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ScienceDirect

Procedia Engineering 149 (2016) 438 – 447

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Manufacturing Engineering and Materials, ICMEM 2016, 6-10 June 2016, Nový Smokovec, Slovakia

Investigation of mechanical properties in welding of shape memory alloys

Mirshahin Hessam Sadati[a]*, Yashar Javadi[b]

[a]*Department of Mechanical Engineering, Semnan Branch, Islamic Azad University, Km. 5 of Semnan-Damghan Road, Semnan, Iran (mirshahin.sadati@gmail.com)*

[b]*Department of Mechanical Engineering, Semnan Branch, Islamic Azad University, Km. 5 of Semnan-DamghanRoad, Semnan, Iran(yasharejavadi@yahoo.com)*
School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, United Kingdom (yashar.javadi@manchester.ac.uk)

Abstract

Shape-memory alloys (SMA) are increasingly used due to the exceptional properties such as shape memory effect (SME), Pseudo elasticity and super-elastic effect (SE). However, mechanical properties of SMA are scantly studied in the field of welding technology. In this study, effect of laser welding on SMA is considered through investigation of mechanical properties as well as microstructure of the weldments. The specimens have been manufactured from NiTi, one of the most popular SMA alloys in the industry, in order to evaluate tensile strength and microstructure before and after the laser welding process. Based on the results, higher ultimate tensile strength and elongation are achieved in the specimens for which the tensile test was carried out in same direction as manufacturing rolling direction. Furthermore, microstructure investigations show that the behavior of solidification is changed from planar to volumetric and/or to dendritic. Due to this evolution, the joint tensile strength and strain reached to 118 MPa and 8%, respectively.

Peer-review under responsibility of the organizing committee of ICMEM 2016

Keywords: NiTi shape-memory alloy; laser weld; homogenous join; functional behavior; microstructure; tensile strength

1. Introduction

Shape-memory alloys (SMA) are of advanced materials beside composites, ceramics, and etc. These are quite useful industrial materials due to their unique features such as shape memory effect (SME) and pseudo-elasticity including super-elastic effect (SE). However, their usage is limited because of difficult extraction and processing. Industrial usages of SMAs are incomparable with other materials due to difficulties in common machining operations such as drilling, turning, and milling and inevitable tools abrasion. Micro-productions and hard junctions are difficult to implement and require advanced technologies. Laser welding is suggested as the best joining method of SMAs specially the homogenous ones. This method has many advantages like high precision, efficiency, and low thermal effect on base material. However, more studies should be conducted to find out its effect on functional features of SMA. In this paper, potential applications of laser welding in joining homogenous SMAs are studied and several pulsed or continuous laser resources are used to join titanium alloys. Homogenous NiTi junctions, designing parameters, structural, functional, and mechanical properties are evaluated in this study. The primary studies are based on the pulse mode, which protects the material features in a better way, and scanning electron microscopy and uniaxial tension test are used in addition to the specific designed methods.

* Corresponding author. Tel.: +989122768976; fax: +0-000-000-0000.
E-mail address: mirshahin.sadati@gmail.com

Peer-review under responsibility of the organizing committee of ICMEM 2016
doi:10.1016/j.proeng.2016.06.690

2. Literature review

Martensitic transformation is introduced as a reversible thermo-elastic process by Otsuka &Wayman, who worked on AU-Cd alloy. SMEs are first observed by Kurdjuov & Khandros in 1949 [1]. Change & Read observed a similar reversible behaviour in an alloy with 47.5% Cd in years 1951-1953 [2-4]. Anderson et al. used SMAs in orthodontics [5].But in the 70s, Memory Alloys at high temperature alloy Ti and Pd and Au were produced that tolerated a higher transition temperature (above 100 degrees) was leading. Memory Alloys in the 80s other applications for medical purposes such as orthopaedics, radiology, and wire guide is also found technology [6].Nickel-titanium-copper alloys showed longer fatigue times in late 90s which made them more attractive in cyclic processes [7]. Nowadays, several usages are found for these materials in aerospace, biomedicine, and etc. Hence, many studies and experiments have been conducted about these materials and joining methods in the last two decades.

