EFFECT OF LASER POWER AND JOINT GAP ON WELD QUALITY OF AEROSPACE GRADE ZE41A-T5 MAGNESIUM ALLOY USING ND:YAG LASER

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ABSTRACT

The effects of laser power and joint gap on the welding quality of 2-mm butt joints of ZE41A-T5 sand castings were investigated using a continuous wave 4 kW Nd:YAG laser system and 1.6-mm EZ33A-T5 filler wire at a welding speed of 6 m/min and surface defocusing. The smooth weld profiles with the minor welding defects were obtained at a laser power of 4 kW and joint gap of 0.3-0.4 mm. The hardness values in the fusion zone are similar to those of the base metal but there is a drop in the heat-affected zone after a natural aging of 18 months.

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INTRODUCTION

The applications of magnesium alloys are increasing rapidly due to the low density, excellent specific strength, excellent damping capacities (good impact and noise reduction), good castability and machinability [1,2]. Therefore, they have found considerable applications in aerospace, aircraft and automotive industries. For instance, ZE41A-T5 (Mg-4.2Zn-1.2Ce-0.7Zr) sand cast Mg alloy has been used in aircraft engine casing, auxiliary gearbox, gearbox casing, etc [3]. This increase in Mg applications highlights the need to develop a proper joining technology. Welding is considered one of the important joining technologies implemented in automotive and aerospace industries.

In general, magnesium alloys are difficult to weld due to the following reasons: oxidation, porosity and crack formation (especially when Mg alloys contain more than 6% Al and 1% Zn [4,5], or more than 3% Zn [3]), large fusion zone (FZ) and heat-affected zone (HAZ) as a consequence of excessive heat input. Therefore, the conventional inert gas arc welding techniques are limited in the case of Mg alloys. Welding difficulties of Mg alloys can be reduced by applying low heat input with high power density and by applying shielding gas. The most suitable techniques that provide these characteristics are laser and electron beam welding processes. Since laser welding can be performed under ambient pressure, it is preferred over the electron beam technique. Therefore, a lot of attention is directed towards laser welding for Mg alloys.

Laser welding process, has many advantages over the conventional welding processes. It has low heat input [6], high power density [6], high welding speed [2], narrow heat-affected zone [6], deep penetration depth [7] and thus high aspect ratio (depth/width), low distortion [8], ease to automate [6], in addition to the possibility of welding with and without filler wire. The use of filler wire in laser welding of Mg alloys is still in its infant stage, but it is getting more attention since it might solve many problems of the autogenous (without filler wire) welding such as: improvement in weld properties [8], welding of thick sections through multi-pass techniques [7], reduction in porosity [4] and crack.

This research is conducted to investigate the laser weldability of ZE41A-T5 with the objective to develop a reliable welding. This paper reports on the effect of gap size and laser power on the laser weldability of 2-mm ZE41A-T5 sand castings using 1.6 mm EZ33A-T5 filler wire.

EXPERIMENTAL PROCEDURES

The experimental material is sand cast ZE41A-T5 magnesium alloy. The cast plates had sizes of approximately 300 x 150 x 4 mm. Every casting was then cut into four small pieces for laser welding each with approximate sizes of 150 x 75 x 4 mm. The magnesium castings were machined to 2 mm thickness. The joint faces were also machined along the length for all the specimens. Prior to laser welding the joint faces and their surroundings were carefully cleaned by acetone to remove any contaminations.

The laser welding machine used in this study is a continuous wave (CW) 4 kW HL4006 Nd:YAG (neodymium-doped yttrium aluminum garnet) laser system equipped with an ABB robotic and magnetic fixture system. A focal length of 150 mm and a fiber diameter of 0.6 mm were employed. Helium was used to shield the top surface and Argon for bottom surface of the workpieces. The flow rates were 18.9 and 21.2 l/min (40 and 45 cubic feet per hour) for the top and bottom surfaces, respectively. The shielding gas was directed to the top surface of the workpiece at an angle of 30° (with the horizontal) and was vertically and uniformly directed to the bottom surface. The workpieces were positioned and clamped in a fixture to obtain butt joint with a different gap sizes from 0.1 to 0.6 mm. Surface defocusing with 0.45 mm focal spot diameter was used.

