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High Temperature Mechanical Properties of AZ91 Magnesium Alloy Weld Joint

M. Stopyra *, J. Adamiec

Faculty of Materials Engineering and Metallurgy, Silesian University of Technology,
Krasińskiego, 40-019 Katowice, Poland
*Corresponding author. E-mail address: michal.stopyra@poczta.fm

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Abstract

Magnesium alloys are widely applied in aircraft and automotive industry, due to their low density and high specific strength. Welding methods can be used to join Mg alloy elements and to repair or regenerate defective or worn-out castings. Therefore the influence of weld joint's microstructure on mechanical properties needs to be studied. In present paper high temperature mechanical properties of AZ91 Mg alloy weld joint was investigated. Tensile tests were conducted in temperature range between 20 and 200°C. Ultimate tensile strength decreased as the temperature increased from 50°C. At temperature up to 150°C rapture occurred in the base metal, at 200°C rupture location switched to the weld fusion zone. Based on metallographic and fractographic observation, the fracture mechanism was described. Macro crack formed from the merger of micro cracks occurring at massive β phase precipitates.

Keywords: Mechanical properties, Magnesium alloys, AZ91, Welding

1. Introduction

The demand to improve fuel efficiency has made magnesium alloys attractive to automotive and aircraft industry. As the lightest structural metal, magnesium and its alloys are characterized by low density, high specific strength, good castability and machinability. AZ91 (Mg-9Al-1Zn) alloy is one of the most popular magnesium cast alloy, due to excellent properties at room temperature. It has been widely used to fabricate many components with working temperature not exceeding 120°C [1]. However, at temperature above 120°C the AZ91 alloy's mechanical properties decrease because of presence of $Mg_{17}Al_{12}$ (β) phase [2] having BCC crystal structure and melting point at 437°C [3].

Welding methods are commonly used for joining and repairing Mg alloys elements [4]. Gas tungsten arc welding (GTAW) is most commonly used method for magnesium alloys welding. In general, magnesium alloys weldability is good. However, there may be some problems associated with hot cracking, β phase resolidifying and shrinkage porosity formation in partially melted zone [5, 6]. Although microstructure and properties of AZ91 alloy as well as the welding of elements made from Mg alloys are well described in literature [2-6], the are only few research on high temperature properties of AZ91 weld joints [7]. The aim of present work was to investigate the influence of temperature on mechanical properties of AZ91 GTAW butt-joint.

2. Material for the research and experimental procedure

Two AZ91 Mg alloy sand cast plates were pre-weld solution treated at 415°C/24h. Then they were butt-joined using gas tungsten arc welding method (141). The chemical composition of base metal and filler wire is presented in table 1. Fig. 1 shows the way of plates' edges preparation and the sequence of bead deposition. The heat input was 3 kJ/cm, specific welding parameters are listed in table 2. Non-destructive tests including visual, liquid-penetrant and radiographic examination were performed. No welding defects were found. Post-weld heat treatment consisted of solution treatment at 415°C/24h followed by ageing at 200°C/10h (T6 heat treatment).

Table 1.
Chemical composition of base metal and filler wire

Melt/Standard	Chemical composition [wt.%]							
	Zn	Al	Si	Cu	Mn	Fe	Ni	Mg
Base metal, 000810	0.56	8.6	0.04	-	0.21	0.003	0.001	bal.
Filler wire, 20099000	0.69	8.6	0.06	0.006	0.18	0.002	<0.001	bal.
ASTM B80	0.4-1.0	8.1-9.3	-	-	0.13-0.35	-	-	bal.

Table. 2.
Welding parameters

Welding current, A	Arc voltage, V	Welding speed, cm/min	Gas flow rate, l/min	Gas nozzle diameter, mm	Type and diameter of electrode
120	15	10	10	12	WT10, 3,2 mm

a)

b)

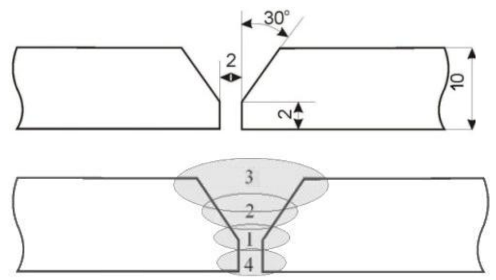

Fig. 1. Plates' edges preparation (a), bead deposition sequence (b);

