THE EFFECT OF THE SHIELDING GAS FLOW RATE ON THE GEOMETRY, POROSITY, MICROSTRUCTURE AND MECHANICAL PROPERTIES OF LASER WELD JOINTS

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Abstract

In this research, studied was the microstructure of AW5083 aluminium alloy butt laser weld joint fabricated under the Ar + 30 vol. % He shielding gas. The light and electron microscopy, computed tomography, microhardness measurements and tensile testing were used for evaluation of the weld joint properties. Porosity volume in the weld metal (WM) was observed by the computed tomography (CT). The volume of porosity in the weld No. 1 was 0.05 mm³, while that in the weld No. 2 was 1.45 mm³. The width of the weld No. 1 was 4.69 mm, the average tensile strength was 309 MPa, and the average microhardness was 55.7 HV0.1. Polyhedral grains with an average grain size diameter of 48 μm were present in the heat-affected zone. The fusion zone (FZ) was of a dendritic structure with an average grain size of 20 μm. Three intermetallic compounds β-Al₃Mg₂, γ-Al₁₂Mg₁₇ and Al₄₉Mg₃₂, which were identified by transmission electron microscope (TEM) analysis, were present in inter-dendritic areas of the WM. The weld joint was characterized by ductile fracture in the base metal (BM). In the FZ, a small number of Al₂O₃ particles of irregular shapes were observed.

Key words
Laser welding, aluminium alloy, microstructure, TEM analysis

INTRODUCTION

Welding by laser beam utilizes heat from the laser’s high energy to melt welding materials. The lower heat input typical for laser welding results in the minimum distortion of the weld parts, as compared to other joining techniques. Light non-ferrous metals, such as aluminium,
are excellent structure materials, since they exhibit excellent weldability, formability, resistance to corrosion, and a high strength-to-weight ratio. To non-heat-treatable wrought alloys magnesium is added for its solid-solution strengthening effect [1-2]. In laser welding of aluminium alloys, evaporation of magnesium and solidification cracking are significant challenges. The laser vapour pressure of magnesium exceeds that of aluminium. So, magnesium is easily evaporated during the pulsed and continuous Nd: YAG laser welding of aluminium alloys in both conduction and keyhole modes. This results in variations in the composition, which, in turn, can alter the mechanical and metallurgical properties of the weld metal. Temperature and composition are the factors affecting the rate of magnesium evaporation [3]. During welding of aluminium alloys by laser beam, the metallurgical porosity and keyhole-induced porosity may occur. The metallurgical porosity is caused by hydrogen and the lightweight elements, such as magnesium and zinc. The other type of porosity can be caused by shrinking or the collapse of a keyhole [4]. Tao et al. investigated the effect of the keyhole and heat conduction welding modes. When combined, these two regimes eliminated porosity in the weld zone [5]. Microstructure of the AW5083 aluminum alloy consists of grains with directional orientation. Along the grain boundaries, there is usually a fine grid of the Mg2Al3 precipitates. The β-phase (Mg2Al3) driving force precipitation develops considerably as soon as the magnesium content is higher than 3.5 wt. %. As soon as magnesium surpasses the solid solubility, it advances to the grain boundaries in the form of Al5Mg3. The Al-Mg system equilibrium phase diagram is represented by two intermediate phases, β-phase Al5Mg2 and γ-phase Al12Mg17. The Al-Mg phase diagram consists of the β-solid solution of the hexagonal crystal structure, liquid γ-solid solution of the α-Mn structure type, R phase of rhombohedral structure at 42 at.% Mg, Al solid solution with the maximum solubility of 18.9 at.% Mg at 723 K, and Mg solid solution with the maximum solubility of 11.8 at.% Al at 710 K [6-7]. The initial microstructure of these materials exhibits a high solid solution supersaturation and can suffer from macro-segregation in the form of central eutectic segregates and of micro-segregation, which scales with the arm spacing of dendrites. Formation of precipitation and its structure is a correlation between hardness and microstructure [8].

