Effect of a nickel-based alloy cladding layer on the strength and toughness of the high-strength steel laser-MAG hybrid welding joint

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Abstract

In this article, a 6 mm thick high-strength steel (HSS) was butt laser-MAG welded using nickel alloy wires as the cladding layer. By preparing the cladding layer on the groove, the microstructure and properties of the weld were adjusted. OM, XRD, SEM, and tensile and impact experiments were used to study the structure and mechanical properties of the welded joints. The results show that the weld structure with the cladding layer corresponds to austenite, while the microstructure of the conventional laser arc hybrid welded joint is a combination of austenite and martensite. Additionally, the tensile specimens of the welded joint are fractured at the weld. The fracture strength of the nickel alloy layer is 809 MPa, and the fracture strength of the conventional laser arc hybrid welded joint is 1149 MPa. The low temperature toughness (−40°C) of conventional laser arc hybrid welded joint is 6.2. The low temperature toughness (−40°C) of prefabricated welded joints with laser-filled cladding has increased to 40.8 J, and this proves to be an effective method to improve the low temperature toughness of the welded joint.

1. Introduction

Laser-MAG (melting electrode active metal welding) hybrid welding technology has been a research hotspot in recent years [1–4]. The technique combines two different heat sources to act on the surface of the workpiece. This technology has the advantages of higher welding speeds, lower heat input, good weld bridging ability, and strong penetration ability, among others. It has been widely used in automobiles, ships, petroleum pipelines and other industries [5–7].

The welds developed in high-speed steel have the characteristics of high strength but poor toughness, so improving the structure and toughness of high-strength steel welded joints has become a relevant challenge for the scientific community [8, 9]. The microstructure, which is determined by the chemical composition of the welding wires and the cooling rate after welding, affects the strength and toughness of the welded metal [10–12]. Rishi et al [9] studied the effects of inclusions and the microstructure characteristics of SAW, SMAW, FCAW, and A-GTAW on the mechanical properties of the weld. It was determined that a higher concentration of nickel in the weld metal improved the sub-zero impact toughness of the weld. Lan et al [13] used three different heat input processes to study the microstructure evolution and corresponding mechanical properties of the HSLA steel joints. The impact properties of the weld are affected by the content of acicular ferrite and inclusions, and are insensitive to thermal input. Wang et al [10] studied the effect of nickel (Ni) content on the mechanical properties and tissue evolution of welded metals in commercial K65oil-gas transmission pipelines. Increasing the Ni content can significantly increase the strength and low temperature impact toughness of the welded metals. This is due to the formation of acicular ferrite (AF). However, grain boundary ferrite (GBF), ferrite side plate (FSP), and martensite/austenite (M/A) content decrease in the weld. Sarkari et al [14] studied on the microstructure and mechanical properties of plain carbon steel and AISI 430 ferritic stainless steel dissimilar welds. Welding is conducted in both autogenous and using ER309L austenitic filler rod conditions through gas tungsten arc welding process. The weld filled with ER309L not
only increase strength but also impact toughness. This is due to the presence of duplex microstructure of martensite and ferrite and strengthening elements. Pouraliakbar et al. [15] connected CK45 to AISI304 stainless steel using GTAW technique with ERNi-1 and ER308L as buttering and filler wire. The studies have shown that the buttered specimen has a higher Cr/Ni ratio, thus forming a fully austenitic weld metal. The unbuttered sample has higher strength and lower toughness which is duplex structure.

Khalaj et al. [16] studied the toughness of high-frequency electrical resistance welded (HF-ERWED) Apl X60 grade steel weld. The treatment cycle is more effective which consisted of two-step quenching and tempering heat treatment. With increasing the temperature of PWHT up to 600 °C (best training temperature), the impact properties were improved. The weld is uniform polygonal ferrite constituted the structure. In order to meet environmental requirements and reduce costs, researchers have developed many novel high-performance steels. However, as the strength of base metal increases, the strength design of weld metal is in a dilemma. Traditionally, weld metal is expected to have super strength with base metal. Conversely, this may result in a decrease in the toughness of the welded joint. The reduced toughness of the welded joint affects the scope of use of the parts and the safety of the structure.

In this study, by prefabricating the cladding layer on the groove, the amount of fusion of the base material is reduced, and the alloy element of the weld is adjusted to improve the low temperature impact toughness of the welded joint and expand the use of high-strength steel at low temperatures. This experiment provides a certain reference for adjusting the structure and performance of the weld in laser arc hybrid welding.

