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Effect of welding speed on microstructural characteristics and tensile properties of GTA welded AZ31B magnesium alloy

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Abstract: The effect of welding speed on tensile and microstructural characteristics of pulsed current gas tungsten arc welded (PCGTAW) AZ31B magnesium alloy joints was studied. Five joints were fabricated using different levels of welding speeds (105−145 mm/min). It was found that the joints fabricated using a welding speed of 135 mm/min yielded superior tensile properties compared to other joints. The formation of fine grains and uniformly distributed precipitates in the fusion zone are the main reasons for the superior tensile properties of these joints.
Key words: AZ31B magnesium alloy; GTA welding; welding speed; tensile properties; microstructure

1 Introduction

Magnesium alloys exhibit the attractive combination of low density and high specific strength (comparable or greater than that of precipitation strengthened Al alloys), along with good damping capacity, castability, weldability, and machinability. Of the various commercial magnesium alloys, those developed from the Al−Zn ternary system (i.e. the as-named AZ alloys) have found the largest number of industrial applications [1,2]. These applications include automotive, industrial, materials handling and aerospace equipment where lightweight materials are needed [3,4]. Presently, gas tungsten arc (GTA) welding process is one of the most well established processes for reactive materials like magnesium alloy due to its comparatively easier applicability and better economy of industrial use, but it also produces the best quality welds amongst the arc welding processes [5,6]. The quality of GTA welds ranks higher than that of any of the arc-welding processes due to the reliability, clearance and strength of the weld. The welding speed is an important parameter in GTA welding, which is used to achieve maximum penetration without excessive heat build-up, and produces a greater extent of constitutional supercooling at the solidification front and this in turn helps heterogeneous nucleation, which is responsible for grain refining in the welds [7,8].

Recently, few studies have been carried out to evaluate the tensile properties and metallurgical properties of gas tungsten arc welded magnesium alloys. PADMANABAN and BALASUBRMANIAN [9] studied the influences of welding processes on microstructure, hardness, and tensile properties of AZ31B magnesium alloy. They successfully joined AZ31B magnesium alloy by gas tungsten arc welding process, without any macro level defects. DONG et al [10] studied the microstructure and mechanical properties of AZ31B magnesium alloy gas metal arc weld, and they suggested that the tensile strength of the magnesium joints was close to or even higher than that of the base metal despite the existence of pores in the weld. They also argued that the microhardness in the weld was higher than that of the base metal due to the second phase strengthening effect of the β-$Mg_{17}(Al,Zn)_{12}$ phases formed in the weld. LIU and DONG [11] examined the microstructure and fracture of AZ31 magnesium alloy joint welded by automatic gas tungsten-arc filler (GTAF) welding process. In their study, the microstructure of gas tungsten-arc welded joint (without filler wire) revealed a HAZ with coarse grains. Because of the coarse grains in

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HAZ, GTA welded joint always leads to fracture in HAZ during tensile test.

MUNITZ et al [12] investigated the mechanical properties and microstructure of gas tungsten arc welded magnesium AZ91D plates. They suggested that backing plates need to be used to prevent melt flow from the weld pool through the molten grain boundaries and might reduce the HAZ. Available literatures are mainly focused on evaluating mechanical and metallurgical properties of PCGTA welded magnesium alloys. However, very little information is available on the effect of welding speed on mechanical and metallurgical properties of GTA welded AZ31B magnesium alloy. Since welding speed has significant influence on fusion zone microstructure and related mechanical properties, understanding the effect of welding speed is very essential. Hence, the present investigation is carried out to study the effect of welding speed on tensile properties and microstructural characteristics of pulsed current GTA welded AZ31B magnesium alloy.

2 Experimental

The rolled AZ31B magnesium alloy plates with a thickness of 3 mm were cut into the required size (150 mm × 150 mm) by machining process. The chemical composition and mechanical properties of AZ31B magnesium alloy sheet are presented in Tables 1 and 2, respectively. A square butt joint configuration, as shown in Fig. 1, was prepared to fabricate the joints. The plates were mechanically and chemically cleaned by acetone before welding to eliminate surface contamination. The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding was normal to the rolling direction. A single pass welding procedure was used to fabricate the joints with the pulsed current gas tungsten arc welding machine (Make: Lincoln, USA). Argon gas was used as a shielding gas with a constant flow rate of 20 L/min. Five joints were fabricated using different levels of welding speed. The other parameters such as peak current to base current ratio, pulse frequency, pulse on time were kept constant. The photographs of fabricated joints are shown in Fig. 2. Heat input is a very important factor, which affects the bead geometry, mechanical properties and metallurgical properties of the weld. Hence, heat input was also calculated and included in this study. In continuous current GTAW process the heat input per unit length is proportional to voltage and current and inversely proportional to the welding speed. Whereas in the pulsed GTAW process, the heat input is calculated from the mean current. The equation for the mean current I_m [9] is given as

