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Fatigue, Fatigue Crack Propagation and Mechanical Fracture Behaviour of Laser Beam-Welded AZ31 Magnesium Sheets

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Abstract. Weight reduction is the main driving force in automotive and aircraft structural design. As a result, magnesium alloys, with their high potential for lightweight construction, have attracted a considerable amount of industrial attention. The determining criterion for the structural applications of magnesium alloys is the availability of efficient joining technologies for the construction of lightweight structures and the availability of reliable data for the assessment of their damage tolerance behaviour. Laser beam welding (LBW), as a high-speed and easily controllable process, allows the welding of complex geometric forms that are optimised in terms of mechanical stiffness, strength, production velocity and visual quality. The work accomplished in this study addresses the challenges of the LBW process for typical joint configurations using the magnesium alloy AZ31HP: butt joints, T joints and overlap joints. LBW processes were developed for use with a 3.3-kW Nd:YAG laser to optimise the mechanical performance of such joints with respect to tensile strength, fatigue, fatigue crack propagation and mechanical fracture behaviour. The relationships between the LBW process and the microstructural and mechanical properties of welds were established. Compared to state-of-the-art aerospace alloys, AZ31HP demonstrates that magnesium alloys have potential for use in structural applications, with AZ31HP being comparable to AA2024T351 and AA6061T6. Welded AZ31HP exhibits better crack resistance than the base material, so fully welded integral structures made from magnesium alloys can be used in lightweight construction.

Introduction

Being the lightest structural metallic material and possessing good mechanical properties, Mg has attracted a considerable amount of attention from various industries, such as the aerospace, automotive and electronics industries. The use of magnesium alloys in various industries is growing as a result of research on the mechanical behaviour of these lightweight alloys. Alloy developments related to corrosion, creep and mechanical strength have received attention from researchers worldwide, in many industries. The use of magnesium can contribute significantly to mass reduction due to the combination of its low density, high specific strength, high stiffness, and good castability [1-3].

This study addresses the challenges of the using LBW to form typical joint configurations from the magnesium alloy AZ31HP, i.e., butt joints, T joints and overlap joints. LBW processes were developed for use with a 3.3-kW Nd:YAG laser to optimise the mechanical performance of the joints with respect to their tensile strength, fatigue, fatigue crack propagation and mechanical fracture behaviour. This research was conducted to fill the gap in the structural integrity investigations of magnesium standard alloys. For example, there is little information available on the fracture toughness of magnesium alloys [4-5], and no information is available on the R-curve behaviour of laser beam-welded magnesium sheet material.

Laser beam welding

LBW was performed using a 3.3-kW Nd:YAG laser with fibre optics (a 400- μm core diameter) and a 200-mm focal length. The laser optic lens was mounted on a KUKA KR30HA industrial robot. Butt joints without filler wire were formed in a 3-axis Ixion CNC machine. An industrial robot arm (KUKA KR30HA) was used to weld butt joints with additional filler wire. The industrial robot arm was used to welding T joints and overlap joints. LBW processes were developed and optimised with respect to the microstructural and mechanical performance of the joints. Details on the process parameters and their influence on the microstructure and mechanical properties of the laser beam-welded magnesium alloys can be found in [5-10]. With the chosen laser welding parameters, joints with low porosity were produced (Fig. 1 and 2). All of the joints exhibited the typical keyhole welding effect of narrow welds. No heat-affected zone was observed.

