EFFECT OF PROCESSING PARAMETERS ON ZERO-GAP LASER WELDS MADE ON MULTI-COATED STEEL

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Abstract

We are presenting a study on zero-gap CO_2 laser lap welding of multi-coated steel using alloying additives. Steel coated with multiple elements like zinc, nickel, aluminum, epoxy resin etc., being considered for use in fuel tanks for newer alternative fuels, was experimented and the effects of welding parameters on properties like porosity, hardness, bead quality etc. was investigated. An L-9 Taguchi experiment design was used to incorporate multiple multi-level processing factors. The results indicated optimal operating window for the material, which can be further optimized for real-time production.

Introduction

With increasing fuel costs and environmental pollution, there has been a strong move towards design and development of leaner and greener automobiles. This has also led to the development of newer alternative fuels for example, alcohol based fuels, bio fuels etc. Conventionally, the material for fuel tank in automobiles has been high density polyethylene (HDPE) which has the advantages of being a) light in weight and b) durable with gasoline. However it has been observed in ongoing research that HDPE is not as durable with newer alternative fuels, especially the alcohol based ones.

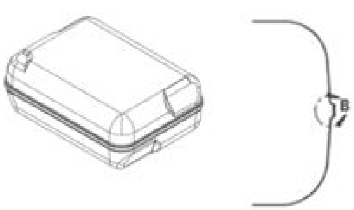

Figure 1 Flangeless fuel tank design

This finding has brought back steel and other metal based materials in picture as possible materials for new fuel tank manufacturing in future. Having identified this future potential, the Strategic Alliance for Steel Fuel Tanks (SASFT), based in Michigan is already investigating the feasibility of making a new type of fuel tank for alternative fuels. The design under consideration eliminates the huge flange (conventional steel fuel tank design) that is needed for resistance welding of the tank [1, 2]. Their new flangeless tank design, as shown in figure 1, is expected to reduce the weight and manufacturing cost of steel fuel tanks significantly. Keeping this new design in mind, our study investigates laser lap welding of a multi-coated steel, provided by SASFT, for fuel tank manufacturing. In addition to a zinc coating of about 70 gm. per sq. m of surface area, the steel has multi-material protective coating to suit the design requirements of new generation of fuel tanks. The composition and ranges of these coatings are given in table 1.

Table 1 Range of composition of different materials in steel coating

Coating Material	Composition Range (%)
Epoxy resin	33.0 - 37.0
Aluminium	22.0 - 25.0
Nickel	21.0 - 24.0
Phosphorous	1.0 - 4.0
Magnesium Oxide	1.0 - 4.0
Silicone Dioxide	1.0 - 4.0
Clay	1.0 - 4.0
Polytetrafluoroethylene	0.5 - 2.0
Oleic Acid	0 - 1.0

Since we were dealing with a problem involving coated steel, which had significant amount of zinc in it, we decided to extend our alloy based welding approach [3, 4] in this study. The basic approach we decided to follow was to incorporate an external alloying medium consisting of copper between steel sheets in lap configuration. By doing this we wanted to make sure that there was zero gap between the steel sheets before laser lap welding. We also decided to use a Taguchi experimental design for our study, the details of it are given below.

Taguchi Experimental Design

Taguchi technique is a tool often used by engineers to design robust systems and/or processes. In other words, system or process control parameters can be optimized for minimum noise, cost and high performance and quality [5].

This technique is a subset of the comprehensive Design of Experiments (DOE) methods. It is unique and attractive to most practical applications due to its capability of optimizing multiple multi-level parameters without the need for a complete DOE. For example, if a system has four input parameters with three levels of each then according to DOE theory a set of 3^4 = 81 experiments will be required to study and optimize the system. However, Taguchi method requires only 9 experiments for a quick understanding of process sensitivity, variability and optimal control parameters. With reduced number of experiments the degree of error in Taguchi method is definitely higher, but at the same time easy and quick understanding of complex processes is a huge benefit in real time manufacturing situations.

The reduced number of experiments in Taguchi method is due to the use of simple and standard orthogonal arrays [6] to study large number of variables with a small number of experiments. The output being a set of linear graphs of dependent variables and/or signal to noise ratio (S/N ratio) plotted against individual control factors. Taguchi method reveals the dominant control factors along with optimal values of each control factor for achieving desired values of dependent parameters. Typically a “smaller the better” or “larger the better” type of analysis is performed for each dependent parameter. If needed, combined effects of control factors on dependent parameters can also be performed.

In most practical cases the results of Taguchi analysis has been found to be valid over the experimental domain defined by the range of control factors. As an example a standard Taguchi orthogonal array for analysing four variables (A,B,C,D) with three levels each (1,2,3) is shown in figure 2. It is also termed as a L-9 Taguchi matrix.

	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Figure 2 L-9 Taguchi matrix

In our study, we used the same L-9 matrix to study the effects of four laser welding control parameters (independent variables) viz. laser power (P), welding speed (S), helium shielding gas flow rate (G) and mesh size of copper powder in alloying medium (C). The dependent weld parameters were a) porosity b) hardness c) heat affected zone (HAZ) hardness and d) bead width. Laser welding experiments were then designed accordingly and performed on the steel samples.

