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Investigation on Mechanical Properties of Pulsed Nd:YAG Laser Welding on AISI 304 Stainless Steel to AISI 1008 Steel

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Abstract. Product with low cost, lightweight and enhanced mechanical properties were the main reasons welding dissimilar materials thrived by most of the industries. The laser welding technique which has high-energy density beam was found suitable of carrying this task. This paper attempts to investigate welding of AISI 304 stainless steel to AISI 1008 steel through Nd:YAG pulse laser method. The main objective of this study was to find out the weldability of these materials and investigate the mechanical properties of the welded butt joints. Peak power, pulse duration and weld speed combinations were carefully selected with the aims of producing weld with a good tensile strength, minimum heat affected zone (HAZ) and acceptable welding profile. Response surface methodology (RSM) approach was adopted as statistical design technique for tensile strength optimization. Statistical based mathematical model was developed to describe effects of each process parameters on the weld tensile strength and for response prediction within the parameter ranges. The microstructure of the weld and heat affected zones were observed via optical microscope. The results indicate the developed model can predict the response within ±9% of error from the actual values.

Introduction

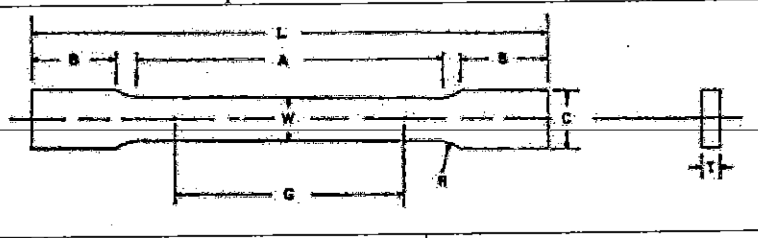
Rapid advancement in welding technology offers a promising quality of joining for dissimilar materials. Eventhough joining of dissimilar materials is one of the challenging tasks facing by manufacturers, the technological sophistications in laser welding able to cope with this problem. Commonly, the ultimate aims of many industrial consumers in their preference towards laser welding process are to produce products with low cost, lightweight and improved mechanical properties. Laser welding is used extensively due to its small and narrow welding zone. Due to narrow focusing zone of the laser beam, a very low heat input is produced in the weld bead which in turn creates no HAZ or a very narrow HAZ [1]. The selection of filler metals, fixtures and equipments, along with suitable preparation of samples and welding parameters can lead to creation of a sound joint. In order to laser weld two dissimilar materials with two different metallurgical and mechanical properties, the selection of proper welding variables is very important [2]. The variations in the material properties of dissimilar materials, such as laser beam attractions, melting points and heat conductions can influence on the quality of the joint [3]. Numerous researches had been done in laser welding by huge number of researchers. Nevertheless, limited investigations were carried out for laser welding of AISI 304 austenitic stainless steel to AISI 1008 low carbon steel. Anawa [8], investigated the welding dissimilar material of austenitic stainless-steel AISI-316 and low carbon steel AISI-1009. In his study, Taguchi method was used for designing the experiments with L25 orthogonal array. DOE was selected based on the three welding parameters with five levels each namely laser power, welding speed and defocusing distance. He found that the welding pool and penetration are controlled by the rate of heat input, which is a function of laser power and welding speed. The focusing parameter is mostly affecting the weld pool surface width. Welding speed and laser power also have the strong effect on the fusion area size. The focusing position parameter has insignificant effect. Thus, it can be concluded that the laser welding can produce small welding pool to reduce HAZ effect. Laser welding on two dissimilar metals of 304 austenitic stainless steel and 420 martensitic stainless steels was found studied by Barretta [9]. A consideration was made on the effects of laser position on the properties of these two dissimilar metals. In his study, the effects of deviation of the laser diameter in the range of 0.1–0.2 mm away from both materials were investigated. He found that the weld geometry was not affected by the change of laser diameter. However, the HAZ microhardness of the 420 martensitic stainless steel reduced if the laser position was moved toward the austenitic stainless steel. The optimum properties were found when the laser was positioned in the interface of both metals. In this study, weldability and weld tensile strength of AISI 304 austenitic stainless steel and AISI 1008 low carbon steel were investigated. The effects of machining parameters in particular laser peak power (kW), pulse duration (ms) and welding speed (mm/min) were also considered. Response surface methodology (RSM) was utilised to optimize the tensile strength performance where total 20 experiments with two duplications were conducted and the factorial design is full factorial design with all combinations of the factors at the two levels was applied.