MATERIALS AND METHODS

A 2 mm thick of the AlMg4.5Mn aluminium alloy sheet with dimensions of 30 mm x 100 mm was used as an experimental material. The weld joints were produced using the 5087 (AlMg4.5Mn0.7) filler wire with a diameter of 1.2 mm. A TruDisk 4002 disk laser was used in this experiment. During the laser beam welding, the weld beads and weld root were protected from the ambient atmosphere. For each weld joint, 2/3 of the shielding gas volume was applied to the weld surface, and the rest to the weld root. The gas flow rate at the output of the nozzle was measured by flowmeter. The shielding gas flow rates were 30 and 10 l/min. The diameter of the nozzle used for delivering shielding was 10 mm. During laser welding, the shielding gas flowed on the surface of the material through two nozzles out of four. The position of the nozzle was placed 5 mm above the surface of the base material. Shielding gas was delivered through the tube connected to the side face of the fixture. The shielding gas started flowing 10 seconds before the start of welding. After welding, the shielding gas flowed for another minute to prevent oxidation of the weld metal. The scheme of the experimental procedure is shown in Figure 1. Aluline He30 (Ar + 30 vol.% He) was used as a shielding gas. The following welding parameters were used: laser power (1.9 kW), welding speed (20 mm/s), wire feed rate (110 cm/min) and the shielding gas flow rate (30 and 10 l/min). The samples were etched with Barker’s reagent after cross-sections metallographic preparation of the weld joint (chemical composition: 3 ml HBF₄ + 100 ml distilled H₂O). The etching parameters: 24.5 V voltage of DC and time of etching 2 min. Light microscopy via NEOPHOT 32 light microscope was used.
to analyze the microstructure. A JEOL 7600 F scanning electron microscope (SEM) was used to study further details of the heat-affected zone. TEM analysis was used to study IMC’s in the BM and the WM. The fracture surfaces were studied by SEM. For the TEM investigations, thin foils were mechanically cut from the characteristic area of the weld joint, and ground to a thickness of about 80 µm. Disks of 3 mm in diameter were punched out of the thin sheets and electropolished using the TENUPOL 5 twin-jet electropolisher in a 70% methanol and 30% nitric acid electrolyte at -30 °C and 19 V, polishing time 1 min. The TEM characterization was performed using a JEOL 200 CX operating at 200 kV. Zeiss Metrotom 1500 computed tomography-based coordinate measuring machine was used to identify the porosity present in the laser weld joints and its location within the welds.

RESULTS AND DISCUSSION

The appearance of the weld bead and the weld root of AW5083 aluminium laser weld joints is given in Figure 2 (a-d). The welding parameters were as follows: laser power of 1.9 kW; welding speed of 20 mm/s; wire feed rate of 110 cm/min; shielding gas flow rate of 30 and 10 l/min; focal position of 0 mm. Argon possesses a low ionization energy (15.8 eV) in comparison to helium (24.8 eV), and it makes it easier for argon to ignite the plasma on its own, which is undesirable for laser welding. Composition of the shielding gas affects the heat distribution in the weld, thereby controlling the weld shape and the welding speed. The extra heat potential of helium can reduce the gas entrapment, and thus porosity levels, by broadening the weld fusion and penetration [9]. Katayama et al. found that defocusing of the laser beam by plasma above
the metal surface produces shallow weld beads [10]. Ahn et al. found that the width of the weld joint fabricated in argon was wider than that of the weld joint produced in the helium shielding atmosphere [9]. Reisgen et al. found that weld joints were shallow when Ar was used as the shielding atmosphere. They explained that this was due to a plume formation above the weld metal, and thus instability of the welding process, which caused spatter and a poor surface appearance of the weld joint [11]. As shown in Figure 2 (a-b), the weld bead and the weld root are smooth with a regular shape without presence of spatter. Figure 2 (c-d) shows the given the weld joint which was fabricated under 10 l/min shielding gas flow rate. The weld bead is smooth and of a regular shape. The spatter is present on the surface. The weld root is of irregular shape. Yang et al. achieved similar results in their research. They observed that the most significant effect on the weld bead geometry has the welding speed, while the wire feed rate has an influence on the upper width and FZ [12].

![Figure 2](image_url)

*Figure 2 Appearance of (a-b) weld bead and root (30 l/min), (c-d) weld bead and root (10 l/min)*

