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Reliability of Laser Welding Process for ZE41A-T5 Magnesium Alloy Sand Castings

Haider Al-Kazzaz[1], Xinjin Cao[2,*], Mohammad Jahazi[2] and Mamoun Medraj[1]

[1]*Department of Mechanical Engineering, Concordia University, Montreal, Canada*
[2]*Aerospace Manufacturing Technology Centre, Institute for Aerospace Research, National Research Council Canada, Montreal, Canada*

Laser welding is a promising joining method for magnesium alloys. The process reliability of 2-mm ZE41A-T5 butt joints welded by a 4 kW Nd:YAG laser was investigated from weld geometries, defects and mechanical properties using Weibull statistical distribution. Smooth, geometrically regular and macroscopically defect-free sound joints were obtained. However, sag, undercut, surface misalignment, and some variations in weld width and fusion zone area were also observed. The results indicated that tensile strength and elongation at fracture can be more accurately described by Weibull distribution. The modulus values of 31.98 and 22.52 were obtained for tensile strength in the as-welded and the aged conditions, respectively, indicating that tensile strength becomes more scattered after artificial aging. The aging treatment does not significantly affect mechanical properties, although it can provide stress relief. After laser welding, there is some degradation in tensile properties, especially elongation at fracture. [doi:10.2320/matertrans.MRA2007622]

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1. Introduction

The applications of magnesium alloys are expanding rapidly in aerospace, aircraft, automotive, electronics and other industries. However, there has been a lack of effective and efficient welding techniques for magnesium alloys. Conventionally, metal inert gas (MIG) and tungsten inert gas (TIG) arc processes are the two main welding methods, especially for the repair of magnesium alloy components.[1,2)]

Due to their low heat capacity and latent heat of fusion, magnesium alloys usually require relatively low heat input and allow high welding speeds.[1,3)] Magnesium is easy to oxidize due to its high affinity for oxygen. Thus, fluxes or high-purity shielding gases are needed for fusion welding. The surface oxide layers, hydride layers, grease and release agents present on magnesium alloy surfaces may cause porosity and cracking, and therefore should be cleaned or removed prior to welding.[2)] The low viscosity and low surface tension of molten magnesium may cause sag or even drop-through of the melt, particularly for large weld pools, and thereby leads to the formation of notch and underfill defects. Magnesium alloys have a relatively low boiling point (about 1090°C) and high vaporization pressure (360 Pa), leading to substantial spatter, loss of chemical elements, unstable weld pool, poor surface quality and formation of gas pores.[2,4,5)] The relatively low modulus of elasticity and high heat expansion coefficient of magnesium alloys may result in significant residual stresses and distortion.[1,4)] Thus very rigid clamping is needed for magnesium alloy welding.[6)] The high residual stresses will also promote stress-corrosion cracking for some magnesium alloys containing Al higher than about 1.5%.[1)] Magnesium alloys also have a tendency for liquation and solidification cracking because of the presence of low melting-point intermetallics and relatively wide freezing intervals.[4,6)] Preheating prior to welding can greatly reduce the susceptibility to weld cracking, as a result of decreased temperature gradients in the weld zones and the generation of lower thermal stresses during cooling;[1)] however, preheating is not recommended due to the energy waste. For the welding and repair of magnesium alloy castings, the presence of porosity in original castings is also a challenge. Magnesium alloys, therefore, are not easy to weld reliably and even have not been highly recommended for welding at industrial mass production scales.[4)]

Compared with arc welding, high energy-density laser welding has the potential to become an important joining technique for magnesium alloys due to low and precise heat input, small heat-affected zone (HAZ), deep and narrow fusion zone (FZ), high welding speed and productivity, low residual stress and distortion, possible elimination of pre- and post-weld heat treatments, high accuracy, great process flexibility and reliability.[7,8)] As a fusion technique, however, laser welding may experience similar issues such as geometrical defects, loss of chemical elements, porosity, and cracking as encountered in arc welding processes. Therefore, it is important to investigate the reproducibility and reliability of the laser welding process. This study is focused on the reproducibility and reliability of the Nd:YAG laser welding of ZE41A-T5 alloy in terms of welding geometries, defects and mechanical properties using a Weibull statistical distribution model.

