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EFFECT OF PROCESS PARAMETERS ON THE WELD QUALITY IN LASER WELDING OF AZ31B MAGNESIUM ALLOY IN LAP JOINT CONFIGURATION

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Abstract

Magnesium is the lightest structural metal; therefore it has been used in a variety of industries such as automotive, aerospace, electronics and defense. Among different joining processes, laser welding is advantageous due to its low heat input, high depth-to-width weld ratio and good mechanical properties. In this study, a fiber laser is used to weld AZ31B magnesium alloy in a lap joint configuration. Pores were formed in the weld bead that are caused by a thick oxide layer existing on the surface of as-received AZ31B samples. Process parameters including laser power and welding speed are studied to determine their effects on pore formation and maximum lap-shear load of the weld bead. Hardness and tensile tests are carried out to reveal the mechanical properties of the weld bead. A regression analysis is performed that establishes a mathematical relation between the process parameters and the weld maximum lap-shear load. Three regression models are compared in order to determine their accuracy in prediction of the maximum lap-shear load and results revealed that the linear model could best predict the maximum lap-shear load by process parameters.

Introduction

It is advantageous for automotive and aerospace industries to have lighter weight in the body of automobiles and aircraft in order to save energy. Magnesium alloy is one of the lightest structural metals and can be employed to decrease the weight of structures in different industries [1]. The growth in production and consumption of magnesium worldwide is representative of this demand among different industries [2]. Along with the demand for magnesium alloy consumption, different manufacturing processes such as joining, cutting, and forming of this alloy should also progress in order to satisfy industry needs. One of the most important joining processes in industry is fusion welding, which is the most cost effective among the joining processes. Laser welding is the most beneficial due to advantages such as a high depth-to-width ratio, high

welding speed, narrow HAZ and fusion zone, and good mechanical properties of the weld [1]. However, there are different issues in welding a magnesium alloy that make it hard to achieve a sound weld. One of the main issues is pore formation that affects the mechanical properties of the weld. There are different mechanisms that cause pore formation in the laser welding process such as hydrogen pores [1,3], unstable keyhole [4], pre-existing pores, surface coating [1,5], gas entrapment [1,6], and alloy elements with a low vaporization point [7].

In the laser welding process, a variety of process parameters affects the weld joint quality. Laser welding process parameters mainly include laser power, welding speed, shielding gas flow, pulse rate, focal distance and gap [8]. Two main process parameters that affect the weld bead the most are laser power and welding speed. Min et al. [9], evaluated the effect of heat input on weldability of AZ61 magnesium alloy. They reported that by increasing the heat input, the weld bead size as well as defects in the weld bead are increased. They found that pore formation is related to the hydrogen dissolubility in solid magnesium. Pore formation under different heat input condition was studied by Zhao and Debroy [10]. They reported that higher welding speed decreases pore formation. This was related to the interaction of welding speed and pre-existing pores. Wang and his colleagues evaluated the effects of process parameters on mechanical property as well as defect formation in the weld bead [11]. They found that by controlling the heat input in the laser welding process, defects were mitigated and the weld joint with the tensile strength of 94.6% of the base metal could be achieved. In another study, effects of a variety of process parameters were studied on porosity and undercut using two types of lasers [12]. They found that using defocus laser beam; defects were mitigated in the weld bead. Harooni et al. [13] investigated the laser power, welding speed and gap on the quality of ZEK100 magnesium alloy. They revealed that by using lower welding speed and lower laser power better quality of welds could be achieved.

The effect of the oxide layer on the weld quality in a zero-gap lap joint configuration of magnesium alloy sheets was evaluated by Harooni et al [5]. It was found that the removal or preheating of the oxide layer at the faying surface of the magnesium alloy resulted in less pore formation inside the weld bead. Pore generation was related to the decomposition of magnesium hydroxide that was mitigated by using a plasma arc preheating. In order to study the effect of laser welding process parameters on the weld quality, a series of experiments was performed using different levels of laser power and welding speeds. Three regression models were developed to find the best fit model that relates laser welding process parameters to the maximum lap-shear load of the weld.

