THE EFFECT OF PULSED ND:YAG LASER WELDING ON SHEAR FORCE AND MICROSTRUCTURE FOR NITI SHAPE MEMORY ALLOY WITH 304L AUSTENITE STAINLESS STEEL WELDMENTS

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ABSTRACT :
Dissimilar welding of austenitic stainless steel AISI 304L to shape memory alloy SMA NiTi was conducted by utilized Nd: YAG laser beam welding technique. Both AISI 304ASS and SMA have the same dimension (80*20*0.5) mm. The experimental investigation included tensile shear test and microstructure. The results demonstrate that the maximum shear force found in the sample (No/10) reach (2552 N) which has the better laser parameters in this research (peak power of (2.25 KW), pulse duration of (2.4 ms), pulse repetition rate of (40 Hz), and welding speed of (8 mm/Sec). SEM with optical microscope demonstrate the solidification method along the fusion area various in different joints, where they become the planer shape to cellular and transformed the last to dendritic from intra-fusion welding area toward the center because towards weld area interface to weld centerline cooling rate will be rise in all SMA (NiTi) and Austenite stainless steel (ASS) sides.

KEYWORDS : Nd:YAG laser, NiTi, Shape memory alloy, Austenite Stainless steel

تأثيرلحام الليزر النبضي على قوة القص والبنية المجهرية للحام السبيكة النيكل- تيتانيوم الذاكرة الشكل مع الفولاذ المقاوم للصدأ الاوستنايتي

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الخلاصة :
اجريت عملية لحام المعادن غير المتشابهة وهي الفولاذ المقاوم للصدء الاوستنايتي (304L) وسبيكة ذاكرة الشكل نيكل- تيتانيوم بواسطة استخدام تقنية اللحام بالليزر النبضي (Nd:YAG). الفولاذ المقاوم الاوستنايتي وكذلك سبيكة ذاكرة الشكل كلاهما نفس الابعاد mm (0.5*20*80). الاختبارات العملية شملت اختبار الشد، والبنية المجهرية. النتائج تظهر ان العينة العاشرة تعطي اعلى قوة قص تصل الى (2552N) التي نفذت خلال هذا البحث بمتغيرات هي (الطاقة العظمى (2.25KW)، مدة النبضة (2.4ms)، معدل تكرار النبضة (40Hz)، سرعة اللحام (8mm/s). المجهر الالكتروني الماسح والضوئي يضهر ان التجمد عبر منطقة الانصهار يتغير من مستوي الى خلوي وشجيري بسبب الزيادة بمعدل التبريد من الحد الفاصل باتجاة مركز اللحام على جانبي الفولاذ المقاوم للصدء الاوستنايتي (304L) وسبيكة ذاكره الشكل نيكل – تيتانيوم .

الكلمات الافتتاحية: الليزر النبضي، نيكل تيتانيوم، السبائك الذاكرة الشكل، الفولاذ المقاوم للصدأ

