Bending-fatigue performance of the dissimilar joints of Fe-Mn-Si memory alloy and 304 stainless steel

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Abstract. The dissimilar joints of Fe-17Mn-5Si-10Cr-5Ni memory alloy and 304 stainless steel were welded by 5 kw transverse flow CO₂ laser. The fracture morphology, microhardness of the welding joint was analyzed by field emission scanning electron microscopy, micro hardness tester, and bending fatigue test. The results showed that the fracture location of dissimilar joint is in the welding joint, and the fusion zone to weld areas prone to stress concentration while the formation of cracks. The full cyclic fatigue fracture of dissimilar joints consisted of the extension zone and instantaneous fracture zone. In the former, there were fatigue striations, dissociation steps and some arc tearing ridges, showing typical quasi-cleavage brittle fracture characteristics, and in the latter, there were a lot of dimples, showing plastic fracture characteristics. The toughness of dissimilar joint is better than that of the 304 stainless steel joint.

1. Introduction
Fe-Mn-Si memory alloy has been widely used in petroleum, machinery, chemical industry and other industries due to its advantages of high strength, good plasticity, easy processing and forming, moderate memory function and low price [1-5]. Many structural parts of materials are formed by welding processing, so welding processing technology plays an extremely important role in the promotion and application of new materials. Shape memory alloy welding methods include ionic beam welding [6], argon arc welding [7], inert gas tungsten arc welding (TIG) [8], diffusion welding [9], resistance welding [10], laser welding [11], etc. Among them, laser welding has the advantages of good beam orientation, precise machining, small heat affected zone of welding seam, small welding deformation, etc. [12-13]. By properly adjusting the laser process parameters, it can ensure the repeated realization of excellent welding seam formation. Therefore, laser welding is one of the important methods suitable for shape memory alloy welding.

At present, the research on laser welding of Fe-Mn-Si memory alloy and dissimilar metals is still rare. However, it is of great significance to understand the welding behavior of Fe-Mn-Si memory alloy in both theoretical and practical applications to expand its application scope to a large extent. When Fe-Mn-Si memory alloy is welded, the structure of the weld seam and the heat-affected zone will inevitably change. Will the shape memory effect be affected? In this paper, Fe-Mn-Si memory alloy and 304 stainless steel were selected for CO₂ laser welding test. The mechanical behavior of dissimilar welded joints was evaluated by bending fatigue test and microhardness measurement. The
fracture of Fe-Mn-Si memory alloy with 304 stainless steel is analyzed by scanning electron microscopy and the form and its variation rule of weld composition and bending fatigue fracture is revealed.

2. Material and methods

Fe-17Mn-5Si-10Cr-5Ni alloy (mass fraction, %) (Short for Fe-Mn-Si memory alloy) and 304 stainless steel were selected for this test. Fe-Mn-Si memory alloy was smelted with vacuum medium frequency melting furnace, casted mould, and 1200 °C homogenization processing, and then heated to 1100 °C heat preservation for 1 h. The size of the welding sample is 120 mm × 8 mm × 2 mm, which is processed by wire-electrode cutting. The solution treatment of parent metal welding specimen was heated to 1000 °C and heated preservation 1 h with argon gas in tubular resistance furnace.

The experimental equipment adopts 5kW cross-flow CO₂ laser processing system which type is DL-LPM-V, and the optimal welding process parameters obtained through orthogonal test are P=1800 W, v=800 mm/min, z=+0.6 mm. The fracture morphology was observed by SUPRA 5S SAPPHIRE field emission scanning electron microscope.

The microhardness of the sample was tested by MH-6 automatic microhardness tester, the loading load was 200 g and the loading time was 8 s. In order to reduce the effect of surface roughness on microhardness, it is necessary to grind and polish the welding seams of samples before testing.

![Fig. 1. Schematic diagram of a full bending fatigue test](image)

After welding, the sample was cut into sizes of 5 mm ×2 mm ×1 mm and observed under OLYMPUS G 51 metallographic microscope. The sample was polished by 1200 waterproof abrasive paper and corroded with 3g CuSO₄+10 mL HCl+30 mL H₂O solution. In order to further analyze the microstructure of the weld, HCl+HNO₃ royal water with a volume ratio of 3:1 was used to corrode the weld.

The fatigue performance of the welded specimens was investigated, and the full cycle bending fatigue test was carried out on the welded joints. Sample was bending 180°, and kept 10 s, and strain controlled for ε=5%. The cyclic bending deformation process of the test alloy is shown in Fig.1.

3. Results and discussion

Fig. 2 shows the macroscopic morphology of the bending fatigue fracture of Fe-Mn-Si memory alloy and 304 stainless steel dissimilar welded joints. From Fig. 2 (a) it can be seen, the fracture of the dissimilar joint is located at the welding seam, slightly close to the side of 304 stainless steel. The fracture is relatively flat and perpendicular to the direction of maximum normal stress. According to the location of the fracture, it can be concluded that the zone of fusion that is inclined to one side of the weld is the weak link of the fatigue specimen of the dissimilar joint, which is easy to cause stress concentration and form crack, and finally leads to the fracture of the joint. Fig. 2(b) shows the macroscopic cross-section morphology of the bending fatigue fracture of dissimilar joints. The
extended area of dissimilar joint is distributed on both sides of the fracture section, and the distribution is approximately symmetrical with the center of the section as the axis. The transient fracture area is located at the central part of the fracture, which is composed of a dimple belt through the center of the section.

