



Research Progress of Fusion Welding Techniques for TiNi Alloy to Steel

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Abstract: This review aimed to provide a comprehensive overview of the recent progress in fusion welding of steel and heterogeneous metals and to introduce current research and application. Amongst numerous metals, TiNi shape memory alloys and steel have been most heavily investigated for producing excellent joints. However, the base materials on both sides of the traditional fusion welding must melt and the large melting point difference between the two seriously affects the weld formation. The metal compounds formed by the base materials on both sides also hinder the improvement of the mechanical properties of the joint. This review focused on the fundamental understanding of the microstructural characteristics, processing and property relationships in the welding and joining of heterogeneous joints. The primary problem finding intermediate metals with enhanced plasticity and toughness to improve the formation of joints. Welding of light metals and high specific strength metals has a wide range of applications in the aerospace industry, it is committed to reducing the quality of flight equipment.

Keywords: Welding, TiNi Alloy, Steel, Microstructure, Mechanical Properties

1. Introduction

The physical properties between steel and dissimilar metals have considerable differences and the formation of brittle intermetallic phases, thus making welding difficult. Table 1 compares the typical physical properties of pure Mg, Al and Fe. The coefficient of linear expansion and elastic modulus between TiNi SMAs and steel differ. This difference leads to large thermal stress and affects the mechanical properties of the joint. In addition, Ti-Fe IMC is formed in welding molten pools, which reduce the mechanical properties of the joint [1]. Steel remarkably differs from Mg alloy in terms of melting point. In fusion welding, when Mg alloy is burned and evaporated, steel does not melt. Thus, obtaining a good joint of Fe/Mg and Fe/Al is difficult. As shown in Figures 1 and 2, the crystal structures of Mg and Fe showed a big difference; thus, a mutual solution of both elements is extremely difficult in liquid state and they do not form IMC [2]. In addition, the low solid solubility between Al and Fe results in the formation

of intermetallics that adversely affect the strength of the joint [3]. Therefore, a technology that produces dissimilar joints is urgently needed to solve this problem.

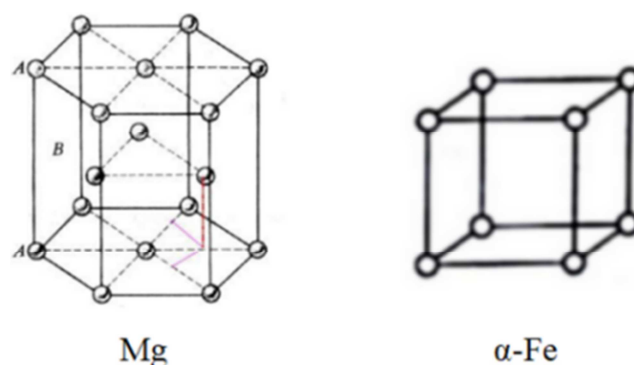
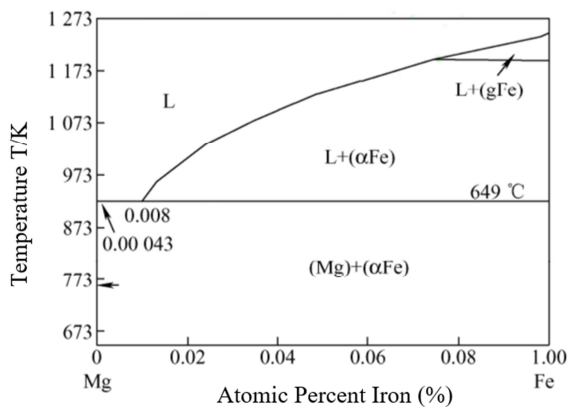


Figure 1. The crystal structure of Mg and α -Fe.

Table 1. Physical properties of steel, TiNi SMA and Aluminum alloy materials.