Experimental procedures

A 4-kW fiber laser was used for welding AZ31B magnesium alloy in a zero-gap lap-joint configuration, as shown in Figure 1. Welding is performed with a focused beam on the top surface of two overlapped sheets. The spot diameter of the focused laser beam was 0.6 mm. Experimental samples were fixed tightly into a fixture to ensure a zero gap. After setting all the required parameters, a 6-axis robot was used to weld the coupons. The weld surface was protected by pure argon, with a flow rate of 60 standard cubic feet per hour (SCFH) in the opposite direction of the scanning speed and under an inclination angle of 30 degrees to the horizontal surface. The selection of shielding gas parameters was referenced from the literature [14]. The nominal chemical composition of AZ31B is shown in Table 1. In order to prepare the samples for welding, coupons of 100 × 100 mm in size were cut by using an abrasive waterjet cutting machine. Before welding, all of the coupons were cleaned by acetone in order to make sure that the surface was free from contaminants.

Figure 1 Schematic view of experimental setup

Table 1 AZ31B magnesium alloy nominal chemical composition [5]

Element	Al	Zn	Mn	Si
Compos.	2.46	1.70	0.58	<0.1
Element	Fe	Cu	Ni	Mg
Compos.	<0.005	<0.05	<0.005	Bal.

To test the mechanical properties of the weld, shear and microhardness tests were performed. The coupons were cut by an abrasive waterjet cutting machine in order to follow the standard for the tensile-test sample (ASTM B 557M). The tensile-test sample size and configuration is shown in Figure 2. A special fixture was used during the tensile test in order to keep the symmetry of the load, refer to Figure 2. A micro-hardness test was performed with a load of 200 g and a dwell time of 15 s in order to evaluate the effect of process parameters on the mechanical properties of the weld.

Figure 2 Dimensions and configuration of tensile coupon

After welding, samples were prepared for metallographic and mechanical property tests. Three pieces of 12 mm × 10 mm in size were cut with an abrasive waterjet cutting machine from each weld for cross-sectional observation. These parts were chosen from the middle of the weld line to ensure that the start and end instability effects were eliminated. Then, pieces were mounted and polished following standard metallographic procedures. After completing the polishing procedure, samples were etched by using a 2% nital solution to reveal the general weld bead geometry. An optical microscope was used to study the cross-sections of the weld beads.

Results and discussions

In order to identify the black layer on the surface of the AZ31B magnesium alloy, Energy-dispersive X-ray spectroscopy (EDS) analysis is applied for the as-received and mechanically treated samples. It should be noted that sand paper is used to remove the layer on the surface of magnesium alloy. The EDS test

results are shown in Figures 3(a) and (b), respectively. By comparing the two figures, it is clear that the oxygen element is obviously decreased on the surface of the mechanically treated sample. This implies that the layer existing on the as-received sample is a dense oxide layer that can be removed through a mechanical procedure. Magnesium starts to oxidize around 450°C [14], and the oxide layer on AZ31B-H24 is the result of the hard-rolling temper during the manufacturing process.

Figure 3 EDS analysis of (a) mechanically removed and (b) as-received samples

The oxide layer existing on the surface of magnesium alloy causes pore formation that was studied by the authors [5]. Magnesium oxide is categorized under porous metal oxides that absorbs moisture from the air [14-19]. Based on the Pilling-Bedworth ratio [1], magnesium oxide is not a stable protective composition, and after exposing it to moisture, it reacts to form magnesium hydroxide ($Mg(OH)_2$) [14,20,21], as described with Equation 1. Magnesium hydroxide has a low decomposition temperature of about 200 °C [20], at which point, the magnesium hydroxide reversely releases the molecular water to the atmosphere [22]. The released vaporized water has no escape path between two overlapped sheets but escapes through the molten pool resulting in pore formation inside the weld bead in the as-received samples. The corresponding pore formation mechanism is comparable to the findings done by Liu et al. [17] in laser adhesive bond welding. They revealed that pores are formed at the interface of two overlapped sheets caused by adhesives with low decomposition temperature.