The cross-sections of the laser weld joints are depicted in Figure 3 (a-b). The weld joint (a) was produced under 30 l/min shielding gas flow rate. The weld joint has slight excess weld metal (0.2 mm) and its root is excessive penetrated (0.35 mm). The width of the weld is 4.69 mm (±0.07), and width of the weld root is 4.17 mm (±0.08). When comparing the measured values to the EN ISO 13919-2, the maximum excess weld metal and excessive penetration belong to the stringent level B. Geometry of the welds mainly depends on the welding parameters and also on the flow rate of shielding gas [13]. In addition to the welding parameters, the use of different shielding gases affects the geometry of the weld [14]. Tadamalle et al. [15] studied the influence of the laser welding parameters on the weld pool geometry. They found that the weld bead dimensions are more sensitive to the peak power input up to 1.7 kW and less sensitive beyond 1.7 kW. El-Batahgy et al. [16] found that the most pronounced effect on the weld profile is from the laser beam power, welding speed and focal distance. According to Matsuoka et al. [17] the weld bead geometry is determined by laser power, scanning velocity and beam spot diameter. The weld joint fabricated under 10 L/min is given in Figure 3 (b). The weld width dropped to 4.24 mm (±0.08) and the measured root width was 3.59 mm (±0.1). At the edge of the fusion zone, excess weld metal of 0.19 mm was recorded. The weld root is characterized by excessive penetration of 0.69 mm. When comparing the measured values to the EN ISO 13919-2, the maximum excess weld metal and excessive penetration belong to the moderate level D. Kuo et al. [18] observed that a weld of a concave shape is a result of higher gas pressure in the downward direction. They also found that the geometry of the weld bead depends on the gas flow rate value. Porosity and cracking of the weld joints are the key problems in welding aluminium alloys. Preparation of the surface reduces the hydrogen source that causes porosity [19].
Figure 3 Cross-section of the laser weld joints produced under (a) 30 L/min and (b) 10 L/min

Figure 4 shows the microstructure of various zones of the 5083 aluminum alloy weld joints. The base metal is shown in Figure 4 (a) and is characterized by a fine grain microstructure with an average grain size of 20 µm. Figure 4 (b) shows the HAZ-WM interface microstructure of the weld No. 1. The average grain size of HAZ is 48 µm. The difference in the size of the grain in the HAZ is due to the low welding speed (20 mm/s), which caused a higher heat input and slow cooling rate. This results in excessive grain growth. At the boundary of the fusion zone, columnar grains were observed. Figure 4 (c) shows the weld metal of the laser weld joint No. 1. The weld metal is characterized by a fine dendritic structure. This fact is caused by the presence of zirconium in the 5087 filler wire. Zhou et al. observed grain refinement in 5083 aluminium alloy with the content of 0.7% zirconium by weight. The presence of zirconium resulted in the formation of fine grains in the molten pool. AW5083 with zirconium exhibited excellent mechanical properties in the state after heat treatment [20]. The presence of pores or cracks was not observed. Figure 4 (d) shows the weld metal which was fabricated with the 10 l/min shielding gas flow rate. It is evident, that the microstructure of the WM is dendritic. The pore with a diameter of 67 µm was captured in the weld metal. The porosity can be caused by a low shielding gas flow rate and evaporation of lightweight alloying elements during welding.

Figure 4 Microstructure of (a) BM, (b) HAZ-WM interface (30 l/min), (c) WM (30 l/min), (d) WM (10 l/min)
Figure 5 (a, b) shows the SEM image of the HAZ – WM interface of the weld joint fabricated under 30 l/min shielding gas flow rate. In our case, the cold-worked alloy is weld; that means the HAZ exhibits both recrystallization and grain growth. The hardness and strength properties of a recrystallized HAZ lose the benefits derived by cold working, and the weld joint strength approaches that of an annealed alloy. The microstructure indicates that directional as-rolled grains disappeared in the HAZ due to the above-mentioned recrystallization and grain growth processes. The WM microstructure is composed mainly of the α-aluminium solid solution matrix. Inter-dendritic areas are supplemented in alloying elements. Brighter regions in the WM prove the presence of elements with a higher atomic numbers. In both Figures, dendritic microstructure and solute enrichment in intermetallic areas can be observed. In the Figures, a columnar dendritic formation with a solute micro-segregation can be observed. The segregated solute is less copious, thick and unbroken.

![Figure 5 SEM images of (a) HAZ-WM interface of shielded joint (30 l/min), (b) higher magnification](image)

SEM images of the fracture surfaces of the weld joints are shown in Figure 6. From the image (Figure 6a) of the fracture surface, a ductile fracture can be observed. This fact is attributed to the dimples present in the fracture surface. The application of 30 l/min was effective, because, after the tensile test, the fracture in the BM was observed. The brittle fracture of the weld joint No. 2 can be observed in Figure 6b. The weld joint was fabricated under a 10 l/min shielding gas flow rate. It is evident, that protection of the weld metal from the ambient atmosphere was insufficient. The sample fractured in the WM.