Experimental procedure

Workpiece plate of AISI 1008 steel and AISI 304 stainless steel with the nominal thickness of 1mm was cut according to ASTM-E8M standard for tensile test as shown in Table 1. Half of each specimen length (L/2) consists of AISI 1008 steel and AISI 304 stainless steel. The chemical compositions of both materials are shown in Table 2. The pulsed Nd:YAG Model GSI - JK300HPS laser machine was used in welding butt joint of these dissimilar steels. A specially designed clamping device was used to align both ends AISI 304 stainless steel and AISI 1008 steel. The gap in butt joint was maintained at 10% of the workpiece thickness using shim liner to prevent beam from defocused which could lead to formation of wide bead.

The laser beam with controlled weld spot size 480μm was focused at the butt joint where peak power, pulse duration, and welding speed were varied to observe the effects of different parameters setting on the welds tensile strength and their microstructure changes. The following parameters were controlled in the experiments: frequency = 15 Hz, focus length (Z-axis) = - 0.325mm (clear spot) and shielding gas of argon = 10 L/min. In this study, optical microscope was used to observe welding microstrcuture, its profile and HAZ of the selected samples. The TestometricTM M500 100kN machine was used for tensile test.

Table 1: The specific dimension of ASTM – E8M [4]



Dimensions	Sub-size Specimen
	6mm
G – Gage length	25.0 ± 0.1
W - Width	6.0 ± 0.1
T – Thickness	Maximum 6mm
R – Radius of fillet	6
L – Overall length	100
A – Length of reduced section	32
B – Length of grip section	30
C – Width of grip section	10

Table 2: Chemical compositions of AISI 1008 and AISI 304

	C	Si	Mn	P	S	Cr	Ni	Nd	Mo	Si	Fe
AISI 1008	0.093	0.027	0.210	0.001	0.005	0.043	0.065	0.024	0.006	~	Bal.
AISI 304	0.08	0.75	2	0.045	0.03	18	8	~	~	0.75	Bal

Design of the experiment

As accordance with the literature consulted and previous researcher works [5, 7, 8, 9], there were three main parameters choosen as shown in Table 3 in this investigation. The ranges of the parameters were selected according to the preliminary experiments conducted where parameters setting that first to yield an acceptable tensile strength and weld quality were taken as a low level setting. The welding process was studied with the standard response surface methodology (RSM) design called central composite design (CCD) that useful for the modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimise this response [12, 13, 14].

In this study, total 20 experiments were conducted and the factorial design is full factorial design with all combinations of the factors at the two levels while the star point corresponds to an α value was 1 hence called face centered, CCD [6]. As aforementioned, there were certain parameters had been controlled to ensure it runs according to the fixed experimental setting and at the same time laser power not exceeding its maximum limit of 300W. The Minitab 16 software was used to assist the response surface methodology analysis.

Table 3: Design scheme of process parameters and their levels

Factor symbol	Parameters	Levels	
		Low(-1)	High(+1)
Pp	Peak power, Pp (kW)	0.8	1.4
w	Pulse duration, w (ms)	2.5	3.5
F	Welding speed, F (mm/min)	86.4	172.8

Results and Discussion

There were 20 experiments conducted in two duplications and the average values of tensile strength along the design matrix were tabulated in Table 4. In this study, data analysis and goodness of fit checking on the model is very much important. Analysis of variance (ANOVA) was performed to check the adequacy of the developed regression model.