Chau et al. identified novel welding techniques in order to create highly resistance junctions between materials like NiTi and Ti-6AL-4V in aerospace industries [8]. Primary tests on butt resistance joints were done in Japan in 1982 using thin wires of Ti-50 at % Ni. This method is without fusion and welding axial force fills the cracks and prevents oxidation or extrusion in fusion area. The results showed that shape-memory features in welded pieces remains the same and tensile strength was 80% of the base material.

As Ikai et al. reported, when using tungsten arc welding, a large thermal area is created, so, mechanical feature degradation is highly probable [9]. Oiao et al. studied microstructure of HAZ, a ferrous-based SMA welded by Teague (Fe-Mn-Si-Cr-Ni) using an electronic microscope and x-ray diffraction. They recorded no change in base material and also, reported the same shape-memory features in tungsten arc welded pieces using flexural bending tests [10].

Budau et al. tested Ultrasonic welding effect on joining homogenous or non-homogenous bands made of SMAs (Cu-Zn-Aland Ti-Ni-Cu) and stated that microstructure is a good interface for making massive connections. However, they found out that the welding technique damages the bands [11].

Plasma welding experiments on homogenous and non-homogenous NiTi by Ejik et al. in 2003 showed that welding doesn't affect Ni/Ti proportion when joining homogenous SMAs. Moreover, mechanical features are degraded and phase transition temperatures are changed. They reported that welding NiTi to stainless steel is quite difficult due to brittle fractures near fusion line and NiTi's tendency to absorb elements of steel [11].

Several studies have been done about laser welding effects. Schlossmacher et al. studied mechanical behaviour of welded NiTi SMAs (Ti-51.5at. % Ni) welded by Nd:YAG laser weld by experimenting 0.5 mm thick panels [12]. Tuissi et al. studied Nd:YAG laser weld effects on Ni-49.6 at %TiSMAs functional properties [13]. Also, CO_2 welding's effect on shape-memory and corrosion of NiTi is studied by Hsu et al. [14]. Falvo et al. studied mechanical and shape-memory behavior of NiTi [15]. Fatigue age of NiTi junctions were studied by Yan et al. using torsion-bending test [16]. Falvo et al. evaluated functional behavior of welded junctions of NiTi focusing on bi-sided shape-memory [15]. Song et al. studied laser welding parameters' effect on microstructures and mechanical properties of NiTi wires [17]. Noaker reports that thermal conductivity is the main mechanism in metals thinner than 0.5 mm.

Yan et al. studied B2 austenitic structure of welded Ti-50.6 at % Ni with Ti2Ni and observe no sediment of Ni4Ti3 related to fatigue strength [16].Schlossmacher et al. reaches the same result for Ti-51.5 at. % Ni [12].

Song et al. studied laser effects on welding area microstructures of NiTi and find out that the structure is column-micro in low cooling rate. This structure includes coarse coaxial elements and some cracks in the welding area and the welding quality is highly depended on the laser power [17].

Gugel & Theisen, in their survey on the NiTi (50.65 at. % Ni), found that welting fusion region, which is made mainly of coarse grains, move to a smaller region of column grain. In this study epitaxial crystallization in fusion line is observed in thermal flow direction while growing grains, and thermal region showed coaxial grain structure [18].

About the effect on functional features, Schlossmacher and et al. in surveying an SMA containing large amount of NiTi found that by applying load until 6 percent strain, significant stress region was observed similar to basic material. Also both martensitic and austenite situations were occurred in expected temperature [12].

Tuissi et al.'s report shows that ND-YAG laser welding on NiTi (49.6 at. % Ti) keeps the SME. Nevertheless, tensile test registered lower ultimate tensile stress in comparison to the basic material and thinner pseudo elasticity window [13].

On the other hand, Falvo et al. discovered that in laser welding, SME of NiTi cords is kept in low strains (about 2.7 percent) while during increasing strain until 6.2 percent, the condition is different and SME is under influence of welding. Moreover, the efficiencies reduced and hence these joints are not proper for the smart components design and under high tensile stresses. This report mentioned that such welds can be used for light applications in lower levels of stress which require lower retrieval stress [15].

Falvo et al. also analysed the application behaviour of the NiTi welded joints and found that the welding process as a heating operation affects stress-strain condition and this matter causes the cold working effects are reduced and plateau stress to be observable[15].

