Microstructure and properties of laser hybrid welding joint of AH36 marine steel

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Abstract. AH36 Marine steel 10mm thick was welded by Laser-MIG hybrid welding process, and the structure and properties of the arc zone and laser zone of the Laser-MIG hybrid welding joint were studied respectively. The results show that the width of welding seam and HAZ in arc action zone is obviously larger than that in laser action zone. The microstructure of the weld was mainly acicular ferrite, bainite, martensite and grain boundary ferrite, and the content of martensite and bainite in the laser action area was relatively higher. The microstructure of the coarse grain zone is mainly thick lath martensite, granular bainite and acicular ferrite, and the microstructure of the arc action zone is relatively larger. The microstructure of the fine crystal region is mainly fine ferrite and pearlite. The hardness of arc zone and laser zone is distributed symmetrically in the weld center, the lowest hardness occurs in the weld center, and the high hardness occurs in the weld HAZ. The tensile specimens in the arc zone were fractured near the HAZ and the laser zone was fractured on the base metal far away from the weld. The lowest value of impact absorption work at 0℃ in arc action area and laser action area appeared at the fusion line +0.5; the highest value of impact absorption work at 0℃ in arc action area appeared at the fusion line +1.0, the fusion line +1.5, and the fusion line +2.0; the highest value of impact absorption work at 0℃ in laser action area appeared at the fusion line. The impact absorption at 0℃ in the laser action area is higher than that in the arc action area.

Keywords: Laser hybrid welding, AH36, Arc zone, Laser zone, Microstructure, Mechanical property.

1. Introduction
With the continuous and rapid development of shipbuilding industry in China, higher requirements have been put forward for the welding quality and welding efficiency of marine steel plate. As a new high efficient welding technology, Laser-MIG hybrid welding technology can effecitvely combine, the arc heat source with laser heat source, which not only can give full play to the advantages of both, but
also make up to some extent compensate for their own defects, so as to achieve the effect of 1+1>2, compared with single laser welding and arc welding, Laser-MIG hybrid welding production efficiency higher, the tolerance of the gaps between the bigger and better the comprehensive performance of welded joint. In the process of Laser-MIG hybrid welding, the arc can reduce the reflection of the material to the laser, and the laser can also guide and stabilize the arc to some extent. Therefore, compared with single arc welding and laser welding, the application field of Laser-MIG hybrid welding will be more extensive [1-3]. This article 10 mm thickness of AH36 steel butt joint as the research object, carries on the Laser-MIG hybrid welding, laser is studied respectively, arc welded joint of microstructure, mechanical properties, and analyses the influence of both laser and MIG compound welding joint performance as a whole, as the theoretical basis for popularization and application in industrial production.

2. Test materials and methods
The chemical composition and tensile mechanical properties of AH36 are shown in Table 1.

| Chemical component(mass fraction, %) | Tensile mechanical property |
|-------------------------------------|----------------------------|
| C        | Si | Mn | S | P | Nb | Fe | Rs/MPa | Rp0.2/MPa | A/% |
| 0.17     | 0.26 | 1.46 | 0.004 | 0.018 | 0.001 | bal | 560 | 445 | 29.5 |

The microstructure of AH36 base steel is shown in Fig1. It can be seen that the microstructure of AH36 base metal is mainly ferrite and pearlite, and obvious banded pearlite can also be observed.

![Fig. 1 Microstructure of AH36 steel](image)

AH36 steel plate with a thickness of 10mm was taken as the test object. After flaw detection, sample cutting and cleaning, two samples with a size of 300mm×150mm×10mm were prepared to be welded. Butt welding groove is Y type, groove Angle is 30°, blunt edge size is 6mm. ER50-6 welding wire is used as the filling material. The diameter of welding wire is 1.2mm, and its chemical composition is shown in Table 2. The Laser-MIG hybrid welding method is adopted. The laser emitter is TRUMMPF LASER TruDisk 10002 fiber laser, and the arc welding machine is Fronius TPS4000 welding machine. The laser welding power is 6500W, the welding speed is 20mm/s, the protective gas is (Ar) 80%+ (CO₂) 20%, the gas flow is 25L /min.

| C | Si | Mn | S | P | Cu | Fe |
|---|----|----|---|---|----|----|
| 0.08 | 0.88 | 1.52 | 0.015 | 0.02 | 0.2 | bal |

