

Research Progress of Composite Materials of NiTi SMA and Stainless Steel

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Abstract: Nickel Titanium Shape Memory Alloys (NiTi SMA) are material with high strength and good biocompatibility, and more and more applications in several industrial domains, like aerospace, automotive, biomedical and power plants. However, there are still facing some restrictions for themselves mechanical property and joining techniques. The composite structure of the NiTi SMA with the Stainless Steel (SS) could better play its characteristics and advantages, and has broad application prospects. Meanwhile, NiTi SMA and SS have great differences in physical and chemical properties. And it is easy to produce brittle metal compounds due to the difficulty of joint welding. Many scholars have studied the dissimilar connection between NiTi SMA and SS, and successfully prepared NiTi/SS orthodontic arch wire according to the research results, but there is still much room for development. This review aimed to provide a comprehensive overview of the recent progress in welding of NiTi SMA and SS, and to introduce current research and application. Lastly, the research status and existing problems of dissimilar metal welding between NiTi SMA and SS in recent years have been summarized. This review focused on the fundamental understanding of the microstructural characteristics, processing and property relationships in the welding and joining of heterogeneous joints.

Keywords: Shape Memory Alloy, Stainless Steel, Dissimilar Metal, Welding, Review

1. Introduction

NiTi Shape Memory Alloys (SMA) has significant study prospects in a wide range of industries including aerospace [1] and medical equipment [2], due to their shape memory effect, superelasticity [3]. In addition to the unique properties, NiTi SMA also has high specific strength [4], good biocompatibility [5-6] and corrosion [7], which increased its functional properties in many industries. And the composite structure with other materials will expand its application range. Such as Stainless Steel (SS), it contains chromium, manganese, nickel and other alloying elements. It has high comprehensive mechanical properties, good corrosion resistance and low cost, and is widely used in industrial manufacturing [8]. The composite structure of NiTi alloy and SS can give full play to the respective performance advantages of the two materials, and has good economic benefits, there are many applications in medical devices or aerospace, such as NiTi SMA wire welded to SS wire to prepare composite orthodontic arch wire,

SS wire in the supporting teeth to provide support, TiNi SMA in abnormal teeth to provide corrective force, effectively improve the treatment time and effect and alleviate the pain of patients during treatment [9].

However, scientists and practitioners are still facing some restrictions in machining processes and joining techniques of NiTi SMAs to dissimilar materials. The primary reason is the physical properties of the two metals were quite different, as shown in table 1, especially their linear expansion coefficient and elastic modulus are very different, and it can be produced welded stress failure joint formation in the welding process. More significant, Ti and Fe, Cr elements in SS are easy to form intermetallic compounds such as Ti_2Fe , $TiCr_2$, etc.

These compounds will reduce the brittleness and toughness of the weld, thus reducing the mechanical properties of the joint [10-12]. In recent years, scholars in various countries have conducted relevant studies on the connection between NiTi alloy and SS on the basis of previous studies. Some scholars adopted the method of adding filler metals to solve the welding problems in NiTi/SS

joints, such as adding Ni, Cu, Co [13] and other metal elements, or using silver-based filler metal laser brazing NiTi SMA and SS [14], and made some progress.

In recent years, many researchers have further researched the NiTi/SS joint, optimized the welding parameters of fusion welding and adopted post-weld heat treatment to improve joint strength. In terms of solid-state welding, new solders or

new welding processes are used to improve the formation of NiTi/SS joints. The welding methods and processes, microstructures and properties of NiTi/SS joint are mainly studied, and made some progress. Therefore, this paper mainly discusses the welding method of NiTi SMA and SS connection and the technology to improve the microstructure and mechanical properties of the joint.

Table 1. Physical Properties of NiTi SMA and SS [14].