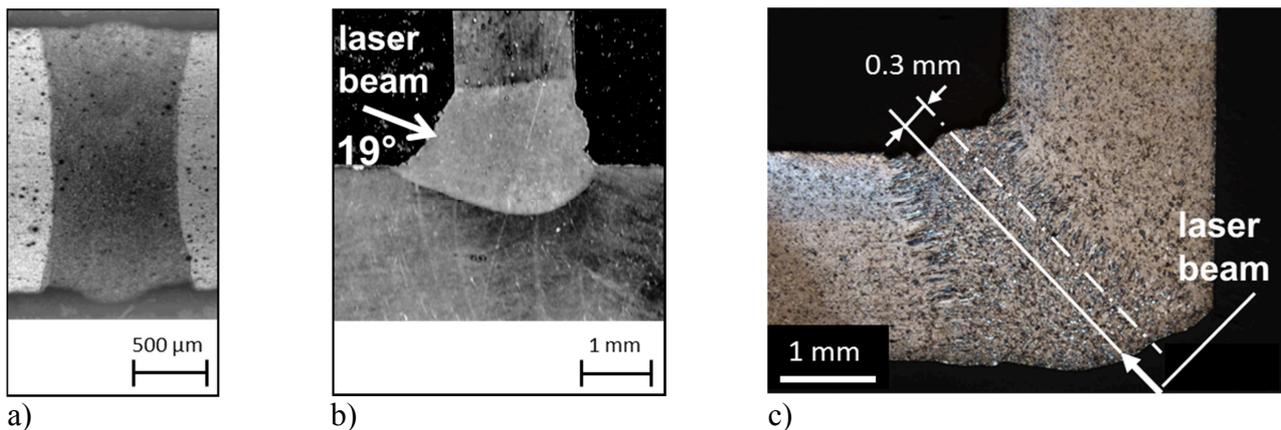


Figure 1. Macrographs of welded specimens: a) butt joint of 2.5-mm AZ31HP welded without filler wire at a 3.0-m/min welding speed with 2.2-kW laser power; b) T joint of 1.6-mm AZ31HP and 2.5-mm AZ31HP welded with AZ31-X wire (at a wire feed speed of 1.25 m/min) from one side, a 5.1-m/min welding speed and 2.1-kW laser power; c) welded square tube of 2.5-mm AZ31HP without filler wire at a 3.6-m/min welding speed and 2.8-kW laser power [10].

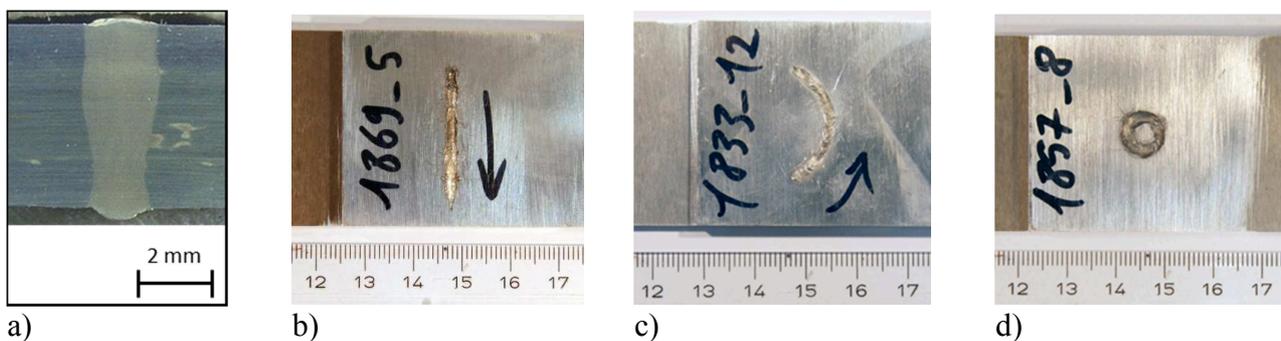


Figure 2. a) Cross section of an overlap joint welded without filler wire at a 2.4-m/min welding speed and a 2.8-kW laser power and various joint shapes investigated in fatigue tests (for a bead width assumed to be 1.5 mm): b) line, c) arc and d) circle. [9]

Mechanical properties

The base material (BM) AZ31HP, in a sheet 2.5 mm thick, exhibits anisotropy in the yield strength in the longitudinal (L) and transverse (T) directions from 133 to 159 MPa (Figure 3a). Anisotropy can also be observed for the fracture strain. The difference in the ultimate tensile strengths (UTS) obtained in the two directions is less than 2%. There are no visible differences in the yield or UTS between the BM in the transverse direction and the laser-welded material (WM) (butt joint); the joint efficiency is greater than 95%. Similar results were reported by Danzer [11]. However, the fracture strain (A_f) is significantly influenced by the laser weld: A_f decreases from

27 % to values between 11 % and 14 %. Similar behaviour was observed in hoop stress tests of T joints [7]. The fracture strain of the welds is approximately 45 % of the fracture strain of the base material.

