MICROSTRUCTURE STUDY AND RESIDUAL STRESS ANALYSIS OF MARAGING STEEL LASER WELDMENTS

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ABSTRACT

Maraging steel finds innumerable applications especially in aerospace and defence applications because of its rare combination of mechanical properties of high strength, high fracture toughness, good weldability, and dimensional stability. Laser welding on MDN 300 maraging steel is considered in this work, to study the microstructural changes and the residual stresses induced after welding. The different regions across the weld bead were studied along with their microstructures. With regard to the residual stresses, the tensile residual stresses are detrimental to the strength of the material. Hence the present work also involves the analysis of the residual stresses across the weld pool. The magnitude of the residual stress is experimentally found using X-ray stress analyzer and the reasons for the variation of the transverse residual stress across the weld pool is studied in detail.

Key words: Residual stress, maraging steel, laser welding, microstructures.


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1. INTRODUCTION

Welding is one of the important manufacturing processes that significantly influences the economy as it is indispensably required for fabrication of a wide range of components used in automobiles, ship building, heavy machinery, bridges, aircrafts, etc. In any welding process, the microstructure of the weld pool and the residual stress play vital role in deciding the mechanical properties of the weldments. The weld bead essentially consists of three zones, viz., fusion zone, heat affected zone (HAZ), and base metal. These regions are studied in terms of the microstructure they acquired during the welding process.
As laser welding is versatile and used for mass production applications, the present work considers the laser welding for analysis. Added to this, Laser welding has the special advantages of low distortion, minimum HAZ, and maximum depth of penetration. In any welding process, there is a close correlation between the mechanical properties of the weldments and the microstructures of the weld pool.

Residual stresses occur in a material because of the manufacturing process it undergoes. These stresses get remained in the material after the manufacturing processes are done. They exist even in the absence of external loads. Consideration of residual stresses is essential under design of a structural body as they significantly influence the reliability under the operating conditions. The effect of residual stresses is detrimental to the fatigue life, creep strength and load bearing capacity of a structure. They also cause the onset of stress corrosion cracking and brittle fracture. Residual stresses are of two types: Tensile and Compressive. The tensile stresses are undesirable while the compressive residual stresses are desirable. In welding, tensile stresses get generated. A structure is to be designed in such a way that stresses should not exceed the yield strength of the material to avoid the plastic deformation of the component. Though the complete elimination of residual stresses is not possible, its magnitude has to be kept as minimum as possible. The important reasons for the generation of residual stresses in a material are of mechanical and thermal variations.

1.1. Residual Stresses in Welding

Residual stresses occur in welded joints due to the following three factors: Quenching, Shrinkage and Phase transformations. They can be due to the combined effect of all the above mentioned factors.

Quenching - Different cooling rates exist at different locations all through the welded area in a weldment. This kind of varied quenching rates is predominant in case of welding thick plates.

Shrinkage - During cooling phase of the welding cycle, the weld metal undergoes shrinkage. This shrinkage causes tensile stresses at the weld center and compressive stresses at the distinct locations from the weld center.

Phase transformations - Residual stresses due to phase transformations are generated because of the transformation metallurgical phases like austenite to ferrite or austenite to martensite in maraging steel. This happens at locations where temperature generated is greater than the critical values for phase transformations. Each mechanism has its own effect on the residual stress.

2. LITERATURE SURVEY

Paradowska et al. [1] measured the residual stress measurement using neutron diffraction where the effect of heat input on the residual stress was studied along with the hardness and macrostructures in welding of a low carbon steel. The welding residual stresses were generated by single-bead-on-plate. Zhang et al. [2] used fiber laser welding to weld ANSI304SS to investigate the residual stress distribution across the weld bead. Microhardness and tensile properties are also investigated.

Kong et al. [3], studied the thermally induced residual stresses in the hybrid laser–GMA welding process through a thermo-mechanical elastic-plastic finite element model. In the work carried out by Costa et al. [4], Residual stresses in laser welding of X.40.CrMoV.5.1 and 40.CrMnNiMo were found. Both X-ray diffraction method and incremental hole-drilling
technique were used and also compared with a numerical method. Sarkani et al. [5] simulated the residual stresses in welding using 2D model in place of 3D model to reduce the computational complexity. A combination of elastic large deflection theory and the rigid-plastic analysis is used to study the effects of welding distortions and residual stresses on the ultimate strength of long rectangular unstiffened plates under uniaxial compression [6].