Table 1 Chemical composition of AZ31B magnesium alloy (mass fraction, %)

Al	Zn	Mn	Ni	Cr	Cu	Mg
2.60	0.67	0.27	0.012	0.008	0.017	Bal

Table 2 Mechanical properties of AZ31B magnesium alloy

Property	Value
0.2% offset yield strength/MPa	160
Ultimate tensile strength/MPa	275
Elongation in 50 mm gauge length/%	14.7
Reduction in cross section area/%	14.3
Notch tensile strength/MPa	253
Notch strength ratio (NSR)	0.92
$HV_{0.49N}$	69

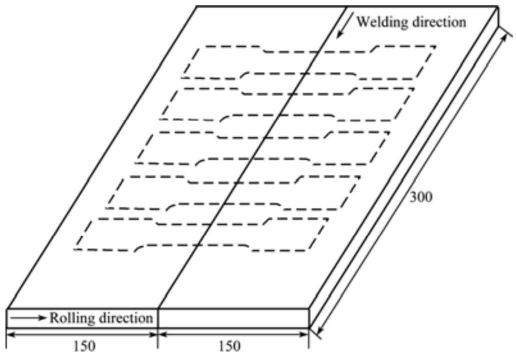

Fig. 1 Joint configuration and scheme of extraction (unit: mm)

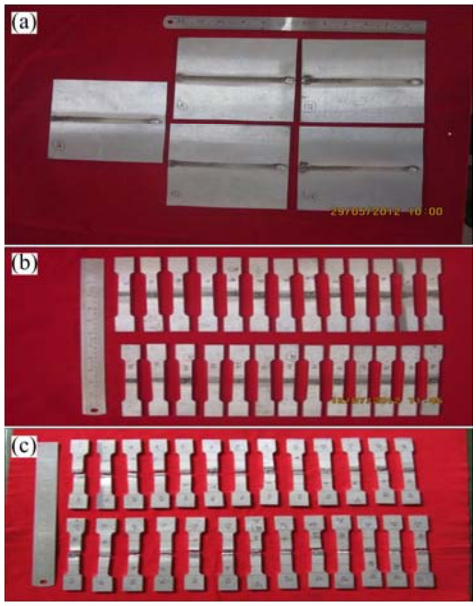

Fig. 2 Photographs of welded joints and tensile specimen: (a) Fabricated joints; (b) Tensile specimens before tensile test; (c) Tensile specimens after tensile test

$$I_m=(I_p\times t_p+I_b\times t_b)/(t_p+t_b) \quad (1)$$

Heat input (Q) is calculated using [10]

$$Q=(I_m\times V\times \eta)/S \quad (2)$$

where I_p is the pulse current, A; I_b is the base current, A;

t_b is the base current duration, ms; t_p is the pulse current duration, ms; S is the welding speed, mm/s; V is the mean voltage, V; η is the efficiency of the welding process.

For the pulsed GTAW process, arc efficiency is taken as 60% based on Ref. [9]. During the experiment, the voltage varied from 14 V to 18 V. Hence, a mean voltage of 16 V was taken for the heat input calculation. The heat input values for different levels of welding speed are presented in Table 3. To measure the temperature during welding, a K-type chromel-alumel thermocouple was used [13]. The thermocouple was located at 10 mm from the weld centre. The hot end diameter of the thermocouple was 1.5 mm, and the cold end was fixed to a thermocouple bank and was in turn connected to the DAQ Labview. The welded joints were sliced and then machined to the required dimensions according to the ASTM E8M−04 standard for sheet type material (i.e., 50 mm gauge length and 12.5 mm gauge width). Two different tensile specimens were prepared to evaluate the transverse tensile properties of the welded joints.

