An Overview on Dissimilar Metals Joining Techniques for Nitinol Shape Memory Alloy to Titanium Alloy Ti-6Al-4V

Ateekh Ur Rehman and Yusuf S Usmani
Department of Industrial Engineering, College of Engineering, King Saud University, Riyadh-11421, Saudi Arabia
arehman@ksu.edu.sa, yusmani@ksu.edua.sa

N. Kishore Babu and M.K. Talari
Department of Metallurgical and Materials Engineering, National Institute of Technology, Warangal-8 506004, India
kishorebabu@nitw.ac.in, talari@nitw.ac.in

Hisham Al-khalifa
Advanced Manufacturing Institute, King Saud University, Riyadh-11421, Saudi Arabia. Email: halkhalefah@ksu.edu.sa

Abstract

Different industries have increased interest to utilize shape memory alloy, nitinol, due to its abilities like morphing, superelasticity, high corrosion resistance, and biocompatibility. On the other hand, Ti-6Al-4V has high tensile strength and toughness, high corrosion resistance, good biocompatibility, and low specific weight. For these reasons, Ti-6Al-4V gets a lot of attention from industries like aircraft and medical engineering. Joints of these two widely different alloys should then offer unique advantages for highly specialized applications. However, problems related to the joining of dissimilar metals like nitinol to Ti-6Al-4V have restricted the widespread use of these alloys. Differences in metallurgical properties and coefficient of thermal expansion, as well as the tendency to form brittle intermetallic phases during welding, lead to cracks in the welds. This mismatch related to the thermal and mechanical properties between dissimilar metals results in the weakening of the overall quality of the joint between these two metals. Therefore, knowledge on joining nitinol to Ti-6Al-4V should be expanded in relation to dissimilar metal joints to overcome these problems, and future solutions can be found. In this study, the shape memory effect and superelastic properties of nitinol are discussed, and how these might get affected during the welding of nitinol to Ti-6Al-4V are presented. An attempt is made to friction weld Nitinol to Ti-6Al-4V using friction welding technique. Both metals start to form flash indicating a positive response to the friction welding cycle and a narrow strip of intermixed zone seen to have formed at the weld interface.

Keywords
Shape memory alloy, Nitinol, Titanium alloy, Ti-6Al-4V, and Dissimilar metal joints.

1. Introduction

Joining involving NiTi is associated with challenges because NiTi is very sensitive to any kind of thermo-mechanical treatments. The welding process can alter the shape memory and superelastic properties of the parent metal near and adjacent to the weld zone. For this reason, the welding of NiTi is considered to be fundamentally different from conventional alloys welding. In conventional alloys welding, it is not very much necessary that the chemical composition and microstructure of the welds match the base metal. However, the mismatch between the two regions basically affects the joint behavior in case of NiTi (Calkins and Mabe 2010).

Fusion welding of NiTi alloys causes embrittlement from oxygen, hydrogen, and nitrogen. Over and above this, precipitation of brittle intermetallic compounds such as Ti2Ni and TiNi3 may result during the solidification of weld zone (Shinoda et al. 1992a). Plasma welding of NiTi to NiTi not only altered the transformation temperatures but also caused deterioration of mechanical properties of the joint (Li et al. 2006a). The same work also concluded that fusion welding of NiTi to dissimilar materials is extremely difficult because of the formation of brittle phases. Although laser welding looks promising with its highly powerful beam creating a lesser volume of molten metal, it also gave rise to cracks when NiTi was welded to dissimilar alloy Inconel 625. These results convey that a welding process that involves extensive melting of parent metals would inherently produce brittle phases or cracks due to residual stresses. Friction welding, which is a solid-state joining technique, showed promising results in an initial study (Shinoda et al. 1992b). It was claimed that after heat treatment, NiTi friction joints reclaimed the base metal properties of shape memory and strength. NiTi was joined to stainless steel using Ni interlayer with the same joining technique, and the joint strength was appreciably high (Fukumoto et al. 2010). However, studies on how to join NiTi to Ti-6Al-4V are limited. Diffusion bonding between these alloys utilizing Ni/Ti interlayers of thin films resulted in sound joints (Simões et al. 2013). This mismatch related to the thermal and mechanical properties between dissimilar metals results in weakening the joint's overall quality between these two metals.