Toosi et al. studied mechanical features of Ni-49.6 at. % TI and find out that welding decreases ultimate tensile stress of SMAs. Tensile testing on welded samples, lower young modulus, smoother diagrams are the results of this research [13].

Falvo et al. reported that the ultimate tensile stress of junctions is significantly lower than the base material (ultimate tensile stress and additional failure length decrease 52.7% and 41.6% respectively). They stated the brittle welding as the main reason for this. However, the believe that malleability is 7% during lengthening until failure [17].

Scholzmaker et al. reported that the brutality decreasing in the welding area due to micro-dentric structure, 20% reduction in ultimate tensile stress, and 67% reduction in additional failure length [12].

Yon et al. studied fatigue age of NiTi SMAs using twisting-bending tests. Their results show that gradual heating up to 400°C in one hour increases fatigue strength; but if the temperature is increased to 500°C in the same duration, fatigue strength decreases. They also believe that Ti3Ni4 sediment size is depended on the fatigue strength and also stated that the fatigue strength is increased by rising particle size. Heating could lower the particle sizes and affect fatigue the resistance positively [16]. Li et al. studied laser brazing effect on behaviour of junctions between NiTi and SS orthodontic wires. They found out that the laser brazing is a suitable technique for SMAs but junctions' satisfactoriness is highly depended on the brazing parameters [19].

3. Methodology

Regarding the review in the literature section, studying in a framework with following specifications is considered:

- Welding methods such as those which include dense radiation with high energy like laser
- Analysis of microstructure welding which makes it possible to perceive laser welding process effect on inductive changes
- Mechanical test and SME evaluation

This study is conducted based on an experimental work and a set of laboratory actions to use laser welding in homogenous SMA joints, microstructure changes analysis during welding, mechanical specifications evaluation, and functional properties measurement of SMA in welded joints. In order to achieve above-mentioned goals, materials and laboratory equipment's are provided to carry out tests and then the results are analyzed eventually. In this section, utilized materials and required laboratory equipment's are introduced and test method is expressed.

3.1. NiTi shape-memory alloy

Because of NiTi SMA availability in markets, the HANT (Heat Activated Reverse Curves) type of this alloy (activated in room temperature) is provided with a diameter equal to 0.36 mm and length of 5 m for welding according to physical and mechanical specifications that are mentioned in table 1.

Because the laser welding purpose is to study SMA's mechanical behavior before and after welding, 8 wire-specimens are provided which are 17 cm long similar to ASTM F 2516 and ASTM F 2063 standards. Also, according to the standards, in tensile test the space between grips must be 150 mm in unloaded situation.

3.2. Nd: YAG laser device

Nd:YAG (PIM-3475, IQL-20 model) is chosen for the welding process. Nd:YAG from the aspect of power is the only device that can weld slim samples (diameter of less than 1 mm). The device has maximum laser power equivalent to 300W, normal power of 250W for piece of specimen, maximum peak power of 9KW, maximum Pulse energy of 50J, maximum frequency of 1000Hz, and interval pulse width between 0.2-20ms. Device condition during welding, in order to providing desirable specimen, is provided in Table 2.

Table 1- NiTi SMA Specifications [20]

Physical specifications							
Thermal expansion parameter ($\times K^{-6}10^{-1}$)		Electrical resistivity (μΩcm)	Thermal conductivity(W/m.k)		Density (Kg/dm^3)	Boiling point (◦C)	
Martensitic	Austenite		Martensitic	Austenite			
Ca.7.6	10-11	50-100	Ca.9	Ca.18	6.45	Ca.1310	
Mechanical specifications							
Tensile stress (percent)		ultimate tensile (MPa)		Poisson's ratio	Tensile modulus (GPa)		
Fully heated	Chilled specimen	Fully heated	Chilled specimen		Martensite	Austenite	
20-60	5-20	Ca.900	Up to 1900	0.33	Ca. 23-41	Ca. 70-80	

Table 2. Device condition during welding

Pulse number	Frequency welding	Focal length	Interval pulse width	Pulse energy	Laser Power
-	Hz	Mm	Ms	J	W
15	3	75	8	3	20

Argon flow in the rate of 26 L/min (10 seconds before welding and 4 seconds after welding) is used to prevent the penetration of N_2, O_2, and H_2 to welding area because they can hurt the joint specifications.