The tensile specimens were cut perpendicularly to the welding direction so that the fusion weld was in the middle of the gauge length (fig. 2). Tensile test was conducted using Kappa 50DS tester at 20, 50, 100, 150 and 200°C. After predetermined temperature had been reached, the specimens were annealed for 30 min. The tensile test speed was 4 mm/min. 3 specimens were tested at each temperature. Metallographic specimens were cut along the tensile specimen's axis and prepared accordingly to the procedure devised in [8]. Olympus GX-71 light microscope (LM) and Hitachi S-3400N scanning electron microscope (SEM) equipped with energy dispersive spectrometer (EDS) were used for the microstructural observation. Fractographic examination was also performed using SEM.

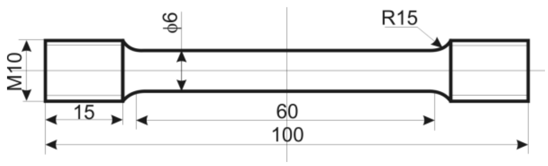

Fig. 2. Geometry of tensile specimen

3. Results

3.1. Tensile test results

The results of the tensile test in the temperature range 20÷200°C are listed in table 3. Ultimate tensile strength (UTS) at 20 and 50°C was 152 and 156 MPa respectively. Tensile strength decreased with further increase in temperature and reached 121 MPa at 200°C. In the temperature range between 20 and 150°C the rupture occurred in the base metal. At 200°C the rupture location switched to the weld. Moreover, the rupture at 200°C was preceded by a larger plastic deformation, as shown in fig. 3.

Table. 3.
The results of tensile tests

Test temperature, °C	UTS, MPa	Strain, %	Rupture point
20	152	3,5	Outside weld
50	156	5,8	Outside weld
100	141	3,3	Outside weld
150	135	2,4	Outside weld
200	121	9,0	Inside weld

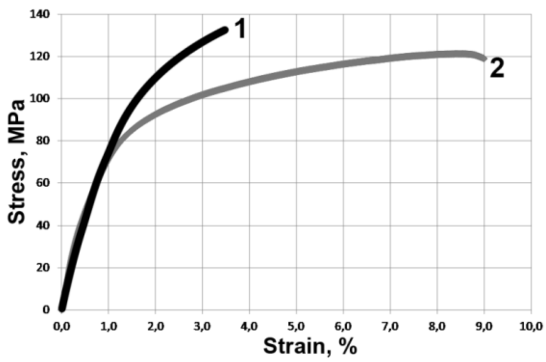

Fig. 3. Stress vs. strain curves at 20°C (1) and 200°C (2)

3.2. Microstructural and fractographic examination

Microstructure of AZ91 in T6 condition consisted of Mg-α solid solution and β phase ($Mg_{17}(Al, Zn)_{12}$) precipitates (fig. 4). The weld's microstructure is refined, compared to base materials'. Heat treatment caused dissolution of massive β phase and it's precipitation as the lamellar phase during ageing. However, both in base material and in the weld the presence of massive β phase was revealed. It proves incomplete dissolution of β phase, despite heat treatment parameters according to T6.

Fig. 5 presents the microstructure of base material near the rupture line after tensile test at 50 and 100°C. The presence of numerous micro cracks occurring at massive β precipitates and oriented perpendicularly to the tension force direction was revealed. Macro cracks were formed by micro crack merging. The same phenomena were observed in the other specimens. Moreover, the presence of Al- and Mn-rich intermetallic phase was revealed at rupture line after tensile test conducted at 200°C (fig. 6).

