Study on the effect of double-sided laser welding of NiTi shape memory alloys wire

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Abstract

NiTi shape memory alloys (SMAs) have important applications in intelligent system design and development due to their flexibility in integration through welding or joining techniques. In this work, both single-sided laser welding and double-sided laser welding processes were used for the welding of NiTi SMAs wire. Then, the macro-morphology, microstructure, phase transformation behavior, mechanical performance, fracture surface characteristics and cyclic tensile properties of the samples obtained under the two welding processes were investigated. The results showed that there were dendrites and equiaxed grains in the fusion zone (FZ) of the double-sided welding samples, without obvious welding defects. Although the phase transformation temperature in the FZ of the samples obtained by the two processes was significantly increased, the temperature rise of the double-sided welded samples was relatively lower. The double-sided welded samples had better tensile strength and elongation, and all samples were ductile fracture. The double-sided welded samples exhibited significant functional fatigue properties improvements compared with the residual strains of the single-sided welded samples in the 1st and 15th cycle tensile tests. This work will improve the performance of NiTi SMAs wire for welding integration applications in smart system design and production.

1. Introduction

In recent years, the development and application of new materials has become an important component of modern high technology. Because of the shape memory effect [1-2], superelasticity [3], corrosion resistance and biological compatibility [4-5], NiTi SMAs have been widely used as a novel type of functional material in aerospace, automotive, biomedicine, and everyday life fields.

As the industry evolves, higher standards for the processing and use of NiTi SMAs are established. No doubt, NiTi SMAs can promote the lightweight, miniaturization and revolutionary application of advanced engineering design. Therefore, advanced manufacturing technologies need to be implemented for the connection or integration of NiTi SMAs. Welding technology can break through the limitations of joint geometry and maximum load.

At present, the most commonly used NiTi SMAs welding technology are: tungsten gas shielded welding [6], laser welding [7-10], electron beam welding [11], resistance welding [12], ultrasonic welding [13], brazing [14], and reactive diffusion welding [15]. Many researchers have conducted extensive research on laser welding and discovered that it has the advantages of fast welding speed, less molten metal, and good welded joint formation. Chan [16] et al. used a fiber laser to weld NiTi SMAs thin plates and studied the influence of welding process parameters on weld grain morphology. Gugel [10] et al. found that the tensile strength of the laser welded NiTi SMAs was only 70% of the base material (BM), and the elongation was also significantly lower than that of the BM. Khan [17-19] et al. studied the variation in Ni content and phase transformation temperature in the FZ of NiTi SMAs processed under various process parameters. The results revealed that as the laser pulse width was increased, the martensite transformation start temperature of the FZ rose.

Despite the fact that many researchers have studied laser welding of NiTi SMAs, some difficulties encountered in the laser welding of NiTi SMAs were still not well solved. High heat input of laser welding will cause Ni to evaporate and generate pores, resulting in stress concentration and easy generation of micro-cracks. At the same time, Ti easily absorbs nitrogen, oxygen and hydrogen at high temperature to form brittle compounds, which will weaken the mechanical properties [3]. Compared with single-sided welding, double-sided welding can reduce the heat input of a single laser beam while ensuring weld penetration. laser welding can remove the effect of cold working by heat conduction, similar to an annealing process, indicating a potential role in improving joint performance [20-21].

In this work, laser welded NiTi SMAs samples were produced by two different processes: single-sided welding and double-sided welding. The effects of different welding processes on the macro-morphology, microstructure, phase transformation behavior, mechanical properties, fracture surface characteristics and cyclic tensile properties of NiTi SMAs samples were systematically studied by comparing with the BM. This work was of great significance for improving the welding process selection of NiTi SMAs during integration and promoting the application in different industrial production.

2. Experiments

NiTi SMAs wire (51.51% at. Ni) with a diameter of 0.7 mm was chosen in this investigation. Before welding, the surface of the sample was polished with 600 #, 1000 #, and 1500 # sandpapers, and ultrasonic cleaning was performed with acetone and deionized water. Finally, hot air was used to blow dry the sample.

A specially designed welding fixture was used in this experiment, as shown in Fig. 1. Argon gas was flowed into the holes at a rate of 15 L/min to avoid oxidation of the welded NiTi SMAs. The W-LTA4030 laser machine with a wavelength of 1070 nm provided by Huagong Laser was adopted for this investigation. The laser was set to pulse mode, and the samples to be welded were processed on single-sided (as shown in Fig. 2 (a)) and double-sided (as shown in Fig. 2 (b)) with a length of 2 mm, respectively. Before welding, the two surfaces of the sample were marked along the axis of the NiTi SMAs wire. During welding, the sample fixed on the fixture was constrained in position according to the previous markings, thus ensuring that the two processed surfaces were symmetrical along the wire axis. The parameters used in the laser welding test are shown in Table. 1.