3.3. Tensile testing machine

The utilized device for the tensile test is H25KS model of HOUNSFIELD. The device capacity is 25KN and according to ASTM standards, as it is mentioned before, the device is regulated on relocation rate of 0.4 mm/s and space between grips of 150mm during the test. Because of cross-section roundness of wires, two ends of specimens are hold by some sand-papers as tabs like figure 1 to join them to tensile grips.

3.4. The SEM device

Scanning Electron Microscopy usually works in vacuum. After creating vacuum, the specimen surface is scanned by electron ray and illustrated on a monitor. With changing registration ray tool, it is possible to achieve pictures contained various information from specimen's surface like ups and downs or phases distribution on scanning surface. For current experiment, Vega II model of SEM device is used.

3.5. The experiment

In this study 4 samples are prepared for welding process and, according to standard, 3 specimens are used to certify results of the tensile test. The last specimen is used for SEM. Also a sample is provided before welding for tensile test to make before-after studies possible. The results are explained in the next section.

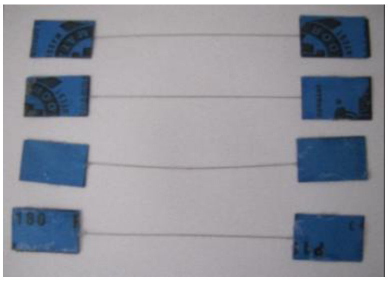


Figure 1. Provided specimens for tensile test

4. Results and findings

4.1. Microstructure and chemical composition of welded junctions

Weight proportion and distribution and penetration way of each element in the welding area is studied in this besides taking photographs of the area.
Figure 2 shows SEM microstructure in welding area and its central axle. The weld area solidification is changed from planar to cellular and to dendritic that is due to increasing cooling rate from edges toward central axle of the area in both sides of NiTi. As it is seen in figure 2, laser welding doesn't change the welding area's structure in NiTi-NiTi joining and the structure is B2 austenitic.

4.2. Point analysis

In order to measure particles and finding out their distribution pattern in two sides of welding area, the area is divided in two segments of A and B (figure 3) and are measured after gold-covering. The results are as stated in table 3, 4, and 5.

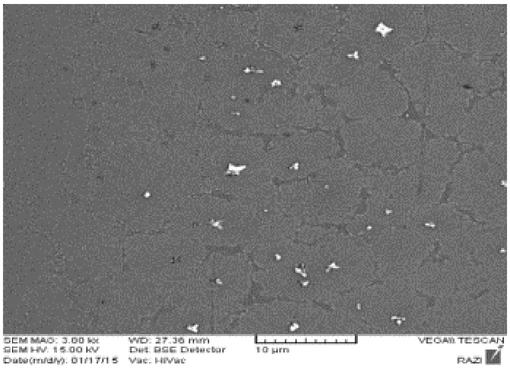


Figure 2. SMA microstructure in welding area's central axle

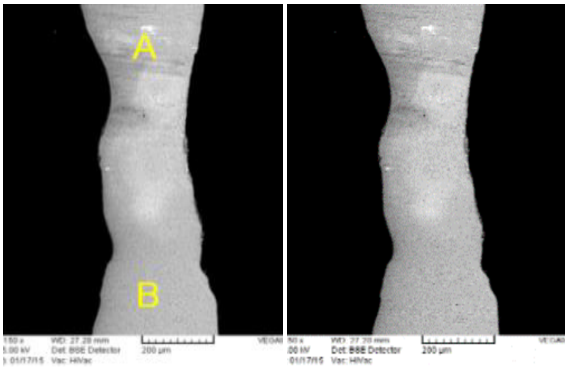
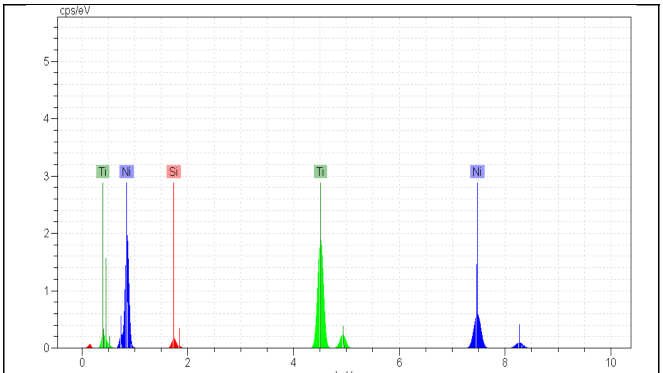


