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Microstructures and properties of welded joint of TiNi shape memory alloy and stainless steel ①

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Abstract: The fracture characteristics of the joint were analyzed by means of scanning electron microscope(SEM). Microstructures of the joint were examined by means of optical microscope, SEM and an image analyzer. The results show that the tensile strength of the inhomogeneous joint of TiNi shape memory alloy and stainless steel is lower than that of the homogeneous joint and a plastic field appears in the heat affected zone on the side of TiNi shape memory alloy. Because TiNi shape memory alloy and stainless steel melted, a brittle as-cast structure was formed in the weld. The tensile strength and the shape memory effect of the inhomogeneous joint are strongly influenced by the changes of composition and structure of the joint. Measures should be taken to reduce the base metal melting and prevent the weld metal from the invasion by O for improving the properties of the TiNi shape memory alloy and stainless steel inhomogeneous joint.

Key words: TiNi shape memory alloy; stainless steel; welding; tensile strength; structure
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1 INTRODUCTION

TiNi shape memory alloy(SMA) is a new kind of functional material used in many fields, such as aviation and spaceflight, atomic energy, ocean development, instruments and medical purposes, etc due to its special shape memory effect (SME) and superelasticity, as well as excellent erosion resistance and outstanding biocompatibility[1-5]. However, successful application of any novel material not only hinges on its inherent characteristics, but also depends on solving problems of secondary operation (welding, machining, etc). As a result, the use of this material will be greatly limited unless problems of joining of the material itself and to other materials are solved. It's more difficult to join TiNi SMA, because required SME must be ensured besides zero defect and satisfactory mechanical properties. Since 1980, the joining of TiNi SMA has become the hot spot and front edge in the weld research field. Great attention has been given to the effects of welding methods and process on structures and properties of the homogeneous joint, using electron beam welding, laser welding, resistance spot welding, resistance butt welding, friction welding and brazing, etc[6-15]. So far, little work has been done to study systematically welding of TiNi SMA and stainless steel. The purpose of the present work was to obtain a better understanding of microstructures and properties of the joint so as to provide the theoretical basis for improving the properties of the joint.

2 EXPERIMENTAL

The composition of TiNi shape memory alloy (TiNi SMA) is Ti 50.2, Ni 49.8 (mole fraction, %). Stainless steel(SS) is 1Cr18Ni9Ti. The dimension of the two base metal specimens is 50.0 mm × 0.55 mm × 0.40 mm.

A micro-beam plasma-arc welder (LHM8-16) was used to weld TiNi SMA to SS. Before welding, surface oxide films on the specimens were removed by chemical treatments. During welding, Ar was ventilated into the weld zone to prevent N, O, H from penetrating into the welded joint zone and reducing the properties of the joint. All mechanical property tests were conducted at room temperature and static tensile and bending tests were carried out by means of electronic universal testing machine (CSS-44100). The principles of the tensile property and bending tests are shown in Fig. 1 and Fig. 2, respectively. The microstructures of the joints were examined using optical microscope, scanning electron microscope (JXA-840) and an image analyzer(VIDAS).

3 RESULTS AND DISCUSSION

3.1 Mechanical properties of joints

Fig. 3 shows a typical stress—strain curve of TiNi SMA with five stages, which is different from common materials. In stage Ⅰ, R-phase elastic deformation took place as the stress increased quickly with increasing the strain. The stress increased slowly

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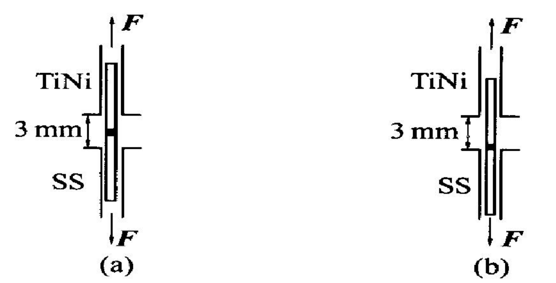

Fig. 1 Principle of tensile property tests
(a) —Tensile strength test; (b) —Elasticity test of joint