Table 4: Design of experimental matrix and results for the weld tensile strength

Exp. No.	Process parameters			Response values		
	Peak power, Pp [kW]	Pulse duration, w [ms]	Weld speed, F [mm/min]	Tensile strength (Mpa) I	II	Average
1	0.8	2.5	86.4	288.83	286.33	287.58
2	1.4	2.5	86.4	326.17	320.00	323.09
3	0.8	3.5	86.4	315.83	316.33	316.08
4	1.4	3.5	86.4	329.33	328.33	328.83
5	0.8	2.5	172.8	281.67	291.50	286.59
6	1.4	2.5	172.8	328.33	324.83	326.58
7	0.8	3.5	172.8	328.67	311.67	320.17
8	1.4	3.5	172.8	330.50	330.83	330.67

9	1.1	3.0	129.6	330.00	327.17	328.59
10	1.1	3.0	129.6	329.67	334.33	332.00
11	1.1	3.0	129.6	334.67	330.33	332.50
12	1.1	3.0	129.6	328.67	326.17	327.42
13	0.8	3.0	129.6	304.33	280.83	292.58
14	1.4	3.0	129.6	325.67	324.83	325.25
15	1.1	2.5	129.6	327.17	326.17	326.67
16	1.1	3.5	129.6	329.33	330.83	330.08
17	1.1	3.0	86.4	327.33	333.50	330.42
18	1.1	3.0	172.8	332.00	327.17	329.59
19	1.1	3.0	129.6	331.67	322.00	326.84
20	1.1	3.0	129.6	330.83	332.00	331.42

Table 5: Results of ANOVA for developed model (after backward elimination)

Source	Tensile Strength Model	
	F-value	p-value
Regression	66.29	0.000
Linear	78.29	0.000
Square	85.29	0.000
Interaction	23.29	0.000
Lack-of-Fit	4.64	0.059

S = 3.82790
Predicted residual error of sum of squares (PRESS) = 406.655
R-Sq = 94.65%
R-Sq(pred) = 90.09%
R-Sq(adj) = 93.22%

Analysis of Tensile Strength

The fit summary shows that the quadratic model is more significant for analysis of tensile strength. The results of ANOVA reduced model as shown in Table 5 concluded that the data are well fitted in this model for tensile strength optimisation. The value of R^2 and R^2 (adj) obtained over than 90%. This means that the regression model produced a good explanation on the relationship between the independent variables (process parameters) to the tensile strength at 95% confident level [11]. The R^2 predicted value is 90.09% which means that the predicted model is slightly lowered in accuracy compared to the real result. The value of S is the positive square root of MSE (mean square error) and also an estimate of the average variability about the regression line where lower value gives a better equation prediction over response [11]. The S value obtained was 3.82790 and considered lower for this model. In this study, the associated p-value for the model is lower than 0.05 (α=0.05 or 95% percent confidence) considered as significant to the model while the lack of fit term is non-significant as desired. After eliminating the non-significant terms, the final response equation for tensile strength is given as follow:

$$\text{Tensile strength} = -120.088 + 560.909\,Pp + 62.9654\,w - 175.667\,Pp2 - 43.5458Pp.w \quad (1)$$

Fig. 1 shows the estimated response surface for tensile strength in relation to the design factors of peak power and pulse duration. This figure depicts the tensile strength increases as the peak power increased until the peak point at 1.1kW and pulse duration 3.5ms. Both peak power and pulse duration have a greater influence over tensile strength characteristic. Thus, the maximum tensile strength is indicated at peak power 1.1kW and pulse duration 3.5ms with the hold values weld speed

129.6mm/min. The normal probability plot of the residuals for tensile strength as shown in Fig. 2 concludes that the errors are normally distributed as residuals falling within the straight line. Fig. 3 shows the plot between the predicted values calculated from the eliminated model with the actual data. From the plot, it can be seen that the eliminated model is fairly well fitted with the observed value but it is not perfect on two points.