In this study, a series of experiments were designed to evaluate the effects of laser power and welding speed on the weld quality in the laser welding of a magnesium alloy. The weld quality was determined

by the maximum shear load, weld bead profile, the shape of the fracture surface, the presence of pores, and hardness. Experiments were 16 runs including four levels for each parameter shown in Table 2, in order to study the effects of the laser power and welding speed.

Table 2 Process parameter values

Parameters	Values			
Laser power (W)	1000	1100	1200	1300
Welding speed (mm/s)	30	40	50	60

The effect of the laser power on the weld quality

The effect of laser power on the weld bead quality and mechanical properties is discussed. Four different cases with a constant welding speed of 50 mm/s and laser power of 1000 W, 1100 W, 1200 W, and 1300 W were chosen in order to study the effect of laser power on the weld quality. In order to view the weld bead quality, cross-sectional views are presented in Figure 4. By increasing the laser power, the penetration depth of the weld is increased. As the weld bead reached its full penetration depth, an undercut appeared on the top of the weld bead. This undercut could be caused by the extremely low viscosity of the liquid magnesium resulting in the dripping of the molten material out of the weld pool [14]. It is clearly shown that pores are formed at the interface of two overlapped sheets pointed toward the top surface of the weld bead. The weld bead width decreased with the presence of pores at the interface of two overlapped metal sheets.

Figure 4 Cross-sectional views of the weld with a welding speed of 50 mm/s and different laser powers (a) 1000 W, (b) 1100 W, (c) 1200 W, and (d) 1300 W

In order to better understand the relationship between the laser power and pore formation in the weld bead,

a pore fraction is determined for different samples. The pore fraction is defined as:

$$\text{pore fraction} = \frac{\text{weld pore area}}{\text{weld bead area}} * 100 \quad (2)$$

MATLAB image processing was used to calculate the pore fraction as shown in Figure 5. It should be noted that the pore fraction was calculated for three weld beads for each parameter and then averaged. It is shown that by increasing the laser power, the pore fraction reached an optimal value. Also for each welding speed, a laser power corresponds to the lowest pore fraction. At the welding speed of 30 mm/s, the lowest pore fraction is achieved at the laser power of 1100 W. However when the welding speed was increased to 50 mm/s, the lowest pore fraction was achieved at a laser power of 1200 W. This relation seems to be reasonable, because by increasing the welding speed from 30 mm/s to 50 mm/s, the laser power should be increased from 1100 W to 1200 W. This increase ensures the same heat input per unit length of weld and causes the lowest pore fraction. When the laser power is increased, the size of the molten pool increased resulting in longer solidification time. Longer solidification time causes pores to escape through the weld pool and fewer pores are formed. However, when full penetration weld bead is achieved, due to extremely low viscosity of liquid magnesium, the molten material is dripped out causing more possibility of having pores at the interface of two overlapped sheets.

Figure 5 The relation between laser power and pore fraction in the weld bead

A shear test was carried out for the parameters shown in Figure 4. The results show that the maximum shear load increases as the laser power increases, as shown in Figure 6. Each test was repeated seven times to ensure that the results were repeatable. It should be noted that the increase in laser power resulted in an increase in the weld bead width at the interface of the

two overlapped sheets that finally resulted in the maximum shear load.

Figure 6 The maximum shear load at a welding speed of 50 mm/s at different laser power

The failure surface of the shear test coupons was examined by a scanning electron microscope (SEM) as shown in Figure 7. It is clear that all the welds have pores at both sides of the weld. The pores are randomly distributed as observed in cross-sectional views shown in Figure 4. In some cases, pores at both sides of the weld bead are coalesced to form a larger pore, bridging the complete weld bead width as shown in Figure 7(d).