The objective of this study is to lead to insights in welding of NiTi in a dissimilar configuration by solid state welding route. Therefore, knowledge on joining nitinol to Ti-6Al-4V should be expanded in relation to dissimilar metal joints to overcome these problems, and future solutions can be found. In this paper, the shape memory effect and super elastic properties of nitinol are discussed and how these might get affected during the welding of nitinol to Ti-6Al-4V are presented.

2. Brief Review

Certain classes of materials that demonstrate the Shape Memory Effect (SME) are referred to as Shape Memory Alloys (SMA). An SMA is cooled below a specific critical temperature and deformed by applying some stress. After this, just by subjecting this deformed SMA to above critical temperature, its original shape can be reverted. This looks as though the alloy has memorized its prior shape; hence the name (Kim et al. 2008). Although there are many materials that come under SMA classification, the most important among them are Ni-Ti, Cu-Al, and Fe-Mn alloys (Calkins and Mabe 2010). And even among these, Ni-Ti alloys occupy the most prominent place and have found wide-ranging applications.

One of the first alloys of Ni-Ti, called nitinol, was developed by W. J. Buhler and R. Wiley in 1961. NiTi denotes a family of alloys having near Ni-Ti composition, atomic percentage-wise (Goldstein 1978). In addition to SME, NiTi behaves in a non-linear superelastic fashion in a certain temperature range (Liu et al. 2008). This is popularly referred to as superelastic or pseudoelastic property. When a material has SE property, it can undergo large deformations in the presence of stress, and on its release, the material regains its original length. Interesting here is the large straining happens at constant stress.

3. Shape Memory Alloy

Shape memory alloy their applications and approaches adopted for joining of NiTi with dissimilar metals are presented here in the following subsections respectively.

3.1 Applications

Shape memory alloy (NiTi) finds many applications in the Biomedical field (Pelton et al. 2008 and Henderson et al. 2011). Stents of NiTi have been used in angioplasty. Such stents are shape set and then compressed before sending through the catheter. The stent, after reaching the blockage in the artery, expands and dilates the lumen (Morgan 2004). The property utilized in such applications is the SE property of NiTi. NiTi can recover up to 8-10% strain inside a suitable temperature range (Huan et al. 2012). While this is so, the SME of NiTi Staples can benefit in fastening bones (Chan and Man 2011). The excellent bio-compatible property of NiTi is attributed to the passive film TiO2 (Huang 1998).

NiTi can be used as an actuator in deployable structures for space applications. NiTi structures can be folded first, and when in orbit, they can self-deploy if heated to a particular temperature. Solar arrays, antennas etc., are some of the structures which can be deployed in this manner (Dong et al. 2008). Likewise, NiTi can be deployed as springs to effect change in aerofoil shapes in a different aerospace application. This way the aerofoil can adapt to other flying conditions on the go (Sharabash and Andrawes 2009). Vibration dampeners are sought in cable-stayed bridges to avoid damages during earthquakes. Twisted SMA wire bundles can be used as dampeners by connecting the deck with the piers and towers in those kinds of bridges (Dieng et al. 2013 and Van Humbeeck 1999). NiTi can also be used as a wear-resistant material or within the electrical field as a smart electrical resistor (Predki et al. 2008). NiTi is offered as a solution for problems in bearing technology (Gugel et al. 2008a).

3.2 Shape Memory Alloy: Dissimilar metals joining

In the medical field, some parts or implants are built by combining NiTi to stainless steel. For this, mostly crimping and clamping are utilized (Gugel et al. 2008b). Welding is strongly desired in such cases. For example, an implant called a Medical occluder can be realized by joining NiTi wires to stainless steel pipe (LÜ et al. 2013). Future aerospace components like adaptive serrated nozzles could become a reality only when a suitable technique for welding NiTi to Ti-6Al-4V is developed (Chau et al. 2006).