Material	Melting Point/ °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
NiTi SMA	1275	545	6.4	10	6.6~10	5.0	98
SS	1535	500	7.9	16	16.6	7.3	206

2. Fusion-based Welding Processes

2.1. Laser Welding of Single Metal Interlayer Added

Laser has large energy density, small heating range and narrow heat affected zone, which could accurately control the heat input. It is the main method for welding NiTi SMA and SS, and filamentous medical equipment is more suitable for welding. For the welding of NiTi SMA and SS, the main method is to add a metal interlayer between the base metal on both sides, and use the performance of filling metal to reduce the stress in welding and the content of Ti-Fe and other compounds in the weld.

Ni has attracted much attention as an excellent interlayer. Chen Yuhua et al. [15] preset Ni wire with a diameter of 0.3 mm, and welded by laser welding the thickness of 0.2 mm NiTi SMA sheet and 321 SS. The results showed that the NiTi/Ni interface area was mainly composed of NiTi eutectic layer and NiTi_3 intermetallic compound layer on the NiTi side, and the microstructure of the interface area is shown in Figure 1. With the increase of pulse width, the melting amount of NiTi base metal increased, resulting in the average width of NiTi eutectic layer decreasing, meanwhile the average width of NiTi_3 intermetallic compound layer was increased. Therefore, with the increase of laser pulse width, the microhardness of the joint increased from 3.97 GPa to 7.48 GPa.

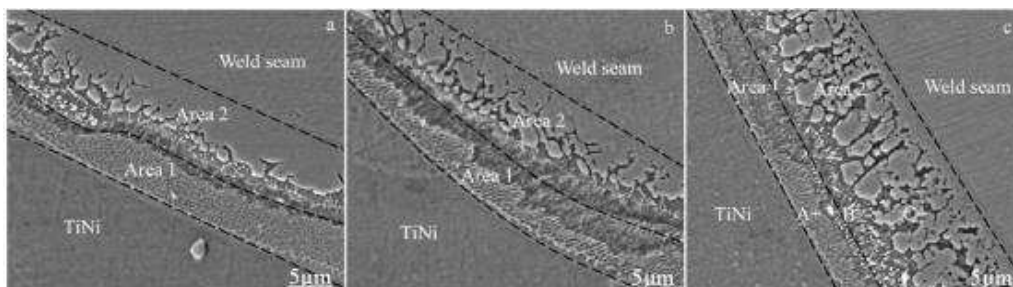


Figure 1. SEM morphologies of interface area on NiTi side under different pulse widths: (a) $t=5.1$ ms, (b) $t=6.2$ ms, and (c) $t=7.3$ ms [15].

Shamsolhodaei et al. [16] used laser welding 400 μm diameter NiTi wire and SS AISI316 wire. They used laser offsetting welding (LOW) or added an Ni interlayer to connect NiTi SMA and SS wire. Laser offsetting welding formed less brittle intermetallic compounds like Fe_2Ti , Cr_2Ti and Ni_3Ti in the weld, and led microhardness of welding decreased from 970 HV to 570 HV, as shown in Figure 2. The same phenomena of decreasing the amount of intermetallics formed, occurred when a 50 μm thickness Ni interlayer was inserted between the two base materials, meanwhile Ni-rich intermetallic compounds (Fe_3Ni and Ni_3Ti) formed inside the weld zone.

Except filamentous Ni, some researchers added Ni powder during welding to connect NiTi SMA with SS. Asadi et al. [17] used laser to weld NiTi archwires and 304 SS archwires, and pure Ni powder was added as the filler metal. The morphology of the joint is shown in Figure 3. The results showed that composition and microhardness of the weld zone

variations were more homogenous after Ni powder was used. Most of the phases in the weld zone were Ni_3Ti and $\gamma\text{-Fe}$. The average hardness of the weld zone decreased from 580 HV down to 325 HV, tensile properties of the joint were improved and reached to a tensile strength of 300 MPa and a fracture strain of 2.9%.

