PAPER

Effect of groove angle and heat treatment on the mechanical properties of high-strength steel hybrid laser-MAG welding joints

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Abstract

12-mm thick high strength steel was welded by a hybrid Laser-MAG welding. The microstructure, the micro-hardness, and the mechanical properties of the welded joints were studied by optical microscopy, scanning electron microscopy (SEM), electron backscattering diffraction (EBSD), and tensile and impact tests. The formation of the weld crack can be eliminated by a heat preservation treatment after welding. The microstructure of the weld and the heat-affected zone (HAZ) is mainly made of martensite. The highest hardness of the welded joint was measured in the HAZ and the tensile fracture is located in the center of the weld. The impact tests show that the impact fracture in the weld is brittle and the impact fracture in the HAZ is ductile. The heat preservation step added after the welding improves the impact toughness of the welded joints.

1. Introduction

Laser-MAG hybrid welding is a new and efficient advanced welding technology. It combines two heat sources with different physical properties and different energy transmission mechanisms that act on the same processing location. It fully uses the advantages of both heat sources. With this approach, a new type of high-efficiency welding heat source [1–3] is formed. It has been widely used on ships, in automobiles, in aerospace, and for petroleum pipelines [4–6].

High-strength steel is affected by the heat treatment and the composition. It has a poor welding performance during arc welding. The welding efficiency is low and a large deformation occurs after welding and the welds are prone to cracks. These problems limit the use of high-strength steel. The combination of a concentrated welding energy distribution, a large weld penetration, a low heat input, and a high welding efficiency improves the welding performance of high-strength steel.

Previous studies focused on getting a deep understanding of the laser-MAG hybrid welding laser and the arc formation mechanism as well as the droplet transfer mode, the hybrid welding stability, and the weld microstructure [7–9].

Nowacki et al [10] studied the microstructure transition and the thermal input of the welding joint of S1100QL steel and its effect on the strength of the joint. Hu et al [11] evaluated the welding performance of 10Ni3CrMoV steel at room temperature and at different pre-heating temperatures. The experimental results showed that the root crack rate was the lowest for a 120 °C pre-heating temperature. Wegowski et al [12] studied the process, the structure, and the mechanical properties of the MAG welding for ultra-high-strength Weldox 1300 steel. They showed that the pre-heating temperature and the heat input of Weldox 1300 cannot be determined by a known formula. They also determined the cold cracking tendency. Liu et al [13] studied the synergistic effect between the laser beam and the arc during composite welding using spectroscopy. The synergistic effect increases the penetration depth, changes the droplet transfer mode, reduces the formation of pores in the welding process, and improves the welding quality. Sun et al [14] studied the tensile and impact...
properties of a 15-mm NVE690 steel double-pass welded joint obtained by laser-MAG hybrid welding. Mazar et al. studied the laser-arc hybrid welding of 12.5-mm thick high-strength steel with different groove geometries. Their results showed that changing the geometrical shape of the groove and increasing the distance between the spacer and the tip of the welding wire reduces the width and the softening area.

These multiple studies demonstrate that laser-arc hybrid welding is widely used for the welding of thick steel plates. The effects of the weld geometry and the heat treatment on the properties of the weld were investigated. However, studies on the Laser-MAG hybrid welding of high-strength and high-hardness steel are still very rare.

In this work, the crack formation is suppressed and the mechanical properties of the welded joint are improved by pre-heating before welding and slow cooling after welding. This lays a technical foundation for the application of laser-MAG hybrid welding.

2. Materials and methods

The welding was performed with a 4 kW Nd:YAG laser (Model HL4006D by TRUMPF) with an adequate power supply (Model YD-350A G2HGE by Panasonic). The arc torch is connected to the laser head on the side at an angle of 30° (figure 1). The arc is in the front of the laser is behind it along the welding direction. The optical system consists of a 600-μm fiber with lenses with a 200-mm focal length and collimated to yield a focal spot diameter of 0.6 mm. The laser had an emission wavelength of 1.06 μm and was operated in the continuous wave (CW) mode. High strength steel plates with dimensions of 12 mm × 400 mm × 100 mm were used as the base material (BM) for this study. The filler wire had a diameter of 1.2 mm and was made of austenitic stainless-steel.