2. Statistical Analysis of Weibull Distribution Model

Usually, there is a large scatter in the mechanical properties of castings and weldments. Many models are available to describe the scattered data, for instance, normal or Gaussian distribution (including log-normal distribution) and various skew-type distributions including Weibull distribution, Jayatilaka-Trustrum statistics based on Weibull distribution, type-1 extreme value distribution, gamma distribution, etc.[9)]

*Corresponding author, E-mail: xinjinc.cao@cnrc-nrc.gc.ca

Statistical distribution models describing the fracture strength of brittle materials and tensile data are based on the weakest-link concept. This concept states that the entire body will fail when the stress at any defect is sufficient for unstable crack propagation. Though there is no universally accepted statistical distribution model to describe the range of strengths measured in a set of experiments, Green and Campbell[10] concluded that the most accurate description of tensile strength for sand castings is obtained by Weibull distribution. The Weibull distribution model is commonly used as a characterization tool in the field of fracture of engineering materials due to its mathematical simplicity and relative success in describing most data. However, few studies have been reported on the reliability and reproducibility of laser-welded joints using a Weibull statistical model.

The Weibull distribution function linearizes most engineering data distributions, making it possible to estimate a population of infinite size from small amounts of data.[9] A normal distribution is symmetrical about the mean strength, whereas a Weibull distribution is skewed, showing a longer tail of low strengths, and a sharper cut-off at high strengths arising naturally because property values cannot go higher than their defect-free values. The behaviour of the data is normally described by a two-parameter function expressed as:

$$P = 1 - \exp[-(\sigma/\sigma_o)^m] \quad (1)$$

where P is the fraction of specimens that fail at a given stress or lower. The parameter σ_o is the stress at which approximately 63.2% of the population of specimens have failed, and m, known as the Weibull modulus, is a constant for that particular population. The modulus value is an assessment of reliability (*i.e.* the degree of scatter). The value of m can be obtained by taking twice the logarithm of eq. (1):

$$\mathrm{Ln}\{\mathrm{Ln}[1/(1-P)]\} = m\mathrm{Ln}(\sigma) - m\mathrm{Ln}(\sigma_0) \quad (2)$$

The $\mathrm{Ln}\{\mathrm{Ln}[1/(1-P)]\}$ vs. $\mathrm{Ln}(\sigma)$ plot is a straight line with slope m and intercept $-m\mathrm{Ln}(\sigma_0)$. This is often referred to as a Weibull plot.

Linear regression analysis is widely employed to evaluate m. The σ values (tensile strength) are arranged in order of increasing value as follows:

$$\sigma_1 \leq \sigma_2 \leq \sigma_3 \cdots \leq \sigma_j \cdots \leq \sigma_n$$

A probability of failure is assigned to each σ such that:

$$P_1 \leq P_2 \leq P_3 \cdots \leq P_j \cdots \leq P_n$$

where $0 \leq P_j \leq 1$. Because the sample tested is considered representative of a large population, the true value of P_j for each σ_j is not known and has to be estimated. Using Monte-Carlo simulations, Khalili and Kromp[10] suggested the optimum failure probability estimator for the j-th fracture, from a total of N results:

$$P = (j - 0.5)/N \quad (3)$$

Generally, a minimum of 20 samples is recommended for a valid characterization of the strength of a brittle material.[11,12]

3. Experimental Procedure

The experimental material was aerospace grade sand-cast ZE41A-T5 (Mg-4.2Zn-1.2Ce-0.7Zr) magnesium alloy, which is widely used for aircraft engine casings, auxiliary gearboxes and motor wheels. The test specimens for laser welding had sizes of approximately $150 \times 150 \times 2$ mm, cut and machined from 25-mm thick sand-cast coupons. The joint faces were also machined along the length. Prior to laser welding, the joint faces and their surroundings were carefully cleaned with acetone to remove any contamination.

The laser welding machine used was a continuous wave (CW) 4 kW HL4006 Nd:YAG (neodymium-doped yttrium aluminum garnet) laser system equipped with an ABB robot. A focal length of 150 mm and a fibre diameter of 0.6 mm were employed. Helium was used to shield the top surface and argon for the 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 He shielding gas was directed to the top surface of the workpiece at an angle of 30° (with the horizontal) and Ar was vertically and uniformly directed to the bottom surface. The main process parameters used were laser power 4 kW, welding speed 6 m/min, and surface defocusing with 0.45-mm focal spot diameter. The workpieces (butt joints) were positioned and clamped in a fixture with a gap size of 0.4 mm. A filler wire of EZ33A-T5 (Mg-3Re-2.5Zn-0.6Zr) Mg alloy with 1.6-mm diameter and 990-mm length was used through a wire feeding mechanism. The filler wire was positioned at the intersection of laser beam and top surface of the workpiece. A delivering angle of 60° was used between the filler and the laser beam axis to reduce the contact area between them. Wire feed rate was determined using volume flow rate constancy. The processing variables used in this work are based on the optimized process for the fully penetrated butt joints of the 2-mm experimental alloy.[13,14] To investigate the process reliability, 8 butt joints were welded using the same process setup.