Figure 3.the welding area and A and B segments

Table 3.Elements of area A

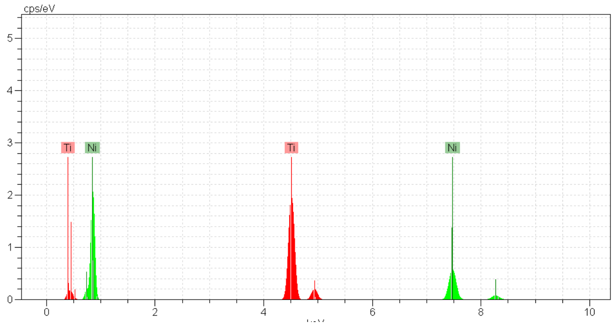


TotalSpectra: 1-ZONE A

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Silicon	K series	1.09	1.25	2.36
Titanium	K series	35.99	41.55	45.99
Nickel	K series	49.55	57.20	51.65
	:	86.6 %		

As stated in table 3, segment A contains 41.55% and 57.20% of titanium and Nickel respectively that is consistent with SMA norms. Moreover, weight percentages shown in table 4 about segment B means that the NiTi SMA is sound.

Table 4.Elements of area B

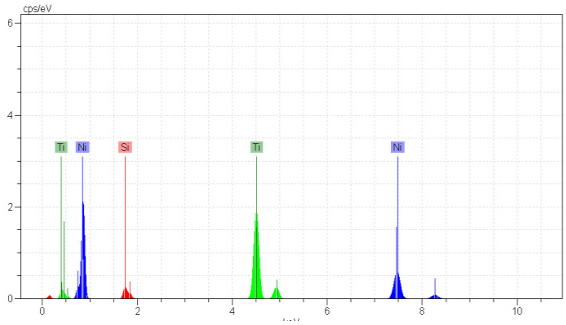


Spectra: 1-ZONE B

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Titanium	K series	38.52	40.80	45.79
Nickel	K series	55.90	59.20	54.21

Total: 94.4 %

Table 5.elements of the welding area



Spectra: 1-WELD

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Silicon	K series	2.43	2.73	5.03
Titanium	K series	41.15	46.24	49.98
Nickel	K series	45.41	51.03	44.99

Total: 89.0 %

4.3. Surfacial analysis

Same as point analysis, the result of surficial analysis also show that laser welding doesn’t change memory structure of SMAs. Table 6 states microstructure results of surficial analysis. Failure analysis/fault analysis.