The filler metal EZ33A-T5 (1.6 x 990 mm for each wire) was used through a continuous feeding mechanism. The position of the filler wire was just above the surface of the workpiece. A delivering angle of 60° between the filler and the laser beam axis was used to reduce the contact area between the filler and laser beam. During laser welding, the workpieces were stationary while the laser beam scanned at a various power from 2.5 to 4 kW at 6 m/min welding speed (optimized in our previous work [9]). Wire feed rate was calculated using the volume flow rate constancy equation [10]:

$$\textit{Wire feed rate} = \frac{\textit{Welding speed x Gap area}}{\textit{Filler wire area}} \qquad (1)$$

Laser fluence was calculated using equation 2 to describe the amount of heat input applied to the sample:

$$\textit{Laser fluence} = \frac{\textit{Laser power}}{\textit{Focal spot diam x Welding speed}} \qquad (2)$$

Tables 1 and 2 list the welding parameters used to examine the effect of gap size and laser power on the weldability:

Table 1 – Welding Parameters Used to Investigate the Effect of Gap Size on the Weldability

Sample #	Gap Size mm	Laser Power kW	Welding Speed m/min	Wire feeding rate m/min	Defocusing mm
1	0.1	4	6	0.8	0
2	0.2	4	6	1.4	0
3	0.3	4	6	2.1	0
4	0.4	4	6	3.0	0
5	0.5	4	6	3.5	0
6	0.6	4	6	4.2	0

Table 2 – Welding Parameters Used to Investigate the Effect of Laser Power on the Weldability

Sample #	Gap Size mm	Laser Power kW	Welding Speed m/min	Wire feeding rate m/min	Defocusing mm
7	0.4	2.50	6	3	0
8	0.4	2.75	6	3	0
9	0.4	3.00	6	3	0
10	0.4	3.50	6	3	0
11	0.4	3.75	6	3	0
12	0.4	4.00	6	3	0

The laser weldability of sand cast ZE41A-T5 magnesium alloy was examined through microstructural and mechanical tests. A length of approximately 20-30 mm was cut from both ends of each joint to exclude the instable segments at the start and end of laser welding. Cross-sectional samples for metallurgical examination were cut from the weld joints at three locations (start, middle and end). These cut specimens were mounted using cold-setting resin and polished to a mirror-like finish. The polished samples were then etched in Nital solution. The microstructure details were examined using Olympus optical microscope equipped with Discover Essential image analyzer software. The average values were calculated from the quantitative measurements of the three specimens (start, middle and end). One of these specimens was also used for the Vickers microindentation hardness test which was carried out using Duramin A-300 hardness tester, under a test force of 200 g and dwell period of 15 seconds.

RESULTS AND DISCUSSIONS

Weld Geometry

Effect of Gap Size on Weld Geometry

The effects of gap size on joint width, height and weld area are shown in Figures 1 and 2. As indicated in Figure 1, there was a tendency to form irregular FZ geometry when the gap size was smaller than 0.3 mm or larger than 0.4 mm. Excessive crown height was observed in the sample welded at 0.2–mm gap, and large shrinkage groove and underfill were observed when the gap was larger than 0.4 mm. Gap size smaller than 0.3 mm may cause difficulties in mixing of the melted filler wire with the melted BM. When the gap size was larger than 0.4 mm, there was a tendency to form large sag defect because of the high fluidity (low surface tension) and low viscosity of the Mg melt [2]. The loss of molten metal due to the sag defects can reduce the total FZ area and average weld width as shown in Figures 1 and 2. The hourglass weld geometry was not attained as the gap size became larger than 0.4 mm. The contribution of the filler wire to the FZ area increased from 7% to 50% as the gap size increased from 0.1 to 0.6 mm. The operational range of the gap size may be increased using a filler wire with smaller diameter [11]. Haferkamp *et al.* [8] reported that a 0.2–mm gap size can be used in butt–

joint laser welding of Mg plates using experimental filler wire with 1.2 mm diameter. In this work, good joint quality was obtained at 0.4 mm gap size during laser welding with 1.6 mm filler wire.

