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Investigation on the functionality of laser-welded NiTi to NiTiCu shape memory wires

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Abstract

NiTi shape memory wires are widely used in several markets, mainly for medical and aerospace applications, due to their excellent properties including superelasticity and shape memory effect. The combination of NiTi alloys with other alloys can provide high flexibility in the design of various smart structures. Nevertheless, the joining of NiTi alloys is really challenging because of the effect of thermal history on the functionality of welded joints. In fact, the temperature can change the microstructure and the balance of the material composition in the welding area, and, consequently, it leads to some alterations in the transformation temperature of the welded zone. The present study reports the effect of laser parameters, namely, laser power and scan speed, on the functionality of laser-welded NiTi to NiTiCu wires. The experimental findings allowed us to identify the best operational windows of the laser parameters, stating welding by high-power diode laser as an extremely promising technique in joining of dissimilar NiTi wires.

Keywords

Shape memory alloys, NiTi, laser welding, functionality

1. Introduction

In recent decades, the applications of NiTi shape memory alloys (SMAs) are widely spreading in various industries, such as aerospace, automotive, microelectromechanical systems (MEMS), and medical and biomedical fields. This is due to the superior thermo-mechanical properties of NiTi alloys compared to the other SMAs, including superelasticity and shape memory effect. In fact, these properties are the result of the reversible martensitic transformation between austenite (higher temperature) and martensite (lower temperature) phases (Mehrpouya et al., 2018a, 2019a).

Machining of NiTi alloys is poor and challenging due to high ductility and work hardening. Accordingly, laser welding is a good solution, as a reliable and precise approach, to overcome the obstacles in joining NiTi alloys. Nevertheless, it is necessary to get additional knowledge on the optimal operational parameters, which have a direct impact on the mechanical properties and transformation temperature of the NiTi welded products (Yang et al., 2014).

Laser dissimilar welding of NiTi alloys can provide an excellent opportunity to create a multi-functional smart component (Mehrpouya et al., 2019b). Accordingly, the welding process has great potential to make a new generation of smart structures such as smart sensors (Zamani et al., 2017). However, to improve the weldability of dissimilar materials, remarkable problems owing to different thermo-physical properties of the base materials (BMs) must be faced. There are various studies on dissimilar laser welding of NiTi alloy to the other materials. For example, Zeng et al. investigated the laser welding of NiTi–Cu joints and the fatigue life of the welded parts. They found a large irrecoverable strain during the cyclic test (Zeng et al., 2017). In another study, Vannod et al. (2011) investigated the laser welding process on NiTi to stainless steel alloy which can mainly be applied in the biomedical industry such as guidewires. They found the effect of the heating process on the chemical composition of the welded area that reduces the ultimate tensile

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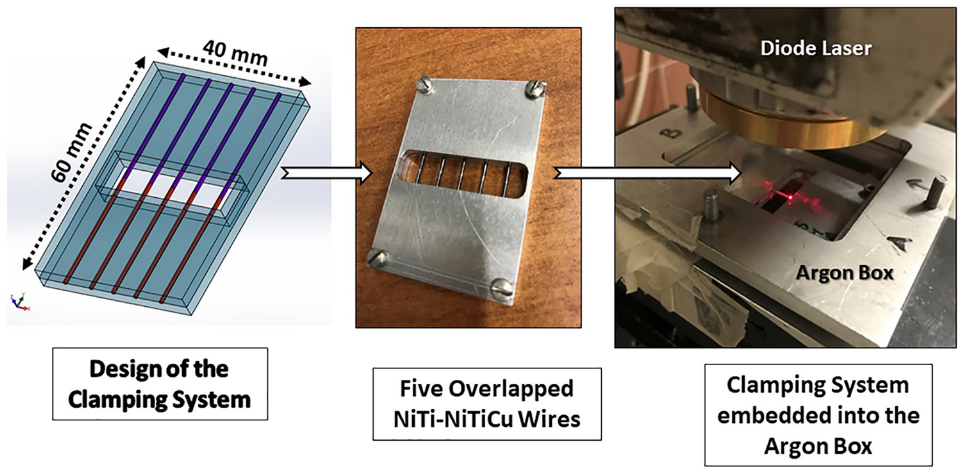

Figure 1. Clamping system and argon chamber.

strength. Using interlayer in dissimilar laser process of NiTi alloy can be really helpful. As Oliveira et al. discovered in their study, the laser welding of NiTi to Ti6Al4V can be improved using niobium interlayer (Oliveira et al., 2016b). They reported it can effectively prevent the formation of the undesired phases during the welding process, therefore improve the weld strength.