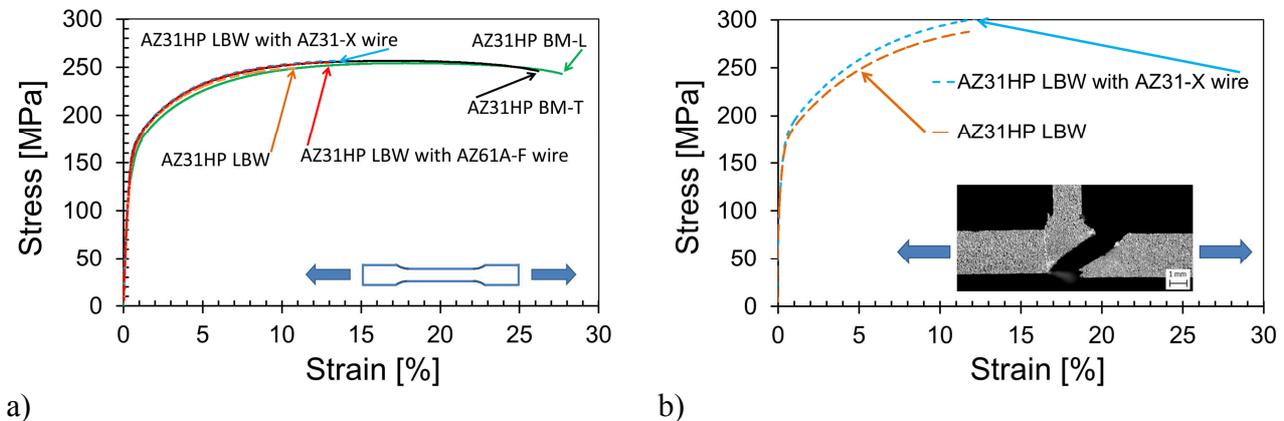


Figure 3. Stress–strain curves of a) butt joints of AZ31HP (2.5 mm thick) and b) T joints of AZ31HP (2.5 mm thick) and AZ31HP (1.6 mm thick) (hoop stress test)

Fatigue

A servohydraulic 25-kN machine with MTS electronics was used for load-controlled fatigue tests at ambient temperature in air with a frequency of 40 Hz and an R-ratio of 0.1 in the case of butt joints and an R-ratio of 0.2 in the case of overlap joints. Details of the fatigue results are summarised in [8-9]. Fig. 4 represents the S–N curves for the base materials AZ31HP, AA2024T351 and AA5083H321 and the welded AZ31HP butt joints. For the calculation of the specific maximum stress, the maximum stress was divided by the density of the material tested (1.77 g/cm^3 for AZ31HP, 2.78 g/cm^3 for AA2024T351 and 2.66 g/cm^3 for AA5083H321). It can be observed, that the base material AZ31HP exhibits better fatigue behaviour than the welded Mg alloy due to surface imperfections and notches in the welds. Similar values are reported by Karakas et al. [12]. When these surface imperfections are removed, the inner flaws become more significant. For the machined specimens, the difference from the base material is 10 %. The fatigue behaviour of the Mg alloy is worse than the fatigue behaviour of the Al alloy. However, with respect to the specific maximum stress, the fatigue limits of the base material and the welded material (milled surface) AZ31HP are very close to the fatigue limit of the aerospace alloy AA2024T351.

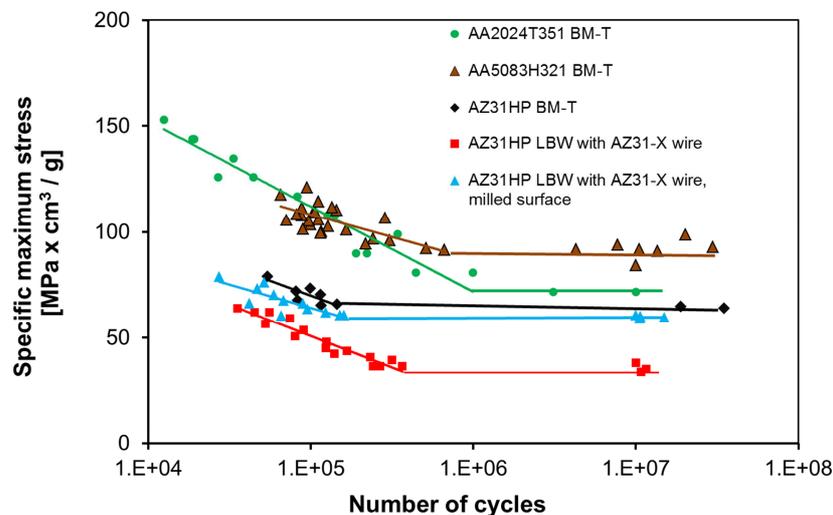


Figure 4. S–N curves of the base materials AZ31-HP, AA2024T351 and AA5083H321 and the laser beam-welded AZ31HP.

The load–lifetime (L – N) curves for the overlap joints are presented in Fig. 5. As LBW is concurring to resistance spot welding (RSW) in terms of its high process flexibility and efficiency, fatigue tests of resistance spot-welded specimens were also conducted. Three different joint shapes, such as arc, circle and line shapes (Figs. 2b–d) were investigated for comparison with the nugget shape of the resistance spot weld. The principle of equivalently resistant areas was used to dimension the three different shapes [9]. The linear, circular and arc variants exhibit similar behaviour under cyclic loading. The difference in the fatigue behaviour between the laser and resistance spot welds is appreciable in the cycle regime up to 10^5 cycles. Below 10^5 cycles, the laser-welded joints exhibit improved fatigue behaviour. However, only minimal enhancement of the fatigue strength was achieved using the linear laser joints in the higher-cycle regime (10^6 cycles).