![Figure 6 SEM images of the fracture surfaces created under gas flow rate (a) 30 L/min; (b) 10 L/min](image)
The microstructure of BM (Figure 7a) observed by TEM exhibited polyhedral morphology and was formed of the substitution solid solution of the alloying elements in aluminium. Significant precipitation of the smaller particles of a regular geometric shape was observed in the matrix. The grain boundary precipitation was observed very rarely (Figure 7b). The particles were identified as the Al_{12}Mg_{17} intermetallic phase (Figure 7c). Slight heterogeneity in precipitate density, as well as dislocation density, was observed, too. The microstructure of WM (No. 1) exhibited a dendritic morphology. The matrix is formed of the solid solution of the alloying elements in aluminium. Compared to the BM, a significantly higher dislocation density was observed in the weld metal. Precipitation of the secondary phases was observed mainly in the inter-dendritic areas. Majority of the particles are of irregular shape. No particles were observed in dendrites. The presence of the intermetallic phases of Mg_{2}Al_{3}, Al_{12}Mg_{17} and Al_{9}Mg_{32} (Figure 7d-f) was confirmed by electron diffraction. Similar results are consistent with Zhou et al [19]. They recorded two IMC’s in the weld metal, namely β-Al_{3}Mg_{2} and γ-Al_{12}Mg_{17}. Goswami et al. [21] detected β-phase in their study by HRTEM analysis. In the weld metal of AA5083-H321 aluminium alloy, Tamasgavabare et al. observed that area fraction of IMC was lower in comparison to BM [22]. They also found a small amount of the Al_{2}O_{3} particles present in the WM (Figure 7g). There are two types of porosity in the weld metal. Generally, the process-induced porosity is of an irregular shape and a relatively large size, compared to metallurgical porosity. The processing porosity is usually induced by an unstable keyhole during penetration welding. However, a metallurgical porosity made of hydrogen gas showed a smaller diameter ranging from tens to hundred micrometers [23-26]. Figure 8 (a) and (b) shows the locations of the pores in the weld metal. In the weld metal No. 1, the biggest pore had the diameter of 0.57 mm and its volume was 0.03 mm$^3$. The total volume of porosity in the weld metal was 0.05 mm$^3$. According to the EN ISO 13919-2, the weld joint No. 1 belongs to the stringent level B. On the contrary, in the weld metal No. 2 (10 l/min shielding gas flow rate), a higher amount of the porosity was observed. The amount of porosity increased in comparison to the previous weld joint. The pores were mainly distributed along the second half of the weld joint length, i.e., along 50 mm. The biggest pore had a diameter of 1.28 mm and its volume was 0.21 mm$^3$. The total porosity volume in the weld metal was 1.45 mm$^3$. In the weld, the porosity appeared in the second half of the weld bead. The porosity in the second half of the weld metal was probably caused by an aperture at the end of the welding fixture used in welding. As can be seen in Figure 1, the shielding gas was supplied from the left side of the welding fixture (i.e. from the beginning of welding process). It follows that the protection of the weld root at the beginning of the welding process (from the left) was more effective than the protection at the end of the welding process. If the aperture was sealed, CT revealed that the porosity formation was not distributed as in that case. Even at a lower shielding gas flow rate, the porosity in the weld metal was lower. According to the EN ISO 13919-2, the weld joint No. 1 belongs to the moderate level D. The higher content of the porosity in the weld joint No. 2 can be associated with the insufficient shielding gas flow rate. If protection of the weld pool is fully effective, hydrogen in the weld pool mainly originates from the surface oxide film. It is well known that aluminium oxide is hygroscopic and promotes absorption of the ambient moisture [27]. And thus, during welding, the gases such as H, N$_2$ and O$_2$ could cause increased porosity in the weld metal. Similar results were achieved by Takahashi et al. [28] who found that, with argon shielding gas, porosity was higher in comparison to helium. Glowacki et al. [29] found that the best combinations are in the range of 0% Ar and 100% He up to 50% Ar and 50% He (per unit volume of the gas mixture). The Ar + He gas mixtures with less than about 50% of He lead to significant defocusing of the incoming laser light in the plume plasma above the laser generated keyhole. Both are often used to protect the weld pool from the atmosphere, where Ar is usually the preferred choice because of its lower cost. Composition of the shielding gas affects the heat distribution in the weld, and therefore controls the weld shape.
and the welding speed. The extra heat potential of the He can reduce gas entrapment, and thus also porosity levels by broadening the weld fusion and penetration [10]. The two-component mixtures of argon and helium are the most satisfactory choices. Katsuna et al. [30] demonstrated that the tendency of metal to become porous is greatly influenced by the vaporization and segregation behaviour of magnesium, as well as the amount of hydrogen dissolved in the molten metal. As a result of their research into the correlations of the factors relating to the formation of pores, it was found that formation of pores is not only caused by hydrogen and magnesium metal vapor, but is also associated with the segregation of magnesium into the solute band. Huang et al. [31] found that the interaction between the vapor plume and the keyhole is considered to induce the oscillation of keyhole and vapor plume.

