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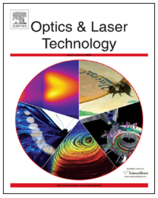

Laser welding of NiTi shape memory alloy: Comparison of the similar and dissimilar joints to AISI 304 stainless steel

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ABSTRACT

The unique properties of NiTi alloy, such as its shape memory effect, super-elasticity and biocompatibility, make it ideal material for various applications such as aerospace, micro-electronics and medical device. In order to meet the requirement of increasing applications, great attention has been given to joining of this material to itself and to other materials during past few years. Laser welding has been known as a suitable joining technique for NiTi shape memory alloy. Hence, in this work, a comparative study on laser welding of NiTi wire to itself and to AISI 304 austenitic stainless steel wire has been made. Microstructures, mechanical properties and fracture morphologies of the laser joints were investigated using optical microscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction analysis (XRD), Vickers microhardness ($HV_{0.2}$) and tensile testing techniques. The results showed that the NiTi–NiTi laser joint reached about 63% of the ultimate tensile strength of the as-received NiTi wire (i.e. 835 MPa) with rupture strain of about 16%. This joint also enabled the possibility to benefit from the pseudo-elastic properties of the NiTi component. However, tensile strength and ductility decreased significantly after dissimilar laser welding of NiTi to stainless steel due to the formation of brittle intermetallic compounds in the weld zone during laser welding. Therefore, a suitable modification process is required for improvement of the joint properties of the dissimilar welded wires.

1. Introduction

Owing to unique properties like super-elasticity, shape memory effect and biocompatibility, nickel titanium (NiTi) alloy is one of the most popular and new smart materials used in many fields such as aviation and space-flight, ocean development, mechanic-electronic and medical devices [1–3]. However, successful applications of any novel material not only hinge on its intrinsic characteristics, but also depends on problem solving and development of processing technologies. As a result, the usage of this material may be limited to specific conditions unless joining of this material to itself and to other materials is facilitated. The possibility of joining this material would expand its applicability to many new circumstances. However, joining of NiTi has been considered as a difficult task because of its high sensitivity to the thermo-mechanical treatment and the deteriorations of super-elasticity and shape memory effect in the weld zone as compared with the base metal due to metallurgical changes. Falvo et al. [4] reported a marked reduction in mechanical and shape memory performance of the NiTi welded joint. Same results were presented by Chan et al. [5] in a later study that showed the onset of transformation temperatures of the weld shifted to the very negative side as compared with the as-received NiTi and also a reduction in pseudo-elastic property in the NiTi welded foil. In recent years, great attention has been given to the influence of the joining method and procedure on microstructure and properties of similar NiTi alloys joints, but joining of NiTi to other materials has not sufficiently been considered [4–7]. Stainless steels (SSs) are one of the dominant materials which are widely used in different applications especially in medical devices owing to their mechanical properties, workability, low cost and corrosion resistance [8]. Therefore, joining of NiTi to stainless steel would be desirable for widening of its applications. It should be noted that, making dissimilar joints between these materials is a rather difficult procedure due to the large differences in their physical and chemical properties. It was shown that the brittle intermetallic phases such as $TiFe_2$ made the resulting weld equally brittle [9]. Li et al. [10,11] showed that laser welding using Ni interlayer and Co filler metal could greatly improve the mechanical performance of TiNi–SS fusion welds. Recently, the particular behavior of cracks, which nucleate and propagate in dissimilar welds, was observed in

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NiTi–SS laser welded sub-millimetric wire couples and analyzed by SEM in-situ tensile testing [12]. This study revealed the fact that tremendous property changes at the interface between the NiTi base wire and the weld area had more impact on the ultimate tensile strength than the chemical composition variation across the welded area. Nevertheless, further research efforts are required to develop sound dissimilar NiTi–SS joints with acceptable mechanical properties.

For the past years, several processes aimed at joining NiTi alloy both to itself and to other alloys have been considered. Friction welding [13,14], tungsten inert gas (TIG) welding [15], plasma welding [16], brazing [12,17] and laser welding [18–23] are some examples. Among these various welding techniques, laser welding is the most important joining technique for this class of materials. In particular, the Nd:YAG source seems suitable for joining of smaller devices with complicated shapes due to the low and precise heat input, low energy density, small fusion and heat-affected zones, low residual stress, low weld distortion and high welding speed.

This work describes laser welding of NiTi to AISI 304 SS wire with 0.36 mm diameter in a butt weld configuration. Nd:YAG source is used for this purpose. A comparison of microstructures, mechanical properties and fracture morphologies of similar (NiTi–NiTi) and dissimilar (NiTi–SS) laser welded joints are also evaluated in the paper.