The fracture morphology is illustrated in fig. 7. A lot of areas characterized by smooth surface (fig. 7a) were present. This can be attributed to the β lamellas relative orientation, parallel to the fracture surface. There were also a few areas where the crack ran across the β lamellas, as presented in fig. 7b.

a) b)

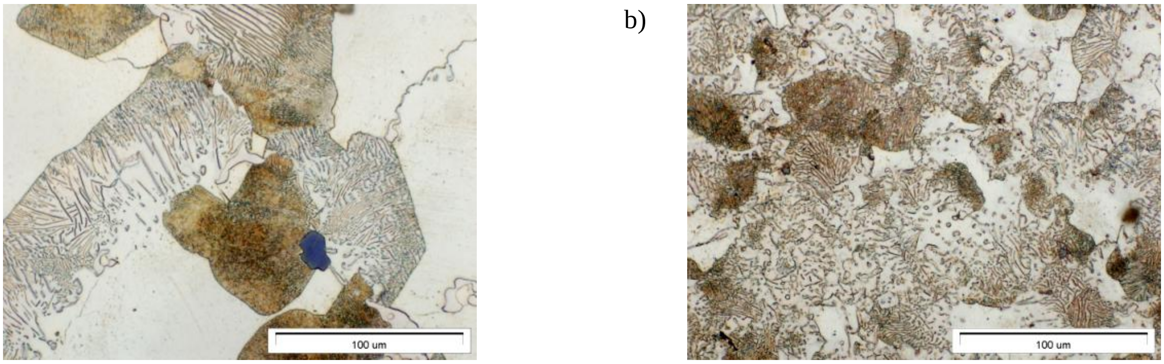

Fig. 4. Massive and lamellar β phase precipitates in base material (a) and fusion weld (b)

a) b)

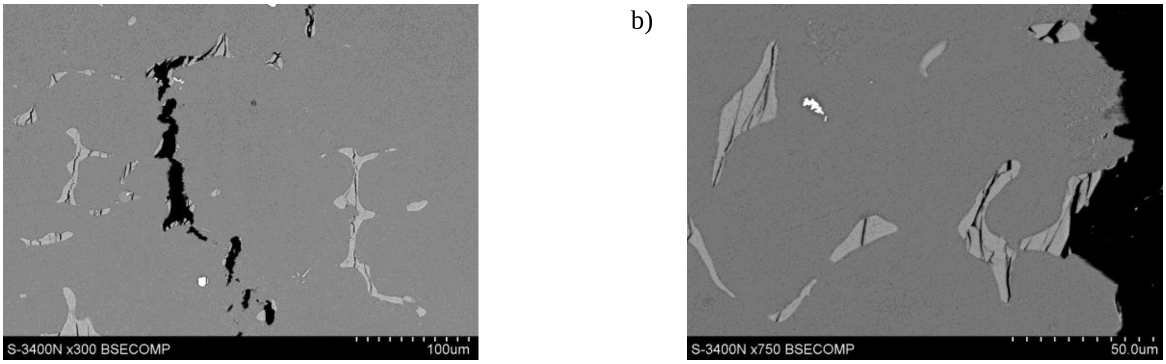

Fig. 5. Micro cracks occurring at massive β phase precipitates during tensile test at 50°C (a); rupture line in the specimen tested at 100°C

a)

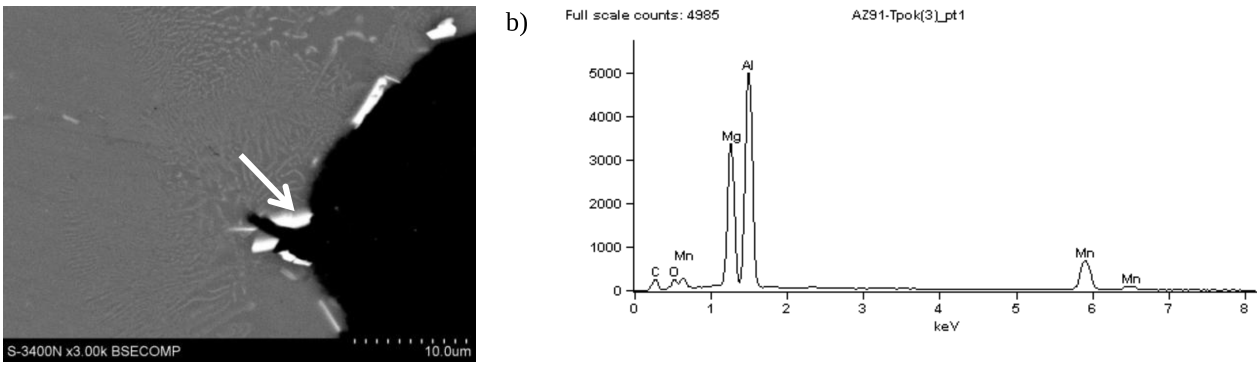

Fig. 6. The weld's microstructure at rupture line (a) and EDS spectra of marked precipitate (b)

a) b)