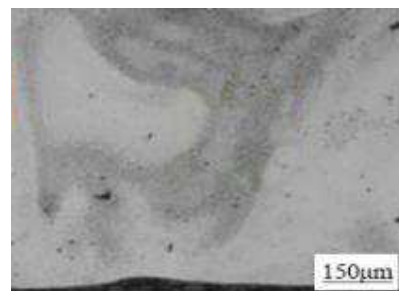


Figure 2. The cross section microstructure of 100 μm laser beam biased AISI 316 SS side join [16].



Figure 3. Cross-sectional view of the NiTi to SS dissimilar laser welded joints [17].

In addition, Cu metal is commonly used in the intermediate layer. Zoeram *et al.* [18] used laser welding to connect 1 mm-thick NiTi SMA and SS sheets, and used different thicknesses copper thin film (100 and 150 μm) as an interlayer. The result showed that the interlayer thickness has influenced the chemical composition of the weld metal.

The increase of interlayer thickness decreased the concentration of Fe-Ti IMCs in weld metal and this made weld metal softer to some extent. When the thickness of the interlayer increased, cracks that originated from thermal stresses and brittleness of weld-metal were eliminated.

Moreover, some copper-rich globules were separated out from γ -Cu-Fe solid solution supersaturated by during cooling, as shown in Figure 4. The globules of Cu and surrounding Fe-rich matrix were formed with no strong bond. It turned these boundaries to be a suitable place and path for nuclear and propagation of crack. The maximum tensile strength of the joint of NiTi/SS was about 150 MPa.

In previous studies, intermediate layers such as Ni and Cu were successful welding NiTi SMA and SS, but the strength needs to be improved. In recent years, the research that single metal intermediate layer focuses on optimizing the welding parameters such as laser width and welding speed has relevant influence on the welding results. More suitable welding parameters have a great improvement on the microstructure distribution and mechanical properties of the

joint. The welding method of heat source offset can reduce the melting amount of the base metal, so as to reduce the content of Ti-Fe compounds in the joint. However, the formation of Ti-Fe compounds cannot be avoided by heat source offset alone, and the mechanical properties of the joint are limited.



Figure 4. Microstructure of welded sample with 150 μm Interlayer [18].

2.2. Laser Welding of Composite Intermediate Layer

Gao XiaoLong *et al.* [19] carried out laser welding of 0.8 mm thick NiTi SMA and 301 SS sheet, added 1.5 mm and 0.15 mm composite Nb/Cu interlayer on the process. As shown in Figure 5, the NiTi SMA side was combined with Nb layer through welding, and the 301 SS side was combined with molten Cu through element diffusion. In addition, no Ti-Fe metal compound was formed, and little of Fe_7Nb_6 metal compound in the joint. The tensile strength of the joint was up to 240 MPa.

Zhang Yan *et al.* [20] used copper-based solder (38Zn-61Cu) for laser brazing of NiTi SMA and SS. The results showed that the filler metal wetted the base metal and proceeded the diffusion between elements, the joint was dense and there was no porosity and other defects. The joint has unmelted base metal on both sides, Ti, Fe, Cr and other elements did not enter the molten pool, so it did not generate Ti-Fe compounds. Fe_3Zn_7 , Ti_2Cu and NiTi compounds were formed in NiTi/SS joints with copper-based filler metal, and the maximum joint strength was 153 MPa.

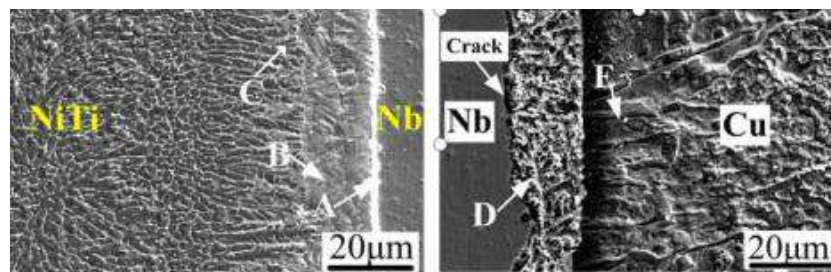


Figure 5. Microstructure of NiTi / Nb (left) and Nb / Cu (right) interface [19].