Table 1
Laser welding parameters.

Samples	Laser Power (W)	Welding Speed (mm / s)
Single-sided laser welding	600	6.0
Double-sided laser welding	400	6.0

All the welded samples were mounted in resin before being ground, polished, and corroded. The corrosion solution was HF: HNO₃: H₂O=1: 3.5: 6.5. Microstructure examinations were characterized using Olympus

Optical microscopy (OM). Differential scanning calorimetry (DSC) was used to analyze the phase change characteristics of the BM and the welded samples. The heating and cooling rate during the test was 5°C / min, and the temperature range was -45°C to 105°C.

The mechanical properties of the BM and the welded samples were tested on tensile testing machine, then the fracture surface was observed on scanning electron microscopy (SEM). At least three selected samples were tested at each welding condition. Finally, the cyclic tests were performed at room temperature to a maximum strain of 5% before unloading to zero stress and repeated for 15 cycles. The residual strain was used to evaluate the functional fatigue properties of all the samples. The loading and unloading rates of the tensile load were both 1 mm / min.

3. Results And Discussions

3.1 Macro-morphology and Microstructure

The Macro-morphology of the laser-processed region of the single-sided welded sample and the double-sided welded sample was shown in Fig. 3. The FZ of the double-sided welded sample exhibited a bright metallic luster compared to the single-sided welded sample. Due to the small energy of each laser beam during double-sided welding, the interaction area between the laser pulse and the BM was small, and the width of the heat affect zone (HAZ) was significantly reduced.

The longitudinal section microstructure of the laser-processed region was shown in Fig. 4. It can be seen that the BM was elongated grains from Fig. 4(b) and Fig. 4(c), which was related to the cold-drawn process when it was manufactured. As shown in Fig. 4(d) and Fig. 4(g), Both welding processes achieved good weld penetration. Meanwhile, the low magnification OM analysis of these microstructures revealed that both single-sided welded sample and double-sided welded sample had the coarse-grained FZ typical of laser welded SMA wires [2,22-23]. The large reduction in grain boundary area, dislocations, precipitates and other structures that limit transformation induced plasticity make these coarse-grained structures less stable than the ideal nanocrystalline NiTi BM during thermomechanical cycling [24].

The distribution, morphology and size of the crystal grains are affected by the laser welding process parameters and play an important role in the mechanical properties of the alloys [25]. BM, HAZ and FZ can be easily distinguished and identified in the laser-processed region. As shown in Fig. 4(e), columnar grains were observed in the FZ of the single-sided welded sample, and some micro-pores were found, which were attributed to the excessively high laser beam energy. The FZ in the double-sided welded sample was revealed as dendrites and a few equiaxed crystals, as shown in Fig. 4(h). There were equiaxed grains in the FZ of the double-sided welded sample, which may be related to the heat treatment effect of the bottom laser beam. Fig. 4(f) and Fig. 4(i) represented representative high-magnification images of the HAZ and FZ boundaries of the single-sided and double-sided welded samples, respectively. Grain recrystallization occurred in the HAZ and no significant coarsening of the grains was observed in the double-sided welded samples. However, coarse equiaxed grains were formed in the single-sided

welded sample. Epitaxial solidification of dendritic or columnar grains can be observed along the HAZ-FZ boundary. In fact, micropores or coarse grains were not conducive to the improvement of mechanical properties.

3.2 Thermal transformation behavior

Figure 5 shows the DSC curves of the BM and the laser welded samples, which were used to characterize and analyze the thermal transformation behavior. DSC analysis of the laser welded samples suggested a modification of the original crystal structure. The coarse grain, low dislocation density and lack of Ni-rich precipitates would lead to single stage transformations in the weld [26]. It is worth noting that both the BM and the two welded samples showed a typical one-step phase change behavior from B19' to B2 during the heating and cooling process, without R-phase process. It is reported that oxygen pickup can lead to the formation of Ti_2Ni and Ti_2NiO_x phases in the FZ, which can induce the R-phase transformation [27].