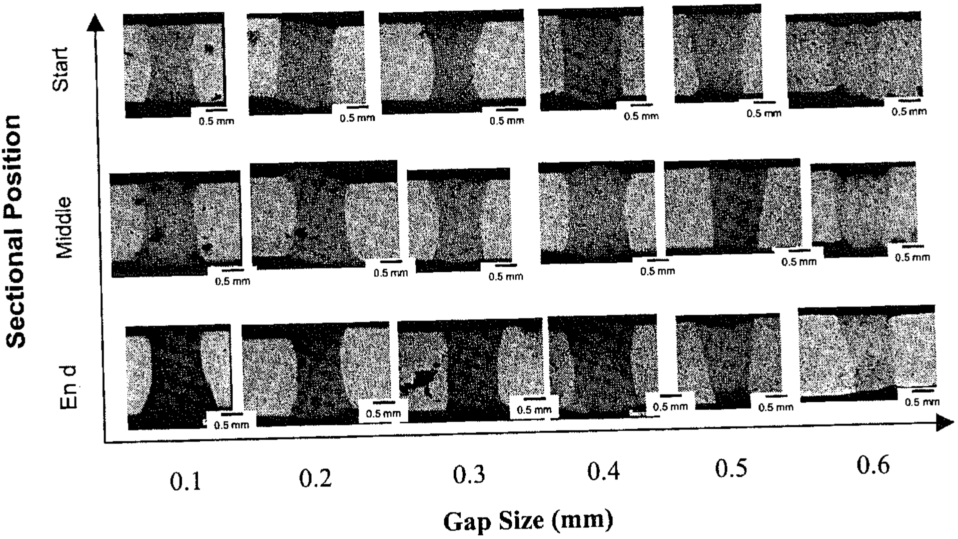
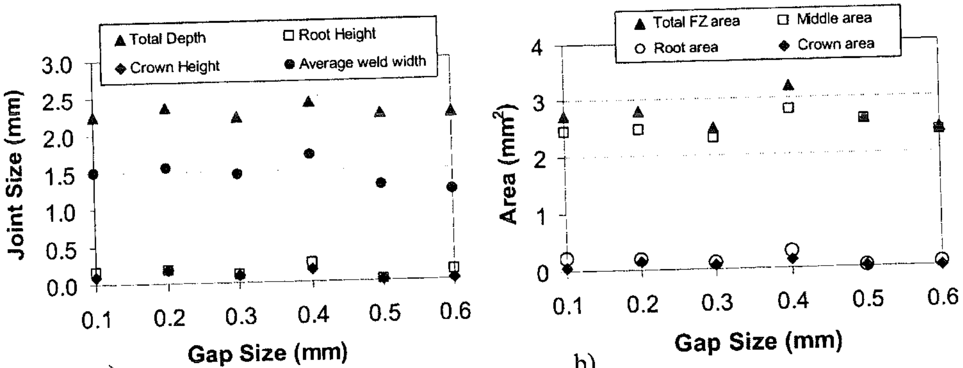


Figure 1 – Effect of Gap Size on Weld Geometry



a) b)

Figure 2 - Effect of Gap Size on (a) Joint Size and (b) Weld Area

Effect of Laser Power on Weld Geometry

The effect of laser power on joint width, height and weld area are shown in Figures 3 and 4. The FZ geometry changed from the partial to the full penetration and the keyhole changed from the closed (blind) to the open profile at root when the laser power increased from 2.5 to 4 kW. The sample welded at 2.5 kW showed a partial penetrated FZ as a result of the partial closed keyhole, and the weld width of the root was smaller than the top weld width. As the power increased to 2.75 kW, a full penetrated joint was obtained but the keyhole was instable because of the fluctuation between the open (start and middle sections) and the close (end section) at the root. The increase in penetration depth in the sample welded at 2.75 kW caused the increase in the FZ area. At 3 kW laser power there was a drop in FZ area due to the formation of a full open keyhole, causing a reduction in the energy coupling efficiency between the laser beam and Mg alloy because of the increase in laser losses at the keyhole root and the reduction in the multiple reflections inside the keyhole. The hourglass FZ profile started to form at 3.5 kW but underfill and shrinkage groove were observed at the root. The increase in laser power from 2.5 to 3.5 kW caused a rise in root width and the laser beam losses at the root which caused more decrease in FZ area. For the samples welded at 3.75 and 4 kW, the FZ area increased with the increase in laser power since the heat gain was larger than the loss of laser power at the root. This variation in melting efficiency of laser welding process and the corresponding variation in weld geometry during the change from partial to full penetration passing through a transitional region from blind to open keyhole was also reported by Krasnoperov *et al.* [12]. Smooth profiles at the top and root, with uniform hourglass shapes were obtained when the laser power was above 3.5 kW.