2. Experimental method

2.1. Materials

Table 1 lists the chemical compositions of the base metal, filler wire materials, and the cladding layer wires. Before the test, the oxide layer and oil stain on the surface of the high-strength steel were removed by mechanical grinding and acetone cleaning. The shielding gas of the MAG welding torch was composed of 15% CO2 and 85% Ar, and the gas flow rate was 15 l.min⁻¹.

2.2. Welding equipments and conditions

The laser-MAG hybrid welding system was produced by an Nd:YAG laser (TRUMPF HL4006D) and a MIG/MAG welding machine (YD-350AG2HGE) produced by Panasonic, composed of a paraxial shaft. The light emitted by the laser consists of a continuous wavelength of 1070 nm and is transmitted by an optical fiber with a core diameter of 600 μm. Two lenses are situated in the laser welding head, which consist of a 200 mm focusing lens and a 150 mm collimating lens. The laser produces a focal spot with a spot size of 0.6 mm on the upper surface of the workpiece. The arc is in front of the laser in the welding direction, and the angle between the laser beam and the torch is 30°, as shown in figure 1. The welding parameters are shown in Table 2.

The size of the welded joints used for observation of their microstructure was of 18 mm × 10 mm × 6 mm. The surface of the specimens were polished to a mirror finish using diamond paste of up to W2.5 with a wet-grinding and SiC sandpaper ranging from 180 to 1500. Then, the welded joints were washed with an ultrasonic bath for ten minutes. The microstructure of the welded joint can be observed after electrolytic corrosion in 10% oxalic acid solution for 30 s.

| Materials          | C  | Si  | Mn  | Cr  | Ni  | S   | P   | Mo  | Nb  | 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  |
| ERNiCr-3           | 0.04| 0.40| 2.80| 20.00| 72.60| 0.01 | 0.01 | —   | 2.5  | 1.00 |

Table 2. Welding parameters.

| Welding parameters | value |
|--------------------|-------|
| Laser power, P[kW] | 2.6   |
| Welding current, I[A] | 216  |
| Welding voltage, U[V] | 27    |
| Welding speed, v[m m in⁻¹] | 0.8 |
| Defocus, Δf[mm] | —2 |
| Angle of welding torch, θ[°] | 30  |
| Distance between laser and arc, DLA[mm] | 3   |
| Extension length, L[mm] | 15   |
The microstructure of the weld seam was observed with a GX-51 Optical Metallurgical Microscope of Japanese Olympus. The distribution of the weld joint elements was done by a Genesis-type energy Spectrometer (EDS). The phase structure of the weld center was analyzed using a D8 x-ray diffraction (XRD) instrument produced by German Bruker, using a Ka ray of Cu target, a wavelength $\lambda$ of 0.154060 nm, a diffraction range of $20^\circ \sim 90^\circ$, and a step length of 0.02°. The micro hardness test was based on the center line of the weld seam, and the left and right sides were equally spaced with a step length of 0.25 mm. The test load was 200 g and the loading time was 15 s.

After the welding was completed, the tensile and impact samples were fabricated with a CNC wire-cutting electric discharge machine, with the standard specifications shown in figure 2. The tensile experiment was carried out at room temperature using a WAW600 computer-controlled electro-hydraulic servo universal testing machine. The Charpy impact tests were carried out according to the ASTM E23 standard at $-40^\circ$C using...
specimens of $55 \times 10 \times 5$ mm in dimension with a V-notch of 1.6 mm in width and 2 mm in depth. The schematic diagram of the cladding layer prefabricated by laser wire filling is shown in figure 3.

3. Results and discussions

3.1. Microstructure of the laser-arc hybrid welding joints

The microstructure image of the laser-MAG hybrid welding (LMHW) joint is shown in figure 4(a). The microstructure of the connector of the laser cladding plus the laser-MAG hybrid welding joint (LCLMHW) is shown in figure 5(a). In figures 4(b) and 5(b), it can be clearly seen that the crystal shoots grow from the edge of the molten pool to the center. This is because the laser and the arc act on the upper part of the molten pool at the same time, so the temperature at the center of the molten pool is higher, in other words, the temperature gradient at the center is smaller.