This article investigates the weldability of NiTi to NiTiCu wires. Cu-based SMAs are a particular group of smart alloys, which have a cheaper price with better thermal and electrical conductivities. So, it makes them a better option for usage in, for example, actuating systems (Oliveira et al., 2017; Zeng et al., 2015). In particular, this study evaluates the influence of welding operational parameters, namely, laser power and scan speed, on the functionality of the welded joints using the microstructural analysis, including optical microscopy (OM), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDXS) analysis, and differential scanning calorimetry (DSC).

2. Materials and methods

In this study, two dissimilar NiTi alloys, Ni52.3Ti wt%, and Ni49TiCu6 wt% alloys, were investigated with a diameter of 1.5 mm, and "austenite start" temperature (As) of + 95° C and + 75° C, respectively. A high-power diode laser (ROFIN-SINAR, Germany) with a maximum power of 1500 W and laser beam wavelength of 940 ± 10 nm was used to carry out the welding process. The beam shape was elliptic with an axis size of 1.2 mm in 3.8 mm, and the scanning pattern was oriented in the direction of the smaller axis.

Figure 1 represents the design and dimension of the clamping system, which was used for fixing five overlapped NiTi and NiTiCu wires. As can be seen, a

Table 1. The experimental plan.

Sample No.	Laser power (W)	Scan speed (mm/s)	Fluence (J/cm^2)
1	726	5	12.85
2	799	5.5	12.85
3	871.5	6	12.85
4	944.5	6.5	12.85

chamber with inert gas (Ar, up to 1-bar pressure) is designed to protect the surface of wires against oxidation during the welding process.

All welded samples were etched chemically for performing microstructural analysis using HF:HNO_3:H_2O solution with a ratio of 1:5:10. The microstructure of the welded samples was analyzed with an optical microscope (DMI5000M, Italy) and an SEM apparatus (HITACHI, S2500, Germany). Furthermore, the composition of the welded and heat-affected zones was studied by the EDXS apparatus (Thermo Fisher Scientific, UK). The transformation temperatures of the welded wires were measured by DSC (Netzsch Group, Germany). For this test, the range of temperatures was considered from −50° C to 220° C with a heating/cooling speed of 10° C/min. Table 1 illustrates the experimental plan including the applied laser parameters for this investigation.

3. Results and discussion

The laser welding of NiTi–NiTiCu wires was carried out for four sets of parameters based on the experimental plan. Except for sample 1, the other samples gave rise to uniform and homogeneous welded joints. Figure 2 shows the cross-section of sample 2 around the welding zone at low magnification. As visible, there are

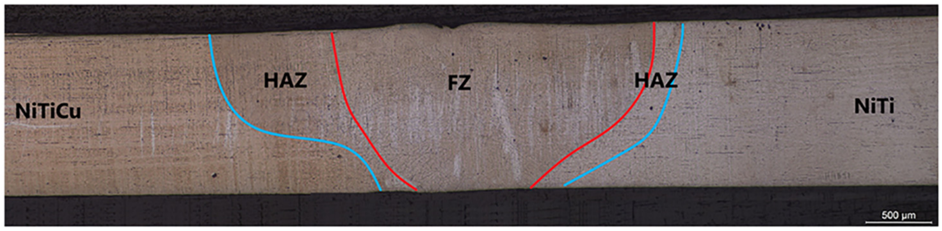

Figure 2. Cross-section of the laser-welded NiTi–NiTiCu wires (P = 799 W, V = 5.5 mm/s).