Figure 7 TEM analysis of (a) polyhedral morphology of the BM, (b) grain boundary precipitation in the BM, (c) γ-phase in the WM, (d) β-phase in the WM, (e) γ-Al12Mg17 in the WM, (f) Al18Mg32 in WM, (g) Al2O3 in the WM.
The sphericity $\Psi$ of a pore was calculated. The sphericity of a pore is given by the ratio of the surface area of a sphere (with a volume equal to the pore volume) to that of the pore:

$$\Psi = \frac{A_S}{A_P} = \frac{\frac{1}{2} \pi \frac{3}{2} \left(\frac{6V_P}{2}\right)^{2/3}}{A_P}$$

where $A_S$ and $A_P$ refer to the surface area of the sphere and pore, respectively, and $V_P$ is the pore volume. Sphericity measures the departure of a shape from perfectly spherical ($\Psi = 1$) and the extent of deformation for a given pore. The smaller the sphericity value, the more irregular the pores' shape [32]. Calculated sphericities $\Psi$ of pores present in weld joint under 30 l/min shielding gas flow rate ranged from 0.57 to 0.65 (Table 1). Calculated sphericities $\Psi$ of pores present in weld joint under 10 l/min shielding gas flow rate ranged from 0.54 to 0.71 (Table 2).

### Table 1

| Radius (mm) | Diameter (mm) | Volume (mm$^3$) | Surface (mm$^2$) | Sphericity ($\Psi$) |
|-------------|---------------|-----------------|-----------------|--------------------|
| 0.28        | 0.57          | 0.03            | 0.82            | 0.57               |
| 0.22        | 0.45          | 0.02            | 0.55            | 0.65               |

### Table 2

| Radius (mm) | Diameter (mm) | Volume (mm$^3$) | Surface (mm$^2$) | Sphericity ($\Psi$) |
|-------------|---------------|-----------------|-----------------|--------------------|
| 0.38        | 0.76          | 0.11            | 1.72            | 0.65               |
| 0.45        | 0.90          | 0.12            | 1.83            | 0.64               |
| 0.64        | 1.28          | 0.21            | 3.17            | 0.54               |
| 0.43        | 0.85          | 0.09            | 1.59            | 0.61               |
| 0.59        | 1.17          | 0.15            | 2.43            | 0.56               |
| 0.4         | 0.79          | 0.09            | 1.50            | 0.65               |
| 0.32        | 0.64          | 0.05            | 1.07            | 0.61               |
| 0.37        | 0.75          | 0.08            | 1.42            | 0.63               |
| 0.27        | 0.54          | 0.05            | 0.93            | 0.71               |
| 0.32        | 0.64          | 0.07            | 1.34            | 0.61               |
| 0.37        | 0.74          | 0.06            | 1.18            | 0.63               |
| 0.46        | 0.92          | 0.13            | 2.08            | 0.60               |
| 0.49        | 0.98          | 0.11            | 1.86            | 0.60               |
| 0.35        | 0.69          | 0.06            | 1.18            | 0.63               |
| 0.4         | 0.79          | 0.09            | 1.75            | 0.55               |

Figure 8 Computed tomography of (a) weld No. 1 (b) weld No. 2
The microhardness course of laser weld joints is given in Figure 9. It is evident, that the shielding gas flow rate had an effect on the microhardness course. When the shielding of the weld metal was sufficient, the average microhardness value was 55.7 HV0.1. On the other hand, insufficient gas flow rate caused an increased average microhardness course value of the weld metal. The average microhardness value was 61.9 HV0.1. This fact was caused by oxidation of the weld metal from the ambient atmosphere. In their research, Prokic-Cvetkovic observed that the tensile strength of the weld was not affected by the composition of the protective gas [33].