Fig. 2. Macrostructure of bending fractured dissimilar steel welding joint (a) Surface morphology; (b) Fracture section

Fig. 3 shows the high-power morphology of the fatigue fracture extension area of Fe-Mn-Si memory alloy and 304 stainless steel dissimilar joints. The upper extension area is called extension area A (Fig. 3(a)), and the lower extension area is called extension area B (Fig. 3(b)). In the extension zone A, there is no obvious surface crack source, but the surface of the extension zone A shows fatigue striations, and cracks appear in some locations of the striations. Such secondary cracks are accompanied by the whole fatigue process from germination until the joint fracture. In the inner part of the extension zone A, there are obvious cleavage steps and a few arc-shaped tearing edges, showing the characteristics of quasi-cleavage brittle fracture. Therefore, the fracture morphology of the extension region A of the dissimilar joint can be divided into two stages: the fatigue striations of the surface is the first stage of crack propagation, and the crack propagation is slow; the inner cleavage fracture is the second stage of crack propagation, and the crack propagation speed is fast. In the extension zone B, the fracture morphology presents a typical river-pattern morphology, and its fracture form is quasi-cleavage brittle fracture. Obvious surface crack sources can be seen on the surface of the extension zone B, and dense cleavage steps can be seen on the morphology. When the cracks extend to the interior through continuous branches, more and more dense cleavage steps will appear at the fracture, up to the instantaneous fracture zone at the fracture, and a few arc-shaped tearing edges also appear at the edge of the instantaneous fracture zone.

Fig. 3. SEM micrographs of bending fracture crack propagation of the dissimilar steel welding joint (a) The region A of crack propagation; (b) The region B of crack propagation
Fig. 4 shows the scanning electron micrograph with 1000 x magnification of the instantaneous fracture zone of the dissimilar joint and 304 stainless steel joint. From Fig. 4 it can be seen, there are a lot of dimple both transient breaking area, which shows the characteristics of plastic fracture. The difference is that the dimple size and depth of the dissimilar joint (Fig. 4(a)) are obviously larger than that of the 304 stainless steel joint (Fig. 4(b)). The larger the size and depth of the dimple, the better the toughness of the joint, indicating that the toughness of the dissimilar joint weld is significantly better than that of the 304 stainless steel joint.

![Fig. 4. Dissimilar steel welding joint with 304SS welding joint: the rupture region (a) Dissimilar steel welding joint; (b) 304SS welding joint](image)

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Fig. 5 shows the microhardness distribution of cross-section of dissimilar joints. From Fig. 5 it can be seen, the overall hardness of the weld is higher than that of the welding base metal, but it decreased near the center of the weld. This is because the center of the weld is the remelting zone of the two materials. Due to the different physical properties and chemical properties of the materials, the heterogeneity of the structure in this zone is the highest in the whole weld. In addition, during remelting, the crystallization in the center of the weld is unstable and it is easy to cause the grain size, which will also lead to the reduction of its microhardness. It is found that the minimum microhardness value is greater than 304 stainless steel and which is closer to Fe-Mn-Si memory alloy, and it also means that the crystallization tissue from the region is better. From the side of 304 stainless steel, the hardness is clearly elevated from the base metal 304 stainless steel to the weld area namely the fusion zone, whereas the the microhardness on the side of Fe-Mn-Si memory alloy are relatively stable. The larger difference in microhardness will easily lead to stress concentration during fatigue test, which will lead to fatigue crack and fracture. Therefore, the side fusion zone of 304 stainless steel of dissimilar joint is the weak zone of fatigue damage of welding seam. The maximum hardness difference between 304 stainless steel and Fe-Mn-Si memory alloy joint weld is no more than 30hv0.2, which indicates that the joint weld has good transition stability.

Fig. 6 shows the microhardness distribution of the cross section of the dissimilar joint after fracture. From Fig. 6 it can be seen, the overall microhardness of the dissimilar joints after stretching is increased, and the hardness of the 304 stainless steel base metal is the smallest before stretching, then transformation to the maximum after stretching. This is because the 304 stainless steel base material has tensile deformation hardening after stretching. In the fatigue test, the microhardness of the materials significantly increase that means the stress concentration is easy to induce cracks, while Fe-Mn-Si memory alloy welding will improve this situation.
4. Conclusion

(1) The fracture position of the dissimilar joint is located at the weld seam, and the fracture is flat and perpendicular to the direction of the maximum normal stress. The area where the fusion zone is biased to one side of the weld is prone to stress concentration and crack formation.

(2) The full cycle fatigue fracture of Fe-Mn-Si alloy and 304 stainless steel dissimilar joints is composed of expansion zone and instantaneous fracture zone. There are fatigue bands, cleavage steps and a few arc-shaped tearing edges in the extension zone, showing typical quasi-cleavage brittle fracture characteristics. There are a large number of dimples in the instantaneous fracture zone showing the characteristics of plastic fracture, and the size and depth of dimples are obviously larger than that of dimples in the instantaneous fracture zone of 304 stainless steel joint, indicating that the toughness of the weld of dissimilar joint is obviously better than that of 304 stainless steel joint.

(3) The hardness of 304 stainless steel base material from the minimum before stretching into the maximum after stretching, this is due to tensile deformation hardening of 304 stainless steel base material produced stress concentration, easy to induce cracks and Fe-Mn-Si alloy and weld low microhardness will improve this situation.

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