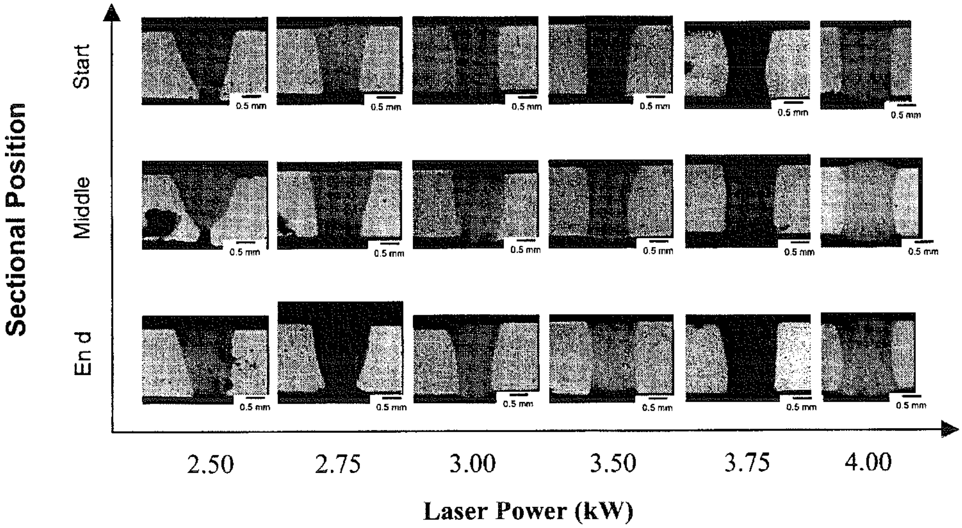


Figure 3 – Effect of Laser Power on Weld Geometry

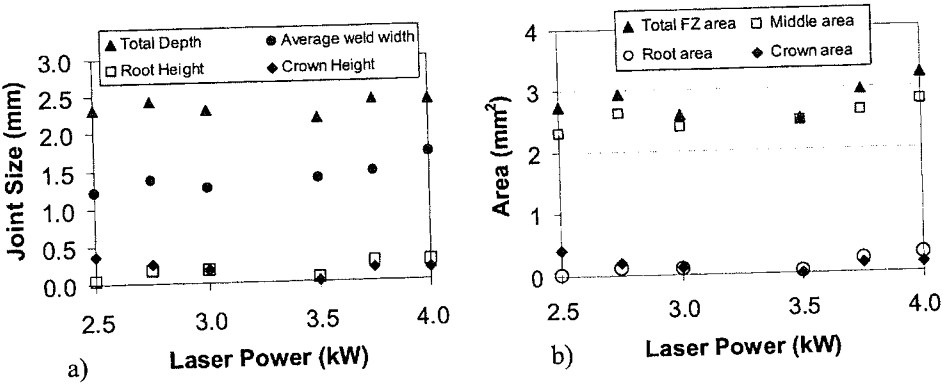


Figure 4 – Effect of Laser power on (a) Joint Size and (b) Weld Area.

Microstructure

In general, the fusion zone microstructure was observed to be fine equiaxed or rosette grains. The grains in the FZ were significantly finer than those in the BM and HAZ (Figure 5), which can be attributed to the high cooling rate (10^5 – 10^6 °C/s) obtained in laser welding process compared with the low cooling rate (10^2 – 10^3 °C/s) obtained in arc welding [9]. The fine equiaxed grains obtained in laser process may partly due to Zr in the ZE41A-T5 alloy [9]. It was difficult to distinguish the difference in microstructure between the HAZ and BM because no grain coarsening was observed in the HAZ.

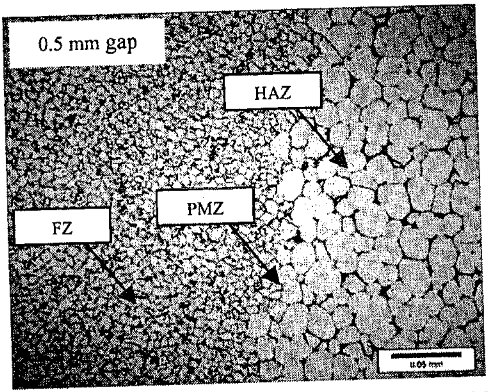


Figure 5 – Micrograph Showing the FZ, PMZ and HAZ.