After rough grinding, fine grinding, polishing, cleaning and corrosion, the welded joints were placed under the JSZ7 microscope to observe the macroscopic morphology of the welded joints, and the welded joints were placed under the 4XC inverted metallographic microscope and TESCAN-MIRA3 scanning electron microscope to observe the microstructure morphology, and the corrosive...
agent was 4% alcohol nitrate solution. According to 《GB/T 2654-2008 Test Method for Hardness of Welded Joints》, Wilson 402-MVD Vickers microhardness tester was used to test the hardness of welded joints with loading load of 500g and holding time of 15s. The tensile test of welded joints was carried out on SHT4016-G microcomputer controlled electro-hydraulic servo universal test machine in accordance with 《GB/T 2651-2008 Tensile Test Method for Welded Joints》. The tensile samples were rectangular cross sections and sampled at arc and laser action areas respectively. The impact test of welded joints was carried out on JBN-300 pendulum impact test machine according to 《GB/T 2650-2008 Impact Test Method of Welded Joints》. V-notch was adopted for the sample, the size of which was 55mm×10mm×5mm, the notch was perpendicular to the weld plane, the notch position was located in the weld center of arc action zone, laser action zone and HAZ, and the impact temperature was 0℃. TESCAN-MIRA3 scanning electron microscope was used to observe the tensile and impact fracture morphology of welded joints.

3. Experimental results and discussion

![Fig. 2 Weld morphology of Laser-MIG hybrid welding](image)

(a) Front side; (b) Back side; (c) Cross section

The welding morphology of Laser-MIG hybrid welding is shown in Fig 2. In combination with Fig 2 (a) and (b), it can be seen that both the front and back of the weld are beautifully formed and bright, and no defects such as collapse, excess height, spatter and weld nodules are found. In combination with Fig 2 (c), it can be seen that there are obvious boundaries in the weld, HAZ and base metal of the cross section of the welding sample, and the overall appearance of the welding seam is a "goblet" shape with width at the top and width at the bottom. In the process of composite welding, the front side of the welding sample is mainly affected by arc action. The diameter of arc column is relatively large, and the energy is relatively dispersed. Therefore, the weld penetration depth is relatively shallow, the weld penetration width and the HAZ are relatively large. The back side of the welding sample is mainly affected by the laser action. The laser beam has a large energy density and a small spot diameter, and the keyhole effect will occur when the laser beam acts on the surface of the workpiece. Therefore, the weld penetration depth, weld penetration width and the HAZ are relatively small [4-5]. In addition, it can be found that the microstructure grains grow along the fusion line toward the weld center.
Fig. 3 Microstructure of arc zone of welded joint (OM)
The microstructure of the arc zone of the Laser-MIG hybrid welding joint is shown in Fig 3, the microstructure of the laser zone is shown in Fig 4, and the microstructure of the characteristic positions of the arc zone and laser zone is shown in Fig 5. It can be seen that the microstructure of welding seam in arc action zone and laser action zone is mainly composed of acicular ferrite, bainite, martensite and grain boundary ferrite. Compared with the laser action area, the content of martensite tissue in arc action area is relatively low, while the content of bainite and ferrite tissue is relatively high. The microstructures in the arc and laser action zones are mainly composed of thick lath martensite, granular bainite and acicular ferrite. Compared with laser action zone, the grain structure in arc action zone is larger. Compound during the welding process, arc area is mainly influenced by electric arc heat source, heat input is high, the cooling speed is relatively slow, high temperature phase change above residence time is relatively long, austenitic grain growing there is plenty of time, and in the subsequent cooling phase change of bulky in the process of martensite, bainite and ferrite. The laser action area is mainly affected by the laser heat source, the heat input is small, the cooling speed is relatively fast, the residence time above the high temperature phase transition point is relatively long.
short, and the austenite grain has no time to grow. In addition, the relatively fast cooling rate in the laser action zone leads to the decrease of phase transition temperature, the larger free energy gap between the old and the new phases, the decrease of critical nucleation energy required, and the increase of nucleation rate per unit time. Therefore, it is relatively easy to obtain fine martensite, bainite and ferrite structures [6-7]. HAZ coarse grain zone is also called hot spots, the regional organization of grain will be fully in the process of welding heat austenitizing, arcing area influenced by electric arc heat source, cooling speed is relatively slow, high temperature phase change above temperature retention time is longer, the austenitic grain size grew up serious, then cooling form relatively rough acicular ferrite, pearlite and granular bainite. Under the influence of laser heat source, the cooling rate is relatively fast, the temperature residence time above the high temperature phase transition point is relatively short, the austenite grain coarsening degree is relatively light, and the martensite structure is formed in the subsequent rapid cooling process. The microstructure of the arc zone and laser zone is mainly composed of ferrite and pearlite. The grain size of laser acting zone is smaller than that of arc acting zone [8-9]. The HAZ fine grain area is relatively far away from the heat source and is less affected by the heat source. The thermal cycling process of welding is equivalent to a normalizing treatment of the base material, which to a certain extent refines the grain structure [10].