![Figure 9 Microhardness course of weld joints](image)

The tensile strength of the weld joints No. 1 and No. 2 is given in Figure 10. The weld joint No. 1 was stronger than the base material. The fracture was observed in the base material. The measured tensile strength was 309 MPa (±2.94). It follows that the shielding gas flow rate was sufficient. The tensile test of the weld joint No. 2 revealed that the base material was stronger than the weld metal. The fracture was observed in the weld metal. The measured tensile strength was 274 MPa (±2.45). It follows that the shielding gas flow rate was insufficient. The fracture in the weld metal was probably caused by oxidation of the weld metal and presence of pores in the weld metal. Bandi et al. used laser beam welding to join specimens, and observed that the tensile properties were significantly worse with an increase of pores volume in the weld metal [34].
CONCLUSION

In this research, the effect of process parameters on the microstructure, porosity and mechanical properties of the AW5083 aluminium laser weld joints was investigated. For joining butt laser welds, 5087 (AlMg4.5MnZr) filler wire, with a diameter of 1.2 mm, was used. Aluline He30 was used as the shielding gas. Additionally, the influence of different shielding gas flow rates on the microstructure, porosity, mechanical properties, and weld shape was revealed. From the results obtained, the following observations can be made:

1. The weld joint fabricated under the 30 l/min shielding gas flow rate exhibited the concave shape of 0.2 mm and excessive penetration of 0.35 mm. A weld width of 4.69 mm and root width of 4.17 mm were measured. In the weld joint fabricated under the 10 l/min shielding gas flow rate, at the edge of the fusion zone, recorded was the excess weld metal of 0.19 mm. The weld root was characterized by excessive penetration of 0.69 mm. A weld width of 4.24 mm and root width of 3.59 mm were measured; the WM was found to be porous. The diameter of the biggest pore was 1.28 mm.

2. The weld metal microstructure is of a dendritic structure with an average grain size of 20 um. This is caused by zirconium, which is an alloying element present in the filler wire, and acts as a grain refiner. The high cooling rate of laser beam welding contributed to the grain refinement. Columnar grains were observed at the fusion boundary. The grains grew in a direction normal to the fusion boundary. Equiaxed grains were observed in the middle of the fusion zone.

3. Three intermetallic compounds, $\beta$-Al$_3$Mg$_2$, $\gamma$-Al$_{12}$Mg$_{17}$ and Al$_{49}$Mg$_{32}$, were observed by the TEM analysis.

4. The minimum porosity was recorded in the weld joint produced under the shielding gas flow rate of 30 l/min; the value was only 0.05 mm$^3$. On the contrary, the high porosity was recorded in the weld joint fabricated under the shielding gas flow rate of 10 l/min; in that case, the value was 1.45 mm$^3$. 

Figure 10 Stress-strain curve of (a) weld No. 1; (b) weld No. 2
5. Lower average microhardness was measured in the weld that was created under the 30 l/min gas flow rate during welding, namely 55.4 HV0.1. An increase in the microhardness was caused by the grain refinement owing to the presence of zirconium in the filler wire and the high cooling rate that is typical for laser beam welding. Conversely, higher microhardness (63.9 HV0.1) was recorded in weld No. 2. Increased values of the microhardness are probably caused by oxidation of the molten weld pool, because of the lack of protection of the WM during laser welding. The recorded values of microhardness indicate that the gas flow rate had an effect.

6. When 30 l/min of Aluline He30 was used, the tensile strength of Rm = 309 MPa was recorded. The weld joint was fractured in the base material. The lower tensile strength (Rm = 274 MPa) was recorded when 10 l/min shielding gas flow rate was used. In that case, a fracture occurred in the weld metal because of a large number of pores.

7. The best results were obtained when the following welding parameters were used: laser power of 1900W, speed of welding of 20 mm/s, focal point of 0 mm, filler wire feed rate of 1.1 m/min, and gas flow rate of 30 l/min. Further research into the use of shielding gas at a higher flow rate and the influence of the gas flow rate on porosity in the weld metal are merited. The use of computed tomography to investigate the microporosity in the weld metal should also be explored.