Plasma welding was attempted to join NiTi to stainless steel and Hastelloy (van der Eijk et al. 2003). Elements from Hastelloy were seen diffused into the weld pool, forming a mixed zone. Brittle phases is thus formed mixed zone severely reduced the strength as well as ductility of the joint. Microcracks were seen in the weld zone. The wide gap in thermal expansion coefficients between the parent materials was the reason behind the microcracks. Brittle intermetallics such as Ti carbides could only have magnified the problem. Brazing by utilizing laser power was investigated to join NiTi to stainless steel (Li et al. 2006b). A silver-based filler metal was used. Due to high laser power settings and brazing times, appreciable grain coarsening happened in both parent materials' heat affected zones. This had an adverse effect on shape memory and superelastic properties of NiTi. This phenomenon of loss in shape memory and superelasticity occurred microscopically because the B19' structure within the heat affected zone partly transformed into B2 structure (Li et al. 2006b). Therefore, it cannot be over-emphasized how important it is to work within a proper window of process parameters in order to achieve a satisfactory joint.

Laser welding was comparatively more successful in producing defect-free NiTi - austenitic steel joints (Gugel et al. 2008b). Nevertheless, the microstructure was heterogeneous with intermetallic compounds, as the microhardness in NiTi base material closer to fusion boundary was in the range 900 HV. The rupture strength (about 623 MPa) was still higher than the plateau stress. A decent 3% plateau strain was observed. Under cyclic loading, the joints showed somewhat similar behavior to parent NiTi. In related studies that involved stainless steel, Ni3Ti and (Fe, NiTi) were intermetallic compounds found in the intermixed zone (LÜ et al. 2013). The joints did not demonstrate any plateau behavior in the stress-strain curve and failed in a brittle fashion.

To avoid the formation of brittle intermetallics, AgCu foil was inserted between NiTi and stainless steel in diffusion bonding (Wang et al. 2009). The bond shear strength increased with temperature and holding time. The improvement peaked at 239 MPa, and after that, it started dipping. The joints sheared at the NiTi-AgCu interface. Hardness was found to be high in fusion zones adjacent to the base material; but in the center, the hardness fell drastically. The interlayer could not prevent intermixing between the base materials elements completely as phases involving elements from the opposite base material were seen in the fusion zone.

The same technique of interlayers - this time, incorporating Ni interlayer between the base materials - was repeated in friction welding (Fukumoto et al. 2010). It was proposed that since friction welding is a solid-state welding process, the chances of the formation of brittle compounds at the interface could be sufficiently undercut by deploying an interlayer. As expected, the interlayer proved beneficial, and the joint strength increased by more than two times to 512 MPa compared to the joints, which were direct. Nevertheless, the interface between NiTi-interlayer interface was not without compounds; the joint failed at that particular location. Process conditions, especially friction time and spindle speed, played an important role in how the reaction compounds come into being.

A pulsed variety of laser was used to lap weld NiTi to stainless steel (Pouquet et al. 2012). It was discovered that the weld bead shape was directly influenced by which metal was placed on top; in other words, metal interacts with the laser. Due to its physical and interaction properties with laser, stainless steel was better off at the top. Such a strategic placement also ensured that Ni-rich zones react with Ti rather than Fe and Ti. But, surprisingly, when Ni interlayers were used to extend the above argument, the welds were not satisfactory. The interlayers played havoc more by slowing down the heat conduction to the bottom-most material.

Because direct joining leads to brittle compounds formation such as TiFe2 and TiCr2, Co interlayer was inserted while joining NiTi to stainless steel by laser welding (Li et al. 2013). It was argued that Co has good solubility with various alloying elements of stainless steel and Ti. On top of it, the linear coefficient of expansion of Co lies in between the parent materials. Only the right amount of Co filler metal helped reduce the amount of brittle compounds, thereby increasing mechanical properties to a certain extent. Beyond a specific limit of concentration, Co also started to form brittle Co-Ti compounds.