The temperature gradient is bigger on the edge of the molten pool, which increases the driving force for grain crystallization toward the center. This also explains the different angles of dendrite growth, because different grain growth directions are consistent with the grain orientation of the molten pool edge [17]. Overall, the molten pool edge grain and the parent metal grain can explain the results of the crystallization as shown in figure 5(d).
Figure 5. Cross-section of LCLMHW joints.

Figure 6. Cross-section of the hardness distribution at the weld.

Table 3. The intensity ratios of crystallographic planes in LCLMHW joint and LMHW joint.

| Series   | (111) | (110) | (200) | (200) | (220) | (211) |
|----------|-------|-------|-------|-------|-------|-------|
| LMHW a   | 0     | 100   | 0     | 12    | 0     | 21    |
| LMHW b   | 0     | 100   | 0     | 11    | 0     | 16    |
| LMHW c   | 72    | 100   | 44    | 15    | 24    | 18    |
| LCLMHW a | 100   | 0     | 30    | 0     | 0     | 93    |
| LCLMHW b | 100   | 50    | 17    | 4     | 43    | 93    |
| LCLMHW c | 0     | 100   | 0     | 7     | 0     | 10    |
As it can be seen in figures 4(b) and 5(b), the grain size in the arc zone is large, and the crystallization pattern is mainly columnar, with continuous and long dendrite growth and large dendrite spacing. As shown in figure 4(c), the grains in the laser zone are small, with a small number of isometric crystals appearing, and the growth direction is toward the center of the weld.

3.2. The microhardness of the laser-arc hybrid welded joints

Figure 6 shows the microhardness distribution diagram of the welded joints. The microhardness test shows that the hardness of the base metal is 420 HV while the hardness of the center of the LMHW weld is 510 HV, and a relatively hardened area appears in the heat affected zone. A temper softening zone with small width appears at a position of 4–5.5 mm from the center of the weld, and its hardness is between 340 and 391 HV. The lowest hardness value of the LCLMHW appears in the center of the weld, while the hardness of the heat affected zone is the highest. The width of this zone is 2–4.5 mm from the center of the weld.

Figure 7 examines the weld by microzone x-ray diffraction (XRD). The x-ray diffraction patterns show that the weld is mainly composed of martensite and austenite. Table 3 lists the peak intensity ratio for (111), (110), (200), (220) and (211) crystallographic planes. The intensity of the diffraction peak of M(110) is highest in the center of the LMHW weld, indicating that there is a large amount of martensite in this area. Accordingly, maximum intensity in LMHW weld was related to M(100) plane. Retained austenite exists in the arc zone, which is due to the use of austenite welding wire. Higher alloying elements in the composition of the welding wire increase the peak intensity ratio (I/Imax) of A(111). The intensity of the diffraction peak of the A(111), A(200), A(220) phase of the LCLMHW sample gradually decreases from the center of the weld to the base metal. The weld center (LCLMHW a) is a complete austenite phase, which presence of more austenite phase in the LCLMHW sample imply higher toughness and plasticity in the weld, while the strength and hardness decrease. The x-ray diffraction profile was found to be consistent with the above-mentioned microhardness distribution of the LCLMHW weld.

The microstructure of the center of the weld and the vicinity of the fusion line is shown in figure 8. A small amount of austenite can be observed in the LMHW weld, mainly lath martensite, while the LCLMHW weld center is composed of austenite phase. Using EDS, the chemical composition of the microstructure near the fusion line of both LMHW and LCLMHW was studied, as shown in figure 9. LCLMHW contains a high percentage of Cr, Ni, and Mn, which are austenite-promoting elements, as confirmed by the presence of austenite in the LCLMHW welds. Additionally, a high Ni content improves the low temperature impact toughness of the weld. The cladding metal (ERNiCr-3) is composed of Ni (72.60%) and Cr (20.00%). The results of the EDS analysis show that the composition of Ni is lower than that of Cr as shown in figure 9(b). It can be hypothesized that Ni has segregated in the fusion boundary due to the Marangoni effect during the Laser-MAG hybrid welding process [18]. The lower hardness also confirmed the existence of the austenite phase in the LCLMHW weld. Only a small amount of austenite is detected in the center of the LMHW weld. Additionally, the microhardness of the LMHW weld (510HV) confirms that its composition is mainly martensite.

