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Research Article

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Welding of AISI 304 to AISI 430 stainless steel by pulsed Nd-YAG laser

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Abstract The effect of pulsed Nd-YAG laser welding of AISI 304 to AISI 430 stainless steel was investigated. Laser parameters such as (peak power, pulse duration and welding speed) were changed and the change in properties was measured. Optical microscope was used to examine cracks, pores and weld geometry of welded samples. The results of tensile shear test for peak power, pulse duration and welding speed were 4.43 KN, 4.292 KN and 4.392 KN respectively. These values represent the best samples for each proposed parameter.

Keywords Laser welding, Stainless steel, Dissimilar metals welding.

1. Introduction

Laser, as a source of intensive light beam, starts to be implemented into industrial welding systems due to its advantages in comparison with classic methods, for example narrow heat affected zone, deep penetration, flexibility and many others. Besides the welding of compatible metals it is also possible to weld plastics [1].

Lasers are able to produce high energy concentrations because of their monochromatic, coherent, and low divergence properties compared to an ordinary light source. As a result, they can be used to heat, melt, and vaporize most materials. The processes for which lasers are commonly used include welding, cutting, surface modification (including heat treatment), and forming [2]. Dissimilar metals that have different physical properties (reflectivity, conductivity and melting temperature) often are joined in the welding of electrical conductors. Special techniques such as adding extra turns of one material to the joint as opposed to the other may be required to balance the melting characteristics of the materials. Some of these concepts also can be applied to structural and assembly welds, but the possibilities are much more limited [3]. While laser welds can easily be performed between two dissimilar metals, a thermocouple may easily be welded to a substrate without much damage to adjacent material. One can indeed simultaneously form the junction and attach the junction to the substrate. This method has been used in attaching measuring probes to transistors, turbine blades, etc. Laser weld not only achieves welding between dissimilar metals but also allows precise location of the weld [4]. The aim of the work is to predict and choose the best welding conditions suitable to produce a strong wed joint with minimum cracks and pores. The method is to choose a set of effective Nd:YAG laser beam parameters which are (peak power, pulse duration and welding speed), each parameter is changed while the other parameters held constant.

Choosing the best conditions depends on the resulted properties of the tested samples. Tests are mainly targeting the mechanical and microstructural properties.

2. Experimental procedure

Two types of stainless steel were used; austenitic stainless steel (304) and ferritic stainless steel (430) samples dimensions are (20 X 80 X 0.5) mm.

Materials were analyzed by using spectrometer (Spectromax) to predict the chemical composition.

Table 1: Chemical composition of the samples

Element wt%	C	Si	Mn	P	S	Cr	Ni	Ti	Mo	Cu	V	W	Fe
304 SS	0.0645	0.356	1.03	0.0540	0.0005	19.56	7.56	0.0074	0.0343	0.0512	0.0595	0.0295	Ball
430 SS	0.0579	0.107	0.281	0.0186	0.0005	18.16	0.0802	0.0010	0.0020	0.0133	0.0898	0.01	Ball

Dissimilar stainless steel samples were welded using pulsed Nd:YAG laser welding machine (IQL-10) at the (Iranian National Centre for Laser Science and Technology INLC), Tehran, Iran. The laser welding machine has a maximum mean laser power of 400 W, pulse frequency of (1-1000) Hz, pulse duration of (0.2-20) ms, pulse energy of (0-40) J, focusing optical system of 3 lenses with 75-mm focal length and the spot diameter of the laser beam 1.2 ± 0.1 mm.

Samples were prepared before welding process by grinding, polishing and cleaning of the surface by using acetone as a cleaning solvent.

After preparing samples surfaces, samples were put together in a lap-joint configuration with 20mm over lapping as in figure 1. The upper metal is austenitic stainless steel (304), the lower one is the ferritic stainless 430. Welding is done by using three different parameters (peak power, pulse duration and welding speed), each parameter was changed five times to predict the best values. Shear strength was measured for the welded samples in order to investigate the change in shear force with changing welding parameters. The cross head speed was 5 mm/s.