In probably one of its first studies, diffusion bonding of NiTi to Ti-6Al-4V was tried (Simões et al. 2013). Multiple interlayers of Ni and Ti were used, but in a novel form, as nano thick coatings on the base materials. The nanometric nature of these interlayers aids in the reaction of these interlayers, thus raising local temperatures as well as stopping the intermixing of parent materials. Although no mechanical property evaluation was carried out, extensive characterization techniques revealed a thin intermixed zone of about 10 microns self-containing finer bands of phases made of (Ti, Ni, Al). About joining of NiTi (Calkins and Mabe 2010), it is suggested that the surface area of NiTi wires can be improved by gas nitriding. With this, TiN dendrites that grow would help in increasing adhesive bonding strength.

4. Experimental Work and Results

An attempt has been made to friction weld Nitinol to Ti-6Al-4V using the rotary friction welding technique. After several attempts, a successful joint was realized between these two highly dissimilar alloys, refer to Figure 1. The friction welding parameters used for this joint are as presented in Table 1. It has to be noted that these parameters are not the ‘best’ parameters as the rods were not tested against any mechanical property. Nevertheless, the welded joints from these parameters were consistently strong in drop test.

Table 1. Welding parameters

Parameters	Set value
Friction Pressure	50 MPa
Upset Pressure	100 MPa
Spindle Speed	1500 rev/min
Burn-off length	4 mm
Upset time	4 sec

Figure 1 A successfully strong joint resulted between Ti-6Al-4V and Nitinol using the friction welding technique.

It could be seen from Figure 1 that the two parent alloys have deformed differently during the weld cycle. Ti-6Al-4V formed in to thinner but wider flash, whereas Nitinol formed in to a smaller circle, but was seen to flow backwards more. This behavior is indicative of the physical properties of the alloys at higher temperatures during the cycle. During friction welding, because of the frictional heat at the interface, the parent alloys enter in to a plastic stage. However, this holds true mainly for similar alloys. In case of dissimilar alloys, the flow properties of the metal at such high temperatures as well as the conductivity of the metals, play a big role on how the flash forms. In the present case, fortunately, both the parent metals have deformed which is advantageous, in the sense that impurities in the interface has a more chance of getting expelled. Also, this indicates that heat generated is sufficiently high.

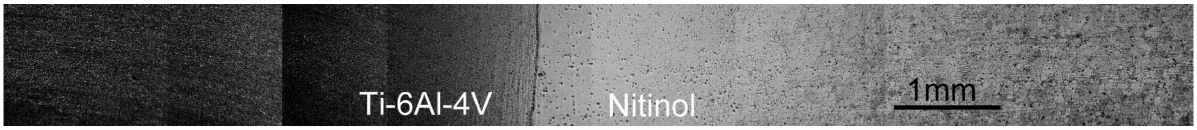

Figure 2 Optical micrograph revealing the different textures of metal flow in the parent metals.

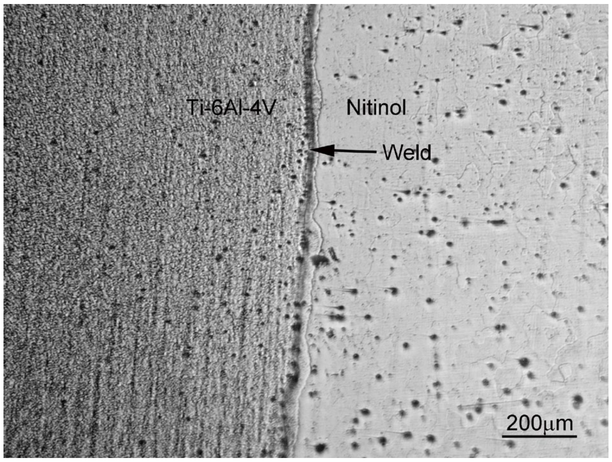

Figure 3 Higher magnification image (optical microscopy) revealing a narrow but clearly present intermixed zone at the weld interface.