The established commercial heat treatment for ZE41A-T5 castings is double-precipitation heat treatment (330°C for 2 hours, air cooled and followed by 180°C for 2 hours), or only 330°C for 2 hours. The T5 aging treatment at 330°C for 2 hours was found to strengthen the alloy but the additional strengthening during subsequent aging at 180°C is negligible.[15] Therefore, 4 randomly selected joints were artificially aged (T5) only at 330°C for 2 hours immediately after laser welding. Then a length of approximately 20–30 mm was cut from both ends of each joint to exclude the unstable segments appearing at the start and end of laser welding. Cross-sectional samples for metallurgical examination were cut from each joint at three locations (start, middle and end). The polished samples were etched in Nital solution. The dimensions of the fusion zone were measured using an Olympus optical microscope equipped with Discover Essential image analyzer software. All other specimens were machined according to ASTM B557M-02A, to give gauge dimensions of 10-mm width, 50-mm parallel length and 139-mm overall length. Tensile tests were carried out using a MTS-100 kN test machine fitted with a laser extensometer (25-mm gauge length was used). The tests were conducted

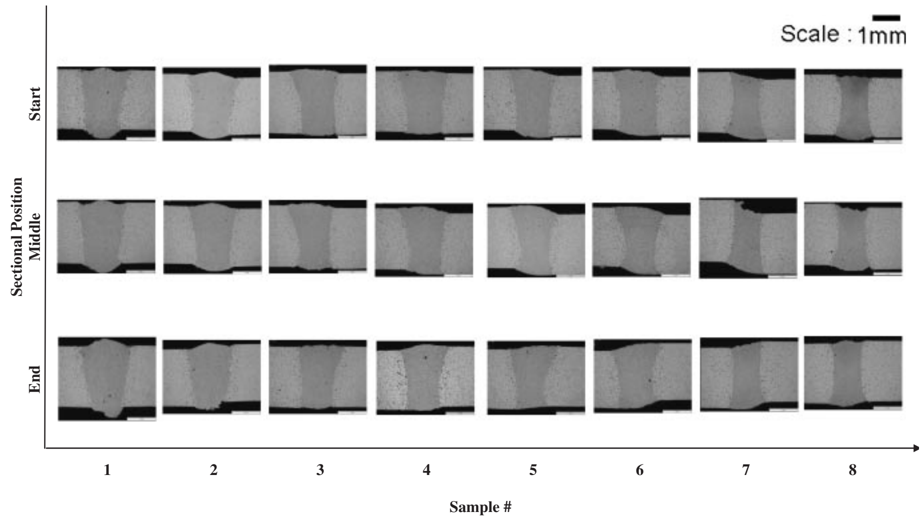


Fig. 1 Transverse sections of the 8 butt-joints.

with a cross head speed of 0.6 mm/min at room temperature. Twenty-four tensile specimens were tested in the as-welded condition and 24 in the aged (T5) condition. Four tensile specimens machined from the base sand castings were also tested. All valid tensile data of the welds were analyzed using Weibull statistical distribution.

4. Results and Discussion

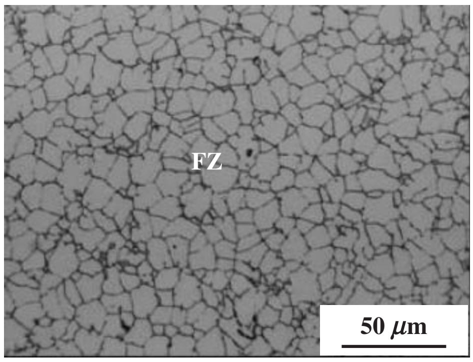
4.1 Microstructures

Figure 1 shows the overall transverse sections for all 8 butt joints, 3 sections for each. Figure 2 shows typical as-welded microstructures in the fusion zone (FZ), partially-melted zone (PMZ), heat-affected zone (HAZ) and base metal (BM). The FZ displays fine equiaxed weld structures while the HAZ has large grains, similar to the cast equiaxed structures in the base metal. It is found that no grain growth or coarsening occurs in the HAZ. The partially melted zone was rather narrow, only one or two grains wide. In the partially melted zone, some branches grow perpendicularly to the surface of the large grains (existing substrates in the PMZ) due to the epitaxial growth (Fig. 2(c)). The fine-grained microstructures are the typical feature of the fusion zone in the laser welded joints due to rapid cooling rate. After aging treatment (T5), no significant differences in the matrix microstructures of the weld joints were observed. However, the strengthening phase Mg_9Ce may precipitate in the aging-hardenable magnesium alloy.[7)]

