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Laser welding of NiTi shape memory sheets using a diode laser

Mehrshad Mehrpouya [a,*], Annamaria Gisario [a], Andrea Brotzu [b], Stefano Natali [b]

[a] Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Via Eudossiana, 18, 00184 Rome, Italy
[b] Dipartimento ICMA, Sapienza Università di Roma, Via Eudossiana 18, 00184 Roma, Italy

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ABSTRACT

NiTi shape memory alloy (SMA) are widely applied in many industrial domains, such as biomedical, aerospace, automotive and power plants, due to its outstanding functionality including superelasticity (SE) and shape memory effect (SME). The machining process of this material is challenging with a lot of barriers. Accordingly, joining techniques can be an alternative approach to design the shape memory components with more flexibility. Among all methods, laser welding process is a reliable and economical technique for joining of NiTi alloys. However, thermal process influences strongly on the strength and functionality of the NiTi welded joints in the Heat Affected Zone (HAZ) and the Fusion Zone (FZ). Indeed, the transformation temperature of NiTi alloy can be altered due to varying in the material composition. Therefore, controlling of the operational parameters, including laser power, scan speed or focal distance lead to an effective improvement in the mechanical and the functional behavior of NiTi joints. It consequently enhances the weldability of this material. This current study investigates the laser welding of NiTi thin sheets with a High-Power Diode Laser (HPDL) and reports microstructural, functionality, and mechanical effects of the process in following.

1. Introduction

Shape memory alloys (SMAs) attract much attention in the last decade because of their unique properties including superelasticity (SE) and shape memory effect (SME). This type of smart materials can recover their original shape by a transformation mechanism, which resulted of a solid–solid phase transformation between martensite and austenite phases that can be actuated by stress, temperature or presence of a magnetic field [1–3]. Many companies have endeavored to take advantage of the SE phenomenon with fully recovery deformation in numerous medical applications such as sensors and actuators. The potential of SME is still discovering, and so far, applied in aerospace, automotive, MEMS (Microelectromechanical systems), and power plants industries [4–6].

Nowadays above 90% of all commercial shape memory applications utilize NiTi and its alloys due to their superior SME and SE characteristics [7]. Their high performance, outstanding fatigue, and corrosion resistance cause to be used in MEMS applications [8]. They are also commercially used in biomedical devices, such as stents, orthodontic wires, and in minimally invasive surgical devices due to their appropriate compatibility [9,10]. However, the machinability of NiTi alloys is so poor due to the high rate of work hardening and ductility [11–13]. Therefore, joining techniques can enhance the possibility of making the complex shape of NiTi components. But it is still challenging, since having an appropriate welded joint is not limited to the joint strength. Indeed, thermal process can strongly affect the microstructure and chemical composition of NiTi joint, and it causes to alter its transformation temperature including martensite and austenite temperatures [14,15].

Among various joining methods, laser welding (LW) is a fast and economical approach for joining of NiTi SMAs in different forms like wires, sheets, and tubes [16,17]. The main advantage of LW process is the tendency of obtaining narrow welds, high penetration, and processing speed due to its intrinsic features such as low heat input and high energy density [18,19]. Accordingly, it causes to make a finer microstructure with a lower thermal stress and strain from the welding cycle [20]. Nevertheless, the laser parameters including laser power, scan speed, focus size and shape, shielding gas and its flow rate significantly influence the efficiency of the welded components. So, controlling of laser parameters leads to the increase of producibility, and it is worth to be investigated [21–24]. On the other hand, operating parameters have a direct influence on the size of heat affected zone (HAZ) and fusion zone (FZ), which considerably effect on shape memory response and superelasticity [25,26].

* Corresponding author at: Department of ICMA, Sapienza University of Rome, Via Eudossiana, 18, 00184 Rome, Italy.
E-mail address: mehrshad.mehrpouya@uniroma1.it (M. Mehrpouya).

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Nomenclature

SMA	Shape Memory Alloy	CW	Continuous Wave
SE	Superelasticity (Pseudoelasticity)	DSC	Differential Scanning Calorimetry
SME	Shape Memory Effect	SEM	Scanning Electron Microscope
HDPL	High-Power Diode Laser	EDS	Energy Dispersive X-ray Spectroscopy
BM	Base Material	M_s	Martensite Start
HAZ	Heat Affected Zone	M_f	Martensite Finish
FZ	Fusion Zone	A_s	Austenite Start
WZ	Welded Zone	A_f	Austenite Finish
MEMS	Microelectromechanical systems	R_s	Rhombohedral Start
LW	Laser Welded		