The smooth (unnotched) tensile specimens were prepared to evaluate the yield strength, tensile strength and elongation of the joints. The notched specimens were prepared to evaluate the notch tensile strength and the notch strength ratio of the weld. The tensile test was carried out in a 100 kN, electro mechanically controlled universal testing machine (Make: FIE-Bluestar, India; Model: UNITEK-94100). The 0.2% offset yield strength was derived from the load−displacement diagram. The elongation was also evaluated and the values are presented in Table 3. The dimensions of the tensile specimen are shown in Fig. 3. The photographs of the tensile specimens are shown in Figs. 2(b) and (c). A Vickers microhardness testing machine (Make: SHIMADZU, Japan; Model: HMV-2T) was used to measure the hardness across the weld cross section with a 0.49 N load for a 20 s dwell time. The specimens for metallographic examination were sectioned to the required size and then polished using different grades of emery paper. A standard reagent made of 4.2 g picric acid, 10 mL acetic acid, 10 mL diluted water and 70 mL ethanol was used to reveal the microstructure of the welded joints. Microstructural analysis was carried out using a light optical microscope (Make: MEIJI, Japan; Model: MIL-7100) incorporated with an image analyzing software (Metal Vision). The fracture surfaces of unnotched tensile specimens were analyzed using scanning electron microscope (SEM) (Make: JEOL, Japan; Model: 5610 LV). To identify the precipitated phase constitution present in the fusion zone, samples were cut from the weld regions and XRD analysis (Make: RIGAKU, Japan; Model: ULTIMA-III) was carried out.

3 Results

3.1 Tensile properties

The transverse tensile properties of the joints made using different welding speeds were evaluated and the average of three results is presented in Table 3. The load−displacement curves are shown in Fig. 4. The joint fabricated with a welding speed of 135 mm/min exhibited high yield strength (165 MPa), tensile strength (214 MPa) and elongation (7.2%). The notch strength ratio (NSR) is the ratio between the tensile strength of the notched specimen at maximum load (NTS) to the ultimate tensile strength of the unnotched specimen. The notch strength ratio was less than unity (<1) for all the joints. This suggests that the AZ31B magnesium alloy is sensitive to notches and they fall into the ‘notch brittle materials’ category. The NSR was 0.92 for the unwelded parent metal and PCGTAW caused a reduction in the NSR of the weld metal. The joint fabricated with a welding speed of 135 mm/min exhibited higher notch strength ratio (0.78). Joint efficiency is the ratio between the tensile strength of the welded joint and the tensile strength of the unwelded parent metal. The joint fabricated with a welding speed of 135 mm/min exhibited the maximum joint efficiency of 78%.

3.2 Macrostructure

The macrostructures of the joints made with different welding speeds are presented in Fig. 5. At

Table 3 Effect of welding speed on transverse tensile properties of joints

Joint No.	Welding speed/ (mm·min^{-1})	Heat input/ (J·mm^{-1})	0.2% yield strength/ MPa	Ultimate tensile strength/ MPa	Elongation in gauge length of 50 mm/%	Notch tensile strength/ MPa	Notch strength ratio (NSR)	Joint Efficiency/ %
1	105	415	143	183	5.5	165	0.90	66
2	115	392	160	196	6.0	137	0.70	71
3	125	381	163	201	6.8	143	0.72	73
4	135	369	165	214	7.2	167	0.78	78
5	145	323	189	193	4.5	150	0.77	70

Current ratio (I_p/I_b)=2.2; Pulse on time=50%; Pulse frequency=4 Hz

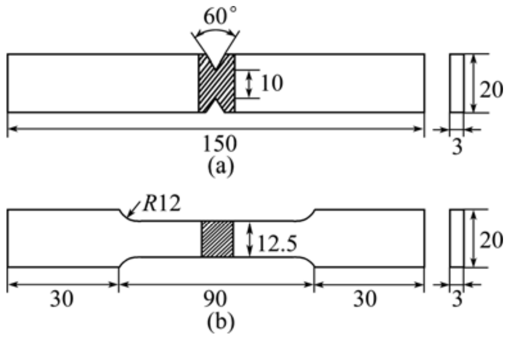

Fig. 3 Dimensions of tensile specimens (unit: mm): (a) Notched tensile specimen; (b) Unnotched tensile specimen