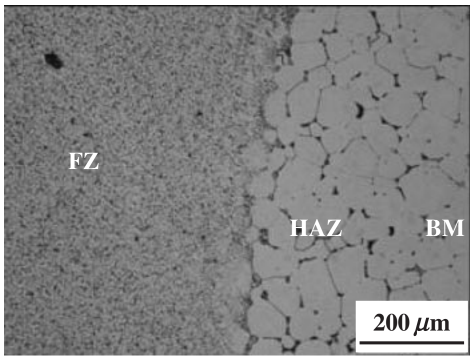
4.2 Weld defects

The majority of the weld joints are smooth, geometrically regular and macroscopically defect-free, but some geometrical defects such as sag, underfill and surface misalignment were observed as shown in Fig. 1. The surface misalignment was related to inadequate fixturing prior to welding. The sag and underfill defects, however, occurred only in some of the joints, indicating that their formation in magnesium alloys is process-sensitive. Magnesium alloys have low viscosity and low surface tension, and thus have a strong tendency to form sag and underfill defects. Slight variations in the welding

(a)



(b)



(c)

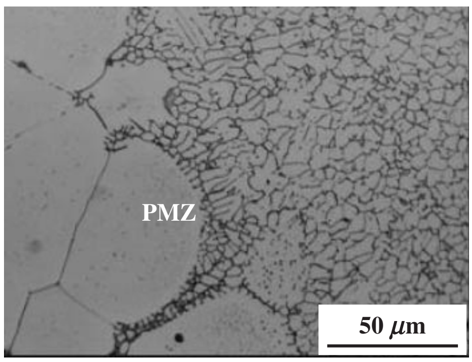
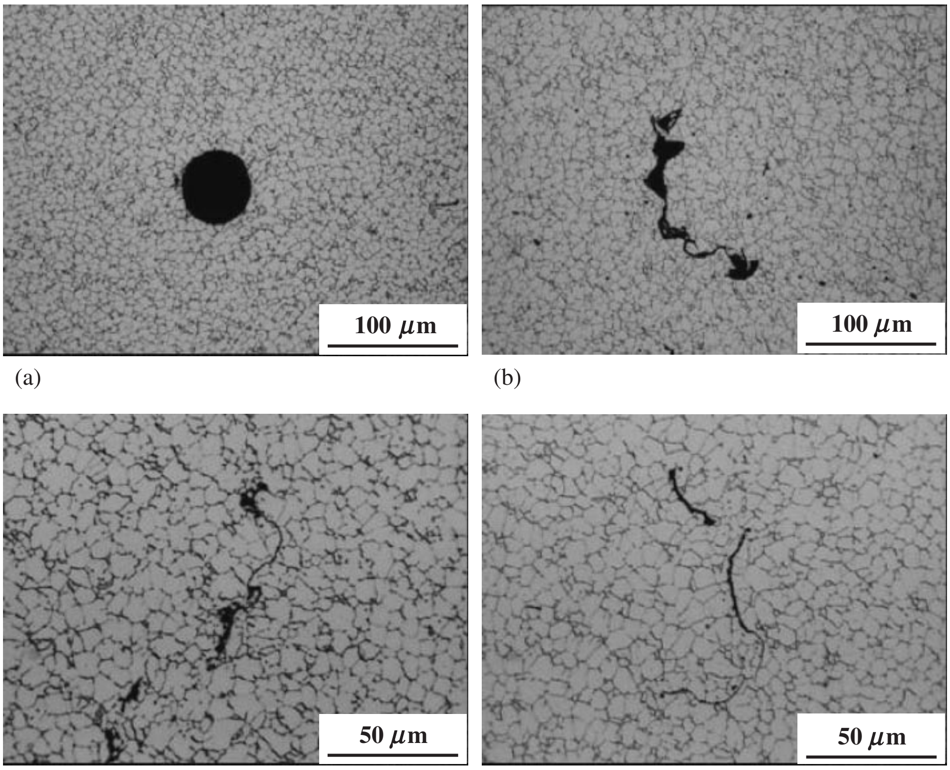


Fig. 2 Typical microstructures in the as-welded joint.



(a) (b) (c) (d)

Fig. 3 Typical porosities and crack defects in the fusion zone.

process might cause these defects. Some typical microporosities and microcracks were observed at high magnification as shown in Fig. 3. The formation mechanisms of these microporosities and microcracks were discussed in detail in Ref. 7). As shown in Figs. 3(b) and (c), the microcracks are frequently observed to be associated with porosities, *i.e.* the microcracks can be initiated and terminated at the porosities. The distributions of porosity area percentage and crack length measured at 100 magnifications are shown in Fig. 4. The welded joints have an average porosity area of 0.13% ranging from 0.03 to 0.27%, and average crack length of 0.11 mm with the longest up to 0.41 mm in the fusion zone (FZ). These cracks with an area of less than 1 mm^2 are termed microcracks according to the European Standard.[16)] No significant differences in the density and size of microporosities and microcracks were observed between the FZ and base sand castings. The high quality base castings were strictly manufactured according to aerospace industrial specifications. Therefore, the laser-welded joints have similar soundness compared with the base aerospace castings.

