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Investigation of Thermo-mechanical Properties of Heat Treated Friction Welded Superelastic Shape Memory NiTinol Alloy

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ABSTRACT
In this paper, NiTinol ($Ni_{56}Ti_{44}$) alloy is fabricated using rotary friction welding process. Samples were welded by varying the spindle speeds at 1800 rpm, 1900 rpm and 2000 rpm respectively in a fully automated direct driven rotary friction welding machine having a capacity of 6 tonne. Annealing heat treatment was performed on friction welded NiTinol samples at 600º C for 1 hr followed by water quenching at room temperature. Ageing was carried out at 450ºC about 30 min. Tests were carried out to find the bending strength and thermal conductivity of the both un heat treated and heat treated samples. Morphological and microstructural analysis were carried out using SEM and EDS to find out the changes occurred in the un heat treated and heat treated samples. Research finding, reveals that an improvement in flexural strength is 31.58%, 26.32% and 27.78 % in heat treated samples compared to friction welded unheat treated samples. Thermal conductivity of the heat treated samples showed an improvement for the lower spindle speed of the welded samples .

Keywords - NiTinol, Friction welding, Flexural strength, Thermal conductivity

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I. INTRODUCTION

Nickel-Titanium is a smart material popularly known for its smart and intelligent behavior makes its use in sensors, controls and environmental applications [1]. Shape memory alloys (SMAs) are a class of metallic materials having properties such as shape memory effect (SME), pseudoelasticity (PE), and damping capacity due to their high internal friction and mechanical hysteresis [2].The field of smart materials and structures is emerging rapidly with technological innovations in engineering materials, sensors, actuators and image processing areas [3]. SMAs are designed to undergo martensitic phase once the thermo-mechanical loads are employed. They also have the memory to restore their initial form as soon as they reach heat above particular temperatures [4]. Other types of shape memory alloys include Copper-Aluminum-Nickel (CuAlNi), Copper-Zinc-Aluminum (CuZnAl), and Iron- Manganese-Silicon alloys (FeMgSi). These are low cost commercially available SMA having limited use in industries due to their instability, brittleness and poor thermo mechanic performance [5]. However, NiTi materials were preferred in many applications due their better mechanical, thermal and chemical properties. Common properties are good electrical and mechanical properties such as high recoverable strain, high strength, long fatigue life, corrosion resistance and high wear resistance.

Material NiTinol is usually in general martensitic state at the lower temperature. Martensite changes to detwinned martensite when the load is applied externally. The material detwinned to become martensitic state when the load is removed. Upon heating the material above the austenite temperature, reverse transformation takes place occurs from detwinned/deformation-induced martensite to parent phase. This results in a regaining of the original shape of the alloy. This regaining of shape of alloy due to changeover temperature condition is called shape memory effect (SME) [6, 7]. Friction welding is the joining process in which two similar are dissimilar rods; thin sheets, plates etc are joined at different rotary speed at a standard temperature to attain the joint to retain its austenitic phase. NiTinol is fabricated using this technique to maintain the above nature of the alloy [8].

Inherent property of the NiTinol helps in automotive, aerospace, marine and biomedical application for joining two pieces of NiTinol pipes, rods, sheets etc. Welding process may lead to the various imperfections causing incompatibility for the use. Therefore, research work is undertaken to evaluate the possibility of impact by friction welding on various properties and aesthetic value of the NiTinol.

II. EXPERIMENTATAION

NiTinol alloy was procured from M/s SMA Wire India Pvt. Ltd, Gujarat, India having 8 mm diameter. Two different length of size 50 mm and 80 mm length were chosen for the friction welding purpose which is shown in Fig 1. The chemical composition and mechanical properties of this material is tabulated in Table 1 and Table 2.