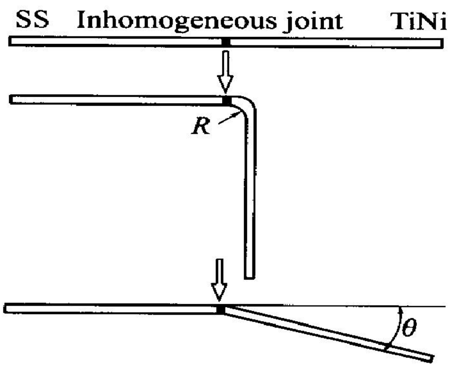

Fig. 2 Principle of bending test

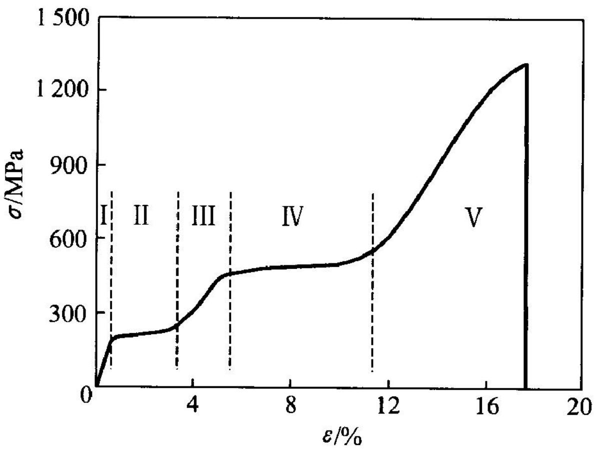

Fig. 3 Stress —strain curve of TiNi SMA

with increasing the strain in stage II due to the reorientation of adaptive R-phase variant. The elongation and the stress in this stage were about 2.2% and 150 − 250 MPa, respectively. In next stage, both the stress and the strain increased greatly and $R \rightarrow B19'$ martensitic transformation occurred. In stage IV, the stress had little change, while the strain increased greatly, corresponding to the reorientation of adaptive martensite variant, ie, with the impact of the stress, adaptive martensite engulfed the martensite which was unfit for deformation and grew up by the migration of martensite lath boundary. Because it didn't need to overcome great resistance, the stress changed little[16]. The elongation in this stage shifted to 8% − 12% and the stress was about 500 MPa. Then, as the stress increased with increasing the strain rate, slip deformation was generated and resulted in fracture with a tensile strength of 1 100 − 1 300 MPa and the elongation of 15% − 18%.

Fig. 4 illustrates a stress —strain curve of the homogeneous joint of TiNi SMA by micro-beam plasma-arc welding. The results indicated that the homogeneous joint possesses strength and strain of certain degree and can recover to a certain position(θ was between 25° and 30°) after it was bended to 90° and then held for 300 s, but both tensile strength and fracture strain are lower than those of the base metal, which is probably caused by the segregation of the solute and impurity elements and the form of coarse-grain and dendrite structure of the weld metal during solidifying[14]. Fracture propagated along the interface of columnar crystals in the center of the weld metal, owing to the boundaries of twin columnar crystals vertical with loading as well as the precipitation of oxidizing impurities along the grain boundaries. With the effect of heating during welding, the heat affected zone (HAZ) recrystallized, which made it soften and form plastic zone, as shown in Fig. 5.

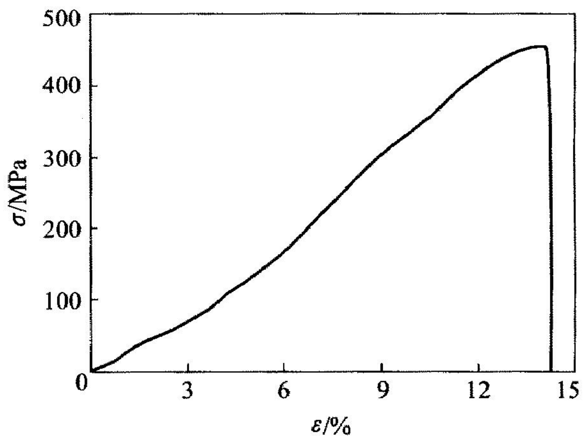

Fig. 4 Stress —strain curve of TiNi-TiNi joint

Table 1 lists mechanical properties of the base metals, homogeneous joint and inhomogeneous joint of TiNi SMA and SS, respectively. As listed in Table 1, the tensile strength of the inhomogeneous joint (TiNi-SS) was lower and more brittle than those of the two base metals(TiNi SMA, SS) and the homogeneous joints(TiNi-TiNi, SS-SS). Inhomogeneous joints could not bear bending strength. The tensile strength of the inhomogeneous joint was just 11.1% of that of the base metal(TiNi SMA) and 28.7% of

