardness and deformation resistance. Although laser-welded specimens may exhibit reduced yield and tensile strength, they exhibit commendable fracture resistance.

5. Conclusions

The results of this investigation allow for a number of inferences to be drawn. There have been reports that:
Regarding the effects of Hot-rolled and solubilised conditions.

- The microstructure of the material in its hot-rolled state exhibits small austenitic grains that are equiaxial and randomly oriented. The formation of such grains is attributed to the refinement of the grain structure through dynamic recrystallisation during the hot rolling process.
- The microstructure of the material in its solubilised state exhibits coarse grain, equiaxial and randomly oriented as compared to the hot-rolled case.
- The hardness of the material under a hot rolled state is always higher than the material under solubilised state because of finer grains and an increase in grain boundaries, which act as an obstacle for dislocation.

Effect of welding technologies on the fusion zone.

- The fusion zone exhibited elongated dendrites along the high gradient direction.
- Due to the following characteristics, it is found fusion zone has a higher hardness value as compared to the adjacent zone of the material (HAZ).
- The following characteristics are found in all welding technologies.

Effect of welding technologies on the heat-affected zone.

- The Heat-Affected Zone (HAZ) is a region in welding where the temperature rises but does not reach its melting point. Atomic diffusion and rearrangement occur due to the slower cooling rate in comparison to the fusion zone. This phenomenon promotes the growth of larger grain structures within the Heat Affected Zone (HAZ).
- Compared to the cladded region, the heat-affected zone (HAZ) consistently had lower hardness. The phenomenon under observation is a result of decreased cooling rates and thermal cycling effects experienced by the Heat Affected Zone (HAZ) during the operation.

Effect of welding technologies on the base material zone.

- The weld’s base material exhibits a microstructural complexity due to the presence of a fine grain structure and a combination of equiaxed and randomly oriented grains.
- The base material of the weld generally reveals the highest value for

hardness in comparison to the remaining material.

Effect of Welding Technologies on the tensile test

- The tensile strength and strain to fracture of the TIG-welded specimens are higher than those of the laser-welded specimens, irrespective of their initial state, i.e., hot rolled or solubilised.
- The fracture mode in all cases are ductile in nature
- In all welding technologies, the solubilised specimens exhibit a greater elongation at fracture but a lower tensile strength compared to the hot-rolled specimen.

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