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References

1. SAHUL, M., VYSKOČ, M., ČAPLOVIČ, L., M. PAŠÁK, M. 2017. Journal of Matteriels Engineering and Performance. Disk laser weld brazing of AW5083 aluminum alloy with titanium grade 2, 26(3). 1346-1357. ISSN 1059-9495
2. YAKO, T., FUKUI, K., NAITO, M., TAKEDA, M. 2018. Precipitation behavior in an Al-Mg alloy with high Mg composition. Materials Science and Metallurgy Engineering, 5(1), 1-4. ISSN 2373-3470
3. BEIRANVAND, Z., GHAINI, F., MOOSAVY, H., SHEIKHI, M., TORKAMANY, M., MORADI, M. 2020. The relation between magnesium evaporation and laser absorption and weld penetration in pulsed laser welding of aluminum alloys: Experimental and numerical investigations. Optics & Laser Technology, Vol. 128. 106170.ISSN 0030-3992
4. KE, W., BU, X., OLIVEIRA, J., XU, W., WANG, Z., ZENG, Z. 2020. Modeling and numerical study of keyhole-induced porosity formation in laser beam oscillating welding of 5A06 aluminum alloy. Optics & Laser Technology, Vol. 133. 106540. ISSN 0030-3992
5. TAO, W., YANG, Sh., 2020. Weld zone porosity elimination process in remote laser welding of AA5182-O aluminum alloy lap-joints. Journal of Materials Processing Technology, Vol. 286, 116826. ISSN 0924-0136
6. ZHANG, R., STEINER, M., AGNEW, S., KAIRY, S., DAVIES, C., BIRBILIS. N. 2017. Experiment-based modelling of grain boundary β-phase (Mg2Al3) evolution during sensitisation of aluminum alloy AA5083. Scientific Reports 7, Article number 2961. ISSN 2045-2322
7. ISLAM, M., MOSTAFA, A., MEDRAJ, M. 2014. Essential magnesium alloys binary phase diagrams and their thermochemical data. Journal of Materials, 704283, 33 p. ISSN 1563-5147
8. WANDERKA, N.; SCHEFFMANN, R.; BANHART, J. 2007. Characterization of precipitates in aluminum based alloy AW 6016. Surf. Interface Anal., 39, 221–226.
9. AHN, J., HE, E., CHEN, L., DEAR, J., DAVIES, C. 2017. The effect of Ar and He shielding gas on fibre laser weld shape and microstructure in AA 2024-T3. Journal of Manufacturing Processes, 29, 62–73. ISSN 1526-6125
10. KATAYAMA, S., KAWAHITOYA, Y., MIZUTA, M. 2010. Elucidation of laser welding phenomena and factors affecting weld penetration and welding defects. In Physics Procedia 5, 9–17. ISSN 1875-3892
11. REISGEN, U., SCHLESER, M., MOKROV, O., AHMED, E. 2010. Shielding Gas Influences on Laser Weldability of Tailored Blanks of Advanced Automotive Steels. Applied Surface Science, 257, p 1401-1406. ISSN 0169-4332
12. YANG, D., LI, X., HE, D., NIE, Z., HUANG, H. 2012. Optimization of weld bead geometry in laser welding with filler wire process using Taguchi’s approach. Optics & Laser Technology, 44(7), pp. 2020-2025. ISSN 0030-3992
13. VYSKOČ, M., SAHUL, M., DOMÁNKOVÁ, M., JURČI, P., SAHUL, M., VYSKOČOVÁ, M., MARTINKOVIČ, M. 2020. The Effect of Process Parameters on the Microstructure and Mechanical Properties of AW5083 Aluminum Laser Weld Joints. Metals 2020, 10, 1443.
14. CHAN, C., MAN, H. 2015. Effect of Process Parameters and Heat Input on Weld Bead Geometry of Laser Welded Titanium Ti-6Al-4V Alloy. Lasers Eng., 30, 247–265.
15. TADAMALLE, A., REDDY, Y., RAMJEE, E. 2013. Influence of laser welding process parameters on weld pool geometry and duty cycle. Advances in Production Engineering and Management, 8 (1), pp 52-60.
16. EL-BATAHGY, A. 2012. Effect of laser welding parameters on fusion zone shape and solidification structure of austenitic stainless steels. Optics & Laser Technology, 44(7), pp. 2020-2025.
17. MATSUOKA, S., OKAMOTO, Y., OKADA, A. 2013. Influence of Weld Bead Geometry on Thermal Deformation in Laser Micro-Welding. In Procedia CIRP, Vol. 6, pp. 492-497.
18. KUO, T., LIN, Y. 2006. Effects of Shielding Gas Flow Rate and Power Waveform on Nd:YAG Laser Welding of A5754-O Aluminum Alloy. In Materials Transactions, 47(5), pp. 1365-1373. ISSN 1347-5320
19. YANG, G., MA, J., CARLSON, B., WANG, H., KOVACEVIC, R. 2017. Materials & Design, Vol. 123, pp 197-210. ISSN 0264-1275
20. ZHOU, L., HYER, H., PARK, S., PAN, H., BAI, Y., RICE, K., SOHN, Y. 2019. Microstructure and mechanical properties of Zr-modified aluminum alloy 5083 manufactured by laser powder bed fusion, Additive Manufacturing, 28, pp. 485-496. ISSN 2214-8604
21. GOSWAMI, R., SPANOS, G., PAO, P., HOLTZ, R. 2010. Precipitation behavior of the β phase in Al-5083. Materials Science and Engineering A 527, pp. 1089-1095. ISSN 0921-5093
22. TAMASGAVABARI, R., EBRAHIMI, A., ABBASI, S., YAZDIPOUR, A. 2020. Effect of harmonic vibration during gas metal arc welding of AA-5083 aluminum alloy on the formation and distribution of intermetallic compounds. Journal of Manufacturing Processes, Vol. 49, pp. 413-422. ISSN 1526-6125
23. RUDY, J., RUPERT, E. 1970. Effects of Porosity on Mechanical Properties of Aluminum Welds. Weld. J., 49(7), pp. 322–336.
24. WU, S., YU, X., ZUO, R., ZHANG, W., XIE, H., JIANG, J. 2013. Porosity, Element Loss and Strength Model on Softening Behavior of Hybrid Laser Arc Welded Al-Zn-Mg-Cu Alloy with Synchrotron Radiation Analysis. Weld. J., 92(3), pp. 64–71.
25. SATO, S., MATSUMOTO, J., OKOSHI, N. 1976. Effects of Porosity on the Fatigue Strength of 5083 Alloy Butt Welds. J. Ipn. Inst. Light Met., 31(4), pp. 398–405.
26. YADOLLAHI, A., SHAMSASEI, N. 2017. Additive Manufacturing of Fatigue Resistant Materials Challenges and Opportunities. Int. J. Fatigue, 98, pp. 14–31.
27. VYSKOČ, M., SAHUL, M., SAHUL, M. 2018. Effect of Shielding Gas on the Properties of AW 5083 Aluminum Alloy Laser Weld Joints. Journal of Materials Engineering and Performance, Vol. 27, pp. 2993–3006.
28. TAKAHASHI, B., MEHMETLI, B., SATO, S. 1998. Influence of Shielding Gas and Laser Irradiation Conditions on Porosity Formation in CO2 Laser Welding of Aluminium Alloy. Weld. Int., 12(5), pp. 347–353.
29. GLOWACKI, M. 1999. The Effects of the Use of Different Shielding Gas Mixtures in Laser Welding of Metals. *J. Phys. D Appl. Phys.*, 28(10), p. 2051.