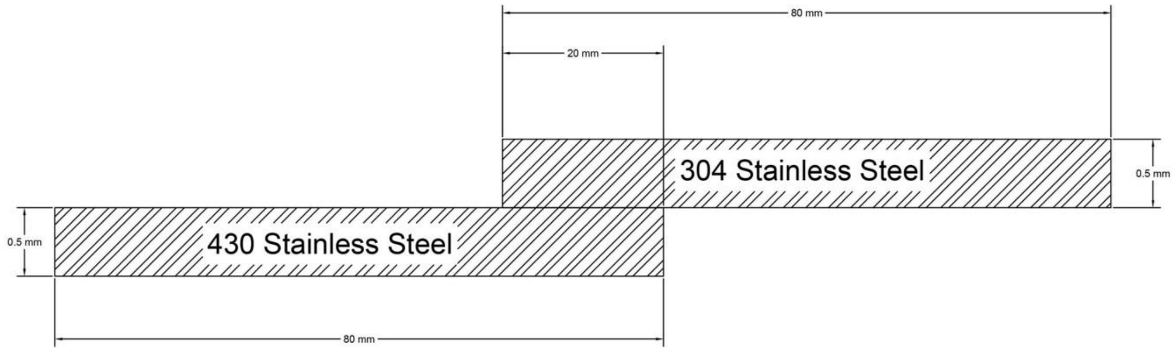

Figure 1

Microstructure of the welded samples has been tested by optical microscope for measuring penetration depth and the effect of laser welding on the structure of the weld zone and heat effected zone.

3. Results and discussion

3.1 The effects of peak power change:

As peak power increase, pulse energy also increase according to the equation (pulse energy = peak power x pulse duration) [5] which is included in table 2, also heat input is calculated as average power (pulse energy · PRR) divided by travel speed [6] as shown in the table 2.

Table 2: Changing of shear force with changing peak power

Sample number	Pulse energy (J)	Peak power (KW)	Pulse duration (ms)	Pulse repetition rate(HZ)	Welding speed (mm/s)	Heat input (J/mm)	Shear force (N)
A	9	1.5	6	20	7	27.5	310
B	10	1.67	6	20	7	31.03	3930
C	11	1.83	6	20	7	34.4	4000
D	12	2	6	20	7	37.9	4200
E	13	2.17	6	20	7	41.3	4430

The effect of peak power change on penetration depth of the welded samples is shown in figure 2 where the difference in penetration is obvious between the first sample (sample A) and the last one (sample E) this proves that with increasing peak power the penetration depth will increase and hence the shear strength will increase as well. Sample A shows that there is no penetration of the second piece of metal (austenite stainless steel 430) due to lack in peak power intensity as a result the tensile shear force is low while sample E have a deep penetration when the laser peak power increase to a level where evaporation of the metal begin forming a deep hole in the welding pool where it is effective in energy absorption and thus heat input increase therefore shear force of sample E is higher than the other samples as shown in figure 3.

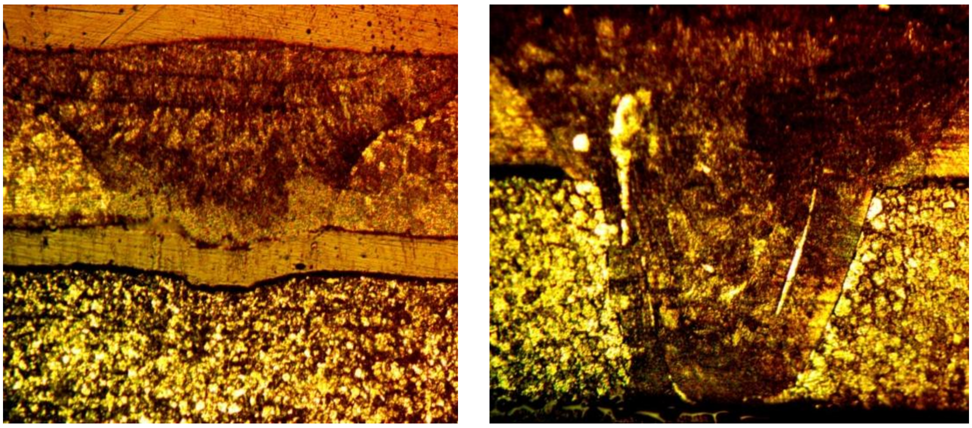

Figure 2: The effect of peak power change on penetration depth of the welded samples sample A) 1.5 KW, sample E) 2 KW.

