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Impact butt welding of NiTi and stainless steel- An examination of impact speed effect

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ABSTRACT

Decreasing the impact speed can extend the effective heating time and escalate the heating rate. Additional flash is generated near the NiTi/SS interface due to the lengthening of the effective heating time. With decreasing impact speed, the plastic deformation zone of the SS is enlarged, and the microstructure in the heat-affected zone (HAZ) is increasingly coarsened, but those of NiTi demonstrate the opposite trends. In all of the NiTi/SS joints, the weld consists of a diffusion layer with a thickness that increases slightly from 1 μm to 1.7 μm as the impact speed decreases from 40 mm/s to 27.5 mm/s. The mechanical properties of the joint deteriorate with decreasing impact speed due to the increased remnant of semi-molten NiTi at the interface. The joint welded at an impact speed of 40 mm/s has the highest strength of 522 ± 41MPa with (7 ± 2)% rupture elongation, and it fractures via micro-void coalescence.

1. Introduction

The practical applications of NiTi shape memory alloys (SMA) usually involve joining and welding (Oliveira et al., 2017a,b) and (Mehrpouya et al., 2018). To date, high-quality joints of NiTi alloys have been obtained via friction welding (Shinoda et al., 1991), with the strengths approaching that of the base metal. The dissimilar joining between NiTi and materials like Ti6Al4V (Simões et al., 2013; Oliveira et al., 2016), CuAlMn (Oliveira et al., 2017a, b), Ti3SiC2 ceramics (Kothalkar et al., 2015) and aluminum alloys (Hahnlen et al., 2012) has recently drawn increasing attention.

Joining NiTi to SS has practical value in the biomedical realm. In fact, NiTi and SS are both widely-used implant materials to fabricate devices such as artificial bones and joints (Elahinia et al., 2012), guidewires (Wang et al., 2015), and stents (Kim et al., 2017, Navarro et al., 2017). Currently, most of these devices are solely fabricated using either NiTi or SS, and the unitary structure places several limitations on their functions. For example, SS orthodontic archwires fail to show satisfactory teeth-straightening performance because their elastic moduli are too high. NiTi guidewires are too flexible to handle. Joining NiTi to SS offers us an opportunity to improve such situation since hybrid properties can be achieved.

Fusion-welding methods have been intensively studied in terms of joining this pair of materials. In the investigations on plasma welding of NiTi and SS by Eijk et al. (2003) and Vondrous et al. (2012), cracks formed in the weld due to both the brittle nature of the weld and the appreciable difference in the thermal expansion coefficients of the two metals. A study of laser welding of NiTi to SS conducted by Li et al. (2010) also demonstrated certain unsatisfactory results. In fact, gas pores and micro-cracks were incorporated in the laser welds. According to XRD and TEM characterizations, numerous intermetallic metal compounds (IMCs) were produced in the laser welds and were primarily responsible for the inferior tensile strength of 289 MPa.

The harmful IMCs in NiTi/SS fusion welds were predominantly Fe_2Ti and Ni_3Ti. According to the thermodynamic calculations by He and Lui (2006), the formation of Fe_2Ti and Ni_3Ti is thermodynamically favored in a fusion pool containing Fe, Ni and Ti elements. NiTi/SS fusion welds were composed of three distinct microstructures, i.e.γ-(Fe, Ni)/Fe2Ti eutectic located next to the SS base metal, Fe2Ti/(Fe, Ni)Ti/Ni3Ti eutectic located in the central weld and Ni3Ti/(Fe, Ni)Ti eutectic located next to the NiTi base metal (Burdet et al., 2013; Li et al., 2017). Severe material embrittlement arose near the NiTi fusion line because of the grain coarsening and the existence of the Ni3Ti/(Fe, Ni)Ti eutectic produced in liquated grain boundaries. In addition, tremendous change of elastic modulus was observed near the NiTi fusion line, which caused significant stress concentration under tensile loading (Vannod et al., 2011). As a result, most of the fusion-welded NiTi/SS joints fractured near the NiTi fusion line, accompanied with low strengths and rupture elongations. There are two avenues open to the researchers to improve such situation, i.e. introducing filler metals in fusion welding to inhibit the formation of IMCs, or applying welding methods involving little fusion of the base metals.

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Li et al. (2012) reported that the tensile strength of a laser-welded NiTi/SS joint increased to 372 MPa with 4.4% rupture elongation when Ni was appropriately added as a filler material. The reason for this observation was that Ni served as a barrier between the base metals and thus prevented IMCs from forming. However, brittle Ni3Ti existed due to Ni addition and caused deterioration of the joint. Other filler metals, including Co (Li et al., 2013a), Cu (Li et al., 2013b) and Ta (Ng et al., 2015), have also been tested in laser welding of this material system. The findings in these studies were similar. In other words, the joint strength can be maximized only with moderate addition. Indeed, these studies attained an optimized joint strength of 520 MPa with 5.1% elongation (Li et al., 2013b). In the laser brazing described by Qiu et al. (2006) and Li et al. (2007a,b), the formation of IMCs was effectively suppressed since the welds were produced through the eutectic reactions of brazing fillers without the melting of the base metals. Unfortunately, due to the low-strength nature of the brazing fillers, joint improvement was limited, with tensile strengths of only 320–360 MPa. In friction welding of NiTi and SS (Fukumoto et al., 2010), welds with tens of micrometers in thickness were created without the use of filler metals, and IMCs were appreciably suppressed. Unfortunately, the joint quality of these welds remained inferior, with the tensile strengths below 200 MPa. Presumably, this reduced quality was observed because the applied welding parameters were not appropriate, and specifically, the welding time might have been lengthy.

