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Review Article

Laser welding of NiTi shape memory alloy: A review

Mehrshad Mehrpouya[a,*], Annamaria Gisario[a], Mohammad Elahinia[b]

[a] Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Via Eudossiana, 18, 00184 Rome, Italy
[b] Department of Mechanical Industrial and Manufacturing Engineering, University of Toledo, 2801 W. Bancroft St. MS 312, North Engineering 2045, Toledo, OH 43606, USA

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ABSTRACT

NiTi shape memory alloys (SMA) are broadly employed in multifunctional systems in several industrial domains, like aerospace, automotive, biomedical and power plants. Their functional properties, which include shape memory effect (SME) and superelasticity (SE), offer a particular flexibility to design many smart components. However, scientists and practitioners are still facing some restrictions in machining processes and joining techniques of NiTi SMAs to both similar and dissimilar materials. Compared to other procedures, laser welding is an economical and reliable joining technique for NiTi SMAs. Nevertheless, it is considered a challenging technique, with many obstacles still to overcome to achieve welded joints characterized by the necessary strength and the required functionalities. In this respect, the present work investigates the effects of laser welding process on the functional properties of NiTi and related alloys. Mechanical, microstructural, and metallurgical effects of the process are reported, as well. Lastly, the impact of the post-weld heat treatment (PWHT) is studied as an effective solution to improve the downsides of the laser welding process.

Contents

* Corresponding author.
E-mail address: mehrshad.mehrpouya@uniroma1.it (M. Mehrpouya).

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1. Introduction

Shape memory alloys (SMAs) are a particular type of material, which show unique properties including shape memory effect (SME) and superelasticity (SE). These transformation mechanisms are the result of a solid-solid phase transformation between martensite and austenite phases, which can be actuated by stress, temperature or presence of a magnetic field [1–3]. In the beginning, the industrial applications of these materials were limited, but they then grew significantly as the functional properties of this class of smart alloys were discovered. Many companies endeavored to take advantage of the SE by generating specific tools with fully recovery deformation for use in human physiology [4,5]. The recent achievements in the basic understanding and manufacturing processes of SMAs are applied in various industries such as medical, automotive, aerospace, and energy applications [6–9].

NiTi alloys are widely utilized in the commercial market compared to the other types of SMAs, due to their superior SME and SE characteristics [10–12]. Nowadays more than 90% of all commercial shape memory applications use NiTi and its alloys like NiTi-Cu and NiTi-Nb [13,14]. NiTi shape memory materials can be employed in multiscale systems and devices ranging from nano-electro-mechanical devices to large-scale system. They are applied in various fields such as aerospace, biomedical, mechanical components. The advantage of using NiTi alloy is its large deformation (up to 8%) which applied in various smart sensor and actuators [15–17]. Shape memory alloys have recently been applied to the field of microelectromechanical systems (MEMS) due to their high performance, excellent resistance to fatigue and corrosion resistance [17–19]. Moreover, their great biocompatibility makes them an ideal choice to be commercially used in biomedical devices, such as stents, orthodontic wires, and in minimally invasive surgical devices [20,21]. The low stiffness of NiTi alloy makes it an ideal material to be applied in bone implant applications [22–24]. Lately, additive manufacturing process (AM) has been studied to make NiTi components by adding successive layers as a rapid manufacturing method for intricate designs [25–28].

Commercialization of SMA products requires applying different joining processes, such as welding, soldering, and brazing [29–31]. Many low-cost and novel products can be manufactured by developing a joining process of SMAs. For instance, a complex actuator including two SMAs with various transformation temperatures has been presented in other works [32]. However, the joining of SMAs is very challenging, since its successful implementation is not only restricted to the joint strength but also the welding process changes the microstructure and chemical composition of SMAs in the joint region and consequently has a considerable effect on the shape memory response and superelasticity [33]. Therefore, the joining of SMAs is fundamentally different when using conventional alloys such as aluminum, steel, and titanium alloys and necessitates special attention in the welding process and the operating parameters [34].

Laser welding process (LW) is a reliable and economical method for the joining of NiTi SMAs in various forms like sheets, wires or tubes among available manufacturing methods [35–37]. Many studies have investigated the laser welding of NiTi alloys to produce smart components with attractive properties. A combination of SME and SE properties can provide a particular functionality which can be applied in a smart application like a sensor-less actuator [32]. Laser welding is an ideal process for joining of NiTi SMAs with a less thermal affected area to produce a combined multi-functional structure. Since the application of laser welding process can provide the required flexibility for the design of SMAs devices, which is less expensive due to using less material by similar or dissimilar joining process [9,38].

Most studies have focused on preserving the mechanical and functional properties of SMAs after the welding process [39,40]. Ni-rich NiTi is investigated more compared to the other SMAs because it typically demonstrates SE properties at room temperature. The achieved joints have up to 80% efficiency with a proper ductility, and the drawbacks usually occur in generating the heat affected zone (HAZ) or fusion zone (FZ), where softening may occur in both of them. This softening is attributed to precipitate dissolution, dislocation destruction, and grain coarsening [20,41]. Ti-rich NiTi joints usually have a reduction in the ultimate tensile strength (UTS) and the elongation. In fact, such reduction arises from the formation of brittle Ti_2Ni alloys, since functional and biocompatibility properties are enormously sensitive to the composition of the alloy and the thermomechanical treatment, which takes place during the laser welding process [1,9].

Due to poor machinability of NiTi alloys [42,43], the optimum parameters and suitable techniques should be developed to improve the functional and mechanical behavior of alloys particularly for complex components and devices, since it is affected by thermal effects during the welding process [44,45]. The present study is focused on challenges and recent findings on NiTi laser welding including mechanical and microstructural evaluations, principal metallurgical effects, and post-weld heat treatment processes (PWHT).

2. Characteristic features of SMAs

SMAs are famous due to their engineering behaviors including SME and SE phenomena [46,47]. In particular, SME occurs as a plastic strain due to the recoverable deformation mechanism of detwinning, which can activate the reverse martensitic transformation by a thermal treatment, or a mechanical load [48,49]. This phenomenon happens at the temperature under austenite start (A_s) and recovers above austenite finish (A_f) due to reversible transformation [50,51].

Fig. 1 shows a typical stress-strain curve of SMAs (dashed line). At a constant temperature, the mechanical loading and unloading (OBC) perform, while the residual deformation (OC) appears as well. By increasing the temperature, the residual strain recovers to the original shape (CDO) from martensite to austenite [30,52]. The SE phenomenon is a large deformation ability which occurs upon unloading at a temperature above A_f as shown in Fig. 1 (DEFGD). SE occurs through a hysteresis loop due to stress-induced martensitic transformation and by reverse transformation. In fact, this crystallographic reversibility is based on the thermoelastic martensite transformation, which is characterized by mobile austenite-martensite interfaces and a small temperature hysteresis [53,54].

2.1. Thermomechanical behaviors

The controlling of phase transformation has a key role in the design of shape memory components in order to perform a par-