Figure 6 shows the variation of FZ grain size with the laser power. As discussed above, different laser power values result in different laser coupling efficiencies which, according to [13], affect the amount of the heat available for the workpiece. However, not all the absorbed heat by the keyhole will be available for melting since portion of the absorbed heat will be lost through the BM. In this case, the weld pool size will mainly depend on the process efficiency (melting efficiency); the higher the melting power, the larger the weld pool will be. Due to the variations in coupling efficiency, the cooling rates were different in these samples. The samples which exhibited higher melting power or larger FZ area would have lower cooling rates due to the increase in the mass of the molten metal (larger weld pool). The lower cooling rate seemed to have longer time available for the growth of the grains. This behavior can be observed in Figure 6; the grain size increased as the laser power increased from 2.5 to 2.75 kW because of the increase in laser coupling and melting efficiencies, whereas the sample welded at 3.5 kW showed a slight decrease in the grain size although there was an increase in laser heat input. This is attributed to the decrease in the coupling and the corresponding melting efficiencies due to laser beam losses at the root and to the reduction in the multiple reflections of the laser beam inside the keyhole.

In respect to the effect of gap size on grain size, no significant variation in grain size was observed when the gap size increased from 0.1 to 0.6 mm since the feed rate of the filler wire was exactly calculated to fill the butt joint gap, resulting in less variation in energy balance and the coupling efficiency.

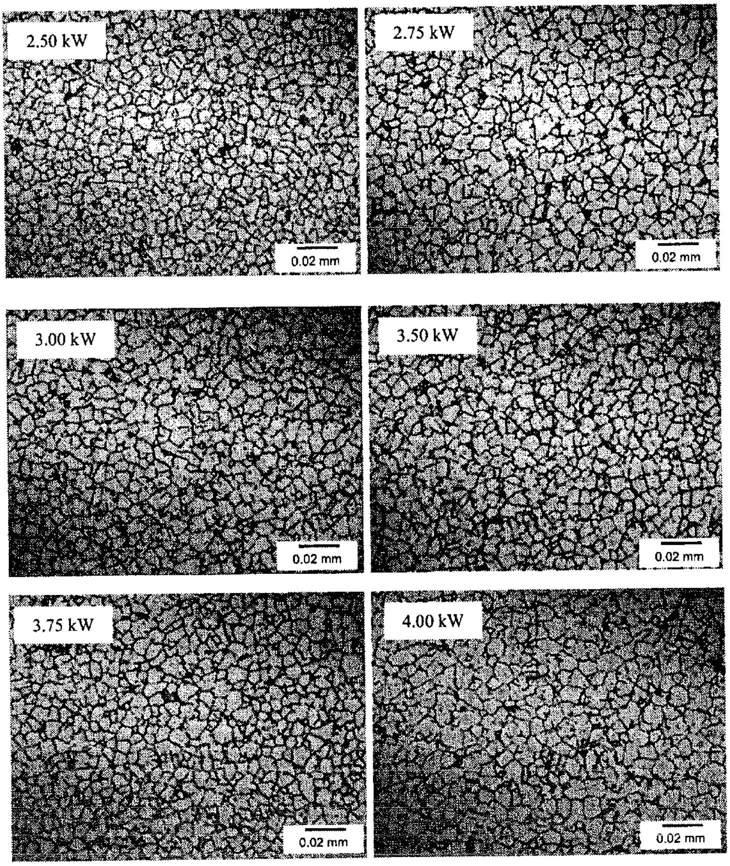


Figure 6 – Effect of Laser Power on the FZ Microstructure

Porosity Formation

Effect of Gap Size on Porosity

The relationship between porosity area percentage and number of pores with gap size is shown in Figures 7. The porosity area percentage decreased from 0.75% to 0.27% as the gap size increased from 0.1 to 0.4 mm, but almost remained constant above 0.4 mm. Figure 8 shows that the majority of pores were smaller than 50 μm, with typical size about 15 μm. Gap size smaller than 0.3 mm may cause difficulties in mixing of the melted filler wire with the melted BM; which might have resulted in entrapment and expansion of large pores. Another possible reason is that using smaller gap size means an increase in the contribution of the BM to the FZ which has more pre-existing pores than the filler wire. It was reported that FZ weld quality is related to the original casting quality [14].