The phase transformation temperature of the laser welded samples was significantly higher than that of the BM, as shown in Table. 2. At room temperature, the BM was the austenite phase, and the two welded samples were the martensite phase. The onset temperature for A_s of the single-sided welded sample and double-sided welded sample was in the range of $67.7^\circ C \pm 2.0^\circ C$ and $47.5^\circ C \pm 1.5^\circ C$, respectively. The low onset temperature of A_s meant that less heat is required for the sample to transform from martensite to austenite, which is beneficial to avoid overheating fatigue of NiTi SMAs in applications [28]. Grain size, residual stress and chemical composition all affect the phase transformation temperature. Laser welding was equivalent to the solution annealing treatment of the BM [29], which can change the grain size of the BM. The decrease of the grain size will promote the increase of the grain boundary area, resulting in an increase in the nucleation point of the martensite transformation, which was manifested by the increase of the martensite transformation temperature [30]. The precipitation of intermetallic phase and the change of microstructure in the FZ can produce lattice dislocations, which will lead to the increase of residual stress in the alloy after laser welding. Ni_4Ti_3 not only affected the local Ni concentration between the precipitates, but also imposed a local stress field around the precipitates [31-32]. Studies [33] have shown that changes in Ni content had a significant impact on the phase transformation temperature, and a 0.1% decrease in Ni content can cause the phase transformation temperature to rise by about 20 K. Oliveira [14] et al. and Lijima [34] et al. have obtained similar results.

Table 2
Transformation Temperatures of three samples.

Samples	M_s ($^\circ C$)	M_f ($^\circ C$)	A_s ($^\circ C$)	A_f ($^\circ C$)
Base material	15.4	-2.9	2.7	18.2
Single-sided laser welding	53.1	45.3	67.7	73.2
Double-sided laser welding	41.7	29.2	47.5	53.8

3.3 Mechanical performance

The mechanical performance of the BM and the laser welded samples were shown in Fig. 6. It can be observed that the tensile strength and elongation of welded samples were all lower than those of the BM despite the different process conditions. Laser heat input will reduce the Ni content, increase the martensite transformation temperature, and promote the transformation of austenite to martensite. Studies have shown that the strength of the martensite phase in NiTi SMA is lower than that of the austenite phase [35]. The tensile strength of the single-sided welded samples was 819 ± 24 MPa, and the elongation was $9.2 \pm 0.5\%$. The tensile strength and elongation of the double-sided welded samples were significantly improved, increasing by 24.5% and 14.1%, respectively. Heat treatment can reduce the thermal residual stress of the welded joints and improve the mechanical properties of the joint [24]. The bottom laser beam in the double-sided welding process had a similar effect to the heat treatment.

The stress-strain curve of the welded samples followed basically the same evolution path as the BM. Small deflections from the linear detwinning plateaus observed in the welded samples, as shown in Fig. 6 (b), were related to the detwinning of the martensite in the different regions of the material (BM, HAZ and FZ), which have different grain sizes, with respective differences in detwinning stresses [36]. The first yield stress of the BM was 480 MPa, which was the starting point of stress-induced martensitic transformation. The first yield stress of the welded samples was lower than that of the BM, this was due to the residual stress in the FZ caused by laser welding, and the microstructure was changed compared with the BM [24]. The Ni_4Ti_3 phase precipitated in the welded sample will also cause the softening and strength reduction of the welded sample [37]. Compared with the BM, the starting point of the stress platform of the welded samples was lagging, and the end point was earlier, resulting in a shortened total platform length. The laser heat input caused the grain structure to become uneven, resulting in dislocation, which was visible macroscopically as a reduction in the length of the stress plateau [6,26,38].

The fracture surface of the BM and the welded samples was shown in Fig. 7. It can be seen from Fig. 7 (a) that the fracture cross-section of the BM was relatively uniform, and no obvious starting point of fracture was found. Meanwhile, the entire fracture surface was full of dimples, showing a typical ductile fracture, as shown in Fig. 7(b) and Fig. 7(c).

It was observed from Fig. 7(d) that there was a rough annular region with a certain width in the cross section of the welded sample. The brittle fracture surface and silver-white intermetallic compound were observed under high magnification, as shown in Fig. 7(f). Surface scratches and grooves easily cause stress concentration during the tensile loading process and become the source of cracks [39]. It should be noted that some micro-pores were observed on the fracture surface, as shown in Fig. 7(e). The Marangoni effect in the molten pool promotes mixing, so more gas can be absorbed into the melt. Similar vapor retention was also observed in Ti6Al4V fiber laser beam welding [40] and Ti alloy pulsed Nd:YAG laser welding [22]. By using a double-sided welding process to reduce the energy of each laser beam, this kind of porosity can be avoided or reduced in the end, resulting in a better ductile fracture surface, as shown in Fig. 7 (g). It can be seen from Fig. 7(h) and Fig. 7(i) that well-formed dimples can be observed in the cross-section of the double-sided welded sample.

