Research on Microstructure and Properties of Welded Joint of High Strength Steel

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Abstract. BS960 steel plates were welded by Laser-MAG and MAG. The microstructure and properties of the welded joints were investigated by optical microscope, micro-hardness tester, universal tensile testing machine, impact tester, scanning electron microscope (SEM) and fatigue tester. By a series of experiments, the following results were obtained: The grain size of the coarse grain zone with Laser-MAG welded joint is 20\,\mu m, and that with MAG welded joint is about 32\,\mu m, both of the fine grain region are composed of fine lath martensite and granular bainite; the width of the heat affected region with Laser-MAG is lower than that with MAG. The strength and impact energy of welded joints with Laser-MAG is higher than that with MAG. The conditioned fatigue limit of welded joint with Laser-MAG is 280\,MPa; however, the conditioned fatigue limit of welded joint with MAG is 250\,MPa.

1. Introduction

With the development of science and technology, the mechanical manufacturing industry demands high performance materials. High strength steel with good toughness and high strength becomes the first choice of machinery manufacturing industry. However, the defects such as cold crack, hot crack and lamellar tearing in the welding process restrict the wide application of high strength steel \cite{1]. So it's necessary to study the weldability of high strength steel. Shanghai Jiaotong University has studied the relationship between welding parameters of high strength steel and weld formation, and concluded that the welded joint has good mechanical properties \cite{2}. Zhao Hongyun has studied the microstructure and properties of heat affected zone of 800MPa high strength steel under different welding heat input. The results show that with the increase of welding heat input, the grain growth trend of welding heat affected-zone is more significant \cite{3]. Laser-MAG welding has high cladding efficiency and high welding efficiency. It is a hot research direction in welding field. In this paper, the metallographic weldability test of 960MPa high strength steel was carried out by two processes of MAG welding and Laser-MAG welding, and the differences of microstructure and properties between them were studied, which provided the basis for the test steel in the actual welding production.
2. Material and Experimental Procedures
In this paper, the test steel was the quenched and tempered BS960 steel with thickness of 9mm. The composition of steel plate shown in Table 1 was determined by spark direct reading spectrometer. According to the low strength matching principle [4], the solid welding wire Carbopil FK-1000 1.2mm was chosen, and its composition was shown in table 2; The BS960 steel was welded by two kinds of welding methods, Laser-MAG and MAG; The proportion of the shielding gas Ar and CO2 was 8:2.

| Table1 Chemical composition of BS960 steel plate (wt%) |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| C              | Si             | Mn             | Cr             | Mo             | V              | P              | S              |
| 0.075          | 0.236          | 1.231          | 0.692          | 0.258          | 0.006          | 0.01           | 0.001          |
|                |                |                |                |                |                |                |                |

| Table2 Chemical composition of Carbopil FK-1000 (wt%) |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| C              | Si             | Mn             | Ni             | Mo             | B              | Ti             | Cr             |
| 0.09           | 0.55           | 1.68           | 1.10           | 0.13           | 0.0006         | 0.089          | 0.024          |
|                |                |                |                |                |                |                |                |

The metallographic specimen was taken by the wire cutting in the cross section of the welded joint. After grinding and polishing, the alloy was etched with 4% nitric acid alcohol solution, and its microstructure was observed under Olympus PME3 optical microscope. According to GB/T2654-2008, hardness test was carried out in HXD-1000 Vivotinox hardnness tester, the load was 10Kgf and the loading time 10s. The impact specimens were sampled according to GB2649-1989 on the welded joints. The size was (55x10x7.5) mm, and the impact test was carried out at -20 degrees on JB-30B impact testing machine; The tensile and fatigue specimens was shown in Figure 1, the tensile tests were carried out in INSTRON8802 type fatigue testing machine and The strain rate was 0.0025s⁻¹. The fatigue test parameters were R 0.1 and frequency 10Hz and two kinds welding samples S-N were measured; Finally, the morphology of impact fracture was observed by CS 3400 scanning electron microscope.