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INTRODUCTION :-

Welding is mostly known as the method of thermally joining two materials. A broad range of welding operation, such as -gas welding, arc welding, resistance welding, and high energy beam welding have been advanced. Whole these welding processes, products in various weld bead profiles, distortions and weld goodness to weld-pieces as ruled by the innate characteristics of the process and processing parameters. Between the various welding processes, high energy beam welding utilized laser has a key advantage in terms of localized heating, high cooling rate, minimal heat affected zone, and easier incoming that lead to miniature work piece distortion. It is broadly used for welding of metals, dissimilar materials, ceramics and polymers with different thicknesses [Salminen A et al 2010]. Solely after the definition of the first laser by Maiman, in 1960, after that so rapid development of these modern technologies characterized by ever more active, smaller and inexpensive. One important application of these modern technologies can weld several types of metals, in industrial fields, these operation diffusion in so little interval [Narendra B et al 2008, H. Park et al 2010]. The laser beam can be output high energy concentration due to it has good properties different from ordinary light source. Many of the materials are processed by the laser beam .Many of the processes utlized a laser like welding, cutting, surface amendment (involved heat treatment), and forming [E. Kannatey-Asibu 2009]. The excellent properties such as high-elasticity, shape memory effect and biocompatibility, nickel titanium alloy (NiTi) generality communal and modern, clever materials utilized in several uses like flight, spaceflight and medical devices [Predki W et al 2008]. Joining of NiTi has been deemed as a tricky job due to of its altitude sensitivity to the thermo mechanical treatment and the decadence of properties in the weld area this does not happen in base metal because metallurgical variation [Falvo A et al 2005]. In modern years, Welding type affects dramatically on properties similar SMA (NiTi) and microstructure [Chan CW et al 2011]. There are a lot of materials that are utlized in various applications, including medical devices, and this material is stainless steel and utilized this steel to that several of the properties that enable it to work possesses these circumstances, including the mechanical properties as well as the ability to forming and cheap and resistance to high corrosion [Uenishi K et al 2003]. As a result of welding the two types of materials needed and important in several uses and applications such as aerospace , micro-electronics and medical device. It should be noted there is a large difference in the physical and chemical properties which makes welding this is a very difficult material. Has been shown the brittle phases suchas$TiFe_2$ this leads weld equally brittle [Hall PC et al 2004]. Over the past years, many of processes lead to at weding NiTi alloy with same alloy or welding with different alloy have been deem. Many of welding type utilized for weld but laser welding is appropriate for weld this category material. The Nd: YAG source seems appropriate for joining of minimal devices with intricate shapes because the low and accurate heat input, low energy density, teeny fusion and heat- affected zones, low residual stress, low weld distortion and high welding speed [Qiu XM et al 2006, Alberty Vieira L et al 2011]. Numerous studies were conducted in the literature on the pulse Nd:YAG laser welding, few investigates were carried out on the laser welding of NiTi shape memory alloy with Austenite stainless steel. G.R. Mirshekari et al. A comparative study on laser welding of NiTi wire to itself and to AISI 304 austenitic stainless steel wire has been made. Microstructures, mechanical properties and fracture morphologies of the laser joints were carried out utilized optical microscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction analysis (XRD), Vickers microhardness and tensile testing techniques. The results demonstrate that the NiTi–NiTi laser joint reached about 63% of the ultimate tensile strength of the as received NiTi wire (i.e. 835

MPa) with a rupture strain of about 16% .The NiTi–SS stress–strain curve of the NiTi–SS joint showed that ductility and tensile strength were decreased significantly after dissimilar laser welding. This joint likewise enabled the possibility to advantage from the pseudoelastic properties of the NiTi component. However, tensile strength and ductility decreased after dissimilar laser welding of NiTi to stainless steel because the formation of brittle intermetallic compounds in the weld zone through laser welding. Therefore, appropriate modification operation wanted for amelioration of the joint properties of the dissimilar welded wires. The aim of this research at investigating the effect of welding parameters, such as, peak power, pulse duration, pulse repetition rate, and welding speed, on (micro-hardness and microstructure) of lap joints of Austenitic stainless steel AISI 304L, (80*20*0.5) mm to Shape memory alloy (NiTi), (80*20*0.5) mm, and getting in the best condition of this joint.

EXPERIMENTAL WORK :-

Material and sample preparation

The metals that choice to be joined by using pulsed Nd:YAG laser for this study are Austenitic stainless steel AISI 304L and shape memory alloy (NiTi). Ready brought samples from China. Materials were analyzed by using a spectrometer (Spectromax) and conducted this task in the (State Company for Inspection & Engineering, Rehabilitation) to obtain the chemical composition. Table1, shows the chemical composition for the samples. A further preparation steps were conducted for each samples before performing the welding task. At the first each sample was cleaned with pure alcohol for eliminating the dirt and oil. Both surfaces of each sample were grinding along the same direction using various grades of papers for elimination the oxide films and decrease the roughness so as to obtain the best superposition between the welded surfaces. Finally the sample was cleaning by pure alcohol and drying.