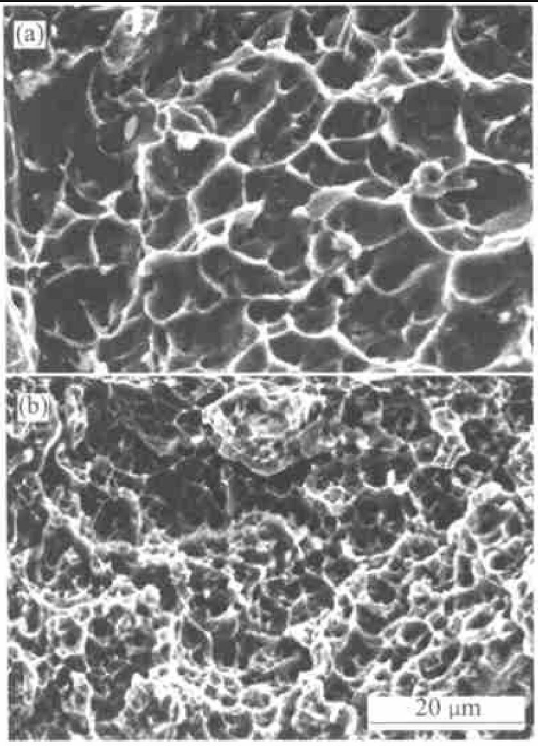

Fig. 5 Fracture surface morphologies of TiNi SMA
(a) —TiNi SMA base metal; (b) —TiNi HAZ

that of the homogeneous joint(TiNi-TiNi). Since the strain in the inhomogeneous joint hardly occurred under loading, it was difficult to get its stress—strain curve. Fracture surfaces displayed a typical brittle facture morphology and cracks could be apparently observed in the fracture surfaces, as shown in Fig. 6.

Table 1 Tensile strength of two base metals and joints (MPa)

TiNi SMA	SS	SS-SS	TiNi-TiNi	TiNi-SS
1 108 – 1 319	1 134 – 1 360	570 – 623	483 – 502	127 – 159
1 264	1 286	600	491	141

Fig. 6 Fracture surface morphology of joint(TiNi-SS)

3.2 Microstructures of joints

For further research on the low strength of the inhomogeneous joint, microstructures of the joints were examined by using optical microscope, SEM and an image analyzer. Fig. 7 illustrates the microstructures of the inhomogeneous joint consisting of weld zone and heat affected zone. The heat affected zone