4.3 Joint dimensions

Figure 5 shows the distribution of top weld width and FZ area. The weld width with an average value of 1.65 mm ranges from 1.11 to 1.90 mm. The FZ area with an average value of 2.95 mm^2 ranges from 2.36 to 3.66 mm^2. It is interesting to note that the weld width and FZ area have a bimodal distribution. Such multiple distributions indicate that joint geometries for magnesium alloys are less stable during laser welding. The observed scatters in geometrical dimensions and fusion zone areas are probably due to the evaporation of low-boiling-point elements (Zn and Mg) and the variations in process stability.

4.4 Mechanical properties

Figures 6 to 8 show the frequencies (histograms), cumulative probabilities and Weibull plots for tensile strength (TS), 0.2% offset yield stress (YS) and fracture elongation (El), respectively, in the as-welded and aged (T5) conditions. The Weibull statistics are not shown for the base castings, as only four tensile tests were carried out. As indicated in Figs. 6 and 8, the tensile strength and fracture elongation are well characterized with Weibull-type distributions. However, Figure 7 shows that the yield stress does not appear as a Weibull distribution since there is a lack of skewed long tails at low values in the as-welded condition. Particularly in the aged conditions, the yield stress tends to have a normal distribution. At the yield point, no substantial deformation occurred, and thus it is logical to assume that the yield stress will be less affected by variations in welding defects. The main effect of welding defects on yield stress is probably due to the reduction in area.

In materials research, Weibull analyses were originally used almost exclusively for brittle ceramics and glasses. Green and Campbell[10)] illustrated the usefulness of this approach to metal castings. This work clearly indicates that the tensile strength and fracture elongation of laser-welded joints for magnesium alloy sand castings can be more accurately described by Weibull distribution than Gaussian distribution. The slope of the Weibull plots (m) is a measure of the reliability of the data. The higher the m values, the less

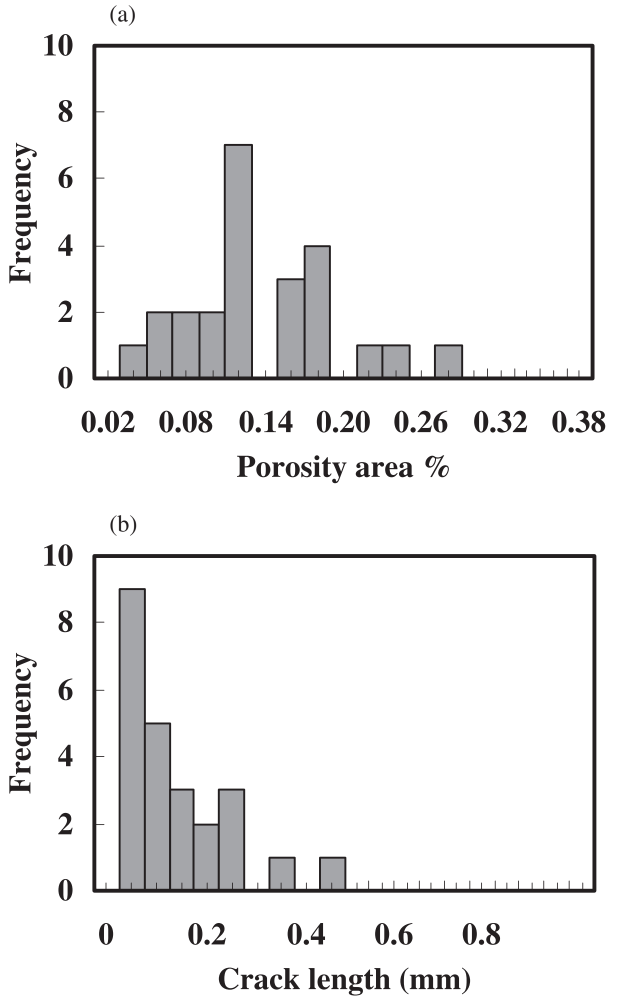


Fig. 4 Distribution of welding defects (a) porosity area % and (b) crack length.