Laser welding

Austenite stainless steel 304L and shape memory (NiTi) samples were welded using pulsed Nd:YAG laser welding machine (IQL-10) in the Iran Tehran, (Iranian National Center for laser Science and Technology INLC). Table 2 shows the specifications of the laser welding machine. Both NiTi shape memory alloy with Austenite stainless steel were cut into small plates of 80mm length and 20mm width and 0.5mm thickness, the overlap between each two pair of welded samples was 20mm. Austenite stainless steel 304L plate was placed above the shape memory (NiTi) plate as shown in Fig 1. The edges of NiTi SMA and AISI 304L stainless steel were grinding, using different abrasive silicon carbide papers to obtain a smooth surface finish. Caution must to guarantee the parallelism of the edges to each other and attain no gap between them.

Microstructural characterization

The Microstructure of the weld samples has been tested by an optical microscope lab in Iran/ Tehran (Razi Metallurgical Research Center) by (optical microscope, model Metallux 3). Weld samples were prepared for the microstructure test as in the following steps. The Polymer is used to Mounting of the cut sample by a punch. Grinding was performed by using grinding papers in the sequence (180, 320, 400, 600, 800, 1000, 1200, 1500) from coarse to fine respectively. Polishing is done to get a shiny and smooth surface and to make the sample reflective, free of defects and prepared for testing by putting diamond solution on polishing papers with a little amount of water. Etching is a process used to make the grain boundaries and the phases of the metal distinctly and obvious for the microscope by using an appropriate chemical solution. The shape memory (NiTi) side of welded sampls was then etched with a mixed acid solution HF: HNO_3:CH_3COOH (1:5:5) and the Austenitic stainless steel side was etched in a reagent HCl: HNO3 (3:1). The samples were immersed in this solution for 25–30 Sec then swills by water and dried by hot air blower.

Shear force test

The test was conducted at the (Polymer materials lab/University of Babylon) by using (microcomputer control Electronic universal testing machine), which has a maximum load of 5kN in order to investigate the changing in shear force with changing welding parameters. Testing the maximum tensile stress for each sample in order to compare it with the maximum tensile test of the welding zone for each welded sample to find out the quality of the welding process and discuss the results for making the best working parameters and conditions .

Laser welding parameters

Welding is achieved by using four different parameters (peak power, pulse duration, pulse repetition rate or frequency and welding speed), each parameter was changed five times to predict the best value table (3), (4), (5) and (6) show the listed these parameters.

RESULTS AND DISCUSSION :-

Microstructure of welded joints

The fusion zone (also known as the weld zone (W.Z)), the heat affected zone (HAZ), and the base metal (BM) were three distinct regions in the welding process. The weld zone experiences melting and solidification and its microstructural characteristics were directly affected the welding quality. An optical microscope and scanning electron microscope were used for observing and examining the microstructure of the base metal (B.M), heat affected zone (HAZ), and weld zone (W.Z) for the most successful sample of all the samples of the four groups which was the sample (No.10) which has the better laser parameters in this research (peak power of (2.25 KW), pulse duration of (2.4 ms), pulse repetition rate of (40 Hz), and welding speed of (8 mm/s). The Microstructures of Austenitic stainless steel base metal consisted of Austenite phase, while the microstructure of HAZ mainly consisted from coarse Austenite phase. The microstructures of NiTi SMA base metal comprised of Martensite phase at room temperature. The microstructures in the HAZ had a coarse Martensite phase because heat from fusion zone increased, This makes a slow cooling rate. while the weld zone consisted of a dendrite structure. The microstructures of welding zone comprised of brittle intermetallic compounds like $TiFe_2$, $TiCr_2$, FeNi, $TiNi_3$ and Ti_2Ni [M.G. Li et.al 2006]. SEM test showed the solidification method along the fusion area various in different joints, where they become the planer shape to cellular and transformed the last to dendritic from intra-fusion welding zone toward the center in all of them NiTi shape memory alloy and Austenitic stainless steel sides due to the increase in cooling rate from the weld zone interface toward the weld centerline in both NiTi side and SS side. Many factors affected the solidified of the weld zone such as temperature gradient, solidification rate and alloy composition. The solidification rate increases while the temperature gradient gradually decreases. Near the fusion line, the solidification process is followed by planar and cellular growth. When solidification front moves to ward the weld centerline, the dendritic growth occurs in the center of the weld. Fig (2) (a, b, c, d, and e) shows the microstructure of the best sample G2/10 that examined using scanning electron microscope (SEM).