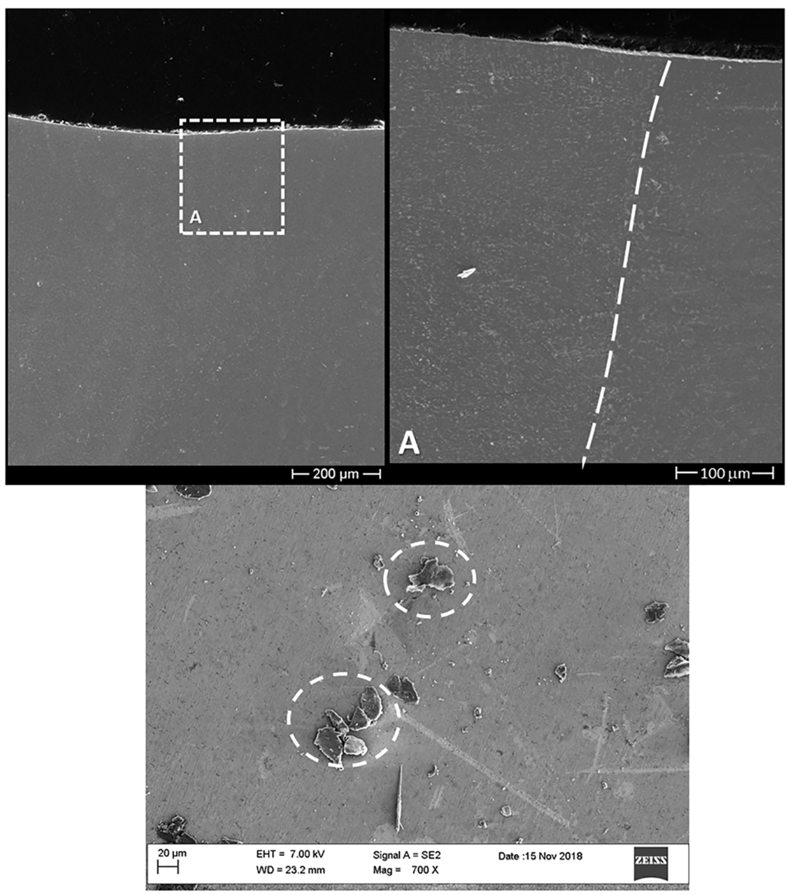

Figure 3. SEM scan of the laser-welded NiTi to NiTiCu wires focused on the melting zone (above); the participates in the FZ region (bottom).

no significant defects or cracks in the welded sample. FZ regions have a coarse grain compared to HAZ and BM regions, and this is ascribable to the higher temperature of the welding process particularly in the melting zone. As a matter of fact, the size of the grains is enlarged due to the effect of high temperature reached in the center of the welding zone (Mehrpouya et al., 2018b). Moreover, the HAZ region in the NiTiCu side is larger than the NiTi side and this is due to the higher thermal conductivity of NiTiCu alloy. According to the data from the manufacturing company, the thermal conductivity for NiTi and NiTiCu alloy is 18 and 120 W/cm.deg, respectively.

Figure 3 (above) provides a higher magnification view of the melting zone which was provided by SEM analysis. It shows that the grain boundary divides the welding zone into two FZ and HAZ regions. As mentioned before, the melting zone has coarser grains, and some second-phase particles are detected in this area. Also, Figure 3 (bottom) gives a better view of these additional phases which are inferred to be Ni_3Ti and $NiTi_2$ based on the binary phase diagram of the NiTi system (Zeng et al., 2015). Also, the temperature of the welding process can reduce Ni solubility in the welding area and generate the precipitation of Ni_4Ti_3 (Frenzel et al., 2010). Overall, these particles can significantly

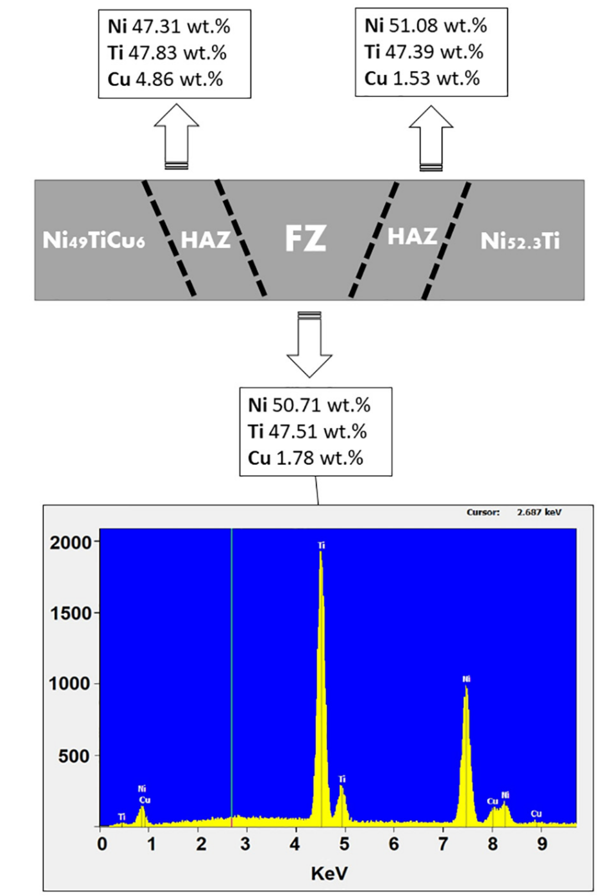

Figure 4. EDXS measurement for a laser-welded NiTi–NiTiCu sample (P = 799 W, V = 5.5 mm/s).