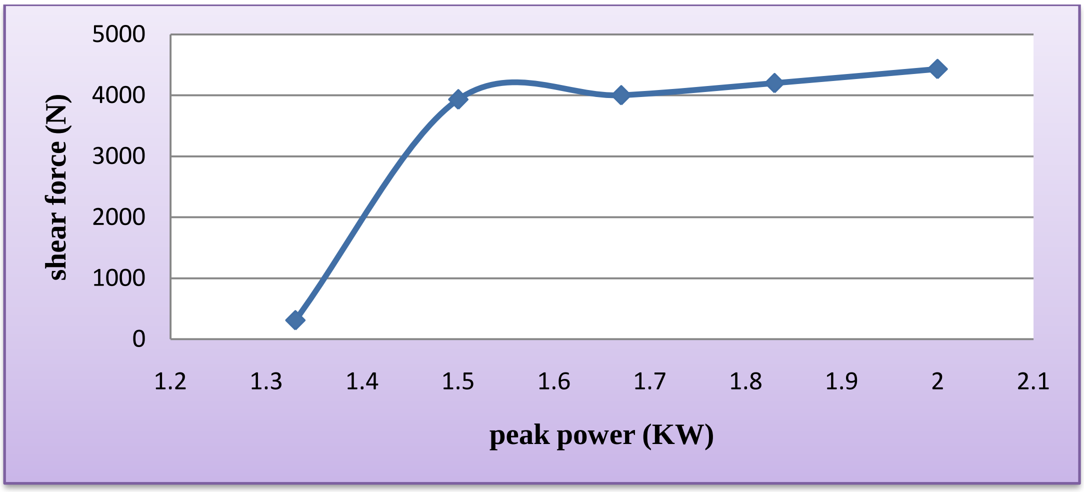

Figure 3: The effect of peak power change on shear force.

3.2 The effect of pulse duration change:

Table 3 and figure 4 show the relation between pulse duration and shear force for the welded samples. It is clear that the maximum value of shear force is (4292 N) for sample C1 where pulse duration is 6 ms. Also it is obvious that with increasing pulse duration, shear force rises due to increasing heat input which grows to the value that the joint couldn't withstand the load then the sample break, this force which broke the sample represents the strength of the joint.

Table 3: Changing of shear force as pulse duration change

Sample number	**Pulse energy (J)**	**Peak power (KW)**	**Pulse duration (ms)**	**Pulse repetition rate(HZ)**	**Welding speed (mm/s)**	**Heat input (J/mm)**	**Shear force (N)**
A1	11	1.5	4	20	7	41.3	4254
B1	11	1.5	5	20	7	41.3	4250
C1	11	1.5	6	20	7	41.3	4292
D1	11	1.5	7	20	7	41.3	3955
E1	11	1.5	8	20	7	41.3	3841

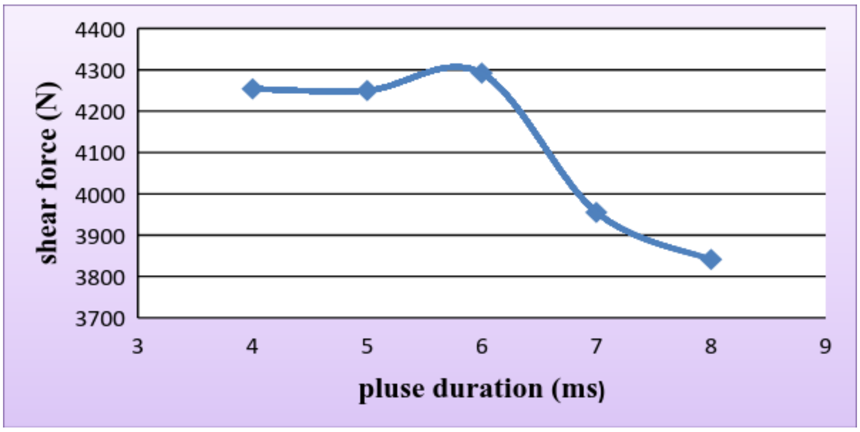

Figure 4: The relation between pulse duration and shear force.

Samples A1, B1 & C1 showed the maximum shear force and C1 is the optimum due to the uniform welding and free of porosity and defects as shown in figure 5.

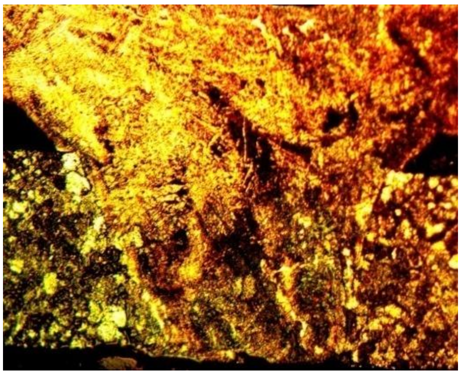

Figure 5: optical microscope image of welding zone

On the other hand sample D1 and E1 have low shear force where sample D1 have a crack at the end of the welding zone Figure 6. Sample E1 have a low penetration depth inspite of the high pulse duration due to the evaporation which reduce beam energy and thus lower heat input this result coincide with F. M. Ghaini et al. [7].