A summary of the mechanical properties of NiTi/SS joints obtained by diverse methods is listed in Table 1. Although reasonable tensile strength and rupture elongation has been achieved via resistance welding, new efforts are still needed. In this work, impact butt welding (IBW), another solid-state method, is applied to the joining of NiTi and SS. During IBW, matter near the interface can be squeezed out once it is heated to a certain temperature. This approach diminishes the propensity for IMC formation. The current investigation also elucidates the effect of impact speed on joint properties. Plastic deformation, interfacial diffusion, and microstructures in the heat-affected zones (HAZs) of the prepared joints are examined to rationalize the impact speed effect.

2. Materials and methods

The NiTi and AISI304 SS wires used in this work, all of which measured 0.33 mm in diameter, were purchased from Fort Wayne Metals. Their chemical compositions are listed in Table 2. The as-received NiTi wires were subjected to cold drawing with 56% area reduction followed by annealing. The as-received SS wires were subjected to 93% area-reduction cold drawing followed by stress-relieving annealing. Prior to IBW, the wire tips were sanded with #800 abrasive paper, ultrasonically cleaned in an acetone bath for 5 min, and dried at atmospheric conditions.

As shown in Fig. 1, NiTi and SS wires were fixed with a copper clamp, which was connected to a charged capacitor. The NiTi-side clamp was movable, but the SS side was stationary. At the start, the NiTi-side clamp, which was driven by a step motor, moved towards the SS-side clampat a given speed (i.e., impact speed). Once the two wires touched, the capacitor began to discharge, thereby generating heat. Subsequently, the plastic deformation of the wires was activated, and bonding developed through interfacial diffusion. During the welding process, the NiTi-side clamp kept moving until it was stopped by its counterpart, and argon gas was blown in to create a shielding atmosphere.

The optimized charging voltage of the capacitor and the extension lengths (see Fig. 1 for definitions) of the wires were determined by experimentation to be 6.3 V and 0.3 mm, respectively. The duration of the capacitor discharge was estimated as approximately 15 ms by applying the equation $\tau = RC$, where C denotes the capacitance of the capacitor and R denotes the electrical resistance of the whole circuit. The welding experiments were divided into three groups according to the impact speed applied, i.e., 27.5 mm/s, 35 mm/s, and 40 mm/s (the highest speed that can be achieved by the apparatus). For example, the joint welded at an impact speed of 27.5 mm/s was referred to as ‘the 27.5 mm/s joint.’

Conventional techniques were used to prepare the metallurgic specimens. To reveal the microstructures, NiTi was etched with a mixture of 10% HF, 40% HNO_3 and 50% H_2O, and SS was etched with a mixture of HCl and HNO_3 at a volume ratio of 3:1. The microstructures were visualized with a Zeiss LAB1 microscope and a scanning electron microscope (SEM, FEI Quanta 450 FEG). The chemical compositions were analyzed using energy-dispersive spectroscopy (EDS). Static tensile tests were performed using an MTS810 material testing system for which the crosshead displacement and the sample gauge length were set to 0.3 mm/min and 50 mm, respectively. The flash of the joint was removed via sanding prior to the tensile test. The tensile strength of the joint was calculated using the diameter at the interface (which was the location near which the joint consistently fractured) and was determined as the average of five specimens per condition. Finally, an SEM was used to examine the fracture morphology.

3. Results

3.1. Plastic deformation

The macro-morphologies and longitudinal sections of the IBWed NiTi/SS joints are shown in Fig. 2. For the joint welded at an impact speed of 40 mm/s, as shown in Fig. 2a and d, remarkable plastic deformation can be observed on both the NiTi and SS sides, yielding a trumpet-like morphology, and minimal flash, i.e., the matter squeezed out from the mating face, was produced. For the 35 mm/s joint, as shown in Fig. 2b and e, the NiTi slightly expanded its section area, whereas the SS significantly expanded its section area. For the 27.5 mm/s joint, the NiTi was minimally deformed (Fig. 2c and f).

Several parameters related to the joint deformation are listed in Table 3. As shown in this table, a decrease in the impact speed resulted in a narrowing of the NiTi deformation zone, a widening of the SS deformation zone, a decrease in the deformation degree (which is represented by the maximum radial expansion), and an increase in the volume of the flash. Furthermore, on the SS side, the location where the maximum radial expansion occurred transferred from the interface to the inner region when the impact speed was decreased, which can be attributed to the enhanced radial constraint imposed by the NiTi. After

Table 1
NiTi/SS joint strength achieved by various welding methods.

Welding method	Tensile strength (MPa)	Rupture strain (%)	Reference(s)
Capacitor discharge welding	150	1.6	Li et al. (2005)
Laser brazing	281–360	8–14%	Li et al. (2006); Qiu et al. (2006); Li et al. (2007a,b)
Friction welding	50–512	–	Fukumoto et al. (2010)
Laser welding	134–620	0.6–5	Gugel et al. (2008); Li et al. (2010, 2012, 2013a,b); Brandal et al. (2013); Mirshekari (2013); Ng et al. (2015);
Transient liquid phase diffusion bonding	239 (shear strength)	–	Li (2011)
Resistance welding	830	6	Li et al. (2017)