Tensile shear test

The tensile shear test for the laser welded lap joint was conducted at room temperature utilizing (microcomputer control Electronic universal testing machine. Max Load 5kN). Utilizing a crosshead speed of 5mm/sec. The greatest withstand load of each weld joint was measured. The maximum shear force found in the sample (No.10) reached (2552 N) which has the better laser parameters in this research (peak power of (2.25 KW), pulse duration of (2.4 ms), pulse repetition rate of (40 Hz), and welding speed of (8 mm/s). This test was conducted because most applications require high shear force and a private medical applications. All The samples welded likewise break in the middle of the weld area because of exist together Steel and Titanium in the melt pool This will be form of brittle intermetallic compounds like ($TiFe_2$,$TiNi_3$ and Ti_2Ni) at the weld region through this type form welding of Shape memory alloy NiTi to Austenitic stainless steel stainless steel AISI 304L as appeared in the figure (2). Therefore; Brittle breaking happened because of the brittle intermetallic compounds created in the weld area of SMA NiTi–ASS weld.

Effect of laser welding parameters

The shear force increment with increase peak power and reaches a maximum (2421 N) at peak power of (2.75 KW), therefore; sample (No/5) is accomplished maximum value of shear force of (2421N). Increment the laser power lead to increasing the penetration depth. Peak power has a minimal effect on together weld profile and heat affected zone width in comparison with its effect on the penetration depth [A. Costa 2010]. Shear force increment with increase pulse duration because they get to heat input in this case which permits longer interaction time between the laser pulse and the sample. As a result, high quality weld joint represented by minimal thermal distortion, and free from micro-cracks and porosity and reaches a maximum (2552 N) at a pulse duration of (2.4 ms), therefore; sample (No/10) is accomplished maximum the shear force value (2552 N). Completed high the shear force value (1194N). Sample (No/13) is accomplished high the shear force value (1194 N). A laser beam is often pulsed. Frequency is defined as the number of pulses per second. Heat depends on the frequency that means increasing frequency increases the heat and vice versa. Initially shear force increment with increment pulse repetition rate reached an optimum value (1194 N) at a pulse repetition rate of (35 Hz). Increased shear force in the samples (No 11,12,13) this was due to increase the penetration depth with increase pulse repetition rate. After that shear force was less in the samples (No 14,15), because the continuous increase in the frequency led to affect the weld quality, it may drop dramatically. The shear force increases with increasing welding speed. After reaching to the optimum value of shear force (1329 N) [G.R. Mirshekari et al], It begins decreases as the welding speed decreases likewise. Increase welding speed output weak weld zone because the insufficient heat input because of the insufficient interaction time. As it were, before the metals to be completely joined the laser bar moves to another position. But when decrease welding speed will cause increased heat input due to the interaction time will be as extended as sufficient to evaporate the weld pool as shown in Figure (4) .

CONCLUSIONS :-

1. The best sample which is G2/10 was executed at Peak power of 2.25kW, Pulse duration of 2.4msec, Pulse repetition rate of 40Hz, and welding speed of the 8mm/Sec achieved maximum breaking force (2552)N at the weld zone (W.Z).
2. The solidification method along the fusion area various in different joints, where they become the planer shape to cellular and transformed the last to dendritic from intra-

fusion welding area toward the center in all of them NiTi Shape memory alloy and Austenitic stainless steel sides.

3. Few brittle intermetallic compounds create at the weld area of NiTi SMA–ASS joint.
4. Breaking happen in a brittle mode in middle of the SMA NiTi–ASS fusion area.
5. The best properties in terms of microstructure (the SEM examination showed a dendritic grained microstructure), and tensile shear test (2552) KN, were observed for sample G2/10 .