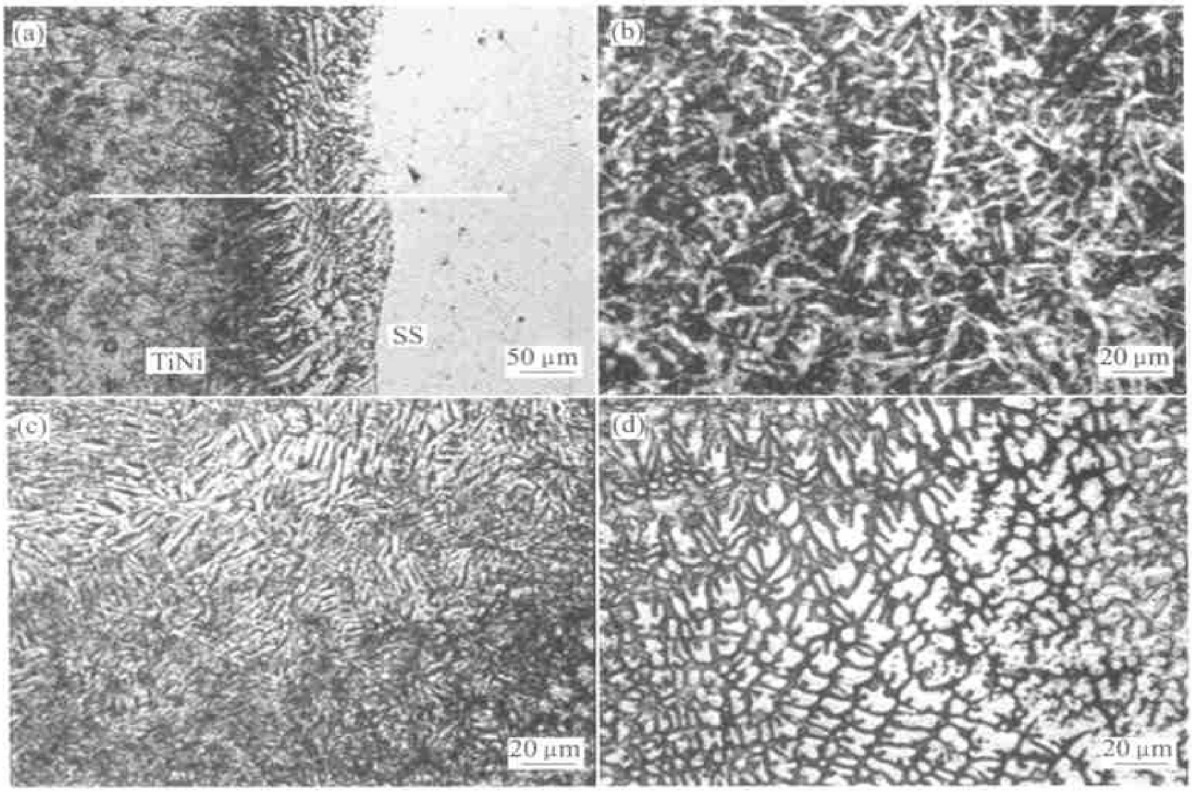

Fig. 7 Microstructures of inhomogeneous joint
(a) —Microstructure of joint; (b) —Microstructure of base metal(TiNi SMA);
(c) —Microstructure of heat affected zone(TiNi SMA); (d) —Microstructure of weld zone

of the base metal (TiNi SMA) was still wide after welding, though micro-beam plasma arc welding benefited from high-energy density, concentrated heating and quick welding. Parts of base metals (TiNi and SS) were melted during welding and the weld zone consisting of two molten base metals was formed during cooling. The low tensile strength of the joint is mainly attributed to brittle as-cast structure of the weld zone (Fig. 7(d)). It implies that the SME and superelasticity will be also seriously affected due to the changes of the composition and structures of the welded joint.

The reason is that deformation mechanism of Ti-Ni SMA is martensitic reorientation transformation induced by stress and reversible transformation, owing to the propagation of twin grain boundaries or intercrystalline interfaces in martensite crystals. As a result, the alloy with SME must possess orderly structures and the crystal structures must be symmetrical. There is only one way for the lattice rearrangement to revert to the original crystal structure and orientation of the base metal during the phase transformation. When TiNi SMA was welded with the high-temperature source, the weld zone and the heat affected zone were dissatisfied with the confinement conditions forming the crystal structure with SME due to the changes of the structures in both the weld zone and the heat affected zone. So the SME of the SMA joint will be greatly affected after welding. At the same time, when welding TiNi SMA to SS, SS melted, one part of which incorporated with TiNi SMA, leading to the formation of brittle as-cast structure, and another part diffused to the side of Ti-Ni SMA in the weld zone and diluted TiNi SMA as well as changed its composition and structure, as illustrated in Fig. 8. Energy spectrum analysis further confirmed that TiNi SMA strongly reacted with O

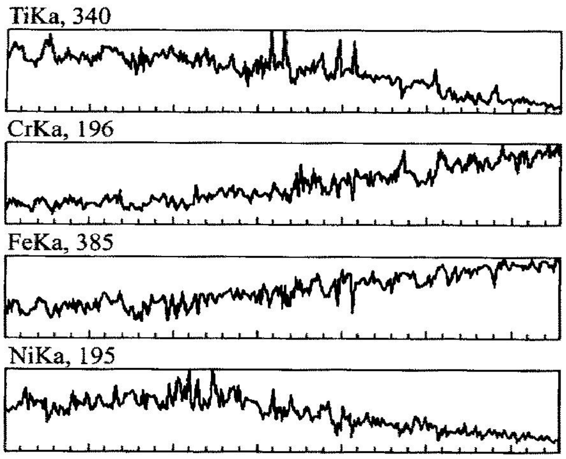

Fig. 8 Composition change of inhomogeneous joint (along line in Fig. 7(a))

during welding, leading to oxygen contents in excess of 16.04% (mole fraction) in the weld zone, which was 1.3 times of that in the heat affected zone on the TiNi SMA side, and 2.2 times in the heat affected zone on the SS side. Due to the invasion by O, Ti_4Ni_2O would precipitate in the weld, which was the main reason to form the brittle joint. As a result, TiNi SMA superheating and excessive fluxing should be avoided and the weld zone should be protected from the invasion by N, O, H for improving the mechanical properties of the inhomogeneous joint (TiNi-SS).

4 CONCLUSIONS

The microstructures and mechanical properties of TiNi SMA are highly sensitive to temperature changes. The tensile strength and the SME of the inhomogeneous joint (TiNi-SS) by micro-beam plasma-arc welding is strongly influenced by the changes of the composition and the structures of the joint, owing to the melting of TiNi SMA and SS and the invasion by O. As a result, superheating of TiNi SMA should be avoided and measurements should be taken to decrease the base metal melting too much and to prevent the weld metal from the invasion by O during welding in order to realize the welding of TiNi SMA to SS and improve the properties of the joint.

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