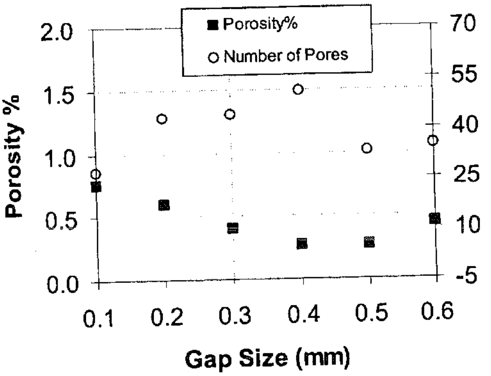


Figure 7 – Effect of Gap Size on Porosity

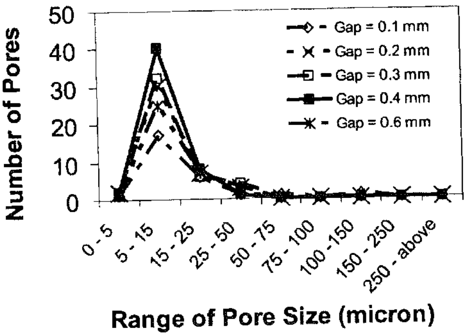


Figure 8 – Effect of Joint Gap on Porosity Distribution

Effect of Laser Power on Porosity

The relationship between porosity area percentage and number of pores with the laser power is shown in Figure 9. The porosity area percentage decreased from 3.4 to 0.27% as laser power reached 3 kW. Large pores were observed in the samples welded at 2.5 and 2.75 kW as shown in Figure 3. As discussed earlier, these two samples encountered fluctuation between the full and partial penetration as a consequence of low laser power density. When the close keyhole mode occurs, the vapor had only one way to escape from the FZ which was the top keyhole opening [12]. In this case, the high welding speed may cause an entrapment of the vapor during the welding process. When the power reached 3 kW, the keyhole became open at the root, which formed another escaping route for the vapor, and that significantly reduced the porosity. Figure 10 shows the average pores size distribution for the studied samples. It can be seen that the majority of pores were smaller than 50 μm, with typical size about 15 μm.

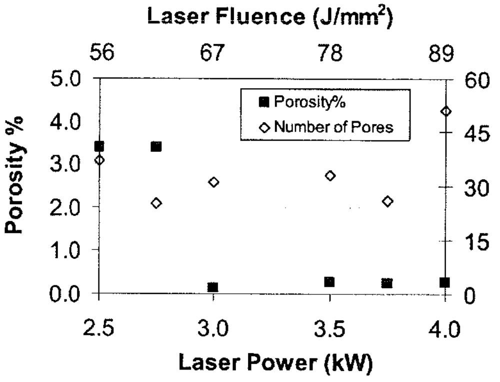


Figure 9 – Effect of Power on Porosity

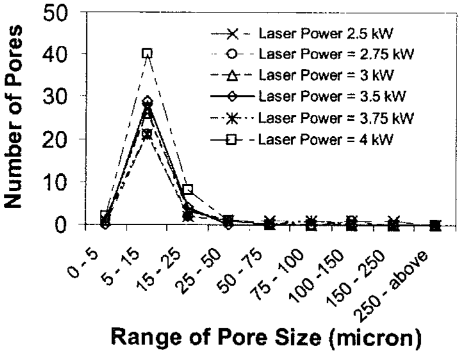


Figure 10 – Effect of Power on Porosity Distribution

Crack Formation

Effect of Gap Size on Crack Formation

Weld cracks were observed in laser welded ZE41A-T5 alloy. In all samples, the area of solidification cracks was less than 1 mm^2, thus these cracks are micro-cracks [9]. The maximum total crack length in the fusion zone was 1.41 mm (for the sample welded at 0.2 mm gap), and the maximum average width was 1.6 μm (for the sample welded at 0.5 mm gap). It was observed that the increase in the gap size slightly reduced the total crack length in the FZ as shown in Figure 11.

It was found that there are basically four groups of crack types: (i) cracks that initiated from or around large pores (Figure 12-A), (ii) cracks initiated from the casting defects in the BM and extended to the FZ, (iii) cracks initiated from high stress zones at crown and root (Figure 12 – B), and (iv) cracks formed near the PMZ. Therefore, the solidification cracks were mainly formed due to irregular weld geometry, pores and BM defects since the laser heat input were constant [15]. At 0.3 and 0.4 mm gap size, the crack length was reduced since they had less porosity and defects in the crown and root areas.