3. MATERIALS & METHODS
In this work, maraging steel grade 300 containing 18wt% of Ni was used. Maraging steel grade 300 has good weldability in solution annealed condition. The work pieces having the dimensions of 20mm(length) X 20mm(width) X 3mm (thickness) were considered for experimentation and the surfaces of the specimens were fully cleaned with acetone prior to welding.

Initially all the samples in solution annealed condition were laser welded with the following parameters: Pulse frequency – 18Hz, Pulse width – 11ms, welding speed – 75mm/min, Pulse energy- 16J. A pulsed Nd:YAG laser beam machine was used for experimentation. Fig.1 exhibits the photograph of the experimental set up. This optic fiber delivered pulsed Nd: YAG laser beam system bearing the model no. JK300D was made by M/s.GSI Lumonics. The equipment is available with M/s. OptilaseTechniks (I) Pvt. Ltd. Chennai.

![Figure 1 Photograph of the experimental setup](image)

4. MICROSTRUCTURAL ANALYSIS
To visualize the microstructures, the welded samples were prepared in accordance with the standard metallurgical procedure. However, to get the clearer micrographs for the chosen maraging steel, a mixture of 15mL H₂O, 15mL acetic acid, 60mL HCl, and 10mL HNO₃[7] was used to etch the samples. At the process conditions mentioned, the weld pool has the dimensions of bead width 1.214mm, HAZ 0.581mm and depth of penetration 1.308mm. As the weld pool is get exposed to different temperatures during welding, different microstructure zones get generated in the weldment.

As it is observed from the Fig.2(a), the microstructure of the weldments basically consist of three distinctly visible regions: Fusion zone, HAZ, and Base metal zone.
**Fusion zone:** It is noted from Fig. 2(b) that the fusion zone (A) essentially comprises coarse equiaxed grains. These grains are resulted from the transformation of austenite to martensite during cooling phase of laser welding. During heating the base metal in the fusion zone is heated to austenitic region and transforms fully to martensitic structure upon the cooling. The grain size in the fusion zone was measured to be close to 35μm.

**HAZ:** From Fig.2(c), the martensitic grains of HAZ are observed to be smaller when compared those of the fusion zone and dendritic microstructure is observed where the grains are generated in the opposite direction to that of the fusion zone.

Unlike the heat affected zone in conventional alloys where the total area has the uniform characteristic, the heat affected zone of the chosen maraging steel, MDN 300 essentially comprises different sub zones namely i) Light band and ii) Dark band. Light band(B) is just adjacent to the fusion zone(C) while the dark band is next to the light band. The HAZ obtained has the length of 0.581mm. Out of which, light band takes 0.19mm and the rest of 0.391mm by dark band. The width of the dark band is observed to be more than that of the light band.

The martensitic grains of HAZ are observed to be smaller when compared those of the fusion zone and dendritic microstructure is observed where the grains are generated in the opposite direction to that of the fusion zone.

The HAZ as noted comprises both the coarse and the fine microstructures and its grain size varies in between those of the fusion zone and the base metal. The grain size was measured to be close to 18.5μm. In HAZ, the light band has coarser grain structure as it is close to the fusion zone. The coarse grain structure formed in the fusion zone gets continued to the light band.
**Base metal zone:** This zone is unaffected due to welding and hence it retains the original microstructure of the metal. The base metal was taken is in the solution annealed condition. The chosen materials as observed from the microstructure in Fig. 2 (d) appeared to have heavily-dislocated lath martensite. The average grain size of the material in the unaffected zone was 9.8μm which is smaller than that of the fusion zone and the HAZ.

**5. RESIDUAL STRESS ANALYSIS**

In the present work, the residual stress measurements were carried out by the X-ray diffraction stress analysis equipment made by “PROTO Manufacturing”. The model used [8] is “iXRD” which is compliant with ANSI N43.2 regulations. The equipment provides full radiation protection against the X-ray beam. It has the in-built software called PROTO XRDWin 2.0 for the stress analysis and other functions.