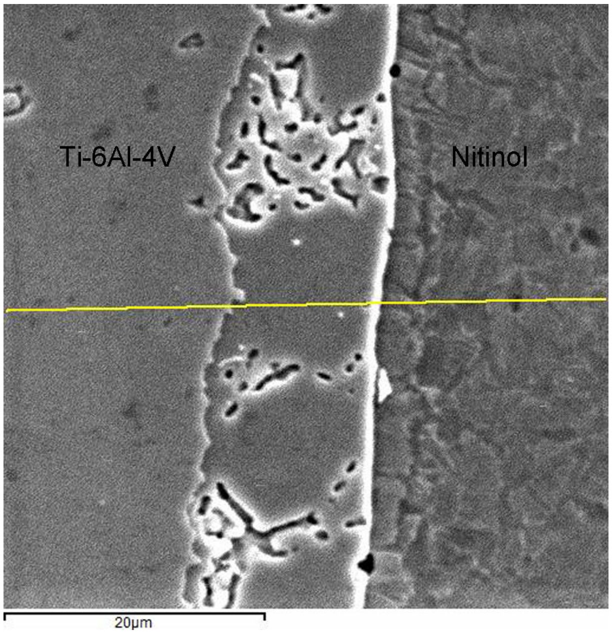

Figure 4 SEM image of the weld interface showing an intermixed zone of third kind.

Figure 2 shows optical microstructure of Ti-6Al-4V and Nitinol welded joint interface. There were no visible defects between the two alloys indicating a sound joint. However, refer to Figure 3, at higher magnifications, there does seem to a dark region along the interface. This suggests the two alloys have mixed and led to a third kind of metallurgical zone. This could even be harmful intermetallic compounds. In certain combination of metals, when the solid solubility is low, there is a good chance of forming intermetallic at the weld interface. These hard but brittle regions significantly reduce the strength and ductility of the joints. From Figures 2 and 3, material flow is more clearly visible on the Ti-6Al-4V side than Nitinol. This is because of the difficulty in etching of the interface with different etchants. In the present case, more emphasis was placed on the revealing Ti-6Al-4V, hence the clarity on this side. The material flow lines appear more vertical in the weld center and they slowly start to become horizontal and finally merge in to the typical base metal finish. As flash is formed during friction welding, the metal gets squeezed out and this is the reason for the vertical flow texture at the interface. Figure 4 confirms the proposition that a third kind of metallurgical zone has indeed formed at the interface. The scan electron microscope (SEM) image at very high magnifications reveals such a new kind of zone. An energy-dispersive spectroscopy (EDS) line scan would be able to inform us about the chemical makeup of this zone.

5. Conclusion

It can see that there is near-unanimous understanding that suitable welding technology for joining NiTi is lacking. Only when such a technology is made available, there would be a substantial jump in NiTi usage for wide-ranging applications, particularly in Bio-medical and aerospace fields. Although attempts are seen in open literature as early as 1991, they are still few and far between. Fortunately, the recent past is seeing an increased frequency of reports on welding of NiTi, at least in the open literature to these authors' knowledge. Aerospace companies are one of the prominent pushers to develop joining technology for NiTi. Adaptive serrated nozzle development being a case in point.

Though quite a few existing joining technologies were tried joining NiTi as discussed above, only few among them offer promising results. Laser could be said to be one of the best-joining methods for similar welding. Especially, thin sections of NiTi were quite successfully joined. The laser beam's capacity to melt instantaneously is its main strength. The homogenous structures seen in similar welds of NiTi more than prove this point. However, laser welding may not lead itself well in joining thick sections. Poor laser interaction properties of NiTi would be one among other reasons why laser welding suffers in those conditions. Further, it can be reasonably concluded that laser welding did not prove to be a worthy candidate when called upon to join NiTi to a different material.