Material	Melting point/ $^{\circ}\text{C}$	Specific heat capacity/ $(\text{J}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1})$	Density/ $(\text{g}\cdot\text{cm}^{-3})$	Thermal conductivity/ $(\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1})$	Linear expansion coefficient/ $(10^{-6}\cdot\text{K}^{-1})$	Resistivity/ $(\mu\Omega\cdot\text{m})$	Elastic modulus/ GPa
TiNi	1275	545	6.4	10	6.6-10	5.0	98
Al	660	900	2.7	220	12	9.78	71
Mg	650	-	1.7	156	248	-	45
Cu	1083	385	8.9	388	17.5	0.017	120
SS	1535	500	7.9	16	16.6	7.3	206
Low-carbon steel	1500	500	7.8	77.5	11.76	13	206

**Figure 2.** Mg-Fe binary phase diagram.

For TiNi SMAs, how to suppress or avoid the formation of Ti-Fe IMCs in the weld is a hot issue. Mg and Fe could not easily have a mutual solution in liquid state and they do not form IMC. The key to achieve an effective connection is to select a metal interlayer that has a good intersolubility with both Mg and Fe. Reducing heat input to avoid burning and evaporating Mg alloy is also needed. For Al alloys, suppressing or avoiding the formation of Fe-Al IMCs is the most important.

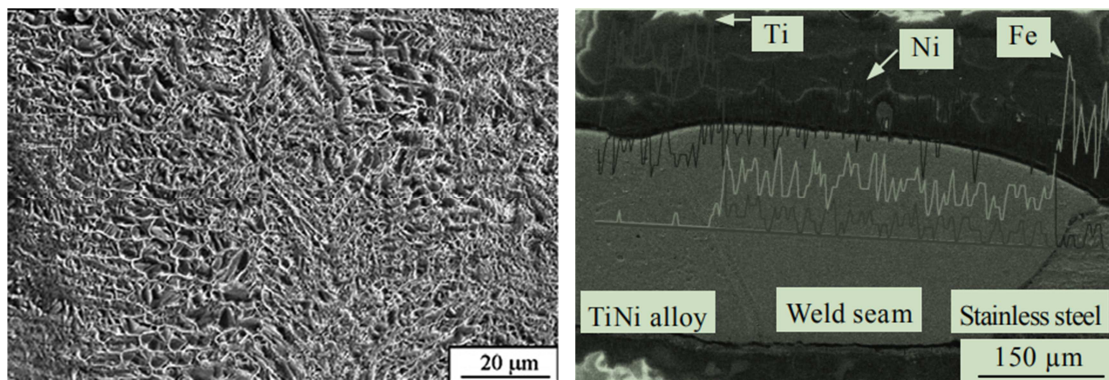
Previous studies regarding dissimilar joining have been reported in the past years [4, 5]. Many researchers have developed various methods, such as fusion welding, brazing, TLP diffusion welding, FSW and RSW, for welding dissimilar alloys and steels. Some progress was demonstrated by most research on the welding methods and processes of dissimilar welded joints and the structure and properties of these joints.

2. Research Status

Adding an intermediate layer during the welding process of

TiNi SMA and SS could reduce or avoid the formation of Ti-Fe IMCs in thine weld and improve the mechanical properties of the joint. Ni, Cu and Co have good mutual solubility. Ti has great solubility in Ni and Co. It forms a Ti-Cu IMC with less hardness with Cu, thus helping improve TiNi/SS joints. The linear expansion coefficient of Ni and Co is between that of TiNi SMA and SS. Cu has low melting point and yield strength. It has good plasticity and deformability, it also reduces the residual stress of TiNi/SS joints, thus improving their mechanical properties [6]. Therefore, Ni, Cu and Co are appropriate materials of the intermediate layer in welding.