For the stress measurement, the X-ray beam having the wave length of 2.291Å was used along with the tube diameter of 30mm and aperture of 1mm. Two detectors were in place having the angle of the goniometer varied from 30°C to -30°C. The kβ filter of Vanadium and the Cr K-α anode tube were used. The slope of the $d/\sin^2\psi$ curve was calculated based on the XRD measurements made at different position tilts.

The transverse residual stresses across the weld pool were also measured in this work. The transverse residual stresses were considered as they have higher magnitude than the longitudinal stresses. The transverse stresses at the surface of the weldments are studied as they influence the fatigue strength more than that of the stresses below the surface.

With regard to the present work, as it employs laser welding, where the heat generated is more than the critical temperature of the phase transformation, martensite transforms to austenite during heating and austenite transforms back to martensite during cooling. This transformation from austenite transforms to martensite takes place at very low temperature. At this temperature, diffusionless transformation takes place in which martensite is the solitary phase exists in the material. This results in the generation of compressive stress in the weld fusion zone.

![Figure 3 Obtained transverse residual stress distribution](image)

The compressive stress was generated due to the transformation of austenite to martensite. During this transformation, volumetric expansion takes place due to the difference in the atomic packing factors of martensite and austenite. The resultant martensite when the
The weldment is cooled to ambient temperature has the BCC structure unlike BCT in case of conventional steel. This martensite has the atomic packing factor of 0.68 while the austenite has the atomic packing factor of 0.74. This difference in atomic factor leads to the volumetric expansion during cooling and subsequently results in compressive stress.

In the present case, the stresses generated due to the phase transformation dominates the magnitude of residual stresses generated due shrinkage. During shrinkage, the tensile residual stresses are generated. During welding, the localized heating makes the material expand. However, it is constrained by the surrounding material which has lower temperature and during cooling the material contracts. When the material undergoes contraction, tensile stresses get generated. Though the tensile stresses are generated, they are, in the present case, dominated by the stresses due to phase transformation. Stresses due to quenching are negligible as the chosen workpiece has less thickness.

As it is evident from the Fig.3 the compressive stresses were generated in the fusion zone as the compressive stresses due to phase transformation had dominated the tensile residual stresses. Maximum compressive stresses were generated at the centre of the weld as the fusion zone cools slowest when compared with the HAZ and the interface regions. The residual stress was gradually reduced away from the weld centre till the point is reached where temperature falls down below the critical temperature of the phase transformation. When there is no transformation, tensile stresses due to shrinkage appear in the metal. These tensile stress have the onset in the dark band.

Form the Fig.3 it is observed that maximum residual stress of 338Mpa is obtained at the centre of the weld. The compressive residual stress is desirable as it improves primarily the fatigue strength of the weldment and reduces stress corrosion cracking and brittle fracture. The compressive residual stresses are existent till it reaches the dark band. From there onwards, the compressive residual stresses disappear and tensile stresses got generated as the tensile stresses due to shrinkage dominate the stresses due to phase transformation. The maximum tensile stress of 144.67Mpa was generated at the interface of the dark band and the base metal. As the magnitude of the tensile stress is very low when compared with the yield strength of the maraging steel, the weldment is treated as safe which otherwise has to be subjected to either annealing or shot peening operation to minimize it.

6. CONCLUSIONS

The present work has investigated the microstructural analysis of the laser weldments. Different regions of the weld pool were observed and their microstructures were analyzed. It is observed that the heat affected zone of the maraging steel essentially contains two distinct parts of light band and dark band. These two parts have different microstructures as they are subjected to different temperatures during welding. In addition to the microstructural analysis, the magnitudes of the residual stresses across the weld pool were also measured using the X-ray diffraction analyzer. It is observed that the magnitude of the residual stress is maximum at the center. It is compressive in nature and is gradually declining away from the center line. As the nature of the residual stress is compressive mostly across the weld pool, it can be said that the weldment is safe.
REFERENCES