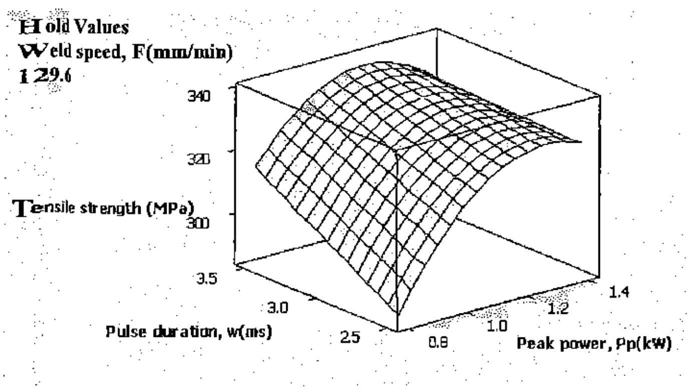


Fig. 1: Surface plot of tensile strength versus welding parameters.

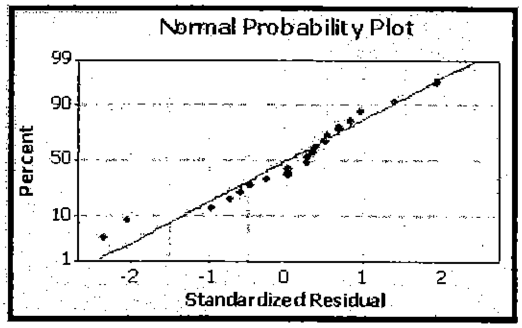


Fig. 2: Normal probability plot residuals for tensile strength

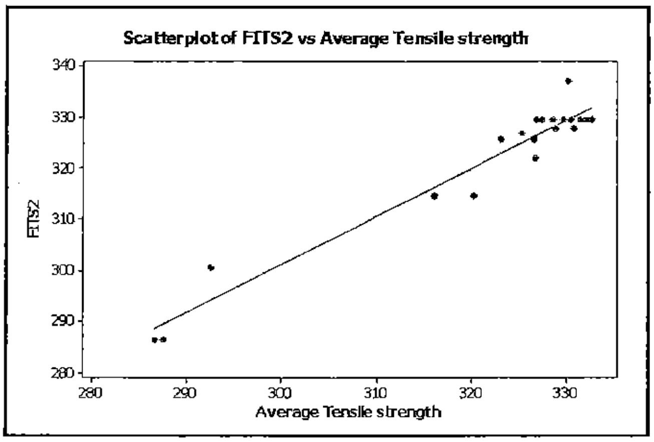


Fig. 3: Plot of actual versus fits2 (fits is predicted response from the elimination equation) data.

Results of Experimental Validation

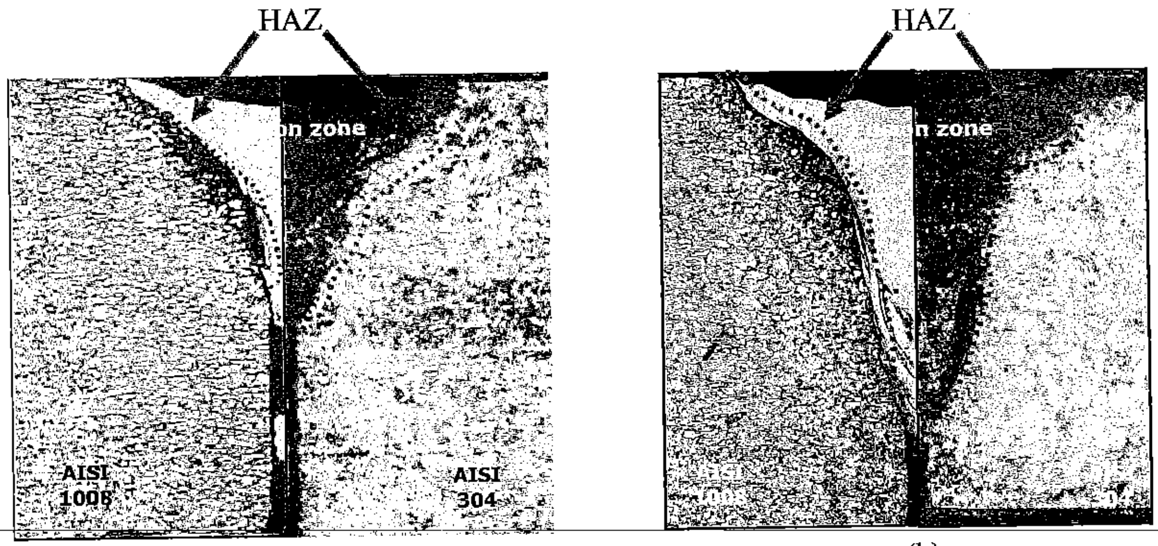
Several experiments were repeated randomly to verify the validity of the developed quadratic regression model using parameters setting from experiment no. 1, 5 and 11. From data in the Table 6, it can be observed that the calculated error is small where the error calculated between experiments and predicted values for the tensile strength are in range of 7.5% to 8.7% or lie within ±9%. Obviously, these results have confirmed excellent reproducibility of the experimental conclusions.