![Hardness distribution curve of welded joint](image)

**Fig. 6** Hardness distribution curve of welded joint

The hardness distribution curve of the composite welded joint is shown in Fig 6. Where, L_S is 1mm away from the upper surface of the welded joint, which represents the hardness distribution in the arc action zone; L_X was 1mm away from the lower surface of the welded joint to represent the hardness distribution in the laser action area. It can be seen that the hardness of the composite welded joint is distributed symmetrically in the weld center, and the hardness of the weld joint is softened to varying degrees, and the minimum hardness is in the weld center, while the high hardness is in the welding heat affected zone. The minimum hardness of the weld in the laser action zone is about 220HV, the average hardness of the rest weld is about 250HV, and the maximum hardness of the HAZ is about 330HV. The minimum hardness of welding seams in arc zone is about 230HV, the average hardness of other welding seams is about 240HV, and the maximum hardness of HAZ is about 360HV. The hardness of base metal is about 195HV. It can be found that the hardness of HAZ in arc action zone and laser acting zone is higher than that of weld seam, mainly because the martensite content of HAZ is higher than that of weld seam. The hardness of welding seam in laser action zone is higher than that in arc action zone, which is mainly due to the higher martensite content in laser action zone. The hardness of laser action zone HAZ is lower than that of arc action zone, which is mainly due to the smaller width of laser action zone HAZ and the finer grain of martensite structure [11-12].

|          | R_m/ MPa | ReH/ MPa | ReL/ MPa | A/%  | Fracture location |
|----------|----------|----------|----------|------|------------------|
| Arc zone | 568      | 456      | 456      | 13.49| HAZ              |
| Laser zone | 528      | 414      | 403      | 15.17| Base metal       |

**Table 3.** Tensile properties of welded joints
The tensile test results of the composite welded joints at room temperature are shown in Table 3. The tensile fracture specimens are shown in Fig 7, and the microscopic morphology of the tensile fracture is shown in Fig 8. Combined with the results of tensile test, it can be seen that the tensile strength and yield strength of the welded joints in the arc zone are higher than that of the laser zone, but the elongation of the welded joints in the arc zone is slightly lower than that of the laser zone. The final fracture position of the welding sample in the arc zone was located near the HAZ, and the final fracture position of the laser zone was located on the base metal far away from the weld. The fracture contour lines were basically 90° from the tensile direction, and there were obvious necking phenomena near the fracture. The tensile fracture morphology in arc area is mainly ductile fracture with a small amount of brittle fracture morphology. The tensile fracture morphology in laser area is ductile fracture morphology. Combined with Fig 3 to Fig 5 microstructure analysis shows that the parent metal group is mainly composed of a large number of ferrite and a small amount of pearlite, weld organization is mainly composed of martensite, bainite and the composition of ferrite and martensite and bainite than ferrite and pearlite has higher strength and hardness, the strength of the weld is higher than the parent metal, lead to the laser effect of tensile specimen fractures on the parent metal; The microstructure grains at HAZ of arc action zone are relatively large, and the content of martensite and bainite is less than that of laser action zone. Therefore, the strength near HAZ of arc action zone is low, leading to the fracture of tensile samples near HAZ of arc action zone [13-14].
Table 4. Impact test results of welded joints (0℃)

| Impact notch position | measured value/J | mean value/J | Impact notch position | measured value/J | mean value/J |
|-----------------------|------------------|--------------|-----------------------|------------------|--------------|
| Arc zone weld         | 145, 147, 148    | 146.7        | Laser zone weld       | 152, 154, 155    | 153.7        |
| Arc zone FL           | 109, 112, 114    | 111.7        | Laser zone FL         | 204, 207, 209    | 206.7        |
| Arc zone FL+0.5       | 75, 78, 79       | 77.3         | Laser zone FL+0.5     | 83, 85, 88       | 85.3         |
| Arc zone FL+1.0       | 181, 183, 184    | 182.7        | Laser zone FL+1.0     | 182, 183, 185    | 183.3        |
| Arc zone FL+1.5       | 184, 186, 189    | 186.3        | Base metal            | 71, 75, 76       | 74           |
| Arc zone FL+2.0       | 181, 184, 185    | 183.3        |                       |                  |              |

