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 essential 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 tensile strength and elongation of the double-sided welded samples were higher, and all the samples had a ductile fracture. The residual strains of the 1st to 15th cycle tests revealed that the double-sided welded samples exhibited significant improvements in functional fatigue properties compared to the residual strains of the single-sided welded samples. The improved performance of laser-welded NiTi SMAs obtained from this work could benefit these alloys for welding integration applications in smart system design and production.

Keywords Laser welding · NiTi shape memory alloys · Phase transformation behavior · Mechanical performance · Cyclic tensile properties

1 Introduction
In recent years, the development and application of new materials have 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 is regarded as a breakthrough when it comes to limitations related to joint geometry and maximum joint strength.

At present, the most commonly used welding technology are: tungsten gas shielded welding [6], laser welding [7–10], electron beam welding [11], resistance welding [12], ultrasonic welding [13], ultrasonic frequency pulsed arc [14, 15], brazing [16], and reactive diffusion welding [17]. 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 et al. [18] used a fiber laser to weld NiTi SMAs thin plates and studied the influence of welding process parameters on weld grain morphology. Gugel et al. [8] 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 et al. [19], Khan and Zhou [20], Tam et al. [21] 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 increasing the laser pulse width increased the martensite transformation start temperature of the FZ.

Despite the fact that many researchers have studied laser welding of NiTi SMAs, some difficulties encountered in the laser welding of NiTi SMAs are 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 [22, 23].

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 samples.

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 a 2-mm-long weld was produced on the single-side (as shown in Fig. 2a) and double-side (as shown in Fig. 2b) of the samples. 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. Several experiments were performed to optimize the welding parameters. The parameters used in the laser welding test are shown in Table 1.
All the welded samples were mounted in resin before being ground, polished, and etched. The etching solution was prepared from HF:HNO$_3$:H$_2$O using a mixing ratio of 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 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 from Fig. 4b, c that the BM was composed of elongated grains, which should be related to the cold-drawing process during its production. As shown in Fig. 4d, g, both welding processes resulted to a 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, which is typicality of laser-welded SMA wires [2, 24, 25]. 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 [26].

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 [27]. BM, HAZ, and FZ can be easily distinguished and identified in the laser-processed region. As shown in Fig. 4e, columnar grains were observed in the FZ of the single-sided welded sample, and some micro-pores were found, which should be 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. 4h. There were equiaxied grains in the FZ of the double-sided welded sample, which may be related to the heat treatment effect of the bottom laser beam. Figure 4f, i depicts 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. The results from the DSC analysis of the laser welded samples indicate that the original crystal structure was modified. The coarse grain, low dislocation density, and lack of Ni-rich precipitates would lead to single stage transformations in the weld [28]. It is worth noting that both the BM and the two welded samples...
samples showed a typical one-step phase change behavior from B19′ to B2 during the heating and cooling process, without any R-phase in between. It is reported that oxygen pickup can lead to the formation of Ti₂Ni and Ti₂NiOᵓ phases in the FZ, which can induce the R-phase transformation [29].

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 in the austenite phase, and the two welded samples were in the martensite phase. The onset temperature for austinite (Aₛ) of the single-sided welded sample and double-sided
welded sample was in the range of 67.7 °C ± 2.0 °C and 47.5 °C ± 1.5 °C, respectively. The low 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 [30]. 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 [31], 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 [32]. 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$_4$Ti$_3$ not only affected the local Ni concentration between the precipitates, but also imposed a local stress field around the precipitates [33, 34]. Some studies 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 [16, 35, 36].

### 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 that of the BM despite the different processing 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 [37]. The tensile strength of the single-sided welded samples was 819 ± 24 MPa, and the elongation was 9.2 ± 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 [26]. 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. 6b, 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 [38]. Due to the uniform cold-drawn elongated grains, there were no small deflections in the BM. 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 [26]. The Ni$_4$Ti$_3$ phase precipitated in the welded sample will also cause the softening and strength reduction of the welded sample [39]. Compared with the BM, the starting point of the stress plateau of the welded samples was lagging, and the end point was earlier, resulting in a shortened total plateau 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, 28, 40].

The fracture surface of the BM and the welded samples was shown in Fig. 7. It can be seen from Fig. 7a that

| Samples                        | $M_s$ (°C) | $M_f$ (°C) | $A_s$ (°C) | $A_f$ (°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       |

Table 2 Transformation temperatures of three samples
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. 7b, c.

It was observed from Fig. 7d 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. 7f. Researchers [17, 37] have found that such intermetallic compounds are typically Ti2Ni and Ni3Ti, which will degrade mechanical properties of joints. Surface scratches and grooves easily cause stress concentration during the tensile loading process and become the source of cracks [41]. It should be noted that some micro-pores were observed on the fracture surface, as shown in Fig. 7e. The Marangoni effect in the molten pool promotes mixing, thus, more gas could be absorbed into the melt. Similar vapor retention was also observed in Ti6Al4V fiber laser beam welding [42] and Ti alloy pulsed Nd:YAG laser welding [24]. This kind of porosity can be avoided or reduced by using a double-sided welding process to reduce the energy of each laser beam, resulting in a better ductile fracture behaviour, as shown in Fig. 7g. It can be seen from Fig. 7h, i that well-formed dimples can be observed in the cross section of the double-sided welded sample.

Fig. 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.
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 to 5% strain. As shown in Fig. 8, the residual strain of the BM, the single-sided welded sample, and the double-sided welded samples 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 [42–44].

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. 8d. Refinement and reduction of Ni4Ti3 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 [45]. High-energy laser heat input can promote the transformation of austenite to martensite in the BM [46, 47], 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

Fig. 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
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 means that they could be used as an actuator in the multiple-functional smart structure, supplying different kinetic displacements 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 the double-sided welding process inputs energy by two laser beams, which can avoid residual stress and pore defects caused by excessive laser energy in single-sided welding. Both welded samples showed a ductile fracture mode.

3. The residual strains after the 1st 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.

Author contribution Study conception and design: FG, LC, and ZZ; material preparation: FG; methodology: ZZ and BP; data collection and analysis: FG and FBT; writing—original draft preparation: FG; writing—review and editing: FG, LC, FBT, and ZZ. All authors read and approved the final manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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