Welding performance of the dissimilar joints of Fe-Mn-Si alloy and 304 stainless steel

Linlin Liu¹, Jinqiao Du¹, Chaoyu Zhou²

¹ School of Mechanical Engineering, Dalian Jiaotong University, Dalian, Liaoning, 116028, China
² Department of Mechanical and electrical, Weihai, Shandong, 264210, China

*Corresponding author’s e-mail: good_linlin@163.com

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 microstructure, morphology and composition of the welding of the dissimilar joints were analyzed by metallographic microscope, field emission scanning electron microscopy. The results showed that the crystals of dissimilar joints of Fe-17Mn-5Si-10Cr-5Ni memory alloy and 304 stainless steel were symmetrically distributed on both sides of the joint weld center. At Fe-17Mn-5Si-10Cr-5Ni memory alloy close to the side of the weld, ε martensite phase was also found, which was caused by the γ→ε martensite transformation induced by the residual stress. The distribution of dissimilar joint weld elements was in zones obviously, the distribution mode was related to the unique keyhole effect of laser welding, and the weld center metal was still Fe-Mn-Si memory alloy, which had the characteristic of the inverse phase transition of the stress induced martensite.

1. Introduction

Among the numerous shape memory alloys (SMAS), the Fe-Mn-Si based alloys have attracted much attention because of their good shape memory effect, mechanical properties, low cost and latent use [1-4]. So far, a lot of research has been done on the composition design, phase change mechanism and solid solution treatment of Fe-Mn-Si shape memory alloy[5-7]. Fe-Mn-Si alloy inevitably involves welding problems or connection with other dissimilar metal materials in the practical application process, however, at present, there are few reports on the welding of Fe-Mn-Si alloy and dissimilar metals[8]. Therefore, 304 stainless steel and stainless Fe-Mn-Si alloy were selected for CO₂ laser welding test. The mechanical behavior of dissimilar welding joints was evaluated through the analysis of welding area morphology and fracture, and the welding composition, microstructure and change rule of dissimilar welding joints were revealed through the observation of micro-area composition and microstructure.

2. Experiment Material and Method

In this study, the Fe-16.86Mn-4.50Si-10.30Cr-5.29Ni-0.08C(wt%) (shortened form Fe-Mn-Si alloy) and 304 stainless steel were prepared, and Fe-Mn-Si alloy was prepared by vacuum median frequency furnace, the cast ingot was first homogenized at 1200℃, reheated to 1100℃ for 1h. Welding specimens with efficient dimensions of 4mm×1mm×28mm were wire cut by electrical discharge
machine. The solution treatment was carried out by austenitizing at 1000°C for 1h in the presence of argon atmosphere.

A continuous wave (CW) CO₂ laser of 10 μm wavelength (5 kW maximum power) was utilized for material processing, and the optimal welding process parameters were obtained through orthogonal test: P=2000 W, V =250 mm/min, z=-0.5 mm.

Metallographical specimens were observed by OLYMPUS G×51microscope. The sample was polished with No. 1200 water sandpaper. In order to further analyze the microstructure of the weld,etched with a solution of 3g CuSO₄+10mLHCl+30mLH₂O and followed by etching with a solution of volume ratio of 3:1 HCL+HNO₃. Microstructure morphology of weld was analyzed by scanning electron microscope (SEM).

3. Result and Discussion

Figure 1 shows cross section of laser welding seam of 304 stainless steel and Fe-Mn-Si alloy. It can be seen that the welding joint of Fe-Mn-Si alloy and 304 stainless steel is well formed with good symmetry, no obvious pores or cracks, presenting an X shape, which is a typical laser penetration welding. The minimum welding width is located in the position above the middle of the welding seam, and the welding width ratio is close to 1:1, which indicates that the laser heat is evenly distributed along the thickness of the plate during welding. There are significant differences only at the bottom of the weld in figure 1, which indicates that metal melting and the inhomogeneity of heat conductivity present slightly larger at the bottom of the weld in the condition of laser welding.

Figure 2 shows microstructure of the fusion zone of dissimilar steel joint. It can be seen that the fusion zone of 304 stainless steel side is obviously smaller than that of Fe-Mn-Si alloy side. From the perspective of crystal morphology, the distribution of 304 stainless steel base material to the weld center is in order of plane crystal, cellular crystal and dendrite cellular crystal [9], as shown in figure 2 (a), while the same distribution of microstructure also exists between Fe-Mn-Si alloy base material and the weld center. The difference is that the crystals size of Fe-Mn-Si alloy side is larger than that of 304 stainless steel, and the fusion zone is wider, as shown in figure2(b).
It is worth noting that there are a large number of fine cellular crystal compositions in the planar crystal on the side of 304 stainless steel (figure 3). The interleaving phenomenon of grain boundary is more serious than that of Fe-Mn-Si alloy. This microstructure morphology can improve the tensile strength of the weld, but too much boundary interleaving means that the resistance to deformation increases. In the bending fatigue test, due to repeated alternating stress, excessive stress concentration will occur near the area, which is easy to germinate tiny micro-cracks.