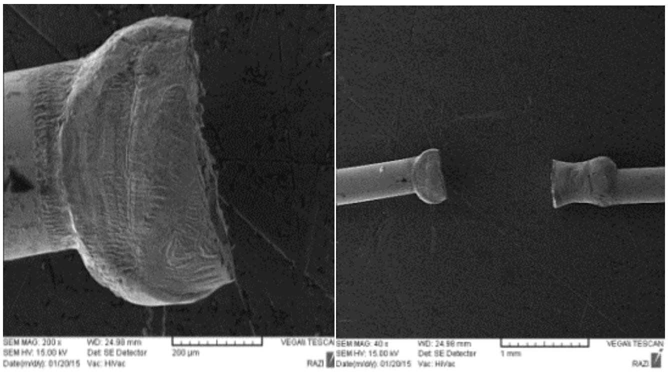
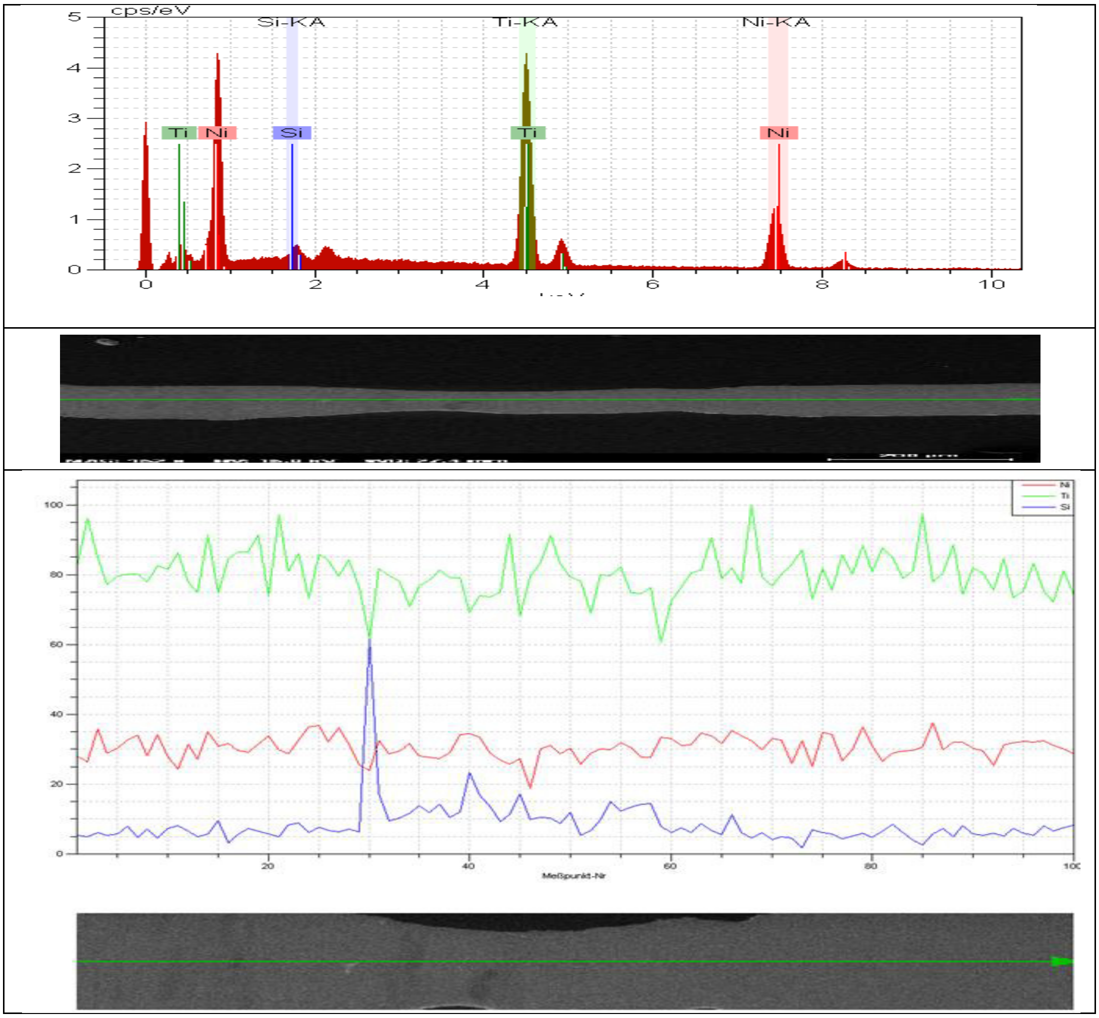


Figure 4. Failure picture taken by SEM

Some photos are taken from failure occurred in one of the samples, as demonstrated in figure 4, the failure is occurred in the welding area in proximity of its central axle.

Table 6. SMA joining's surficial analysis



4.4. Tensile testing

The tensile tests done on base materials and the welded samples are of the same technique with equal crosshead interval based on ASTM standards. Mechanical properties of the base material and welded samples are measured and diagrammed. The results show that the ultimate tensile strength and additional maximum elongation is higher when the sample is subjected to tension along RD.

4.4.1. Tensile test of NiTi primary sample

Tensile testing machine's output is a force-elongation diagram which could determine the stress-strain diagram as shown in figure 5.

In order to determine Young's modulus of NiTi, slope of the stress-strain diagram should be figured out which is equal to 40GPa according to figure 6.