Table 6: Results of the experimental validation

Exp. No	Tensile Strength [Mpa]		
	Predicted	Experiment	|Error (%)|
1	286.53	263.50	8.7
5	286.53	266.50	7.5
11	329.55	303.67	8.5

Analysis of Microstructure

The microstructure analysis solely focused on the specimen with the highest and lowest tensile strength. Different etchants were used to reveal the microstructure of AISI 1008 and AISI 304. Etching was done one after another by 4-6 swabbing strokes at the region of AISI 1008 and followed by AISI 304. Table 4 shows the highest tensile strength was obtained at the specimen no.11 with peak power 1.1kW, pulse duration 3ms, and weld speed 129.6mm/min while the lowest tensile strength was occurred at the specimen no.1 with peak power 0.8kW, pulse duration 2.5ms and weld speed 86.4mm/min. Figure 4(a) and 4(b) show the HAZ obviously formed at the fusion zone adjacent to low carbon steel AISI 1008 and less applicable at the stainless steel side. The reason why the HAZ at the AISI 304 boundary was minimum is due to the thermal conductivity of this material is far lower than AISI 1008 low carbon steel. Low thermal conductivity can bring good energy absorption on the material. The high cooling rate and high penetration at the weld pool of specimen no. 11 favors the formation of a fine microstructure and normally improved mechanical properties [12, 13]. Notwithstanding, too high cooling rates could generate the martensitic phase in the microstructure, and this phase could jeopardize some of the mechanical properties of the weld [10]. In the specimen no. 1, there was only 50% of weld penetration and the tensile test has resulted 287.58Mpa and the break point was occurred within the low carbon steel region adjacent to the fusion zone. Poor penetration and slimmed formation of the fusion zone were the main reasons of low tensile strength at the specimen no. 1. Thus, it was important to ensure that proper setting of the laser welding parameters have been followed in order to produce weld with improved mechanical properties.



(a) (b)

Fig. 4: The weld microstructure under optical microscope 20X: (a) specimen no.1; (b) specimen no.11

Summary

Pulse Nd:YAG laser welding of stainless steel to low carbon steel has been successfully conducted in this study. The main factors affected the tensile strength and weld bead geometry were the peak power, Pp followed by the pulse duration, w. To achieve high quality of weld joint, peak power must be set higher than 0.8kW for the 1mm thickness steel joining. The best peak power value is 1.1kW where it produces the strongest weld strength. Welding speed and percentage of weld bead overlap contributed to minor effects on the tensile strength performance. In this study, the analyses of variance revealed that the peak power (Pp), pulse duration (w), quadratic effect of peak power (Pp^2) and the interaction of peak power*pulse duration (Pp*w) are the most influential parameters on predicting the weld tensile strength. The confirmation tests showed that the error between experimental and predicted values of tensile strength are within ±9% or lie in 7.5% to 8.7% range. The dissimilar joints performed also found to produce better tensile strength compared to the tensile strength of the base material of AISI 1008 steel.

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