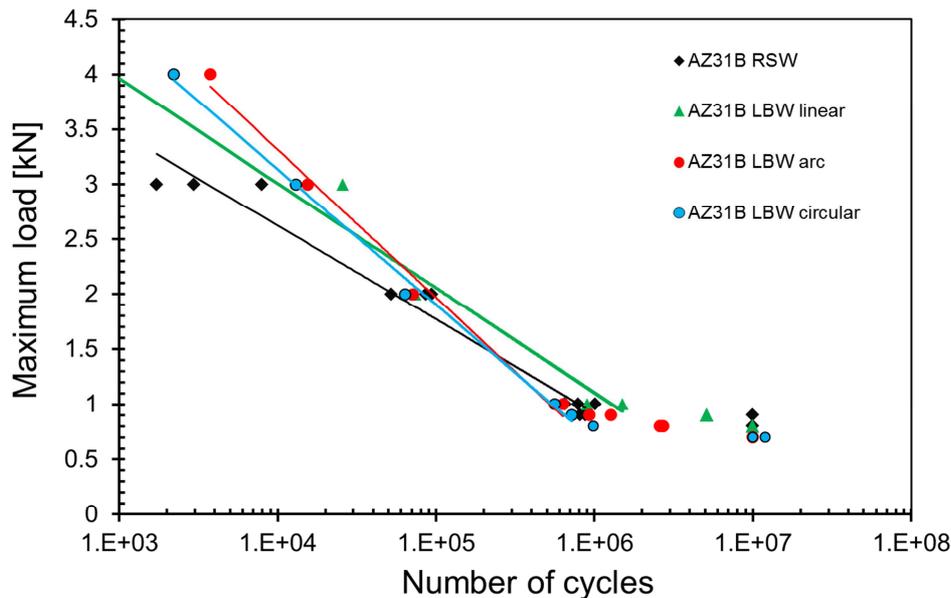


Figure 5. S–N curves of overlap joints

Fatigue crack propagation

For the fatigue crack propagation (FCP) tests, a 100-kN servo-hydraulic machine was used. The tests were carried out in air at a constant load amplitude using a 10-Hz sinusoidal wave form. The R-ratios were $R = 0.1$ and $R = 0.7$ [8]. The welded 2.5-mm specimens exhibited similar FCP behaviour for $R = 0.1$ and 0.7 . However, compared with the AZ31HP BM, the FCP-rate in the WM was slower at $R = 0.7$ and faster at $R = 0.1$. The smaller amplitude at $R = 0.7$ led to a lower FCP-rate than the large amplitude at $R = 0.1$. Zeng observed the same behaviour for AZ80 and R-ratios between $R = 0$ and $R = 0.5$ [13]. The reduction of the FCP-rate in the WM could be caused due to intercrystalline crack growth. Intercrystalline crack growth would be slowed because the absolute crack length will be longer than the optically measured length or the COD-calculated crack length. Higher amplitudes mean higher deformation, so the small precipitates cannot pin the crack at lower R-ratios [8]. Compared to the aluminium alloys AA2024T351 and AA6156T6, the investigated magnesium alloy exhibited inferior performance in terms of the FCP behaviour. However, due to the very good weldability and low density of magnesium, there is a high potential for the design of lightweight integral magnesium structures that can exhibit damage tolerance behaviour comparable to that of aluminium structures.

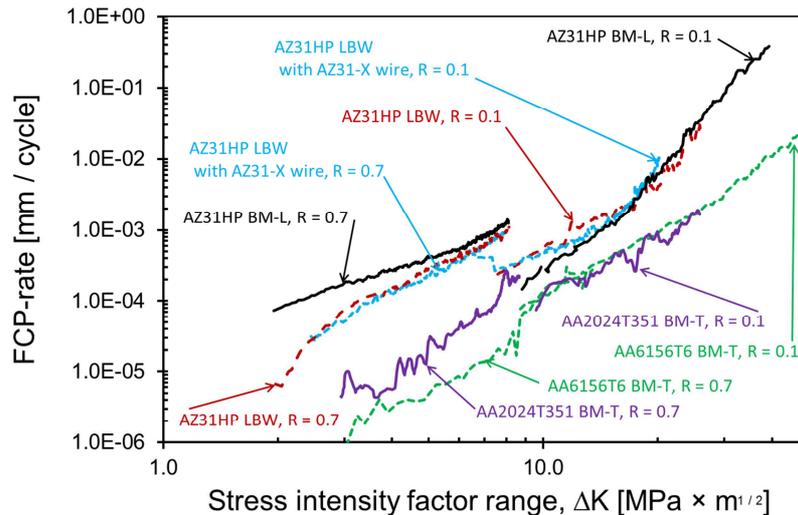


Figure 6. Comparison of the FCP-rate (da/dN) vs. ΔK curves for base and welded materials tested at R-ratios of 0.1 and 0.7.