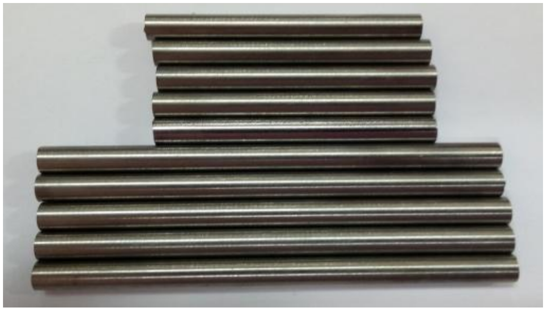

Fig 1:NiTinol Alloy

Fig 2: Direct drive rotary friction welding machine

Table 1: Chemical Composition (%)

Ti	**Ni**	**Co**	**Cu**	**Cr**	**Fe**	**Nb**	**C**	**H**	**O**	**N**
Remaining	55.78	0.0050	0.005	0.005	0.012	0.005	0.040	0.001	0.035	0.001

Table 2: Mechanical Properties

Tensile Strength, Mpa	**Yield Strength, Mpa**	**Elongation, %**
750	200	11

III. FRICTION WELDING PROCESS

Friction welding is a solid state welding process in which the work pieces are joined by the heat generated due to friction at the interface of the work pieces. Fully automated direct driven rotory friction welding machine as shown in the Fig 2, with a capacity of 6 tonne is used for the welding process. Two symmetrical work pieces with the dimensions of 8 mm dia, 50 mm and 80 mm length were taken for welding.

During friction welding the following parameters were considered: upset force as 2.1 tones, upset time as 1 sec, soft force as 0.3 tones, soft force time as 2.5 sec, friction force as 1 ton and friction burn off length as 6 mm is kept constant and varied spindle speed. Readings were recorded at 1800 rpm, 1900 rpm and 2000 rpm respectively. A visual inspection of weld quality was done based on the shape of the bead formed around the outside perimeter of the weld as shown in Fig 3. Deflashing was done by turning and hand grinding to remove the flash which is obtained at the joining of two work pieces due to friction welding.

Fig 3:NiTinol rods welded

IV. HEAT TREATMENT PROCESS

Annealing heat treatment was carried out in a electric furnace for friction welded samples as shown in Fig 4a. These samples temperature was raised to 600 °C and maintained at the same temperature for the duration of 1 hr followed by quenching immediately in water. After quenching, these samples are subjected to undergo ageing process at 450 °C for 30 min (spontaneous hardening of a metal which occurs if it is quenched and then stored at ambient temperature) and allowed for air cooling as shown in Fig 4b.

Surface morphology of NiTinol samples were tested using XRD machine: Rigaku Smart Lab with high resolution X-ray diffractometer (XRD) machine having Smart Lab Studio II software . System consists of Photon Max rotating anode X-ray source of high-flux 9 kW. Microstructure of NiTinol is carried using Scanning Electron Microscopy (SEM-GEMINI TECHNOLOGY, SUPRA 55 the ULTRA).

Fig 4: a) Muffle Electric furnace b) Heat treated sample

V. FLEXURAL STRENGTH

Flexural test was performed on samples using three point bending method as shown in Fig 5. The specimen was mounted on shackles and were fitted to the universal testing machine. Load-elongation of UTM adjusted to read zero. The hydraulic button is switched on and the load is applied gradually. For every 1 kN of load corresponding displacement reading was noted. The load is applied until the specimen's breaks and then breaking load is recorded.

VI. THERMAL CONDUCTIVITY TEST

Thermal conductivity was carried out by measuring the dimension of the specimen. It is fixed between reference specimens by confirming the thermocouple lead positions as shown in Fig 6. Water is allowed to flow to the bottom of the reference specimen through the pipe and watt meter reading was set to 25 w. After 10 minutes temperature readings were recorded in the interval of 2 min till the stabilization of temperature reached. Further the recorded readings were used in the formula for determination of thermal conductivity.

Fig 5 :Sample on bending test

Fig 6:Thermal Conductivity apparatus

Thermal conductivity is defined as

$$K = \frac{(Q/A)}{(\Delta T/\Delta L)} \text{ --- ---------------------------Equation 1}$$

Where Q – amount of heat passing through a cross section (A) and causing a temperature difference (T), over a distance of L. (Q/A) is therefore the heat flux which is causing the thermal gradient (T/L).