30. KATSUNA, M., QU, Y. 1998. Study on Porosity Formation in Laser Welds of Aluminum Alloys (Report 2) Mechanism of Porosity Formation by Hydrogen and Magnesium. *J. Light Met. Weld. Constr.*, 36, pp. 1–17.

31. HUANG, Y., SHEN, C., JI, X., LI, F., ZHANG, Y., HUA, X. 2020. Correlation between gas-dynamic behaviour of a vapour plume and oscillation of keyhole size during laser welding of 5083 Al-alloy. *J. Mater. Process. Technol.*, 283, 116721.

32. PADILLA, E., JAKKALI, V., JIANG, L., CHAWLA, N. 2016. Quantifying the Effect of Porosity on the Evolution of Deformation and Damage in Sn-Based Solder Joints by X-ray Microtomography and Microstructure-Based Finite Element Modeling. *Acta Mater.*, 60, pp. 4017–4026.

33. PROKIC-CVETKOVIC, R., KASTELEC-MACURA, S., MILOSAVLJEVIC, A., POPOVIC, O., BURZIC, M. 2010. The Effect of Shielding Gas Composition on the Toughness and Crack Growth Parameters of AlMg4,5Mn Weld Metals, *J. Min. Metall. Sect. B Metall.*, 46(2B), pp. 193–202. ISSN 2217-7175

34. BANDI, B., DINDA, S., KAR, J., ROY, G., SRIRANGAM, P. 2018. Effect of weld parameters on porosity formation in electron beam welded Zircaloy-4 joints: X-ray tomography study. In *Vacuum*, Vol. 158, pp. 172-179. ISSN 0042-207X

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