The use of conforming interlayer can completely avoid the formation of Ti-Fe compounds, and greatly improve the mechanical properties of the joint. However, due to the complex welding process, too many welding interfaces will make the formation mechanism more complex. On the other hand, there must be formed other.

2.3. Heat Treatment After Laser Welding

As the laser welding is fast speed, short cooling time and other factors, NiTi/SS joint is uneven organization distribution and there is a large amount of welding stress. The

postweld heat treatment as a material treatment method, improves the mechanical properties of metallic joints. Asadi et al. [21] were annealing after weld orthodontic archwires of NiTi SMA with SS to improve microstructure and mechanical properties. The NiTi/SS joints were annealed at temperatures of 100°C, metal compounds, even if the formation of Ti-Fe metal compounds was avoided. Although their harm is not as huge as that of Ti-Fe, the number of them to a certain extent will still destroy the forming of the joint, thereby reducing the mechanical properties of the joint.

200°C, and 300°C for 1 h and then they were quenched in water. The tensile strength increased 1.91 times through post weld heat treatment at 200°C. Chen et al. [22] used post-weld heat treatment at 650°C to 850°C were applied on a defect-free NiTi/SS joint to improve its mechanical properties. The results showed that more Ni₃Ti was observed at the weld metal, resulting in the average hardness of the weld metal increasing from 375 HV0.2 to 493 HV0.2. Owing to the homogenization of microstructure, the highest joint average strength reached 643 MPa at 850°C PWHT, which was about 2 times higher than that of the as-welded joint.

Post-weld heat treatment, as a material process, is a helpful method to improve the microstructure distribution of NiTi joints and to reduce the residual stress in the joints. In particular, laser welding, a welding method with fast cooling rate and welding speed, is widely used. The microstructure distribution of the joint after heat treatment is more uniform, which was helpful to improve the mechanical properties of the joint.

2.4. Other Heat Source Welding

In addition to laser heat source, some researchers use arc or electron beam as welding heat source. Oliveira et al. [23] used micro gas tungsten arc welding (GTAW) to connect NiTi SMA and AISI 304 SS thin sheets by using NiTi and Inconel 625 as filler metals. The morphology of some joints is shown in Figure 6. The joints exhibited a heterogeneous weld zone due to the formation of intermetallic elements along with embrittlement of the weld metal. Some joints

partial diluted zones with distinct morphology, chemical composition and hardness were formed. It was possible to increase the mechanical strength of the joint up to 286 MPa by using an intermediate layer of Inconel 625 at the junction between dissimilar metals and by applying heat treatment for stress relief. Niu et al. [24] welded NiTi/SS sheets via a vacuum electron beam welding process, with offsetting electron beam to SS side without interlayer, adding Ni interlayer and adding FeNi interlayer three methods to promote mechanical properties of the NiTi/SS joints. The joints were attributed to the enrichment of intermetallic compounds including Fe₂Ti and Ni₃Ti with different interlayers in the weld zone near the NiTi side. Added Ni interlayer main compounds in weld Fe₂Ti were replaced with Ni₃Ti, some joints are shown in Figure 7. The composite structure of Ni₃Ti and Fe₂Ti will be formed when the FeNi alloy is taken as the interlayer, which provided the joint excellent mechanical properties, with rupture strength of 343 MPa. Aiming at achieving good cavitation erosion resistance, shi et al. [25] used NiTi cladding with/without Ni interlayer was prepared on SS (SS) by tungsten inert gas (TIG) surfacing process. Due to their higher micro-hardness and superelasticity, the cavitation erosion resistance of NiTi-TIG and NiTi-Ni-TIG claddings was better than SS substrate. Other welding heat sources can be used as a fusion welding method in addition to laser welding, which could assist laser welding to find its shortcomings and improve the welding process.