Li et al. [7] performed laser welding with pure Ni foil of different thicknesses (10–100 μm) added to a 0.64 mm \times 0.48 mm TiNi SMA and AISI304 SS wire. The research results showed that the content of Fe and Ti decreased, whereas that of Ni increased. The weld was mainly composed of γ -Fe, B2, B19', TiFe₂, TiCr₂, TiNi₃ and Ti₂Ni phases (B2 and B19' phase are from TiNi). As the thickness of the Ni foil increased, the γ -Fe phase in the weld zone increased, whereas the content of IMCs, such as TiFe₂ and TiCr₂, decreased. The optimal thickness of Ni foil was 50 μm , the weld zone presented the characteristics of austenite structure (Figure 3, left). The tensile strength and ductility elongation of the joint reached 372 MPa and 4.4%. The tensile strength nearly doubled compared with that of TiNi/SS joint without Ni foil. Chen et al. [8] laser-welded a 60 mm \times 40 mm \times 0.2 mm TiNi SMA and 1Cr₁₈Ni₉Ti SS sheet and added 0.3 mm pure Ni wire during the welding process. As shown in Figure 3 (right), the joint was formed without cracks and pores. The central area of the weld exhibited a small equiaxed crystal structure. The main elements were Ti, Ni and Fe. The main fusion zone of TiNi SMA was 10–20 μm . A metal compound layer, such as TiFe, was formed and the average tensile strength of the joint was 580 MPa.

**Figure 3.** SEM microstructure of weld seam with 80 μm thick Ni foil (left), Element distribution in the weld zone of TiNi/SS joints (right).

Li et al. [10] welded 0.64 mm \times 0.48 mm TiNi SMA and AISI304 SS alloy wire and added a 20–120 μ m Cu intermediate layer. The research results showed that the joint was well formed without porosity nor cracks. The content of Cu increased, whereas that of Ti, Ni, Fe and Cr decreased. The content of metal compounds, such as TiFe₂ and TiNi₃, decreased. The mechanical properties of the joint improved. When the thickness of the Cu foil was 80 μ m, the tensile strength of the joint could reach up to 521 MPa. Zoeram et al. [11] laser-welded a 1 mm-thick TiNi SMA and AISI316 SS sheet and added 100 and 150 μ m Cu intermediate layers during the welding process. As shown in Figure 4 (left), the

weld was well formed without cracks nor pore defects. The content of Fe₂Ti, FeTi and other IMCs was reduced to form Ti-Cu metal compounds with low hardness. The maximum tensile strength of the joint reached 150 MPa. Li et al. [12] performed laser welding on 0.64 mm \times 0.48 mm TiNi SMA and AISI304 SS wire and added 10, 20 and 50 μ m of Co interlayer during the welding process. As shown in Figure 4 (right), the structure after welding was uniform; the joint was well formed; the IMCs, such as TiFe₂ and TiCr₂, in the weld were reduced and the joint performance improved. When the Co middle layer was 20 μ m thick, the tensile strength of the joint reached a maximum of 347 MPa.

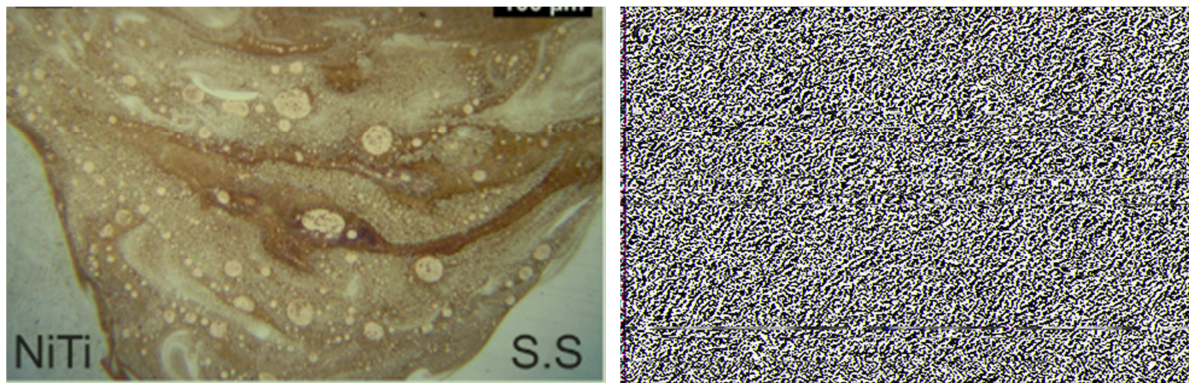


Figure 4. Microstructure of 150 μ m thick copper intermediate layer sheet base material joint.