Mechanical fracture behaviour

Mechanical fracture behaviour was assessed in accordance with the EFAM-GTP-01-procedure [14]. Welds exhibited a lack of a heat-affected zone, so only specimens with a crack in the middle of the weld were tested. C(T) specimens with a ligament of 50 mm were used for the investigations of the fracture toughness and R-curve behaviour. It is interesting to note that the welded AZ31HP exhibits better crack resistance than the base material AZ31HP and the base materials AA2024T351 and AA6061T6 (Fig. 7). Despite the reduced formability of AZ31HP, due to its hexagonal crystal structure, it exhibits high fracture toughness due to its fine-grained microstructure.

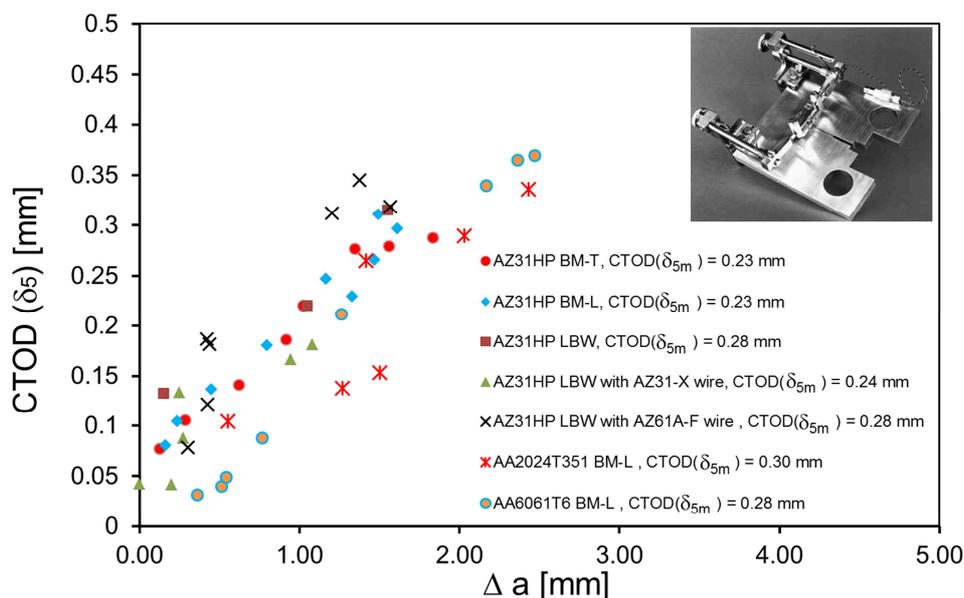


Figure 7. δ_5 -R curve with the fracture toughness values CTOD (δ_{5m}).

Summary

Laser beam welding processes for the typical joint configurations used with AZ31HP sheet material were developed to optimise the microstructure, mechanical properties, fatigue, FCP behaviour and fracture toughness of the joints. The following conclusions can be drawn:

(1) LBW demonstrated the very good weldability of AZ31HP sheet materials. Using the LBW technique, high joint efficiencies for all of the investigated configurations can be achieved. LBW of precipitation hardened Al-alloys causes significant local loss in strength.

(2) Due to the notch sensitivity of magnesium alloys, the as-welded sheets exhibit inferior fatigue behaviour. To achieve good fatigue performance, the LBW process must be optimised to produce welds with very smooth surfaces. Using a post-mechanical surface treatment such as fine grinding, the fatigue performance of welds can be improved so that it is comparable to the fatigue performance of the base material.

(3) The FCP-rate of the welded magnesium joints is at least equal to that of the base material, but it is higher compared to AA2024T351 and AA6061T6.

(4) Compared to state-of-the-art aerospace alloys, AZ31HP demonstrates that magnesium alloys have potential for use in structural applications, with AZ31HP being comparable to AA2024T351 and AA6061T6. Welded AZ31HP exhibits better crack resistance than the base material, so that integral structures produced from magnesium alloys by laser beam welding have a high potential for being used in lightweight construction, where the design criterion is residual strength.

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