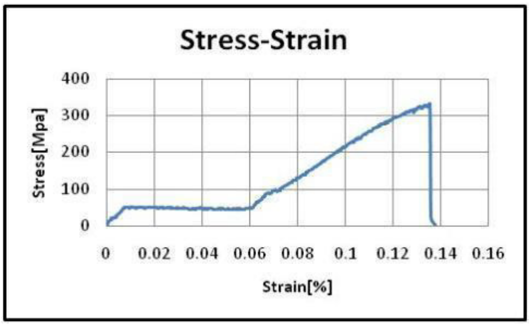


Figure 5.stress-strain diagram of NiTi SMA

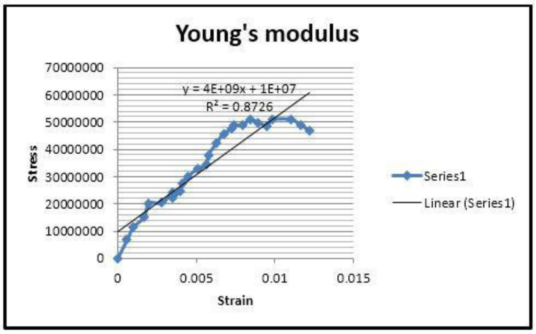


Figure 6.young's modulus of NiTi SMA

4.4.2. Tensile testing of NiTi SMA welded samples

The stress-strain diagrams of the welded samples are drawn in the same way of the base material as shown in figures 7 and 8.

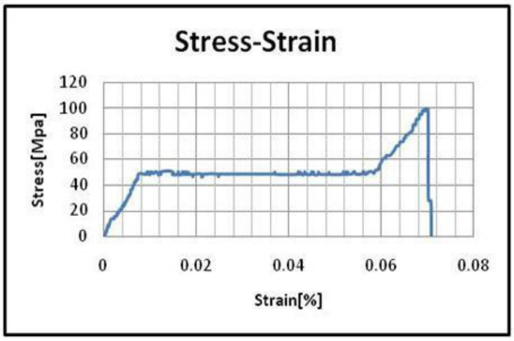


Figure 7.stress-strain diagram of the first welded NiTi SMA

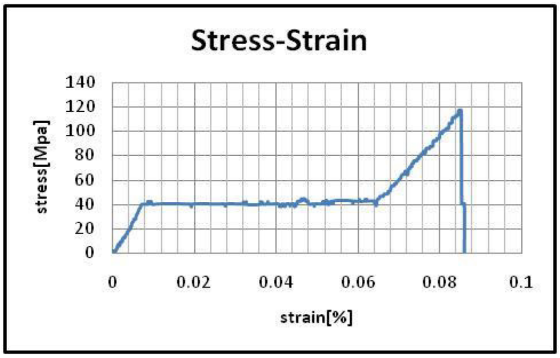


Figure 8.stress-straindiagrm of the second welded NiTi SMA

5. conclusion

Laser welding of two NiTi pieces was done successfully. Consequently, laser welding effect on structure and mechanical features of this material were studied and the results were as following:

1. Junctions were created sound based on optimization parameters. However, microstructure monitoring showed tiny and outspread holes. Tensile tests demonstrated that the ultimate tensile strength and additional maximum elongation is higher when the sample is subjected to tension along RD.
2. Micro-structural investigations showed that the behavior of solidification across the fusion zone is changed from planar to volumetric and/or to dendritic from the weld zone interface toward the weld centerline of NiTi. The welded junction had a uniform chemical distribution. Moreover, the welding area has B2 Vald phase and no sediments (same as the base material).
3. The NiTi-NiTi junction had an acceptable stress-strain behavior which was comparable with the base material (NiTi wire before welding). The junction also reach tensile strength of 117 Mega Pascal and strain of 8%. In addition, failure occurred in the NiTi-NiTi junction in welding area and in proximity of the central axle as normal.

6. Suggestions

Although SMAs have been of high industrial usage in recent years, it could be even more useful by doing more researches about it. For instance, taking the same steps for SMA plates, using different welding techniques, figuring out residual stress after laser welding, or studying failure mechanism in SMAs are suggested for further studies.

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