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Short communication

# Microstructure, mechanical properties and shape memory behaviour of friction stir welded nitinol

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ABSTRACT

For the first time, NiTi shape memory alloy was successfully joined by Friction Stir Welding (FSW). The weld showed significant grain refinement without formation of detrimental phases. The yield strength of the weld joint increased by 17% as compared to the base metal without substantial change in shape memory behaviour.

## 1. Introduction

Nickel-Titanium alloys are smart materials which are widely employed as sensors, actuators and also structural elements owing to their distinctive properties such as shape memory effect, superelasticity and biocompatibility. The highest work density and large deformation recovery have made them attractive for applications in aerospace, automotive, robotics and biomedical fields [1,2]. To extend the application of these alloys, it needs to be fabricated into more complex structures. As the formability of NiTi alloys is quite low, welding of these alloys is pivotal to improve the freedom of design. In this regard, investigations for welding these alloys have been carried out using several fusion welding techniques. The fusion welding of NiTi alloys imposes several challenges, as the shape memory behaviour is highly sensitive to microstructural and chemical changes. During fusion welding of NiTi, the defects such as voids, micro cracks, gas porosity and embrittlement have been reported [3–6]. These macroscopic defects tend to reduce the weld strength and fatigue life of the joint. The fusion welding process also leads to the formation of undesirable intermetallics, the transformation of austenitic to martensitic phase and vice versa [7,8]. These changes in the weld will significantly alter the shape memory transformational temperatures. If the difference in transformational temperatures of the weld and the base metal is large, the welded SMA structures cannot be actuated at the same temperature and also makes the actuation control difficult. The composition of the filler material if not correctly matched with the base metal will exponentially increase these issues. In order to overcome these challenges, a process which can successfully weld NiTi alloys with good mechanical and shape memory properties is required.

FSW is a solid-state welding process, where a rotating tool with a probe is plunged and traversed along the abutting edges of the plates [9,10]. The stirring-traverse motion of the tool plasticizes the material and welds the workpieces together. Unlike the fusion welding, filler metal is not required; hence the composition compatibility is not an issue. The NiTi plates have been processed by friction stir processing, a derivative of FSW. The processed NiTi has shown good mechanical properties with retention of shape memory behaviour [11,12].

Although many studies have been reported on fusion welding of SMA, to the best of authors' knowledge, there are no studies on welding of SMA using FSW. We present here, the process of successful joining NiTi SMA using FSW. A detailed experimental study was carried out to understand the mechanical and shape memory behaviour of the friction stir weld joint.

## 2. Experimental

The rolled NiTi sheets of 1.2 mm thickness, with equiatomic nominal composition were used for welding. The NiTi sheets were austenitic at room temperature. The sheets of dimension 50 mm×70 mm were welded in butt configuration along the rolling

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**Table 1**
Shows the process parameters used for welding.

| Tool material | Tool geometry (mm) | Tool rotation (rpm) | Dwell time (s) | Traverse Speed (mm/min) | Plunge depth (mm) | Tool tilt (degrees) |
|---|---|---|---|---|---|---|
| Densimet (W alloy) | Shoulder ø −22<br>Pin ø−5, length−0.9 | 1000 | 30 | 50 | 1.05 | 2 |

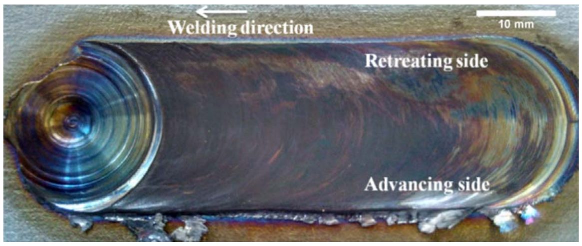


**Fig. 1.** The top surface of the weld accomplished at 1000 rpm and 50 mm/min.

direction. The welding was carried out on a five-axis FSW machine (*BiSS-ITW, Bangalore*). Initially, trial experiments were performed to optimise FSW parameters. Based on the trials, the process parameters mentioned in Table 1 were selected for welding. The weld joint was characterised for microstructure, phases, mechanical and shape memory behaviours to analyse the effect of FSW on the NiTi alloy. The samples for metallography and hardness were cut in a direction perpendicular to the weld direction. The metallographic and hardness samples were mechanically polished and etched (14 mL $HNO_3$ +4 mL HF +82 mL $H_2O$). The micro-hardness was measured on the cross section of the weld. The tensile samples were cut in the transverse direction of the weld with a cross section of 1 mm×2 mm.