Figure 4 shows the microstructure of the base material on both sides of the weld seam of the dissimilar joint. It can be seen that the structure of 304 stainless steel base material is still pure austenite (figure 4(a)), and the structure has not changed, which has the black pock markings are still austenite after welding. The formation of pock markings is because the arrangement of orientation is difference with different austenitic grain. The corrosion rate is different under the same etching condition, and the black one corrodes faster, forming pock markings. In addition to parent austenite, ε martensite is also observed in Fe-Mn-Si alloy base material (figure 4(b)). This is because the rapid heating and cooling of the laser in the welding process will lead to residual stress at the welding seam, which drives γ→ε martensite transformation of Fe-Mn-Si alloy. The behavior of stress induced ε martensite transformation of the dissimilar joint of Fe - Mn - Si alloy can release residual stress and improve the mechanical properties of the welding joint.

Figure 5 shows the scanning electron microscope photos of the dissimilar joint and 304 stainless steel joint with the instantaneous fault area. It can be seen that there are a large number of dimples in the instantaneous fault area of both of them, which shows the characteristics of plastic fracture. The difference is that the dimple size (figure 5(a)) and depth of the dissimilar joint are significantly larger...
than that of the 304 stainless steel joint (figure (b)). The size and depth of the dimple is greater, the toughness of the joint is better, which indicates that the toughness of dissimilar joints welding seam is better than that of 304 stainless steel joints.

Fig. 4 Microstructure of the base material on both sides of the weld seam of the dissimilar joint (a) 304 stainless steel base material; (b) Fe-Mn-Si alloy

Fig. 5 SEM of the dissimilar joint and 304 stainless steel joint with the instantaneous fault area (a) Dissimilar steel welding joint; (b) 304 stainless steel welding joint

Figure 6 shows the composition test location of dissimilar welding joint. Figure 7 is the element content of each region according to the test position in figure 6. It can be seen that the change of weld element follows the principle that solute diffuses from high concentration to low concentration. From both sides of the welding base material to the center of the weld, the content of each element is continuously "neutralized", and the balance is reached at the center of the weld at 4 positions, which indicates that the unique keyhole effect of laser welding makes the butt joint approximate "paste" together which plays a positive role in maintaining the characteristics of the dissimilar joint base material. In terms of composition, there are differences in composition between 3# and 7# regions, but the weld metals belong to Fe - Mn - Si alloys, which have the characteristics of stress induced martensite positive and inverse phase transformation. Therefore, most of the weld positions of the dissimilar joints have the feature of crack stop, while the weld fusion area (2# area) near the base material of 304 stainless steel has the characteristic of the crack stop disappears, which is exactly consistent with the location of the fracture of the dissimilar joints in the bending fatigue test.
4. Conclusion

(1) The welding joint of Fe-17Mn-5Si-10Cr-5Ni alloy and 304 stainless steel was well formed and presented an X shape. The crystallization of the dissimilar joint started from the fusion zone on both sides of the welding base material and spreaded to the weld center at the same time. The distribution of crystal morphology was symmetrical on both sides of the weld center, followed by plane crystal, cellular crystal and dendrite crystal. E martensite was found in Fe-17Mn-5Si-10Cr-5Ni alloy near the weld, which was caused by residual stress induced $\gamma\rightarrow\varepsilon$ martensite phase transformation.

(2) The size and depth of the dimple of the dissimilar joint between Fe-17Mn-5Si-10Cr-5Ni alloy and 304 stainless steel were obviously larger than that of the dimple of the instantaneous fracture zone in the weld fracture of 304 stainless steel joint, which indicated that the toughness of the dissimilar joint weld was obviously better than that of 304 stainless steel joint.

(3) The composition distribution of laser weld elements in Fe-17Mn-5Si-10Cr-5Ni alloy and 304 stainless steel dissimilar joints was obviously regional, and the distribution mode was related to the keyhole effect of CO$_2$ laser welding. The weld metal near the side of Fe-17Mn-5Si-10Cr-5Ni alloy still belonged to Fe-Mn-Si memory alloy, which had the characteristics of stress induced martensite positive and reverse phase transformation.

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