Solid-state welding processes such as friction welding and friction stir welding showed some initial and promising results. The near-absence of fusion zone formation puts these processes a step ahead from the rest. This way the formation of intermetallic phases from the solidifying molten pool can be bypassed which is the first and foremost benefit when joining dissimilar materials. Notwithstanding their benefits, solid-state welding processes are not completely problems free. Chances of formation of new phases still exist, though reduced to a large extent. This is because, large plastic deformation associated with near fusion temperatures creates solid-state diffusion paths in dissimilar joints. One of the other significant advantages in league with friction welding and friction stir welding techniques is their ability to join comparatively thicker sections.

Hence, as future scope proposed that friction welding could be developed as a joining route for NiTi to itself and Ti-6Al-4V. Although the immediate applications for these joints are in aerospace field for realizing adaptive serrated nozzle, the accruing benefits can also be extended to the bio-medical field. The reason being that is both NiTi and Ti-6Al-4V have excellent biocompatibility.

The initial experiments presented in this work, show promise in realizing strong joint between Ti-6Al-4V and Nitinol. When welding parameters are within an optimum window, both the parent metals start to form flash indicating a positive response to the friction welding cycle. Even though, an intermixed zone was seen to have formed at the weld interface, it was only a narrow strip. It is hoped that with further developments regarding the welding trials, we will generate better understanding of the behavior of this intermixed zone and how it will affect the mechanical properties.

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Biographies

Ateekh Ur Rehman is Professor in Department of Industrial Engineering, College of Engineering, King Saud University, Riyadh, Saudi Arabia. He earned Bachelor of Engineering Degree in Production Engineering from SGGS College of Engineering, Masters in Advance Manufacturing Systems from Barkatullah University, Bhopal, India and PhD in Industrial Engineering from Indian Institute of Technology Bombay (IIT Bombay), Mumbai, India. His areas of interest are lean, agile and reconfigurable manufacturing system, supply chain management, multi criteria decision support systems for manufacturing systems and joining of metals.

Yusuf S. Usmani is a Lecturer in Industrial Engineering Department, College of Engineering, King Saud University, Riyadh, Saudi Arabia. He earned Bachelor of Engineering Degree in Production Engineering from S. S. B. T's College of Engineering. & Technology and, Masters in in Production Technology and Management from V.J.T.I. Mumbai, University of Mumbai, India. His areas of interest are operations management, manufacturing engineering, joining of metals and supply chain management.

Nagumothu Kishore Babu is currently working as an Associate Professor in the Department of Metallurgical & Materials Engineering department at National Institute of Technology, Warangal, India. He did post-doctoral research in the Safety of Joined Components division of the Federal Institute for Material Research and Testing (BAM), Berlin, Germany in 2009. He did his master's degree in Metallurgical Engineering from Banaras Hindu University, Varanasi, India. He received a PhD in Metallurgical and Materials Engineering from Indian Institute of Technology Madras, Chennai, India. His research interests are Joining of materials, Metal additive manufacturing using fusion based and solid state technologies, Solid state joining- friction stir welding and mechanical behaviour of materials.

Mahesh Kumar Talari is currently working as Associate Professor in Metallurgical & Materials Engineering department at National Institute of Technology, Warangal, India. He worked as Assistant Professor at Universiti Teknologi MARA, Malaysia. He obtained PhD degree from Indian Institute of Technology Madras (IIT Madras), India. His research interests are metal joining, hard facing, additive manufacturing, light metals, high temperature materials, functional materials and metal matrix nanocomposites.

Hisham Alkhalefah received the master's and Ph.D. degrees from the Industrial Engineering Department, King Saud University. He is currently serving as a Supervisor of the Advanced Manufacturing Institute, College of Engineering, King Saud University. His research interests include advanced manufacturing technologies especially additive manufacturing, digital manufacturing, manufacturing systems, non-conventional machining to name a few. He has published several research articles in internationals journal and conferences of repute.