Table 1: Chemical composition of base alloys (wt%)

Materials	C	Si	Mn	P	S	Cr	Mo	Ni	Ti	Al	Co	Cu	V	Fe
ASS 304L	0.02	0.41	.948	.037	.0005	19.66	.069	7.68	-	.001	.218	.128	.090	Bal
SMA(NiTi)								55	45					

Table 2: Specifications of the laser welding machine

Parameter	**Value**
Maximum mean laser power	400 W
Pulse frequency	(1-1000)Hz
Pulse duration	(0.2-20) ms
Pulse energy	(0-40) J
Focusing optical system	3 lenses with 75-mm focal length
Laser beam spot diameter	1.2 ± 0.1 mm

Table (3) : Variation of laser pulse peak power

Sample number	Peak Power (kW)	Pulse Duration (ms)	Frequency (Hz)	Laser Power (W)	Welding Speed (mm/s)	Average radiated energy (j/mm)
1	1.75	2	40	140	8	17.5
2	2	2	40	160	8	20
3	2.25	2	40	180	8	22.5
4	2.5	2	40	200	8	25
5	2.75	2	40	220	8	27.5

Table (4): Variation of laser pulse duration

Sample number	Peak Power (KW)	Pulse Duration (ms)	Frequency (Hz)	Laser Power (W)	Welding Speed (mm/s)	Average radiated energy (j/mm)
6	2.25	1.6	40	144	8	18
7	2.25	1.8	40	162	8	20.25
8	2.25	2	40	180	8	22.5
9	2.25	2.2	40	198	8	24.75
10	2.25	2.4	40	216	8	27

Table (5): Variation of Pulse repetition rate (frequency)

Sample number	Peak Power (KW)	Pulse Duration (ms)	Frequency (Hz)	Laser Power (W)	Welding Speed (mm/s)	Average radiated energy (j/mm)
11	2.25	2	25	113	8	14.1
12	2.25	2	30	135	8	16.9
13	2.25	2	35	158	8	19.75
14	2.25	2	40	180	8	22.5
15	2.25	2	45	202.5	8	25.3

Table (6): Variation of the laser welding speed

Sample number	Peak Power (kW)	Pulse Duration (ms)	Frequency (Hz)	Laser Power (W)	Welding Speed (mm/s)	Average radiated energy (j/mm)
16	2.25	2	40	180	8	22.5
17	2.25	2	40	180	9	20
18	2.25	2	40	180	10	18
19	2.25	2	40	180	11	16.4
20	2.25	2	40	180	12	15

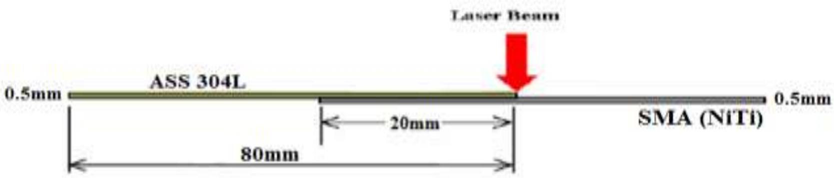


Fig 1: Schematic diagram illustrating the centerline welding lap join

Fig (2): Failure across tensile shear testing load.