## 3. Results and discussion

The top surface of NiTi weld is shown in the Fig. 1. It shows a surface without any defects such as cracks, lack of fill etc.

The optical and Scanning Electron Microscopy (SEM) images are shown in Fig. 2. The Base Metal (BM) (Fig. 2a and c) consisted of equiaxed coarse grains with clearly visible twins. For the present weld, the nugget, Thermo-Mechanically Affected Zone (TMAZ) and heat affected zone were not distinguishable. Hence, the nugget zone was taken as equivalent in width to pin diameter [13]. The weld nugget consisted of recrystallised fine grains. Also, only a few deformation twins were observed unlike the BM. The recrystallization in FSW is a known phenomenon in many alloy systems. The recrystallization in NiTi weld nugget is attributed to dynamic recrystallization during FSW [14,15]. During hot compression tests of NiTi alloy, Shu-yong Jiang et al. have observed dynamic recrystallization for all strain rates for temperatures above 700 °C [16]. The recrystallization temperature range of hot compression test is in the same range of operating temperature of FSW, which is between 0.75 and 0.8 times the melting point of the material [17]. Generally, the region next to the weld nugget experiences lower strain and high temperatures which results in the formation of TMAZ with deformed grains instead of recrystallised grains [9]. In the present weld, the absence of TMAZ could be the result of two co-acting properties of the material, primarily, the cubic austenitic B2 phase has less than 5 slip systems [18] to accommodate global plastic deformation and secondly at lower strain rates and high temperature dynamic recrystallization occurs in NiTi [16,19].

The micro-hardness profile recorded across the weld is shown in the Fig. 3a. The hardness in the weld zone was reduced slightly. The mean hardness of the BM and the weld were 277 HV and 262 HV respectively. The tensile behaviour of the weld at room temperature is depicted in the Fig. 3b. The yield strength and tensile strength of the

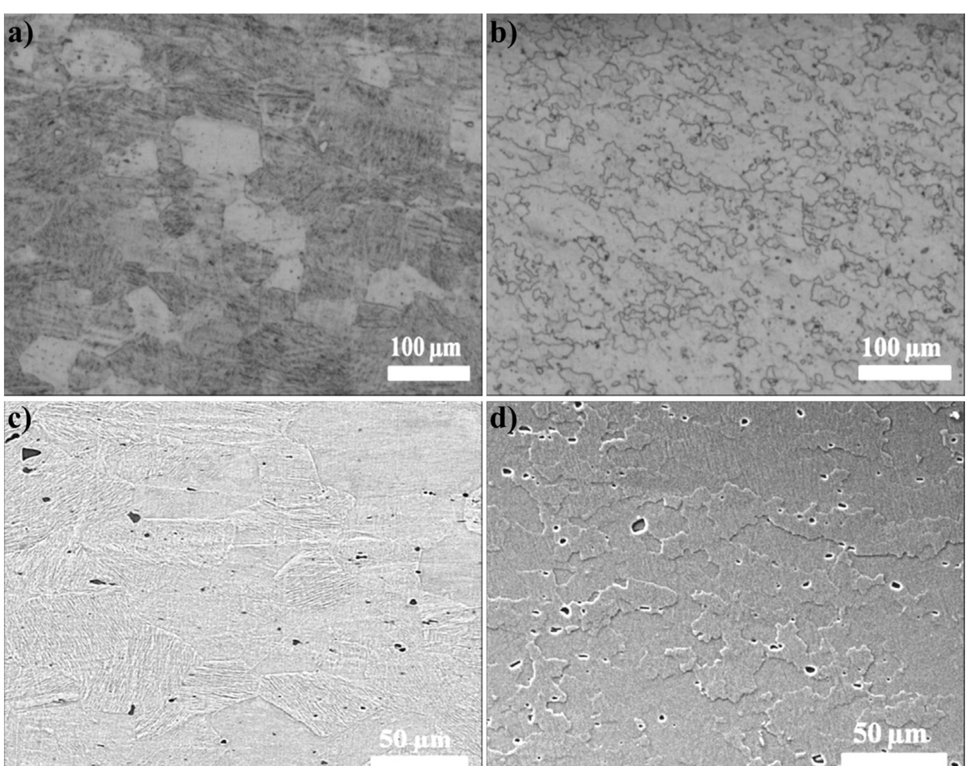


**Fig. 2.** Optical images of the a) BM, b) weld; SEM images of the c) BM and d) weld.