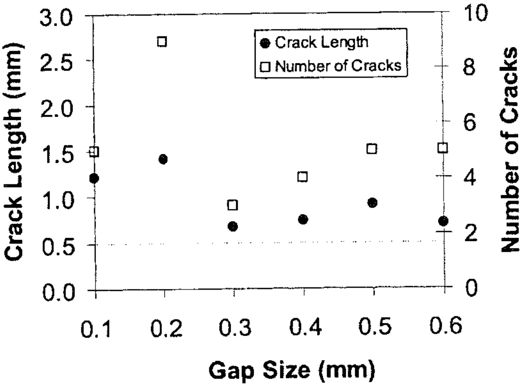


Figure 11 – Effect of Gap Size on Crack Length and Number of Solidification Cracks in the FZ.

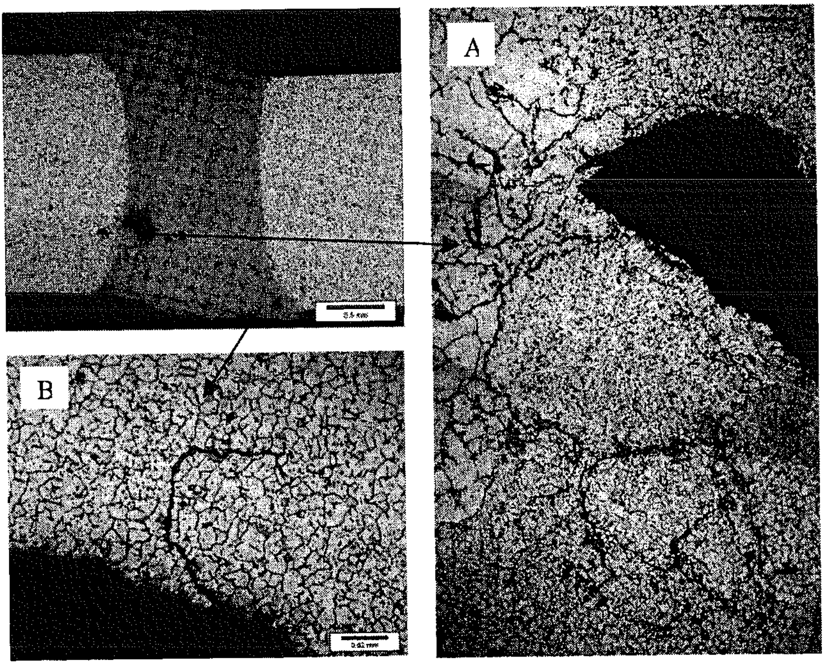


Figure 12 – Solidification Cracks in the Sample Welded at 0.2 mm Gap (Middle Section)

Effect of Laser Power on Crack Formation

The maximum total crack length in the fusion zone was 2.17 mm (for the sample welded at 3.75 kW power), and the maximum average width was 1.4 μm (for the sample welded at 2.5 kW). The minimum crack length and number were observed for the sample welded at 4 kW as shown in Figure 13. In general, the solidification cracks can be reduced by applying less heat input [9]. It is known that the laser heat input, or laser fluence can be reduced either by increasing the welding speed or decreasing the laser power. The general observation from Figure 13 indicates that the crack length varies slightly with the laser power but the peak crack length was reached at a laser power of 3.75 kW. Laser fluence of 89 J/mm^2 seems to be suitable to weld the 2–mm plate at 6 m/min which produced the minimum crack length. Abbaschian and Lima [15] reported that cracking susceptibility of Al alloys was mainly affected by welding speed; the higher the welding speed, the lower susceptibility for cracking. Whereas the effect of laser power showed different behavior than the welding speed; at low welding speed, the decrease in laser power led to decrease in cracking susceptibility, but at high welding speed the laser power showed opposite behavior [15].

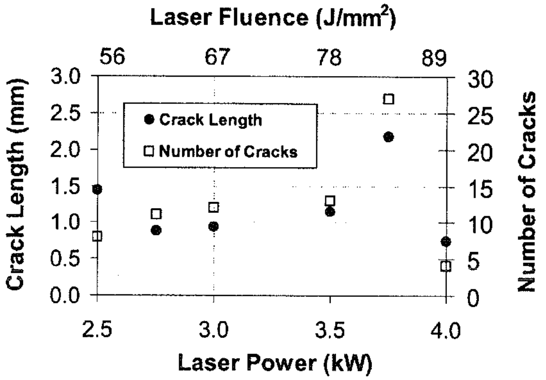


Figure 13 – Effect of Laser Power on Crack Length and Number of Solidification Cracks in the FZ.