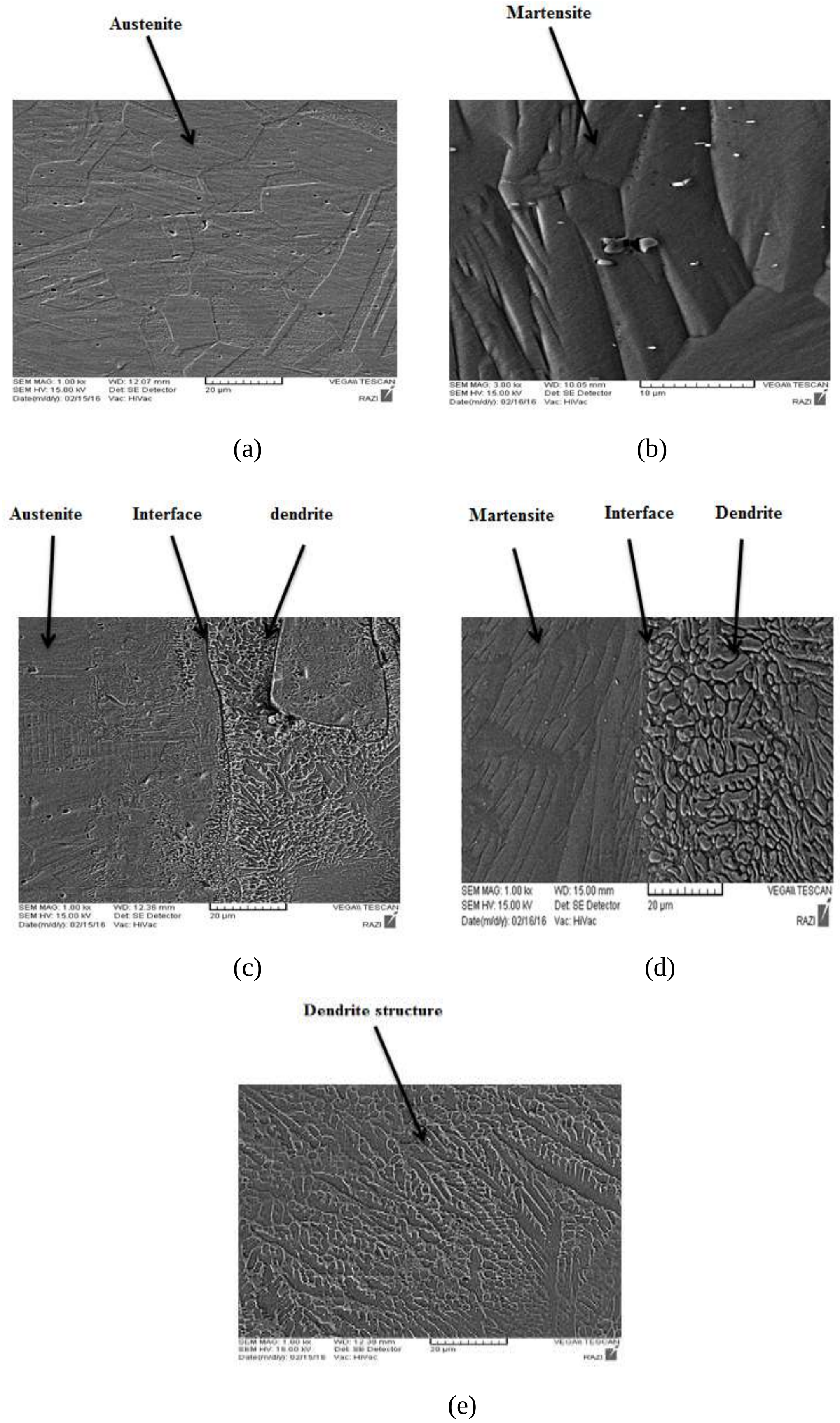
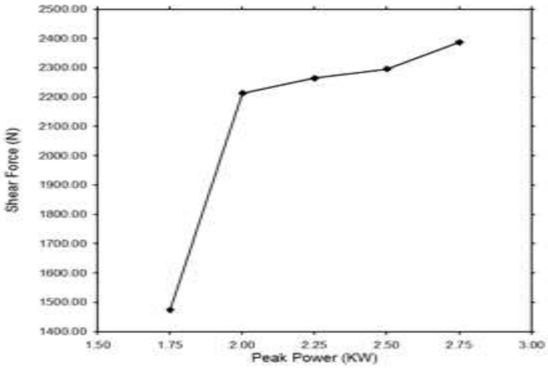
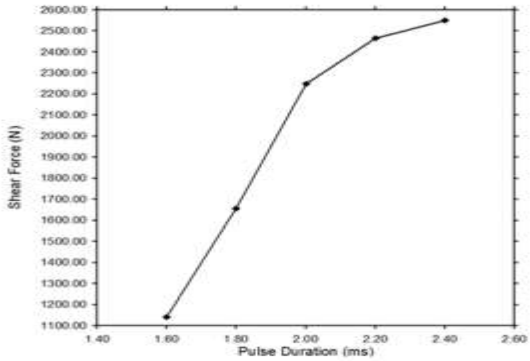


Fig (3) : The microstructure of sample G2/10, (a); B.M. (ASS), (b); B.M. (SMA), (c); HAZ (ASS), (d); HAZ (SMA), (e); W.Z. (ASS & SMA).