Only a few studies have investigated the laser welding of similar NiTi sheets. Some prestigious research works have been described in the following. Tuissi et al. used a Nd:YAG laser for welding Ni49.6Ti sheets with 0.54 mm thickness. They investigated SE and SME characteristics of the two different microstructural states of the NiTi alloys. The annealing process strongly affected SE and improved the recovery mechanisms in the Welded Zone (WZ) [27]. With the same approach, Khan et al. reported that higher peak power and lower pulse frequency could improve the mechanical performance of NiTi joints [28]. Vieira et al. applied a Nd:YAG laser operating in continuous-wave (CW) mode for the laser welding of Ni50.8Ti sheets. The SE effect during cycle loading showed superior functional behavior with a recoverable strain level more than 6% [29]. Gong et al. studied the laser welding of Ni50.6Ti sheets with 0.2 mm thickness by using an impulse laser. They achieved a good butt welding with 97% tensile strength of the cold rolled BM and the same ductile fracture mode as well as the BM [30]. Oliveira et al. also investigated the SME with various laser powers from 790 to1485 W to study the functional effect of NiTi alloys on the FZ and HAZ. They found that the material in the WZ could fully recover to its original shape. The base material at room temperature had an austenitic structure while both martensite and austenite phases existed in the FZ and HAZ regions. They reported that it had no effect on the SME recovery [31].

Most studies on laser welding of NiTi alloys mainly made use of Nd:YAG lasers. Chan et al. applied a fiber laser for welding NiTi foil with a thickness of 0.25 mm since they found that fiber laser has a smaller beam size and higher power intensity compared to a normal Nd:YAG laser. The welding took place with a full expectable penetration of welds with an appropriate mechanical property [32]. They also applied Post-weld heat treatment (PWHT) to enhance the microstructural and functional properties of NiTi in the WZ [33,34]. Various Ni-rich precipitates, like *Ni4Ti3 Ni3Ti2*, and *Ni3Ti*, might appear in FZ and HAZ after the thermal process that restricts a full recovery of SE and SME [35–37]. In fact, *Ni4Ti3* is the most usual metastable, which usually appear in lower temperature and shorter aging time [38].

The present work investigates the laser welding process of NiTi sheets with shape memory effect. In fact, the effect of various laser parameters, including laser power and scan speed, on weldability of NiTi sheet is studied. Microscopy analysis (including micrographs, SEM/EDS), transformation temperature, and hardness measurement are reported as well.

2. Experimental study

2.1. Material and equipment

In this study, Ni 54.76 wt.% Ti shape memory sheets (Memry GmbH, Germany) were chosen with a dimension of 15 × 20 mm and thickness of 0.50 (±0.05) mm. The chemical composition of the NiTi sheets is listed in Table 1. All samples are annealed by a heat treatment process for obtaining an oxide-free surface and improve the mechanical and microstructural properties of the material.

High-Power Diode Laser (HPDL) source (ROFIN-SINAR, DL 015, Hamburg, Germany) was employed for the laser welding process with a maximum power of 1.5 KW, continuous mode, and a beam wavelength of 940 nm ± 10 nm. In this process, the laser spot had an elliptical shape with 1.2 mm × 3.8 mm axes sizes, which the direction of the laser scanning pattern was along the small axis. Fig. 1(A) shows a schematic of a designed clamping system for fixing the two NiTi sheets rigidly. As shown in Fig. 1(B), the fixture system was designed to be enclosed in a box under argon during the laser processing to prevent oxidation of the NiTi sheets. Since using Argon gas can reduce the dimension of the FZ and HAZ regions due to the generated temperature of the thermal process [39,40]. A comprehensive picture of the experimental equipment is shown in Fig. 2 including the diode laser, the fixture system, Argon input and shield, and the positioned NiTi sheets.

A cutting machine with a diamond blade was employed with a low cutting rate to provide a cross-section cut of NiTi welded specimens for the metallography process. The cross-section sample polished on Silicon carbide paper (SiC, P2400, 200 mm) and one-micron alumina in distilled water. In order to study the microstructure of welded zone and remove the surface oxide, the polished surface chemically etched with an acid liquid in an HF: HNO3: H2O solution with a dilution of 1:5:10.

Also, the etched surfaces observed with both of an optical microscope (DMI5000M, Leica, Italy) and with a Scanning Electron Microscope (SEM, S2500, Hitachi, Germany). An elemental study was performed using energy dispersive X-ray spectroscopy (EDS) (NORAN System Six, Thermo Fisher Scientific, UK) to assess nickel and titanium concentration in the FZ and HAZ regions. Furthermore, the micro-hardness measurement was performed using Vickers Harness-tester (Leitz, model Dialux 22-RZD-DO) and with a load of 981 mN.

Table 1
The chemical composition.

Ni (wt.%)	Ti (wt.%)	Cr (wt.%)	Cu (wt.%)	Fe (wt.%)	Nb (wt.%)	Co (wt.%)	C (ppm)	O (ppm)	H (ppm)
%54.76	balance	<0.01	<0.01	0.011	<0.01	<0.01	260	272	7