Compared with the tensile strength of TiNi/SS joints without intermediate layer, that of joints with Ni, Cu, and Co intermediate layers substantially improved, as shown in Table 2. The content of Ti-Fe and Ti-Cr metal compounds in the welds was reduced but the formation of these metal compounds could not be completely avoided. In addition, if the intermediate layer of Ni, Cu and Co was too thick, metal compounds such as Ti-Ni, Ti-Cu and Ti-Co could be formed, thus reducing the mechanical properties of the joint. Ng et al. [13] added a Ta intermediate layer that does not form an IMC with Ti and laser-welded TiNi SMA with a diameter of 1 mm and AISI316 SS wire. The content of Ta in the weld increased, whereas that of the Ti-Fe IMC decreased. The mechanical properties of the joint improved. When the thickness of the Ta intermediate layer was 50 μ m, the maximum tensile strength of the joint was 251 MPa. However, Ta formed metal compounds, such as TaCr₂ and Ni₃Ta, in the weld. In addition, an intermediate layer that was too thick could reduce the mechanical properties of the joint.

Gao et al. [14] performed laser brazing of a 0.8 mm-thick TiNi SMA and 301 SS sheet and added a Nb/Cu intermediate layer with thicknesses of 1.5 and 0.15 mm. As shown in Figure 5, the Nb intermediate layer was melted and combined with TiNi SMA through eutectic reaction. The melted Cu intermediate layer and 301 SS were joined together by welding. A small amount of Fe₇Nb₆ IMC was formed in the joint but the formation of Ti-Fe, Ti-Cr and other IMCs was avoided, thereby improving the mechanical properties of the joint. The tensile strength of the joint could reach 240 MPa.

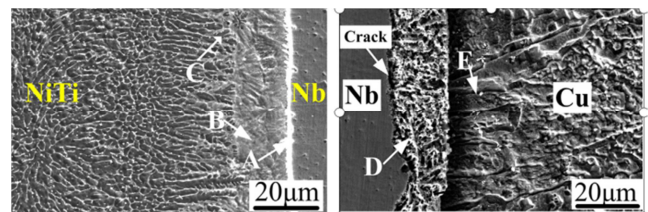


Figure 5. Microstructure of the interface between TiNi/Nb and Nb/Cu.

Table 2. Strength of TiNi/SS joints with different intermediate layers.

Author	Interface	Welding Method	Base Metal Shape	Middle Layer Thickness	Joint UTS
H. M. Li	Ni	Laser	Filamentous	50 μ m	372 MPa
Y. H. Chen	Ni	Laser	Sheet	300 μ m	580 MPa
H. M. Li	Cu	Laser	Filamentous	80 μ m	521 MPa
Zoeram	Cu	Laser	Sheet	100 μ m	150 Mpa
H. M. Li	Co	Laser	Filamentous	20 μ m	347 MPa
C. H. Ng	Ta	Laser	Filamentous	50 μ m	251 MPa
X. L. Gao	Nb/Cu	Laser	Sheet	1500/500 μ m	240 MPa
M. J. C. Oliveiraa	Inconel 625	Micro-plasma arc welding	Sheet	...	286 MPa

3. Conclusions

Most of the current methods depend on the intermediate layer to connect the Mg alloy and steel. Therefore, the performance of the interlayer decides the mechanical properties of the joints. However, the weld tissues in Fe/Ti joints are mainly composed of Fe-Ti IMC. Thus, the primary problem finding intermediate metals with enhanced plasticity and toughness to improve the formation of joints. Welding of light metals and high specific strength metals has a wide range of applications in the aerospace industry, it is committed to reducing the quality of flight equipment. Welding of corrosion resistant metal and steel can be applied to marine equipment. The connection of dissimilar metals continues to meet the needs of future industrial development.

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