Table 1 lists the chemical compositions of the BM and the filler wire. Specimens with dimensions of 18 mm × 10 mm × 12 mm were cut from the welded plates. After wet grinding using SiC abrasive papers with grit ranging from 180 to 1500, the surfaces of the specimens were polished to a mirror finish using diamond paste of up to W2.5. Next, the samples were washed with absolute ethanol, dried immediately, and wiped with the diluted aqua regia for 20 s. 2,4,6-trinitrophenol (picric acid) was used to etch the weld joint to expose the outline of the crystal grain, which allows the size of the crystal grain to be calculated. The schematic diagram of the experimental setup used for the laser-MAG hybrid welding process is shown in figure 1 and the experimental setup is depicted in figure 2. The parameters used are given in table 2.

The microstructure of the weld and the heat-affected zone (HAZ) was analyzed by optical microscopy (OM). The tensile strength and the impact fracture morphology were analyzed by scanning electron microscopy (SEM,
model JEOL JSM-6510 LA). The microstructure of the weld was observed using a scanning electron microscope (SEM) equipped with an electron backscattering diffraction (EBSD) module. The micro-hardness measurements were performed on the center line of the weld, at an equal spacing between the left and right edges. A step size of 0.25 mm was used for the hardness test. The test load was 200 g and the loading time was 15 s.

The dimensions of the tensile test sample and the impact mechanical properties test sample are shown in figure 3(a) and (b). When using a Y groove shape, the blunt edge (h) and the docking clearance (Δ) remain unchanged as shown in figure 5(c). Four groove angles (α) were selected, as depicted in the schematic diagram of figure 4.

To compare the effect of pre-heating on the cracking of the weld, we defined two groups of samples with the same groove shape and each groove group had a sub-group of samples that were pre-heated before welding at a temperature of 250 °C. The cross-section and surface morphology of H0–H8 are shown in Figure 5. All samples were placed into the heat preservation furnace immediately after welding at a preservation temperature of 200 °C for a duration of 2 h. Then, the furnace was slowly cooled down to room temperature. The welding used pure Ar at a flow rate of 15 l min⁻¹ as the side-blowing protective gas. The welding gas for MAG welding is 15% CO₂ and 85% Ar. Table 3 details the experimental design used.

Table 1. Chemical compositions of the base metal and the filler wire in wt%.

| Materials      | C     | Si  | Mn   | Cr  | Ni  | S    | P    | Mo  | Fe  |
|----------------|-------|-----|------|-----|-----|------|------|-----|-----|
| Base metal     | 0.22  | 0.28| 1.40 | 0.32| 0.95| 0.008| 0.002| 0.50| Bal |
| Filler wire    | 0.09  | —   | 1.60 | 21.12| 9.14| 0.01 | 0.02 | 0.37| Bal |

Table 2. Welding parameters.

| Welding parameters | Value          |
|--------------------|----------------|
| Laser power, P [kW]| 3.5–4.0        |
| Welding current, I [A]| 260–280     |
| Welding voltage, U [V]| 28–30        |
| Welding speed, v [m min⁻¹]| 0.6          |
| Defocusing, Δ [mm]| –4            |
| Angle of the welding torch, θ [°]| 30       |
| Distance between the laser and the arc, DLA [mm]| 3          |
| Extension length, L [mm]| 15         |

Figure 2. Photograph of the actual experimental setup.
3. Results and discussions

3.1. Analysis of the profile of the laser arc hybrid welding

The surface morphology indicates that samples H0 and H5 have a significant wall undercutting. Sample H1, sample H3, and the negative surface of sample H5 suggest irregular welding. Un-welding occurred in sample H7. The transition of the front surface of sample H4 is uniform, whereas the transition on the front surface of samples H6 and H8 are not uniform. There were no cracks in the weld of samples H1-H8. The non-destructive tests (NDT) shows that there are welding cracks in the center of sample H0. The temperature gradient before and after the welding of sample H0 is large, which results in a too high cooling rate and the apparition of a crack in the center of the weld along the crystal. Figure 6(a) shows the main crack in the near vertical direction and figure 6(b) shows the linear path of the crack propagation along the original austenite grain boundary. It indicates an inter-granular fracture (IF).