Thermal conductivity of unknown sample K_s

$$Ks = \frac{Kr * L}{Lr} \quad \text{------------------------------Equation 2}$$

Where,
K_r - Thermal conductivity of the reference
= 130 W /m^{-1} K^{-1}
K_s - Thermal conductivity of specimen
L_s - Length of specimen = 50 mm
L_r - Length of reference specimen = 50 mm

VII. RESULTS AND DISCUSSION

1. PHASE ANALYSIS

XRD results of welded samples of NiTinol alloy was shown in Fig 7. The presence of both austenite phase and martensite phase are given by B1 and B2 points [9]. B1 is stable austenite phase whereas B2 is the low-temperature martensite phase. Austenite is having simple cubic structure, but martensite is monoclinic in nature. Details of presence of elements present in the samples are shown as a peak in the graph.

2. FLEXURAL STRENGTH

Flexural strength of the welded NiTinol at various rotary speeds for unheat treated and heat treated samples were shown in Fig 8. Flexural strength of heat treated samples has shown improvement in the strength compared to unheat treated NiTinol welded samples. This is due to change in the structure from the austenite to martensite phase which is also observed in the phase diagram. However, within the friction welded samples higher strength is observed [10] in the sample B at 1900 rpm. But higher rotary speed decreases the strength of the NiTinol which is due to dislocations of grains during increased temperature during welding. Marginal decrement of strength from 3.29 GPa to 3.11GPa has negligible influence whereas strength in the sample B to sample C has higher in the decreased value indicating that NiTinol welding at higher speed has lower significance. An improvement in fletural strength by an amount 31.58%, 26.32% and 27.78 % in heat treated samples compared to friction welded samples were observed due to the heat treatment leading to phase changes.

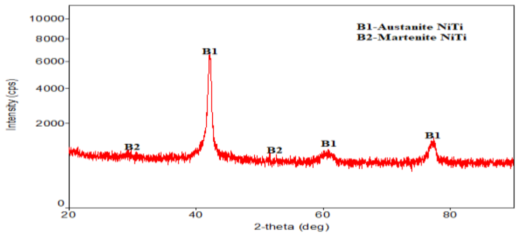

Fig 7: XRD analysis of NiTinol with various intensity parameters

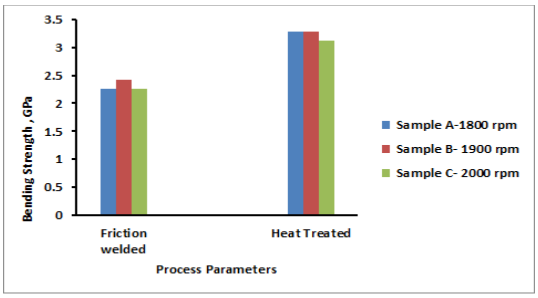

Fig 8: Bending strength of NiTinol samples

3. THERMAL CONDUCTIVITY

Thermal conductivity of the friction welded NiTinol samples recorded was shown in the Fig 9. Lower thermal conductivity is observed at 1800 rpm speed. Increase in the thermal conductivity of NiTinol manufactured at 1900 rpm and 2000 rpm driven speeds showed higher values [11].