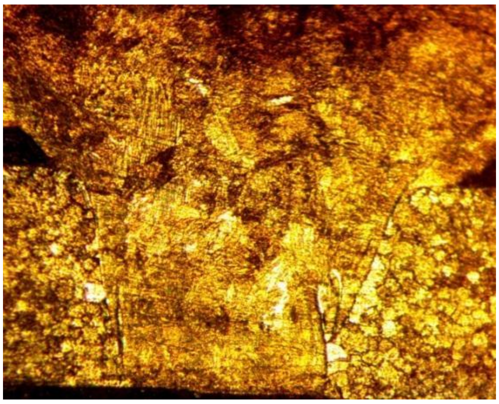

Figure 6: Optical microscope image of sample D1 showing a crack at the deep

3.3 The effect of welding speed change:

Table 4 shows the changing of shear force with changing welding speed.

Table 4: Shear strength of welded samples in case of welding speed change

Sample number	Pulse energy (J)	Peak power(KW)	Pulse duration (ms)	Pulse repetition rate(HZ)	Welding speed (mm/s)	Heat input (J/mm)	Shear force (N)
A2	11	1.5	6	20	6	48	4230
B2	11	1.5	6	20	7	41.3	4392
C2	11	1.5	6	20	8	35.82	4148
D2	11	1.5	6	20	9	30	4120
E2	11	1.5	6	20	10	26.66	4010

From figure 7, as welding speed rises the shear strength falls due to the lower time intervals needed for the welding to grow deeper in the sample and thus low heat input and consequently the strength decrease.

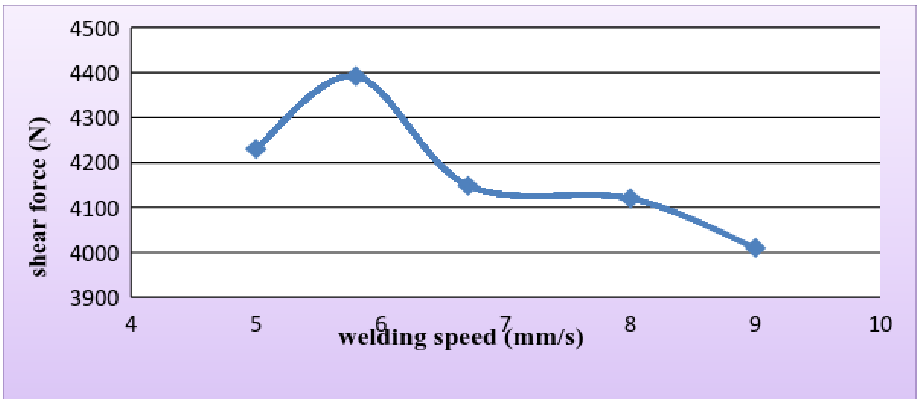

Figure 7: The relation between speeds of laser welding and shear force.

By increasing the speed of welding the time of exposure of the laser will decrease so that the heat input decrease and hence the shear strength decrease.

Welding zone width of samples C2, D2, E2 is lower than A2 and B2 samples and the shear strength is lower due to the high speed welding which lowers the strength of the weld joint and insufficient heat input required to melt weld zone.

3.4 Microstructure

Optical microscope was used to investigate the microstructure of the welded samples**.** This test is necessary to observe the changes in phases of the welded samples in the weld zone and heat affected zone (HAZ) after exposure to the laser beam.

Coarsening of ferrite grains can be noticed at both sides of the welding zone in the heat affected zone due to high temperature of laser welding as shown in figure 8. In the heat affected zone (HAZ) grains grow in size as peak power increases (heat input increases) because they absorb a certain amount of heat energy from the welding process.

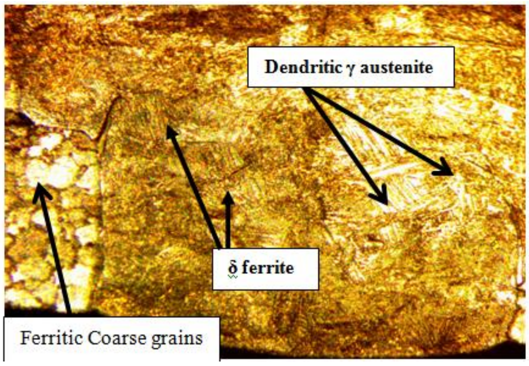

Figure 8: Microstructure showing Grain coarsening of ferritic stainless steel after welding.