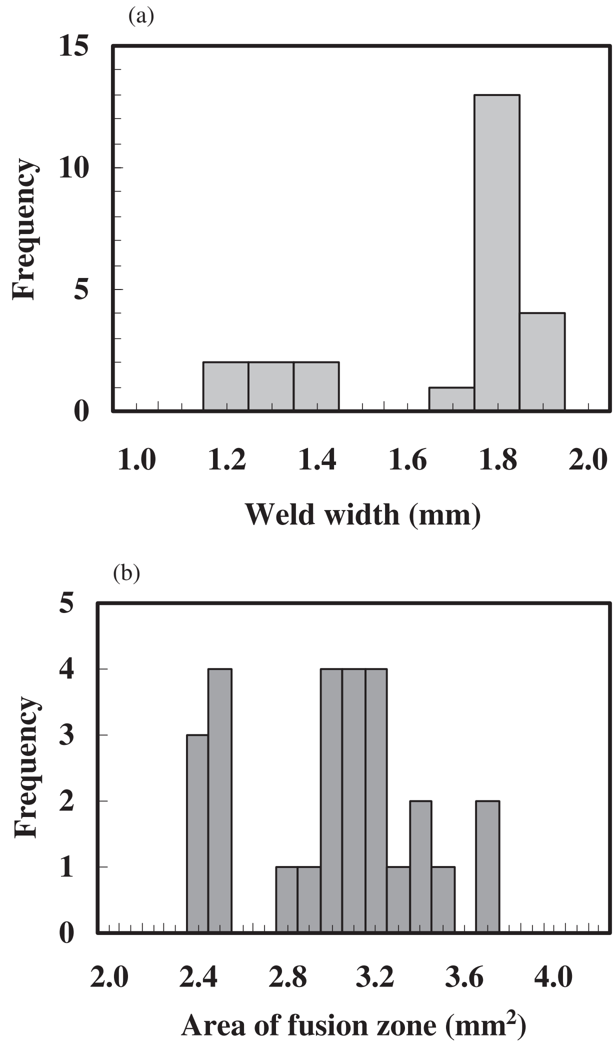


Fig. 5 Distribution of welding dimensions (a) top weld width and (b) area of fusion zone.

scattered the properties and the higher the reliability (or reproducibility). This is well demonstrated in the cumulative distributions and Weibull plots illustrated in Figs. 6(c)–(d). It can be seen that a narrower range of tensile strength values is observed in the as-welded specimens and thus a higher Weibull modulus is obtained, indicating that the tensile strength is more scattered after post-weld aging (T5). The Weibull modulus values of 31.98 for the as-welded specimens and 22.51 for the aged specimens are in agreement with those obtained in castings.[17,18] For yield strength and fracture elongation, no significant differences were found for the Weibull modulus values in the as-welded and the aged conditions (Figs. 7–8 and Table 1).

For the statistical properties as shown in Table 1, there were some losses in the tensile properties after laser welding, in particular fracture elongation (approximately 6.5% for tensile strength, 5% for yield strength and 26% for fracture elongation). No significant variations in mechanical properties were found in the as-welded and the aged conditions. By contrast, the T5 treatment was found to increase tensile strength and particularly 0.2% YS for sand castings.[15] Thus, the aging (T5) of the magnesium alloy weldments mainly provided stress relief without significantly affecting the mechanical properties. This heat treatment may even become unnecessary due to the low heat input of laser welding.

As shown in Table 1, the aging treatment significantly influences the fracture locations during tensile tests. Almost all welded joints failed in either the base metal or the FZ. More joints were fractured in the base metal in the as-welded specimens. However, more were fractured in the FZ after the aging treatment. If a similar defect structure is assumed in both the as-welded and the aged joints, this significant difference in the failure locations indicates that some variations in microstructure may have occurred during the aging treatment. Further work is needed to investigate the precipitates appearing during the aging treatment using transmission electron microscopy.

5. Conclusions

The process reproducibility (reliability) of the 2-mm butt joints of ZE41A-T5 magnesium alloy sand castings welded by a 4 kW CW Nd:YAG laser was investigated. Some conclusions can be drawn as follows:

(1) The tensile strength and elongation at fracture can be more accurately described by Weibull distribution than by normal distribution. The Weibull modulus values of