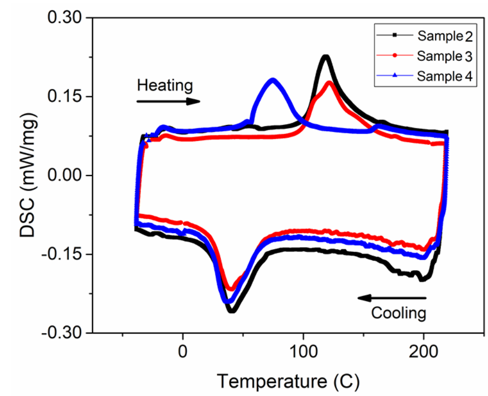

Figure 5. DSC diagram for the laser-welded NiTi to NiTiCu wires.

Table 2. Transformation temperature of NiTi–NiTiCu welded wires.

Samples	Cooling curve		Heating curve	
	M_f (°C)	M_s (°C)	A_s (°C)	A_f (°C)
Sample 2	21.25	69.86	102.83	139.59
Sample 3	21.62	70.90	98.46	144.77
Sample 4	23.32	67.56	54.45	102.61

alter the transformation temperature and consequently the functionality of the welding zone. Any changes in the microstructure of the welded parts can principally affect the welding strength. The mechanical properties of the welded NiTi–NiTiCu wires are investigated in a separate paper using tensile test and microhardness analysis (Mehrpouya et al., 2019b).

The EDXS analysis was employed to measure the amount of Ni, Ti, and Cu elements in HAZ and FZ regions. Figure 4 shows the material composition of welded NiTi to NiTiCu wires. According to the experimental results, the Cu element decreased from 6 wt% in the BM of NiTiCu wire to 4.86 wt% and 1.53 wt% in the HAZ of NiTiCu and NiTi wires, respectively. In addition, the Ni element reduced from 52.3 wt% to 51.08 wt% in the HAZ of the NiTi side. It also decreased from 49 wt% to 43.31 wt% in the HAZ of the NiTiCu side. This can be ascribed to the effect of the high temperature of the laser welding process in these areas, which vaporized the Ni element during the process (Mehrpouya et al., 2018b).

Thermal analysis was performed to estimate the transformation temperature in the HAZ and FZ sections of the welded wires based on various operational parameters. Generally, both martensite and austenite phases can be found in the welding area (in HAZ and FZ regions). The martensite appears at room temperature, while external stress can generate an irrecoverable strain in the material. Nevertheless, this deformation can be recovered in higher temperatures in the austenite phase (Oliveira et al., 2016a; Otsuka and Ren, 2005).

Figure 5 reports the results of the DSC tests on laser-welded NiTi–NiTiCu wires. The DSC curves show the phase transformation from the martensite phase (lower temperature) to the austenite phase (higher temperature) during the heating process and reversely from austenite to martensite in the cooling process (Mehrpouya et al., 2019c-d). The austenite phase includes austenite start (A_S) and austenite finish (A_f) in the heating curve, and the martensite phase includes martensite finish (M_f) and martensite start (M_S) in the cooling curve.

As shown, the achieved curves are very close to each other, particularly in the cooling process (from austenite to martensite). Table 2 summarizes all captured temperatures in the FZ region of the welded NiTi–NiTiCu samples. Although there is no significant variation in martensite temperatures, the temperature of austenite start reduces from 102.83° C for sample 2 to 98.46° C for sample 3. Then, it decreases to 54.45° C for sample 4 as well. As a result, sample 3 matches better the BM, which is $+95°$ C for NiTi wire and $+75°$ C for NiTiCu wire.

4. Conclusion

This study investigates laser welding of dissimilar NiTi–NiTiCu shape memory wires to achieve an optimal and high-quality weld. Laser operational parameters, namely, laser welding and scan speed, were investigated using an experimental approach. In particular, optimal laser parameters were obtained, focusing them to preserve both microstructure and transformation temperatures of the welded samples and, consequently, the functionality of the final product. In particular, the following pointwise considerations can be made:

- Except sample 1, the other welded samples boasted a good quality and homogeneous welded joint. Based on the microstructural analysis, the FZ region had coarse grains compared to the other sections, being this attributable to a higher temperature in the center of the welding area. The SEM analysis allowed the second-phase precipitates in the welding zone to be identified, which were inferred to be Ni_3Ti and $NiTi_2$.
- The composition of the welded zone is close to the reference materials, as found by EDXS. Therefore, there is no significant variation in the austenite and martensite temperatures and the functionality of the welded sections can be preserved better.
- Transformation temperatures of all welded wires were measured by thermal analysis for the different scenarios. Sample 3 showed characteristic temperatures closer to the reference materials.

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Supplemental material

Supplemental material for this article is available online.

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