Figure 7 Failure surfaces of the shear test coupons with a welding speed of 50 mm/s and different laser powers (a) 1000 W (b) 1100 W, (c) 1200 W, and (d) 1300 W

In order to reveal the mechanical properties of the weld bead, a micro-hardness test was carried out for the samples welded at various laser powers. The results are presented in Figure 8 and exhibit a trend of decreasing hardness from the base metal to the HAZ area. By comparing the HAZ area hardness obtained for the two laser powers, it is clear that the hardness decreased with an increase in laser power. Higher laser power causes HAZ area grains to be exposed to higher heat, resulting in a higher rate of grain growth causing lower hardness values [14]. It should be noted that since the base metal was

produced under mechanical work (hard-rolling), it shows a higher hardness at the base metal than in the fusion zone.

Figure 8 Micro-hardness results for coupons with different laser powers at a welding speed of 50 mm/s

The influence of welding speed on the weld quality

In order to study the effect of welding speed on the weld bead quality and mechanical properties, four cases were examined. The laser power was held constant and the welding speed was chosen to be 30 mm/s, 40 mm/s, 50 mm/s, and 60 mm/s. The cross-sectional views of the weld bead obtained by different welding speeds are shown in Figure 9. It is evident that by increasing the welding speed, the penetration and size of the weld bead decrease due to the lower heat input into the material. The pores are formed at the faying surface of two overlapped sheets for all four welding speeds. The increase in the welding speed results in lower heat input to the weld bead causing a mitigation of the undercut. As discussed earlier, extremely low viscosity of the molten magnesium causes the material to drip out resulting in the formation of undercut in the fully-penetrated weld beads.

Figure 9 Cross-sectional views of the welds with 1300 W laser power and different welding speeds (a) 30 mm/s, (b) 40 mm/s, (c) 50 mm/s, and (d) 60 mm/s

To study the relation between the welding speed and pore formation in the weld bead, the pore fraction is calculated by Equation 1. As discussed earlier, the pore fraction was calculated by a MATLAB image processing module for three cross sections of weld beads for each parameter and then averaged. The results are shown in Figure 10. The results reveal that the pore fraction increases at the lower welding speeds and decreases for welding speeds above 50 mm/s. Therefore, a maximum pore fraction is related to the welding speed, which is also reported by Marya and Edwards [16]. A low welding speed allows sufficient interaction time (beam diameter/welding speed [14]) for pores to form and escape through the weld pool before solidification. When the welding speed increases, the interaction time decreases. Therefore, gases do not escape through the weld pool and are trapped to form a gas pore. However, when the welding speed increases even to higher values, there is not enough time for the pores to nucleate and grow [14].

Figure 10 The relation between the welding speed and pore fraction in the weld bead

The corresponding lap-shear test of samples obtained with different welding speeds was carried out in order to study the influence of welding speed on the maximum shear load. Figure 11 presents the results of shear test with a constant laser power of 1300 W. The results show that by increasing the welding speed, the maximum shear load decreases. When the welding speed increases, the total heat input to the weld bead decreases, and results in a smaller weld bead width at the interface of the two overlapped sheets. This decrease of the weld bead width cause a decrease in the maximum lap-shear load.

Figure 11 The maximum shear load at 1300 W laser power with different welding speeds

In order to evaluate the weld quality at the interface of two overlapped sheets, failure surfaces of shear-tested coupons were observed by SEM. As the results show in Figure 12, two sides of the weld bead are filled with pores that are randomly distributed in size and shape. It is evident that the increase in the welding speed decreases the weld bead width at the faying surface.