Figure 6. Microstructures of M25NC Joint [23].

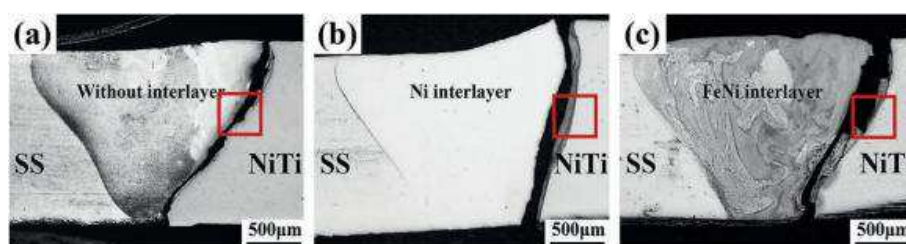


Figure 7. Lateral micrographs of NiTi/SS electron beam welded joints. (a) without interlayer; (b) Ni interlayer; (c) FeNi interlayer [24].

3. Solid-state Processes

Li et al. [26] was employed to join NiTi SMA and SS by resistance welding. The results showed that the weld was comprised of a reaction layer of 10 μm (Figure 8) in size at a welding current of 40 A. The maxed tensile strength of the

joint was 440 MPa. After cold drawing, the microstructures in the heat-affected zones (HAZs) were refined and the tensile strength of the joint increased to 830 MPa. With decreasing impact speed from 40 mm/s to 27.5 mm/s, the volume of the flash increased, and the radial expansion rate of the joint decreased, the diffusion layer formed at the interface thickened slightly, and the tensile strength averaged

decreased from 522 MPa to 375 MPa [27]. Vaporizing Foil Actuator Welding (VFAW) as a new welding method provided new solid phase welding technology for welding of NiTi SMA and SS. Li *et al.* [28] used the rapid ablation of a foil in a lab-scale process that was similar to explosive welding. The results showed that the microstructure was heterogeneity, and had an unwelded zone in the center. However the fracture position was on the NiTi base metal illustrating the tensile strength was very high.

Solid-state welding generally performs metallurgical reactions through instantaneous high-speed impact or high-power current. There is no melting of the base metal, and the strength of the joint is high, even it can be higher than the base metal. So it was an excellent welding method. However, the welding process of solid-state welding is generally complex, and the cost is high, which could not be applied on a huge scale. During the welding process, more metal compounds are generated in the oxide, and the hardness of the joint is high.



Figure 8. Microstructure of Reaction Layer at 40 A [26].

4. Conclusion

NiTi shape memory alloy and SS dissimilar metal welding joint have good mechanical properties, which could lay the foundation for the biomedical field such as orthodontic arch wire and other medical equipment research and development. At the same time, it is beneficial to promote the development of welding NiTi SMA and SS, which having important theoretical significance and application value. The state-of-art shows that the main method of welding NiTi SMA and SS was fusion welding, which had high strength and flexible welding size. The content of Ti-Fe metal compound in the weld can be reduced by heat source offset and adding intermediate layer, which improving the strength of the joint. The formation of Ti-Fe metal compound can be completely avoided by adding composite intermediate layer or laser brazing. At present, the main fusion welding researchs focus on welding parameters, post-weld heat treatment to further improve the joint forming and to improve the mechanical properties. Solid-phase welding joint has high strength, which would be more advantageous to controlling intermetallic compounds than fusion welding. However, the current solid-phase welding process is complex, and the method used is cumbersome, which could not be applied on large scale. Therefore, to NiTi/SS fusion welded joints, the properties of interlayer materials mainly determine the mechanical properties of NiTi/SS joints. How to prepare

interlayer metals or solders with better properties is the main direction for further development of fusion welded NiTi SMA and SS. Most of the joints used successfully are filamentous metal. The properties of the welded joints between NiTi SMA sheet and SS sheet have big room for improvement. The plate of NiTi/SS joint will further expand the application in several industrial domains.

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