Micro-Indentation Hardness

Vickers microindentation hardness was measured after a natural aging over a period of approximately 18 months after the welding. Most of the samples showed that the hardness values in the fusion zone were recovered to those in the base metal. However, there was a drop in the hardness in the heat affected zone as indicated in Figure 14. The width of the heat affected zone was between 1.5 – 2.0 mm. There was no significant variation in the hardness profile as function of gap size (Figure 14). Whereas the average hardness value in the FZ fluctuated within 6 HV as the laser power increased from 2.5 to 4 kW as indicated in Figure 15. The purpose for presenting the middle FZ area in Figure 15 is to identify the transitional zone between the blind to the open keyhole and also to give an indication of the weld pool size. The hardness decreased as the profiles of the keyhole changed from the blind to the open keyholes, whereas the hardness increased as the keyhole became fully open at the root. The hardness variation depends on the variation in the grain size which is function of the cooling rate inside the weld pool as discussed earlier.

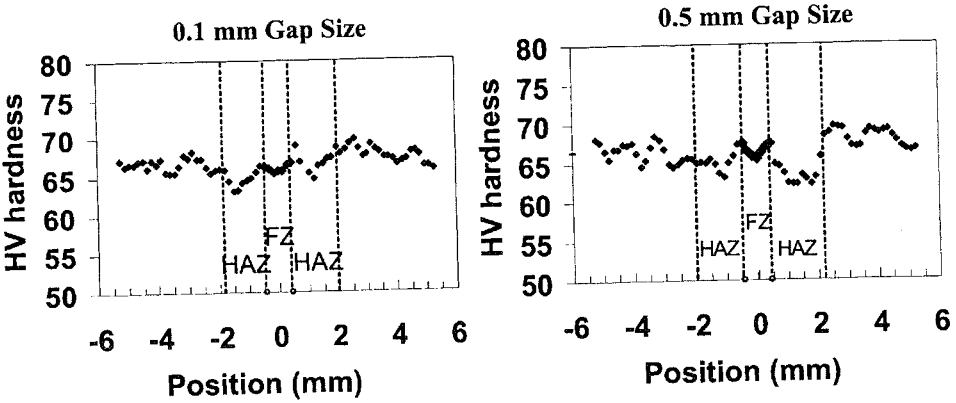


Figure 14 – Effect of Gap Size on Hardness Profile

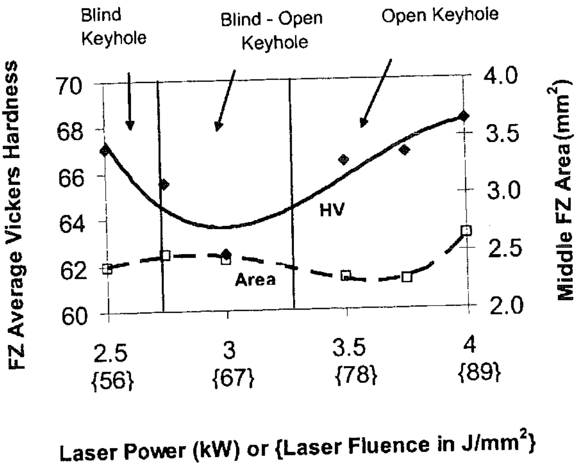


Figure 15 – Effect of Laser Power on the Average Hardness Measured in the Center Line of the FZ

CONCLUSIONS

A continuous wave Nd:YAG laser system was used to weld 2–mm butt joints of ZE41A-T5 sand castings using EZ33A-T5 filler wire at surface defocusing, 6 m/min speed, power varied from 2.5 to 4 kW, and joint gap from 0.1 to 0.6 mm. The following conclusions can be drawn:

- Good FZ profiles with minor defects were obtained at 0.3-0.4 mm gap size and 4 kW laser power.

- No significant effect of gap size (feed rate) on the FZ area, grain size or hardness profile was observed.

- Increasing the laser power results in variations in the FZ geometry from the partial to the full penetration welding and the keyhole changes from the blind to the open mode. This variation in keyhole mode may result in change in the cooling rate, grain size and hardness in the FZ.

- The blind and blind – open mixed keyhole modes may increase the porosity percentage in the FZ.

- A significant grain refinement was observed in the FZ due to high cooling rate and prolific Zr nuclei. No grain coarsening was observed in the HAZ.

- The microindentation hardness in the FZ was similar to that of the BM after a natural aging of approximately one and half year. There was a drop in the hardness within the HAZ which had a typical width of 1.5 to 2.0 mm.

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