Figure 12 Failure surfaces of the shear test coupons with the 1300 W of laser power and different welding speeds (a) 30 mm/s (b) 40 mm/s, (c) 50 mm/s, and (d) 60 mm/s

The micro-hardness of the coupons obtained with different welding speeds is presented in Figure 13. In both cases, results show a decreasing trend in hardness in HAZ. It is well known that in the HAZ area grains grow, resulting in decreases of hardness [14]. Therefore, as seen in Figure 13, the HAZ area has a lower hardness than base metal. It is clear that hardness is higher for the welding speed of 60 mm/s. When the welding speed is higher, the weld pool size decreases resulting in higher cooling rate that forms grains with smaller size. The formation of smaller grain size results in higher hardness. Also, it should be noted that HAZ area is larger for 30 mm/s velocity as a result of higher heat input.

Figure 13 Micro-hardness results for coupons with different welding speeds at a laser power of 1300 W

To calculate the efficiency of the weld bead achieved with different welding speeds, the melted base metal area (MBMA) is calculated based on the real area of the weld cross section. Pores, undercuts, bumps, and drips out are not considered. The MBMA is the red color area that is shown schematically in Figure 14. In order to use MBMA, it should be assumed that the sample has a conservation of volume [23].

Deutsch et al. [23] used the following equation to calculate melting ratio (MR) or welding efficiency:

$$MR (\%) = \frac{\rho \cdot MBMA (C_p (T_m - T_0) + H_f)) L}{\frac{P}{v} L} * 100 \quad (3)$$

Where ρ is density, C_p is specific heat, T_m is melting temperature, T_0 is room temperature, H_f is latent heat of fusion, P is laser power, v is welding speed, and L is the length of the weld. For this study the constants were taken from the American Society for Metals (ASM) handbook as the following: $\rho = 1.77 \text{ kg/m}^3$, $C_p = 1.18 \text{ kJ/kgK}$, $T_m = 903 \text{ K}$, $T_0 = 293 \text{ K}$, $H_f = 340 \text{ kJ/kg}$ [24].

Figure 14 The melted base metal area (MBMA) [24]

Figure 15 illustrates the relation between MBMA and the welding speed for different laser powers. As shown, an increase in the welding speed decreases the heat input to the material resulting in a lower MBMA value.

Figure 15 Melted base metal area of the weld bead as a function of the welding speed for different laser powers

Figure 16 presents the results of the melting ratio (weld efficiency) calculated from Equation 2.2 as a function of the welding speed. As the results show, an increase in the welding speed causes an increase in the melting ratio. Also an increase in the welding speed increases the efficiency of the welding process. It should be noted that MBMA decreases with an increase in the welding speed (Figure 15). This is also reported in literature [24]. The maximum melting ratio is 26%, which is comparable with the results obtained by Powidajko et al. [24].

Figure 16 The melting ratio of the weld bead vs. welding speed

Development of mathematical models to correlate tensile load to the process parameters

In order to correlate the maximum lap-shear load to the process parameters in the weld bead, three different models are compared by performing regression analysis. There are different methods to model a process such as the mathematical model, regression model [25], Taguchi [26], neural network [27], and so on. The response function can generally be written as:

$$\hat{y} = f(P, v) \quad (4)$$

In the current study, a regression model is performed in order to correlate the tensile load in the weld bead to the welding process parameters. Different regression models can be defined based on the order and nonlinearity of the variables [25]. In this study, three different regression models were tested to fit the input variables to the response including the linear model (1), model (2), called curvilinear by [28], and the multiple nonlinear model (3). The general function can be transformed to the following functions [25]:

$$\hat{y} = a_0 + a_1x_1 + a_2x_2 \quad (5)$$

$$\hat{y} = a_0x_1^{a_1}x_2^{a_2} \quad (6)$$

$$\hat{y} = a_0 + a_1 \ln x_1 + a_2 \ln x_2 \quad (7)$$

It should be noted that x_1 and x_2 are variables that are defined as the laser power and welding speed, a_0 - a_2 are the constant coefficients, and y is the response function defined as the tensile load.