Experimental Details

0.8 mm thick coated steel sheets, supplied by SASFT, were first cut into 5 inch x 1.5 inch size coupons. The coupons were then cleaned with acetone and dried in air. Coupons were then selectively coated with a solution of 100, 200 and 325 mesh size copper powder and arranged in lap configuration for mounting in a welding fixture. A schematic of the experimental setup is shown in figure 3.

Figure 3 Laser welding setup

Once mounted, the samples were then welded using a 6 kW CO_2 laser in presence of helium as shielding gas. The welding parameters viz. laser power P, welding speed S and helium shielding gas flow rate G were varied for each weld according to the Taguchi L-9 matrix shown in table 2 below.

Table 2 Experimental design based on L-9 Taguchi matrix

Weld Identifier	P (W)	S (ipm)	G (SCFH)	C (mesh)
A	3700	85	30	100
B	3700	95	40	200
C	3700	105	50	325
D	4150	85	40	325
E	4150	95	50	100
F	4150	105	30	200
G	4600	85	50	200
H	4600	95	30	325
I	4600	105	40	100

In order to study the effect of addition of alloying medium, another weld J was made with exact same parameters as weld F, but only without copper alloying medium. After welding, the samples were cut, cold mounted, polished and etched for metallurgical analysis.

Results and Discussion

The mounted weld samples were studied for porosity, hardness and bead width. The observed values of these dependent properties are given in the table 3.

The observed values of porosity, hardness and bead width were then used to perform L-9 Taguchi analysis using a computer code [7] in order to find out the optimal welding parameters that would achieve minimum porosity, bead width and hardness. The analysis was also expected to indicate the dominant processing factors or in other words, the welding parameters to which the process was more sensitive.

Table 3 Observed values of dependent properties

Weld	% Poros -ity	Bead Width (mm)	Weld Avg. Hardness (GPa)	HAZ Hardness (GPa)
A	0	1.5	2.055	0.800
B	0	1.25	2.154	0.910
C	0	1.75	2.239	0.829
D	0.1	1.5	2.206	0.857
E	0.2	1.5	2.121	0.838
F	0	1.25	2.117	0.869
G	0	1.6	2.161	0.830
H	0	1.6	2.141	0.878
I	0	1.3	2.209	0.907
J	60	No Bead	3.803	0.871

It was interesting to see the difference in weld porosity between samples A through I and sample J. From figures 4a and b it was very clear that without copper alloying medium the weld porosity was significantly high, mainly due to uncontrolled boiling of zinc during welding.

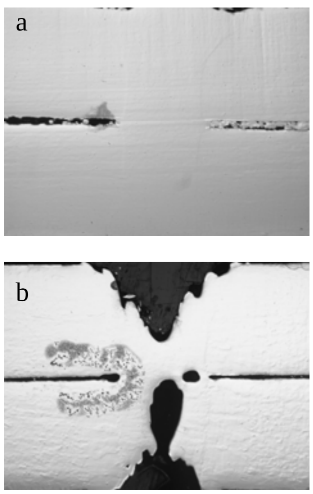

Figure 4 Comparison of weld porosity a) weld made with copper alloying medium b) weld made without copper alloying medium

A sample outcome of Taguchi analysis for bead width is shown in table 4 below.

Table 4 Sample result of Taguchi analysis for bead width

Factor	Level	noise (dB)	Main Effect (%)
Power (P)	3700	7.101	4
	4150	7.101	
	4600	7.101	
Speed (S)	85	5.49	13
	95	7.49	
	105	8.33	
Gas (G)	30	7.49	*41*
	40	9.5	
	50	4.31	
Copper (C)	100	7.49	*41*
	200	9.5	
	325	4.31	

Outcome in the above table indicated that during laser welding the dominant factors for controlling the bead width of welds were, shielding gas flow rate and the size of copper powder in the alloying medium. In other words the variability in bead width was mainly caused by gas flow rate and amount of copper. Laser power and welding speed did not play a significant role in controlling this property. The table also indicated optimal welding parameters to attain the least possible bead width (assumed to be 1.0 mm in this case, considering a beam diameter of 0.6 mm). The optimal welding parameters and dominant factors are shown in *italics* in table 4.

Similar results were obtained for each dependent property. The minimum achievable porosity was considered to be 0.001% and minimum achievable hardness was considered to be the base material hardness of 0.761 GPa. A summary of complete findings is given in table 5. The values shown in each row of table 5 were the optimal processing parameters for minimising the listed weld quality parameter. Also, the shaded boxes indicated the dominant factors for controlling the listed weld quality parameter.

Table 5 Summary of results from Taguchi analysis

Weld quality parameter	Optimal Processing parameter			
	P	S	G	C
HAZ Hardness	3700	85	50	100
Avg. Weld Hardness	-	85	30	100
Weld Porosity	3700	105	30	200
Bead Width	-	105	40	200

In addition to the Taguchi analysis, the observed values of weld properties viz. porosity, hardness and bead width were plotted against the welding parameters to get an understanding of the trend in which the these dependent properties behaved.