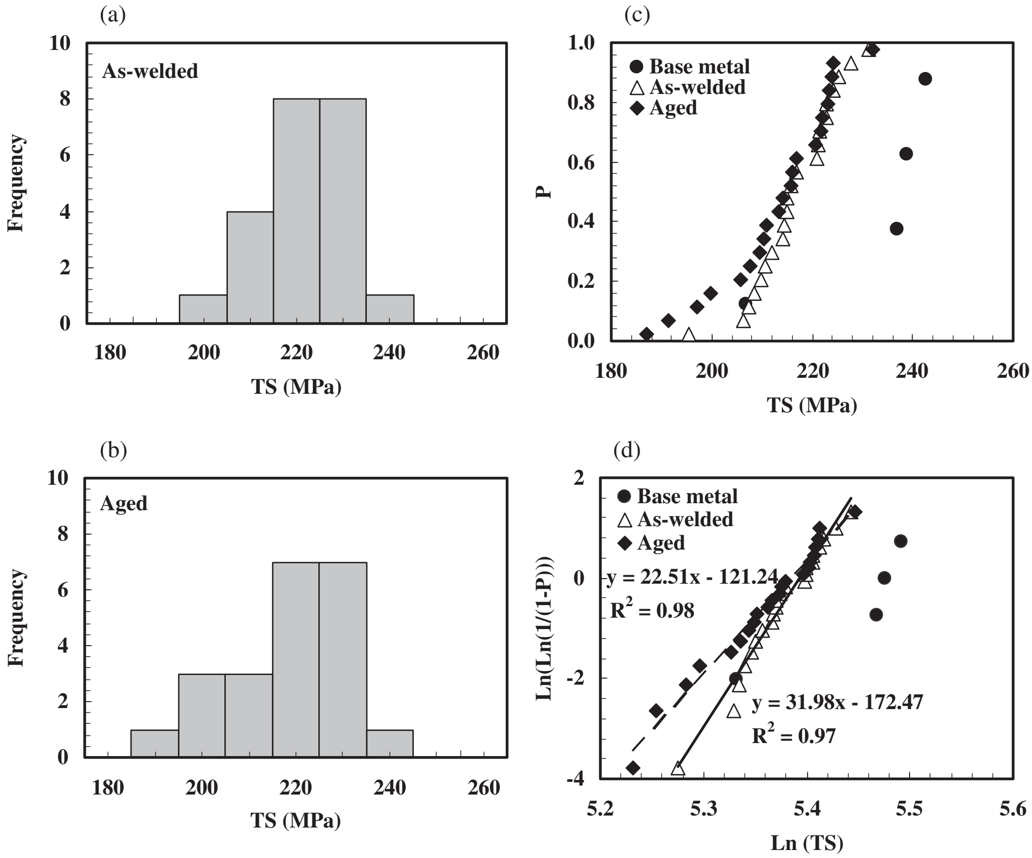


Fig. 6 Histograms (a-b), cumulative (c) and Weibull plot (d) of tensile strength (TS) data.

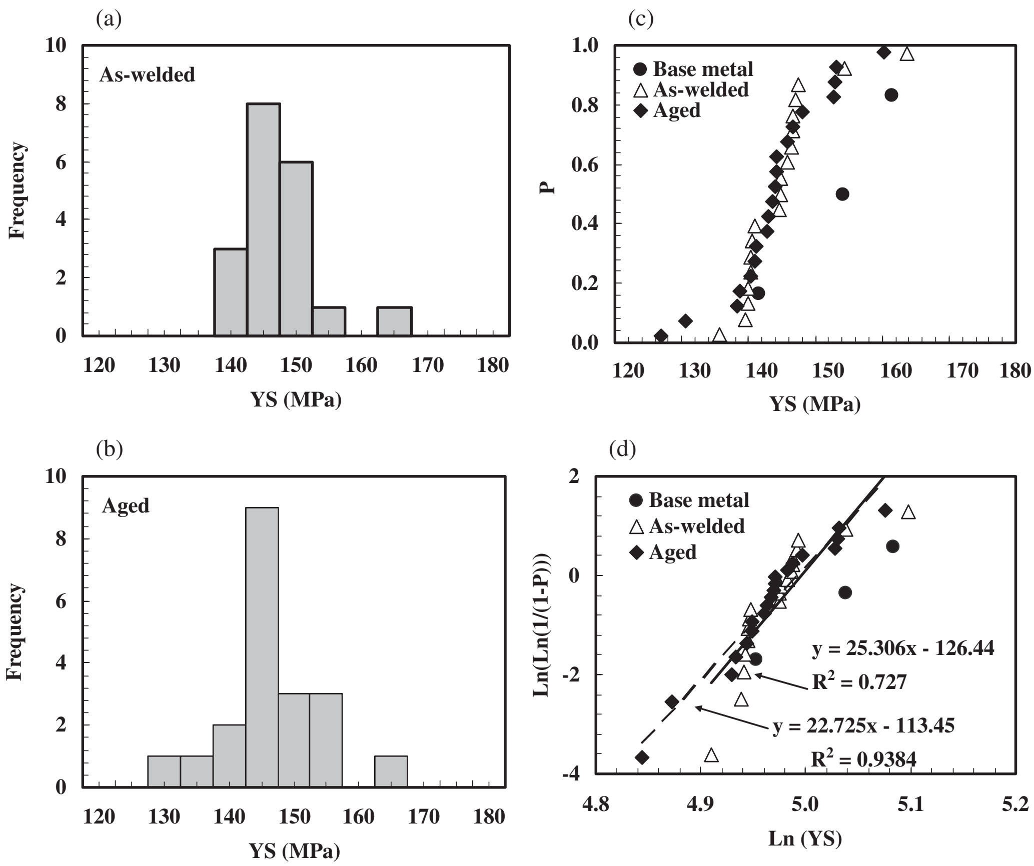


Fig. 7 Histograms (a-b), cumulative (c) and Weibull plot (d) of 0.2% offset yield strength (YS) data.