In the welding zone, there is a dendritic microstructure resulted from the fast cooling rate figure 8. The austenite in the welding zone is transformed to delta ferrite due to the high temperature, then the austenite begins to precipitate at the grain boundaries of the delta ferrite, this diffusion process is controlled by cooling rate and in the fast cooling the delta ferrite does not have time to finish the phase transformation, as a result, there is a large amount of returned delta ferrite in the joint appeared as dark δ-Fe dendritic structure in austenite matrix [8-9].
The region next to FZ boundary shows fully δ-ferrite microstructure at high temperatures. Upon cooling, due to the high cooling rate of LBW, the transformation of δ-ferrite to austenite at elevated temperature is suppressed and therefore, no martensite phase is formed at the grain boundaries at this zone. The ferrite grain growth at the HAZ region can be quite dramatic. Figure 8 shows the microstructure of a welded sample indicating these two phenomena (i.e. no martensite formation and dramatic grain growth) as well as fine distribution of precipitates in this zone.

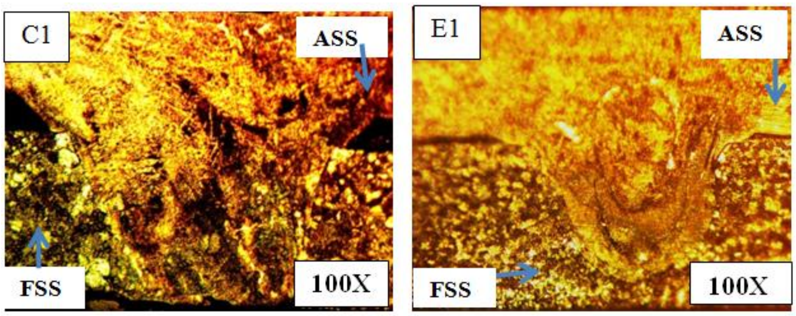

Figure 9: The change in grain size of the welded sample by changing pulse duration in the HAZ C1) 6 sec E1) 8 sec.

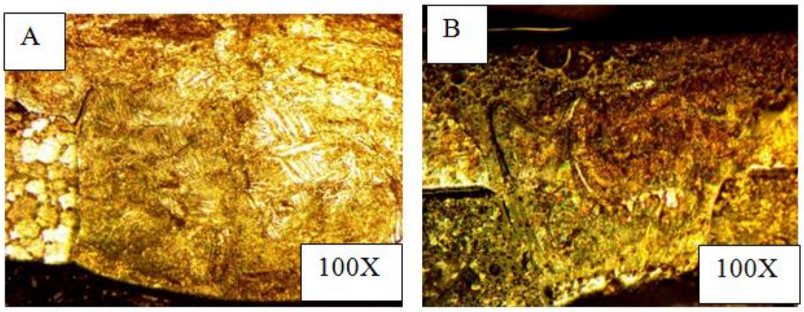

Figure 10: The effect of welding speed on grain growth in HAZ for the welded samples A) 7 ms B) 8 ms.

As peak power increases the microstructure becomes more dendritic in which the heat input increases and hence more of the austenite transforms to delta ferrite and by solidification it returns in to austenite and more returned delta ferrite is formed.
Figure 9 illustrates the change in grain size of the welded sample by changing pulse duration in the HAZ. By increasing the pulse duration of the laser, the grain size begins to rise until reaching its maximum in sample C1, after that the grain size drops reaching its minimum in sample E1 because of the evaporation in the welding zone due to the high pulse duration, this will reduce the heat input to the HAZ and hence reduce the grain size.
From figure 9 which shows the effect of welding speed on grain growth in HAZ for the welded samples in which by increasing welding speed the grain growth decreases due to reduction in heat input and rapid heating and solidification. Similar results were achieved at the research study by Uğur Çalıgülü *et al* [10].

4. Conclusion

1. Nd:YAG laser welding of dissimilar 304 stainless steel to 430 stainless steel was studied by changing laser beam parameters in order to predict the best value of each parameter.
2. Shear strength, microstructure test were done to investigate the change of properties with changing welding parameters

3. The best sample in shear test is sample (E) which has the maximum shear force (4430 N). Its welding conditions are (peak power 2.17 KW, PRR 20 HZ, welding speed 7 mm/s, pulse duration 6 mms).
4. As peak power increases shear force and microhardness are increased. Also there is a noticeable grain growth of the ferritic heat affected zone.
5. As pulse duration increases shear force and ferrite grain size in the heat affected zone are increased until reaching optimum value C1, then the shear strength and grain size begin to fall.
6. As welding speed increases the shear force decrease. Also by increasing welding speed the grain growth in the ferritic heat affected zone is decreased.

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