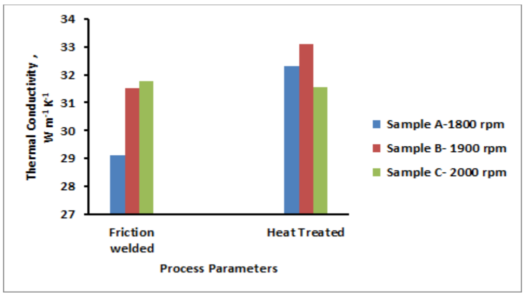

Fig 9: Thermal conductivity of NiTinol samples

However, heat treated friction welded samples joined at 1800 rpm has shown increase in the thermal conductivity compared to unheat treated samples. This fact may be due to the closer grain arrangement of the NiTi atoms. Refining of grains may lead to the finer crystalline structure of the NiTinol. Imperfection at the welded surface may be subjected to the filling of the atomsl by dislocations during heat treatment. At 1900 rpm, maximum thermal conductivity of 33.1 $Wm^{-1}K^{-1}$ is observed. Further increase in the speed up to 2000 rpm, has lower value in the thermal conductivity which is lesser than the 1800 rpm driven speed manufactured samples. Both the, welded (unheat treated) and heat treated samples have shown maximum thermal conductivity for NiTinol manufactured at 1900 rpm speed. Thermal conductivity of the heat treated samples showed an improvement for lower spindle speeds, but showed decrease in the values up to 0.66% for higher spindle speed compared to unheat treated samples.

4. MORPHOLOGICAL ANALYSIS

Morphological structure of friction welded surface drawn from the EDS is shown in Fig 10. Various elements present are Ni and Ti with traces of oxygen. This may be due to the lower amount of the oxygen present in the material as well as oxygen absorbed during welding of the NiTinol.

SEM images for both as manufactured friction welded and heat treated samples are as shown in Fig 11. When the rods are welded by friction welding solid phase weld bead occurs resulting in joining of the two pieces. Flash developed during welding is elliptical in cross section and uniform around the diameter of the sample. However, internally few welding imperfections are observed which are at nano level. After heat treatment these defects are filled due to the grain refinement by the dislocations and leading to change in the grain boundary size. This fact is also due to the austenite to martensitic transformation occurs during the heat treatment. Inclusions which are formed due to the presence of carbides and oxides while joining are removed during heat treatment [12].

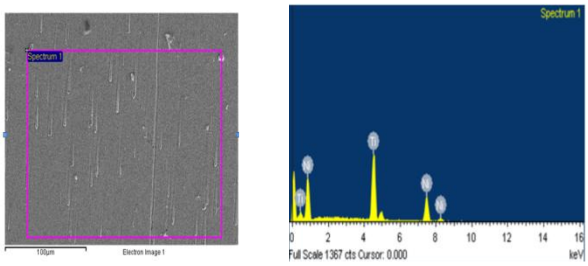

Fig 10: EDS analysis of friction welded NiTinol at 1800 rpm

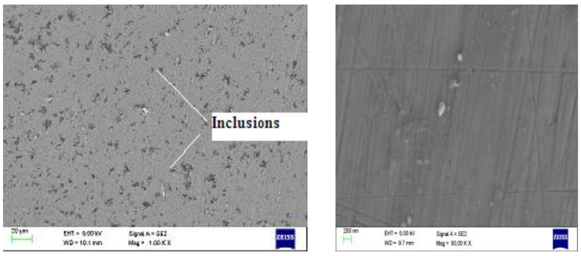

Fig 11: SEM analysis of friction welded NiTinol at 1800 rpm of Unheat treated and heat treated samples

VIII. CONCLUSION

Research results are evaluated to find the behavioral changes of the material after welding of NiTinol to NiTinol material. Following conclusions were drawn after the detailed experimentation and analysis.

- NiTinol of Ni_{56} and Ti_{44} is friction welded by direct driven rotary machine at 1800 rpm, 1900 rpm, and 2000 rpm has shown that welded surface characteristics did not change even after welding and treatment.

- Heat treated welded surface have shown significant improvement in the behavioral characteristics compared to base NiTinol in the flexural strength and thermal conductivity.

- Unheat treated friction welded samples have shown increase in the bending strength in the case of sample B-1900 rpm speed. Similar observations were recorded even in the heat treated friction welded sample.

  - Research indicates that manufacturing of NiTinol by friction welding method beyond 1900 rpm has least significance.

- Thermal conductivity decreases as the spindle speed increases while manufacturing of the NiTinol.

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