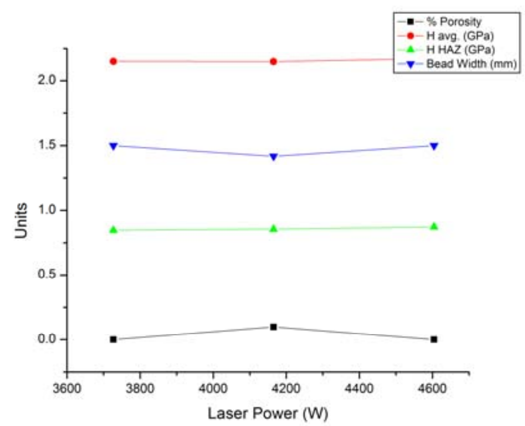

Figure 5 Effect of laser power

Figure 5 shows how porosity, hardness and bead width changed with increasing laser power. There was no significant change observed in weld and HAZ hardness with changing laser power. Bead width appeared to increase with laser power, which is logical. Porosity was found to be lower at lower laser power.

Figure 6 shows how porosity, hardness and bead width changed with increasing welding speed. As with laser power, there was no significant change in weld and HAZ hardness with changing welding speed. Bead width appeared to decrease with higher welding speed, which is also logical. Porosity was found to be lower at higher welding speeds.

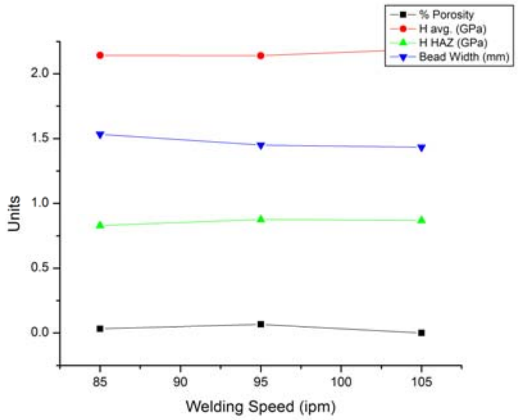

Figure 6 Effect of welding speed

Figure 7 shows how porosity, hardness and bead width changed with increasing flow of helium shielding gas. Unlike previous cases, all properties showed sensitivity to change in gas flow rate. Weld hardness increased with gas flow rate while HAZ hardness appeared to decrease. Weld porosity increased with gas flow. This was due to increased possibility of gases getting trapped in the weld. Bead width also appeared to increase with gas flow rate, this was mainly due to higher positive pressure exerted by shielding gas on the molten metal in weld pool.

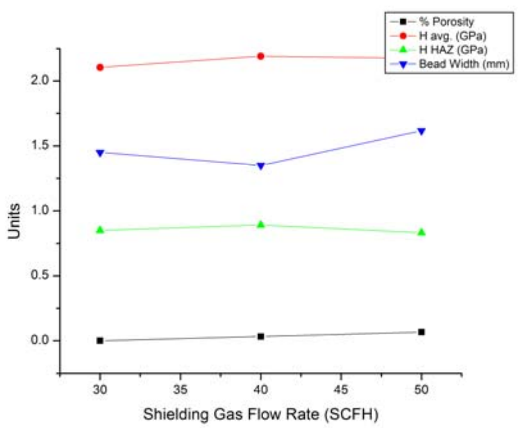

Figure 7 Effect of shielding gas flow rate

Figure 8 shows that the alloying solution with copper powder of mesh size of 200 gave a weld with least porosity and bead width. Weld hardness appeared to increase a little bit with copper powder mesh size. HAZ hardness did not appear to change significantly.

It should now be noted here that the graphical analysis results agree to a good extent with those obtained from detailed Taguchi analysis.

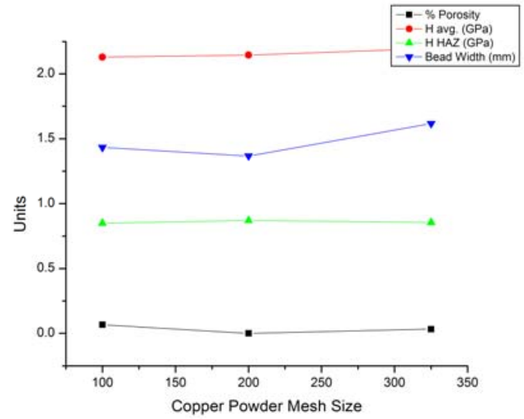

Figure 8 Effect of copper powder mesh size

Conclusions

We conclude that for laser welding of this new multi-coated steel, the processing parameters in order of importance are:-

1) Shielding gas flow rate
2) Mesh size of copper powder
3) Laser power
4) Welding Speed

After combining the results of our analyses, we can suggest that a gas flow rate of 40 SCFH and copper powder mesh size of 200 would be the critical parameters for stable laser lap welding of steel.

Addition of copper does alleviate the problem of zinc induced porosity, just as we expected. Laser power should be kept around 3.7 kW and welding speed should be adjusted accordingly.

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