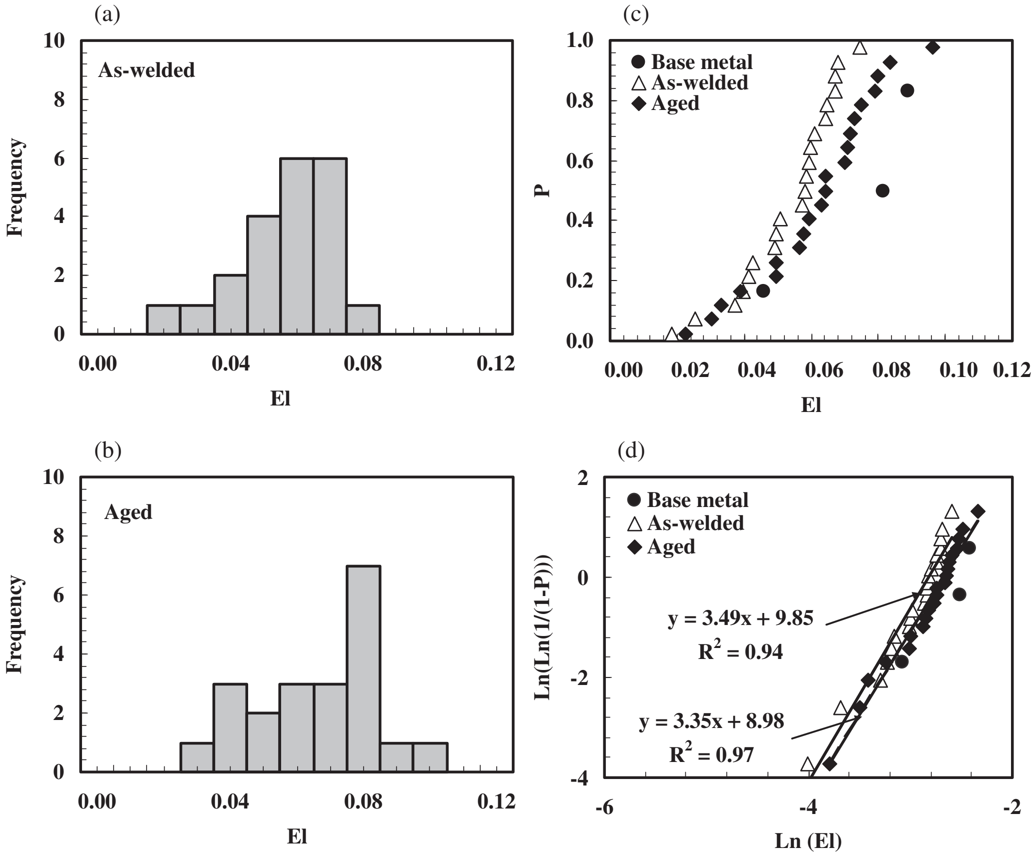


Fig. 8 Histograms (a-b), cumulative (c) and Weibull plot (d) of fracture elongation (El) data.

Table 1 Statistical data on mechanical properties.

Property		Base castings	As-welded	Aged (T5)
Tensile strength	Mean	231.29 MPa	216.30 MPa	213.04 MPa
	Standard deviation	16.48 MPa	8.23 MPa	11.44 MPa
	Weibull modulus	—	31.98	22.51
Yield strength	Mean	152.37 MPa	144.73 MPa	143.90 MPa
	Standard deviation	10.05 MPa	6.23 MPa	7.58 MPa
	Weibull modulus	—	25.31	22.73
Elongation at fracture	Mean	7.21%	5.31%	6.14%
	Standard deviation	2.31%	1.46%	1.88%
	Weibull modulus	—	3.49	3.35
Failure location	Base metal	—	13	7
	Fusion zone	—	8	14
	Heat-affected zone	—	1	1

31.98 and 22.52 were obtained for tensile strength in the as-welded and the aged conditions, respectively, indicating that tensile strength becomes more scattered after artificial aging (T5).

(2) The T5 aging treatment does not significantly affect mechanical properties, although it can provide stress relief for the laser-welded joints.

(3) Some shape defects such as sag and underfill were observed due to the low viscosity and low surface tension of molten magnesium alloys. There are some scatters in the weld width and FZ area values, probably due to the evaporation of low-boiling-point elements and variations in process stability.

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