In order to verify the spread of calculated values versus measured values, the results were plotted in a scatter graph that is presented in Figure 17. As it is shown, there is a good correlation between the estimated and measured data with the trendline slope of almost 1 for all three models.

Figure 17 The relation between the calculated and measured tensile load for different models (a) model (1), (b) model (2), and (c) model (3)

The coefficients of models (1), (2) and (3) are shown in Tables 3-5. The coefficients can be interpreted as the effect of each variable. As seen in these Tables, a_1 is a positive number that shows the laser power has a positive effect on the lap-shear load. However a_2 is negative, showing that the increase in the welding speed decreases the lap-shear load. This result was also observed earlier and shown in Figures 6 and 11.

Table 3 Coefficient values of model (1)

a_0	a_1	a_2
656.67	0.67	-15.28

Table 4 Coefficient values of model (2)

a_0	a_1	a_2
9.87	1.006	-0.73

Table 5 Coefficient values of model (3)

a_0	a_1	a_2
-2398.70	768.51	-596.77

In order to evaluate the accuracy of the regression models and the significance of coefficients, an analysis of variance (ANOVA) was performed on all three models. In the ANOVA analysis, the F-test is a widespread criterion used to evaluate the accuracy of the regression model. F is the mean square of the residual (error) divided by the mean square of the regression. The F-value can be compared to the constant $F(\alpha)$ to evaluate the accuracy of the corresponding model.

The result of the ANOVA analysis of models (1),(2) and (3) are shown in Tables 6-8 respectively. As discussed above, $F(0.05)$ is the value of the F-test for a confidence level of 95%. As it can be seen in these Tables, the value of F is much higher than the value of $F(0.05)$. These results show that all of these models are significant. The accuracy of the regression improves when the subtract of F to $F(0.05)$

is larger. It is worth mentioning that $F(\alpha)$ is a constant number for the same degree of freedom and risk level as can be found in statistic tables [29]. The result of the ANOVA analysis for model (2) is presented in Table 7. It is clear that the F value is much higher than $F(0.05)$. This result shows the significance of this model. Table 8 shows the model (3) ANOVA analysis result as well as the significance of this model by comparison of F-values. By considering F-test criterion, model (1) has the best accuracy among the three models.

Table 6 ANOVA table for model (1)

Factor	Sum of squares	Mean square	F	$F(0.05)$
Reg.	523077	126538	34.53	4.45
Res.	29316	3664		
Total	282394			

Table 7 ANOVA table for model (2)

Factor	Sum of squares	Mean square	F	$F(0.05)$
Reg.	0.074	0.037	27.57	4.45
Res.	0.010	0.001		
Total	0.085			

Table 8 ANOVA table for model (3)

Factor	Sum of squares	Mean square	F	$F(0.05)$
Reg.	251337	125668	32.37	4.45
Res.	31057	3882		
Total	282394			

The calculation of error for the estimated value is another method that can be employed to compare the accuracy of these three models [28]. The errors of predicted results are shown in Figure 18. As seen in this Figure, model (2) has two errors over 10%. However two other models have only one error at this level. Between model (1) and model (3), it seems that model (1) has better accuracy since it has higher values at a lower range of errors. Therefore, it could be concluded that model (1) is better than model (3). Therefore, model (1) is the best model among the three models. The F-test criteria were also showed the same result.

Figure 18 Error analysis of tensile load estimation

Conclusions

The following conclusions can be deduced from the current study:

- (1) Process parameters such as laser power and welding speed affect the maximum shear load of the weld. The increase in laser power increases the maximum shear load. However, the increase in welding speed results in a decrease of the maximum shear load.
- (2) The increase in the welding speed decreases the melted base metal area. The melting ratio (weld efficiency) increases with the increase of welding speed up to 26%.
- (3) Maximum shear load was correlated to welding process parameters by using regression analysis. Among three regression models, linear model (model (1)) showed the best accuracy in correlating the maximum shear load to the process parameters.

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