When observing the cross-section of sample H0, it appears that the crack starts from the center of the root weld and spreads in the weld. High-strength steel has many different alloys with improved hardness that

\[\text{Figure 3. (a) Dimensions of the impact sample. (b) Dimensions of the tensile sample. (c) blunt edge } h, \text{ docking clearance } \Delta, \text{ and groove angle } (\alpha).\]
significantly reduce the plastic reserve of the zone. Under the influence of each cycle, the base metal thermally expands near the molten pool. At the same time, the rapid solidification of the weld leads to the shrinkage of the weld metal, which causes thermal stress and a phase transformation stress generated by the large tensile stress in the fusion zone. Once the stress exceeds the yield limit of the joint, a crack initiates [16]. The crack generated then expands into the interior of the weld and propagates along the crystal.

### 3.2. Analysis of the microstructure of the laser arc hybrid welding joints

The welded joint consists of a weld zone and a heat-affected zone. The weld zone can be divided into an arc zone and a laser zone, as shown in figure 7(a). In figure 7(b), the grain size gradually decreases along the direction away from the fusion line. At the beginning of the crystallization, the temperature gradient perpendicular to the boundary of the molten pool is large and the crystal grain cooling rate is the fastest.

Figure 8 shows that a large number of columnar crystals are formed in the weld bead. The growth direction of the laser zone is perpendicular to the center of the weld (figure 8(b)) and the growth direction of the arc zone is perpendicular to the direction of the fusion line (figure 8(a)) [17]. The grain size in the arc zone is larger than that in the laser zone.

Figure 9(a) shows that the left side of the fusion line is a weld bead that has a uniformly-distributed fine lath martensite structure. There is a coarse lath martensite structure in the heat-affected zone on the right side of the fusion line. The grain in the weld line is {111} and the retained austenite has a face-centered cubic structure. The EBSD-IPF map in the heat-affected zone illustrates the grain growth under the action of the welding heat that forms a coarse martensite structure {101}. Figure 9(d) indicates that misorientation occurs in most of the grain boundary with angles within 0°–10°. The increase in the high-angle grain boundary improves the toughness of the welds. When the crack propagates between the grains, it will turn when a high-angle grain boundary is encountered. Larger adjacent grain misorientation angles provide a greater resistance to crack propagation. When the crack encounters a low-angle boundary, the energy is consumed by the original continuous propagation mode and the energy absorbed by the impact is very low [18].

![Figure 4. Schematic drawing of the groove shape for different groove angles: (a) 20, (b) 30, (c) 40, and (d) 50 degrees.](image-url)
3.3. Analysis of the micro-hardness of the laser-MAG hybrid welded joint

The Vickers hardness of three kinds of samples was tested: samples with a pre-heating and post-welding heat preservation treatment (sample H1), samples with only a post-welding heat preservation treatment (sample H4), and samples with no heat treatment (sample H2-H8).

Figure 5. Weld surface and section morphology of the top and bottom sides for each sample of the study (H0-H8).

(a) P=4.0kW, I=260A, U=28V, the groove angle is 15°.
(b) P=4.0kW, I=260A, U=28V, the groove angle is 10°.
(c) P=4.0kW, I=260A, U=28V, the groove angle is 10°.
(d) P=4.0kW, I=260A, U=28V, the groove angle is 15°.
(e) P=4.0kW, I=260A, U=28V, the groove angle is 15°.
(f) P=3.8kW, I=280A, U=30V, the groove angle is 20°.
(j) P=3.8kW, I=280A, U=30V, the groove angle is 20°.
(k) P=3.5kW, I=280A, U=30V, the groove angle is 25°.
(l) P=3.8kW, I=280A, U=30V, the groove angle is 25°.

3.3. Analysis of the micro-hardness of the laser-MAG hybrid welded joint

The Vickers hardness of three kinds of samples was tested: samples with a pre-heating and post-welding heat preservation treatment (sample H1), samples with only a post-welding heat preservation treatment (sample H4),
and samples without any heat treatment (sample H0). The results are illustrated in figure 10. The hardness of the weld zone and the HAZ is higher. The highest value is found in the HAZ whereas the lowest hardness occurs in the softened zone. The hardness distribution of each region of the sample with only a post-welding heat preservation treatment is the mostly uniform due to the uniform release of the welding stress and the relatively uniform distribution in the microstructure of each part.