(a)



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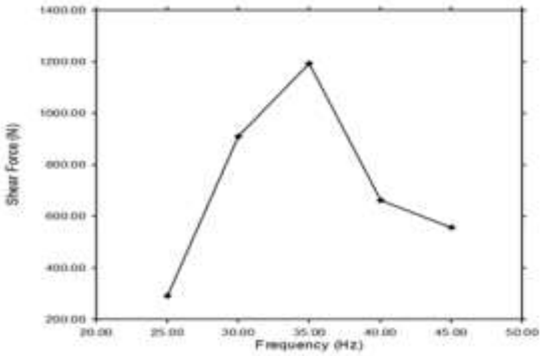
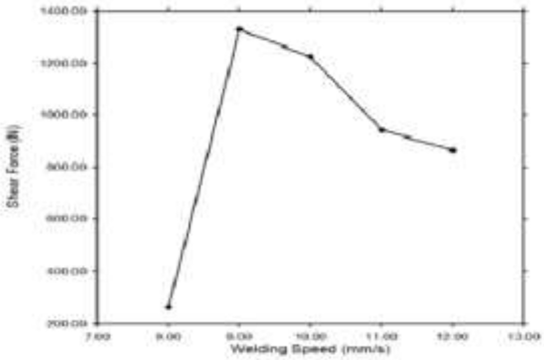


(c)



(d)

Figure (4): The relation between shear force and (a) peak power (b) pulse duration (c) frequency (d) welding speed

REFERENCE :-

Alberty Vieira L, Braz Fernandes FM, Miranda RM, Silva RJC, Quintino L, Cuesta A, et al."Mechanical behavior of Nd:YAG laser welded superelastic NiTi". Materials Science and Engineering A (2011);528:5560–5.

A.Costa, L. Quintino, R.M. Miranda, J. Laser App. 16 (4) (2004) 206.

Chan CW, Man HC, Yue TM. "Effects of process parameters upon the shape memory and pseudo-elastic behaviors of laser welded NiTi thin foil". Metallurgical and Materials Transactions A (2011);42A:2264–70.

E. Kannatey-Asibu,"Principles of laser materials processing ", Inc., Canada, (2009).

Falvo A, Furgiuele FM, Maletta C." Laser welding of a NiTi alloy: mechanical and shape memory behavior". Materials Science and Engineering A (2005);412: 235–40.

G. R. Mirshekari, A. Saatchi, A. Kermanpur, S.K. Sadrnezhaad., "Laser welding of NiTi shape memory alloy: comparison of the similar and dissimilar joints to AISI 304 stainless steel ," Optics & Laser Technology, Elsevier, USA, (2013).

Hall PC. Laser welding nitinol to stainless steel. In: Pelton A, Duerig T, editors. Proceedings of the international conference on shape memory and superelastic technologies SMST-2003. USA, California: SMST Society, Inc.; (2004). p. 219–28.

H. Park and H.Choi "Development of digital laser welding system for car side panels,"in laser welding , Rijeka, Croatia, (2010).

M.G. Li D.Q. Sun, X.M. Qiu, D.X. Sun, S.Q. Yin " Effects of laser brazing parameters on microstructure and properties of TiNi shape memory alloy and stainless steel joint," Materials Science and Engineering, Elsevier, china, (2006).

Narendra B. Dahotre., Sandip P. Harimkar "Laser Fabrication and Machining of Materials" Springer, Tennessee University, pp.3-10, 2008.

Predki W, Knopik A, Bauer B. "Engineering applications of NiTi shape memory alloys". Materials Science and Engineering A 2008;481–482:598–601.

Qiu XM, Li MG, Sun DQ, Liu WH."Study on brazing of TiNi shape memory alloy with stainless steels". Journal of Materials Processing Technology 2006;176: 8–12.

Salminen A., Piili H., Purtonen T.,"The Characteristics of High Power Fiber Laser Welding", Proc I Mech. E Part C: J Mech. Eng. Sci 224, 2010.

Uenishi K, Seki M, Kunimasa T, Takatsugu M, Kobayashi KF, Ikeda T, etal."YAG laser micro welding of stainless steel and shape memory alloy". Proceedings of SPIE 2003;4830:57–62 .