3.4 Cyclic tensile properties

The integration of NiTi SMAs wire into some functional devices requires the characterization of functional fatigue properties. The functional fatigue behavior of the welded samples and the BM was evaluated by checking the residual strain of the sample under 15 loading and unloading cycles at 5% prestrain. As shown in Fig. 8, the residual strain of the BM, the single-sided welded sample and the double-sided welded sample were 0.25%, 1.14%, and 0.73% after the first cycle and reached 0.46%, 1.27% and 0.92% after 15 cycles, respectively. The welded samples had lower superelasticity and higher residual strain than the BM for the previously discussed microstructural and phase transformation reasons. Laser heat input can destroy optimized cold worked and annealed NiTi material, increasing dislocations and grain size [40-42].

In the first cycle, the residual strain of the double-sided welded sample was significantly decreased than that of the single-sided welded sample, which was reduced by about 36.0%. Although the residual strain of the two welded samples continued to increase in the subsequent cycles, the residual strain of the double-sided welded sample was always smaller than that of the single-sided welded sample, as shown in Fig. 8(d). Refinement and reduction of Ni_4Ti_3 phase improved the stability of stress-induced martensite, and had a certain promotion effect on the reverse transformation of stress-induced martensite, which was manifested as a significant increase in superelasticity [43]. High-energy laser heat input can promote the transformation of austenite to martensite in the BM [44-45], which was revealed as a weakening of superelasticity in the cyclic tensile test. Compared with the single-sided welded samples, it can be determined that the double-sided welded samples had better fatigue functional properties. In addition, the residual strains of the single-sided welded sample and double-sided welded sample were different, which meant that they could be the actuators in the multiple-functional smart structure, supplying different kinetic displacement or strain according to the applied temperature.

4 Conclusions

This paper systematically studied the microstructure, phase transformation behavior, mechanical performance and cyclic tensile properties of the NiTi SMAs wires samples welded by double-sided welding and single-sided welding. The key conclusions were summarized as follows:

- (1) The double-sided welding can obtain well-formed NiTi SMAs wire samples compared with the single-sided welding. The HAZ of the single-sided welded samples were coarse equiaxed grains, while the double-sided welded samples were fine equiaxed grains. It is worth noting that the phase transformation temperature of the double-sided welded samples was significantly lower than that of the single-sided welded samples.
- (2) The double-sided welded samples showed better mechanical properties than the single-sided welded samples. This was because double-sided welding process input energy by two laser beams, which can avoid residual stress and pore defects caused by excessive laser energy in single-sided welding. Both welding samples were ductile fracture.

(3) The residual strains after the first and the 15th cycles of double-sided welding were 0.73% and 0.92%, respectively, which were significantly lower than that of the single-sided welded samples. It can be inferred that the double-sided welding process can effectively improve the functional fatigue properties of the welded samples.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Study conception and design: Fuguo Ge, Long Chen and Zhi Zeng; Material preparation: Fuguo Ge; Methodology: Zhi Zeng and Bei Peng; Data collection and analysis: Fuguo Ge and Fisssha Biruke Teshome; Writing—original draft preparation: Fuguo Ge; Writing—review and editing: Fuguo Ge, Long Chen, Fisssha Biruke Teshome and Zhi Zeng. All authors read and approved the final manuscript.

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Figures

Figure 1

Schematic diagram of laser welding.

Figure 2

Schematic illustration of different processes: (a) single-sided laser welding; (b) double-sided laser welding.

Figure 3

Macro-morphology: (a) single-sided welded sample; (b) double-sided welded sample.

Figure 4

Microstructure: (a) NiTi BM; (b) and (c) represented high magnification image of zone A and B, respectively; (d) single-sided welded samples; (e) and (f) represented high magnification image of zone C and D, respectively; (g) double-sided welded samples; (h) and (i) represented high magnification image of zone E and F, respectively.

Figure 5

Phase transformation curves: (a) Heating; (b) Cooling.

Figure 6

Stress-strain curves: (a) all the welded samples; (b) enlarged view of zone A.

Figure 7

SEM image of fracture interface: (a) NiTi BM; (b) high magnification image of zone A; (c) high magnification image of zone B; (d) single-sided welded sample; (e) high magnification image of zone C; (f) high magnification image of zone D; (g) double-sided welded sample; (h) high magnification image of zone E; (i) high magnification image of zone F.

Figure 8

Superelastic curves of cycles 1, 5, 10, and 15: (a) NiTi BM; (b) single-sided welded sample; (c) double-sided welded sample; (d) residual strains for 15 cycles of all samples.