4. Tensile and impact properties

The mechanical properties of the welded joints were further examined by tensile experiments. The yellow area marked in figure 11(a) represents the shear lip area. The LMHW tensile fracture is a brittle fracture, with no obvious dimples, and a ‘river shape’ can be observed. The pattern shows that some areas in the weld
accelerate crack growth. Although the LMHW has a small hardness softening zone, the hardness of the weld is lower than that of the heat affected zone, and the fracture presents at center of the weld, because of the existence of welding pores. The high-strength base metal restrains the weld. From the metallurgical

Table 4. Results of the tensile and impact tests.

| Experiment no. | Ultimate tensile strength(MPa) | Fracture location | Charpy energy-40 °C(J) |
|----------------|-------------------------------|-------------------|-----------------------|
|                | 1    | 2     | 3     |                      | 1  | 2     | 3     |
| LCLMHW         | 821  | 780   | 826   | Weld bead            | 40.5 | 38.4 | 43.4 |
| LMHW           | 1168 | 1131  | 1150  | Weld bead            | 7.5  | 4.4  | 6.8  |
| HSS            | 1360 | —     | —     | —                     | 14   | —    | —    |
| ASS            | 649  | —     | —     | —                     | 24   | —    | —    |
structure, it can be seen that the grain grows perpendicular to the center of the weld, and the tensile stress in
the weld is directed to the center along the fusion line. The strength of the weld is improved, but the
hardenability of the high-strength steel is also one of the reasons for its poor welding performance. The strain
of the weld is extremely low, and no necking phenomenon occurs, indicating that the weld joint has poor
toughness. The LCLMHW joint fractured at the center of the weld and necked down as shown in
figure 10(a).

Combined with the hardness distribution, it can be seen that the hardness of the LCLMHW welding wire
weld on both sides of the fusion line is large, and the center of the weld is the weak link. Moreover, a large
number of equiaxed dimples are present in the LCLMHW tensile fractures, which are ductile fractures as
shown in figure 11(d).

The morphology of the LMHW impact fracture is shown in figure 12, which shows a complete brittle
fracture at −40 °C. From figure 12(a), a river-like pattern can be clearly observed, which is characteristic of a
cleavage fracture. The laser cladding plus laser-MAG hybrid welding (LCLMHW) impact specimen undergoes a
severe plastic deformation, as shown in figure 12(b). The fracture is mainly composed of the fiber zone and the

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**Figure 10.** Photographs of (a) tensile sample (b) impact sample.

**Figure 11.** SEM images of stretch fracture (a) LMHW overview of the fracture surface (b) LMHW enlarged area (c) LCLMHW overview of the fracture surface (d) LCLMHW enlarged area.
shear lip, which shows a ductile fracture. The size of the dimples in the fiber zone is between 2 and 7 μm, with many dimples of less than 5 μm. The crack propagation process is hindered and the crack propagation is delayed.

5. Conclusion

The welding of a 6-mm-thick high-strength steel performed by hybrid laser-MAG welding was studied, which demonstrated a good welded joint shape and excellent low temperature impact toughness.

The following results were obtained:

(1) The phase constitutes of the laser-MAG hybrid welding (LMHW) weld is a mixture of austenite and martensite. The weld of the laser cladding plus the laser-MAG hybrid welding (LCLMHW) is completely austenitic. Combined with XRD analysis, it is concluded that the peak shape of HAZ does not change significantly, M(110) planes preserved the maximum intensity ratios. The laser cladding plus laser-MAG hybrid welding (LCLMHW) specimen changed the XRD pattern in such a way that A(111) had the maximum intensity ratio. The change of the material’s crystallographic characteristics provides LCMHW weld with good low temperature toughness.

(2) The microhardness surface of both LCLMHW and LMHW has a softening zone, which is 4mm-5.5 mm away from the center of the weld. The hardness of the softening zone is between 340 and 391 HV. By analyzing the element distribution near the fusion line by EDS, the austenitizing promoting elements Ni, Cr, Mn improved the hard and brittle tendency of LMHW weld. The hardness of LCLMHW weld center is much lower than that of the LMHW weld center.

(3) The tensile samples were all broken at the center of the weld, and the LCLMHW tensile port showed the presence of a necking phenomenon. The impact sample of the LCLMHW is a ductile fracture, while the impact sample of the LMHW is a brittle fracture. The impact toughness was increased from 6.2J to 40.8J due to the addition of the cladding layer. The method of laser cladding plus laser-MAG hybrid welding effectively improves the low temperature toughness of the welded joints.

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