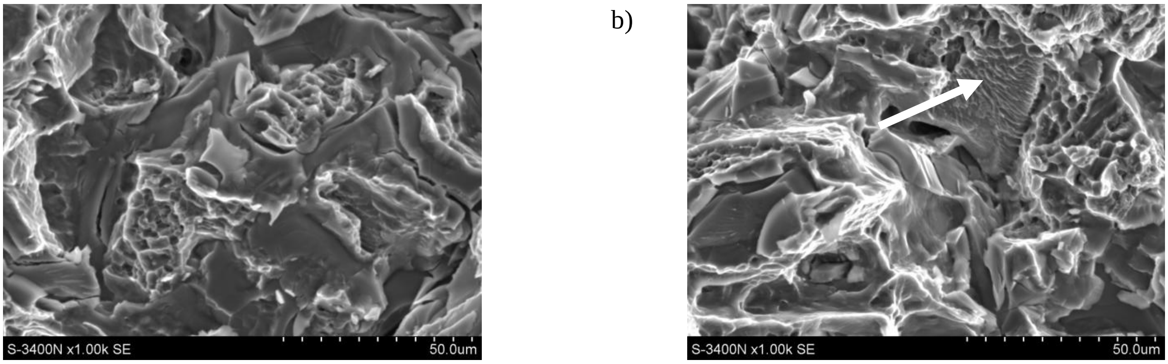

Fig. 7. The fracture morphology revealing parallel (a) and transverse (b) lamellas relative orientation to the fracture surface

4. Discussion

The tensile test conducted in the temperature range between 20÷200°C proved the decrease of UTS with the temperature increase from 50°C. At temperature up to 150°C the weld joint's strength is not less than base material, as indicated by the rupture point location in base metal. Further increase in temperature caused the rupture point location switched to the weld metal.

Microstructure of the base metal and the weld consisted of Mg-α solid solution, lamellar β phase precipitated during the ageing and massive β phase, which remained undissolved. The weld's microstructure is refined, compared to the base metal's, which can be attributed to the higher cooling rate during the weld's crystallization.

The fracture mechanism can be described based on the microstructural and fractographic examination. At first the micro cracks occur at massive β phase precipitates. Merging of the micro cracks leads to formation of macro cracks and finally to the rupture (fig. 5). The crack propagation between massive β precipitates was influenced by β lamellas, as indicated by numerous smooth areas on the fracture surface (fig. 7). This could be caused by the brittleness of α/β interface, which is due to the difference in crystal structure - hexagonal close packed in Mg-α and body-centered cubic in $Mg_{17}Al_{12}$.

The change in rupture location at 200°C could be attributed to the change in fracture mechanism. Exceeding the alloy's maximum working temperature by 80°C conduced plastic deformation, proved by the strain value, significantly higher at 200°C (9%) than at lower temperature (2,4÷5,8) (tab. 3). The rupture was preceded by a local necking, as indicated by the decrease in the stress, which can be seen in the stress vs. strain curve (fig. 3). Intermetallic Al-Mn rich phase precipitates were present at rupture line (fig. 6). They were spots for micro crack initiation and merging, hence they locally influenced cracking trajectory similarly to the massive β precipitates. However, their influence on the overall crack propagation was much weaker then β phase's due to their size, shape and volume fraction.

5. Conclusions

Based on the high temperature tensile tests, the ultimate tensile strength of GTAW butt-joined made from AZ91 Mg alloy sand cast plates decreases from 150 MPa at 20°C to 121 MPa at 200°C.

In the temperature range 20÷150°C the weld metal's strength is not less than base metal's. At 200°C the rupture was located in the weld zone and preceded by higher plastic deformation.

Both in base metal's and weld's microstructure the presence of undissolved massive β phase precipitates was revealed. They were responsible for cracks initiation and propagation.

Acknowledgement

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