Fig. 9 Fracture morphology of impact specimen of welded joint

(a, b, c, d) Arc zone; (e, f, g, h) Laser zone

The impact test results of the composite welded joint at 0℃ are shown in Table 4. It can be seen that the impact absorption work at 0℃ in the arc action zone is ranked from largest to smallest as fusion line +1.0, weld line, fusion line and fusion line +0.5. The impact absorption work at 0℃ at fusion line +1.5 and fusion line +2.0 is close to that at fusion line +1.0. The impact absorption power of 0℃ in the laser action area was ranked from large to small as fusion line +1.0, fusion line, weld line and fusion line +0.5. The impact absorption work at 0℃ in each position of the laser action area was greater than that of the arc action area, and the impact absorption work at 0℃ in each position of the arc action area and laser action area was higher than that of the base metal. According to the analysis, the corresponding structures of arc action zone and laser action zone at the fusion line +0.5 are all large martensite and bainite with relatively poor toughness. At the fusion line +1.0, the structures corresponding to the arc action zone and laser action zone are ferrite and pearlite with relatively fine grain and relatively good toughness. The microstructure grains in laser action zone are smaller than those in arc action zone, so their toughness is better than that in arc action zone. The fracture morphology of impact specimens at different notch positions of the composite welded joint is shown in Fig 9. It can be seen that the fracture morphologies of impact samples at the fusion line +1.0 in arc action zone, the fusion line +1.0 in laser action zone and the fusion line +1.0 in laser action zone are
all typical dimple fracture, but the dimple size is slightly different. The fracture morphs of impact samples at welds, fusion lines and fusion lines +0.5 in arc zone and at welds and fusion lines +0.5 in laser zone were all quasi-cleavage fractures, and there were differences in the size and number of dimples and the number of "cleavage like" planes. The impact absorption power is the lowest at the fusion line +0.5 in the arc area and laser area, the fracture morphology is mainly the large-area "cleavage like" plane, and the number and size of dimples are small [15].

4. Conclusion
Based on the Laser-MIG hybrid welding process, the structure and basic mechanical properties of arc action area and laser action area in the process of composite welding were compared and studied, and the following conclusions were drawn:

The width of welding seam and heat affected zone in arc action zone is obviously larger than that of laser action zone. The microstructure of welding seam in arc action zone and laser action zone is mainly composed of acicular ferrite, bainite, martensite and grain boundary ferrite. Compared with arc action zone, the content of martensite and bainite in laser action zone is higher. The microstructure of the arc action zone and the coarse grain zone of the laser action zone are mainly composed of the thick lath martensite, granular bainite and acicular ferrite. Compared with the laser action zone, the microstructure of the arc action zone is more coarse. The microstructure of the fine crystal region in the arc zone and laser zone is mainly fine ferrite and pearlite.

The hardness of arc action zone and laser action zone is symmetrically distributed in the weld center, and the hardness of the weld is softened to varying degrees, with the lowest hardness appearing in the weld center and the highest hardness appearing in the weld HAZ. The minimum hardness of the weld in the laser action zone is about 220HV, and the maximum hardness in the HAZ is about 330HV. The minimum hardness of arc weld is about 230HV and the maximum hardness of HAZ is about 360HV. The hardness of base metal is about 195HV.

The tensile strength and yield strength of the arc action area are close to the base metal, the tensile strength and yield strength of the laser action area are lower than the base metal, and the elongation after fracture of both are significantly lower than the base metal. The tensile specimens in the arc zone were fractured near the HAZ and the laser zone were fractured on the base metal far away from the weld.

The lowest value of impact absorption work at 0℃ in the arc action area and the laser action area appeared at the fusion line +0.5; the highest value of impact absorption work at 0℃ in the arc action area appeared at the fusion line +1.0, the fusion line +1.5, and the fusion line +2.0; the highest value of impact absorption work at 0℃ in the laser action area appeared at the fusion line. The impact absorption of 0℃ at each position in the laser action zone is higher than that of the arc action zone.

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