3.4. Analysis of the mechanical properties of the laser-arc hybrid welded joints

Table 4 lists the results of the tensile tests. The tensile strength and the extension of the samples subjected to a heat treatment are significantly higher than in the absence of any heat treatment. The tensile strength of the
welded samples with only a heat preservation step after welding is higher. The fracture of the tensile specimen is located in the weld zone and the maximum tensile strength and elongation of the welded joint constitute only 48% and 20% of that of the base metal, respectively.

The tensile samples for samples H4 and for the base metal are compared in figure 11(a). Sample H4 was pulled off in the weld zone and no necking occurred during the tensile test. However, significant necking occurred in the tensile specimen of the base metal, which indicated a weaker weld plasticity in the H4 samples. According to the fracture morphology analysis made by SEM (figure 11(c)), the fracture surface of the base metal mainly consists of a large number of fine dimples, whereas the tensile fracture of the H4 samples is composed of a cleavage surface and coarse dimples (figure 11(b)).
Table 5 indicates that the shock absorption in the HAZ is significantly higher than in the weld zone. The impact absorption of the samples subjected to a heat treatment is significantly higher than for the samples without any heat treatment. The impact performance of the samples with only a heat preservation step after welding is better than for those with a pre-heating and a post-welding heat treatment. The low-temperature impact toughness of the weld is only 72.2% of that of the base metal.

The SEM images of the impact specimens in the weld zone of the H4 samples are shown in figure 12(a). The fracture morphology indicates that the fracture surface of the weld zone is a brittle cleavage fracture with the clear characteristics of a tongue and a sector section. The SEM image of the impact specimen in of the HAZ of the H4 samples is shown in figure 12(b). The majority of the fracture surface in the HAZ is made of small dimples, and the fracture is a ductile fracture.

4. Conclusions

We documented the welding of 12-mm-thick high-strength steel performed by hybrid laser-MAG welding. The weld joint obtained had a good shape. Additionally, we determined the microstructure and the mechanical properties of the weld zone and the HAZ. The following results were obtained:

(1) Welding without cracks can be obtained by pre-heating and performing a post-weld heat treatment. When the Y groove angle is $20^\circ$–$30^\circ$, the blunt edge is 6 mm and the butt gap is 0.8 mm. An ideal weld shape is then obtained for the hybrid laser-arc welding of a 12-mm medium and heavy plate high-strength steel.

(2) The hardness distribution is more uniform for samples with only a heat preservation treatment after welding. The hardness is the highest in the HAZ. The microstructure of the weld is that of martensite with a small amount of austenite retained in the weld. The misorientation results in most of the grain boundary...
consisting of a low-angle boundary. This is the reason for the low weld toughness. The tensile strength, the extension, and the impact toughness of the samples obtained with a heat treatment are significantly higher than those for samples made without any heat treatment. The mechanical properties of the samples subjected only to a heat preservation step after welding are better than for those subjected to a pre-heating and a heat preservation step before welding. The tensile strength of the samples with heat a preservation step after welding is only 48.02% of that of the base metal and the impact toughness at low-temperature is 72.2% of that of the base metal.

Table 5. Results of the impact tests.

| Sample number | Weld | HAZ | Cracks | Heat treatment          |
|---------------|------|-----|--------|-------------------------|
| Base          | 14   | —   | —      | —                       |
| H0            | 2.58 | 6.67| Y      | N/A                     |
| H1            | 5.56 | 11.85| N      | pre-heated + slow cooling|
| H2            | 10.12| 13.6 | N      | slow cooling            |
| H3            | 6.06 | 20.2 | N      | pre-heated + slow cooling|
| H4            | 8.37 | 22.35| N      | slow cooling            |

Figure 11. (a) Dimensions of the tensile specimens. Morphology of (b) the H4 tensile fracture and (c) the base metal tensile fracture determined by SEM.
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Figure 12. SEM image of the impact fracture in (a) the weld zone and in (b) the HAZ of samples H4.
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