2. Experimental procedures

2.1. Materials and samples preparation

NiTi wires (containing B2 phase at room temperature) and AISI 304 SS wires (containing γ-Fe and a few α-Fe phases) with 0.36 mm in diameter were used for joining experiments. Chemical compositions and some physical properties of the wires are listed in Table 1. All wires were immersed in a dilute hydrofluoric and nitric acids solution for 25 s to remove oxide layers and surface contaminants prior to the welding procedure. The samples were then ultrasonically cleaned in acetone bath for 10 min, followed by 5 min of cleaning in distilled water. SEM micrographs of the wires before and after this treatment are shown in Fig. 1.

2.2. Laser welding

The NiTi–NiTi and NiTi–SS assemblies were held in two wire contact position using the fixture constructed for this purpose, as shown in Fig. 2(a). Fig. 2(b) also shows the schematic diagram of laser welded NiTi–NiTi and NiTi–SS wires. Welding was performed using the Nd:YAG laser system (PIM-3475 model IQL-20) that produces a laser beam with a wavelength of 1064 nm. The optimum parameters for successfully joining two similar and dissimilar wires in this experiment were (a) maximum peak power: 1000 W, (b) pulse energy: 3 J, (c) laser pulse duration: 3 ms, (d) welding time: 5 s, (e) frequency: 3 Hz, (f) number of pulses: 15 and (g) laser spot diameter: 0.8 mm. During welding, argon purge at a rate of 26 l/min (before welding: 10 s and after welding: 4 s) was used to prevent penetration of N_2, O_2 and H_2 into the weld zone which could harm properties of the joint.

2.3. Microstructural characterization

Metallographic specimens were prepared by first cold mounting by epoxy. The samples were then ground from 600 to 1200 grit using sand papers followed by a two-step polish using 0.3 μm alumina powder and colloidal silica. The NiTi side of welded specimens was then etched with a mixed acid solution $HF:HNO_3:CH_3COOH$ (1:5:5) and the stainless steel side was etched in a reagent $HCl:HNO_3$ (3:1) for 25–30 s to reveal the microstructure. Microstructural examinations and fracture morphologies of the joints were characterized using optical microscopy and scanning electron microscopy (SEM, PHILIPS XL30) equipped with the energy dispersive spectroscopy (EDS) system. Phase identifications of the weld zones were done by X-ray diffraction (XRD, PHILIPS X Pert-MPD) with Cu Kα radiation and 40 kV and 30 mA operating conditions. Weld spots were made on 10 parallel wire to obtain a weld zone of reasonable size (0.5 cm^2) for XRD analysis.

Table 1
Chemical compositions (wt%), melting and boiling temperatures of NiTi and stainless steel.

Material	Fe	Cr	Ni	Ti	Mn	Co	C, Si, P, S	Melting temp. (°C)	Boiling temp. (°C)
NiTi	–	–	55.0	45.0	–	–	–	1310	2760
304 Stainless steel	69.5	18.5	9.0	–	1.0	0.75	Bal. (< 1% each)	1316–1538	~3000

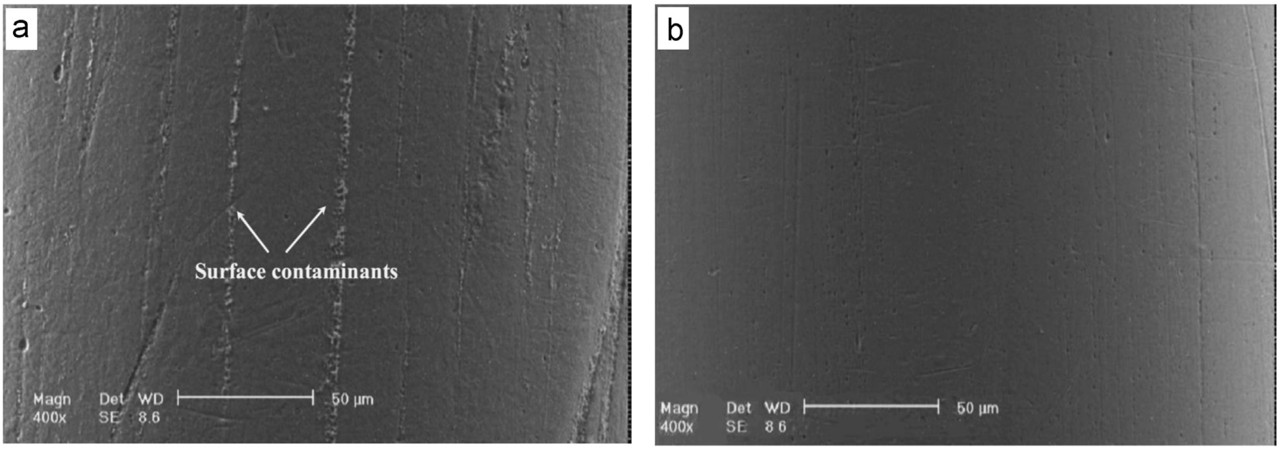

Fig. 1. SEM micrographs of prior-weld wires: (a) before and (b) after preparation treatment.