![Fig. 1 The tensile and fatigue specimen size](image)

3. Results and discussion

3.1. Microstructure of welded joints
It can be seen from Figure 2 and figure 3 that the weld structures of the two welded are both tempered sorbite; Both of them have grain coarsening phenomenon in the coarse grain zone, the lath martensite beam obviously and the coarse austenite grain boundaries can be seen from the figure 2 (b) and figure 3 (b); The average grain size of coarse grain zone is 32μm by MAG, and it’s 20μm by Laser-MAG. This is because the Laser-MAG welding τₜₜ is shorter than that of MAG welding, so the residence time of MAG welding in the high temperature region is longer, and the temperature in this region is generally above Ac₃ 200–300 degrees, which can make the grain coarse; From the figure 2 (c) and figure 3 (c), it can be seen that the fine grained region of HAZ is composed of fine lath martensite and granular bainite; Due to Partial microstructure austenitizing in incomplete recrystallized region, the granular bainite was formed in the subsequent cooling. Because of the diffusion of carbon atoms, the M-A component dissolves and forms coarse ferrite, so the region is ferrite + granular bainite.
3.2. Micro-hardness of welded joints

It’s obvious from Figure 4 that the width of the heat affected zone of Laser-MAG welding joint is 2mm, while the width of the heat affected zone of MAG welding is 3mm. The reason is that the Laser-MAG welding transfers energy to the work piece through the optical fiber, whose energy is concentrated, and the heat input is low. However, the MAG solder joint has low energy density and large heating area[5], which leads to wider heat affected zone. The softening zone appeared in Laser-MAG welding and MAG welding, and the hardness of Laser-MAG heat affected zone is higher than that of MAG. The maximum hardness of Laser-MAG welding and MAG welding heat affected zone both appeared in coarse grain zone, and the minimum hardness appeared in the incomplete recrystallized zone. The maximum hardness of heat affected zone of Laser-MAG welding is higher than the base metal, while the hardness of MAG welding heat affected zone is lower than that.

3.3. Tensile and impact properties of welded joints

It can be seen from table 3 that the tensile and impact properties of BS960 steel welded by Laser-MAG are better than those by MAG. During the stretching process, when subjected to certain pulling
force of welded joints, the parent material is in the elastic stage due to high strength, while the welded joint softening zone is into the plastic deformation stage. The parent material on the softening zone deformation has binding effect, which makes the softening zone in three-dimensional stress states. In the case of a certain cross section area of welded joint, the narrower the softening layer is, the greater the radial stress is, and the more difficult the plastic deformation of the softening layer is, so the strength can be increased [6-8]. According to figure 4, the softening zone of Laser-MAG welded joint is narrow, while the softening band of MAG welded joint is wider, which leads to poor tensile properties of the welded joint.

Table 3. Tensile and impact results of different welded joint

| Welding Technology | $R_{oL}$/MPa | $R_{m}$/MPa | $A/%$ | $KV_2$/J (-20°C) |
|--------------------|--------------|-------------|-------|-----------------|
| Laser-MAG          | 968          | 1038        | 13.5  | 25              |
| MAG                | 913          | 987         | 15    | 10              |

It can be seen from the figure 5 (a) that the fracture mode is ductile fracture. There are many rip beams and dimples in the expansion region of Laser-MAG, which shows that the HAZ zone has excellent impact toughness [9]. The fracture mode is quasi cleavage crack, which has less rip beams and dimples in the expansion region. So the toughness of HAZ zone is poorer than that of Laser-MAG. This is due to the coarse grain and the non-equilibrium microstructure in the coarse grain region of MAG. The peak temperature is higher, and the residence time is longer in the MAG coarse grain region than that in the Laser-MAG coarse grain region, which makes carbide dissolve completely, and no longer hinders the migration of grain boundary. After cooling, the coarse grain is formed, which leads to poor impact toughness [10].

Figure 5. Micro-morphology of impact fracture

3.4. Fatigue properties of welded joints
The fatigue data were fitted [11], and the result was shown in Figure 6. It can be seen from Figure 6 that with the decreasing of load, the cycle times of specimens increases gradually, and the S-N curve tends to be gentle. The fatigue limit of Laser-MAG welded joint under cyclic $10^6$ is 280MPa, and that of MAG welded joint under cyclic $10^6$ is 250MPa.
4. Conclusion

1) The heat affected zone width of BS960 steel plate after Laser-MAG welding is obviously smaller than that of MAG, and both of them have the hardness softening zone in the heat affected zone.

2) The strength and impact energy of BS960 steel welded joint welded by Laser-MAG are higher than that of MAG, and the fracture mode is ductile fracture, while the impact fracture of MAG steel is quasi cleavage crack.

3) The fatigue limit of Laser-MAG welded joint under cyclic $10^6$ is 280MPa, and that of MAG welded joint under cyclic $10^6$ is 250MPa.

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