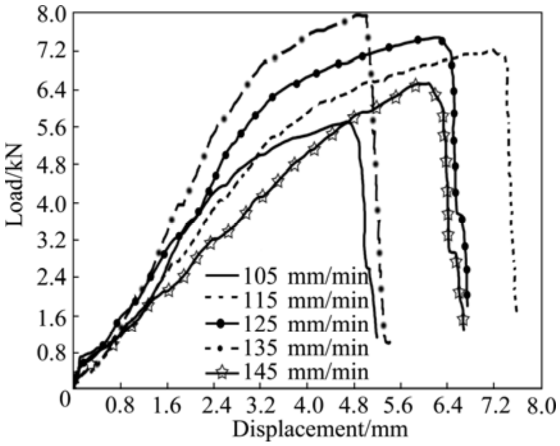

Fig. 4 Load−displacement curves under different welding speeds

higher welding speed (145 mm/min), a partial penetration was observed due to lower heat input. At lower welding speed (105 mm/min), a burn through of the weld and the surface breaking defects were observed due to higher heat input. This may be the reason for the lower tensile properties of these joints. The joint fabricated under the welding speed of 135 mm/min produced a defect-free joint with full penetration. This may be due to the supply of optimum heat input (369 J/mm).

3.3 Microstructure

The optical micrograph of fusion zone of all the joints are displayed in Fig. 5. From the micrographs, it is understood that the welding speed has appreciable influence on the average grain diameter of fusion zone in AZ31B magnesium alloy. The joint fabricated with a welding speed of 135 mm/min contained finer grains (30 μm) in the fusion zone (Fig. 6(d)) compared to other joints. Furthermore, a large number of precipitated particles were observed in the fusion zone and the concentration of precipitates was moderate. This is also one of the reasons for higher tensile properties of the joint compared to other joints. Coarse grains (45 μm) were observed (Fig. 6(a)) for the joint fabricated using a

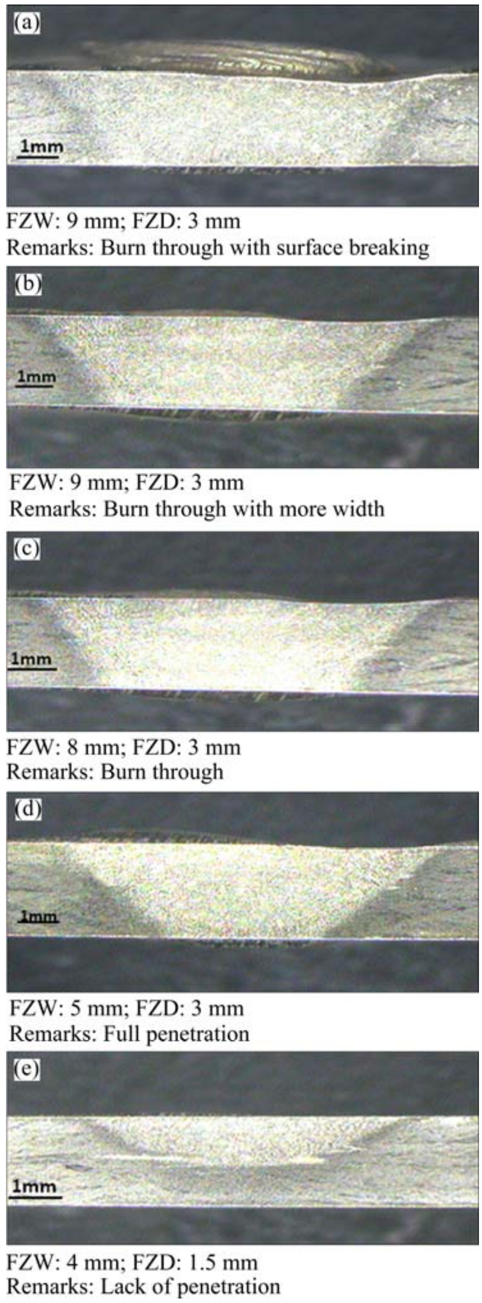

Fig. 5 Macrostructures of cross section of fusion zone under different welding speeds (FZW — Fusion zone width, FZD—Fusion zone depth): (a) 105 mm/min; (b) 115 mm/min; (c) 125 min/min; (d) 135 mm/min; (e) 145 mm/min

welding speed of 105 mm/min. This may be one of the reason for the lower tensile properties of the joints.

3.4 Microhardness

Microhardness survey was done across the weld direction from weld centre to base metal. The micro hardness plot is shown in Fig. 7. The joint fabricated with a welding speed of 135 mm/min showed higher hardness (HV 66) in the fusion zone. The joint fabricated

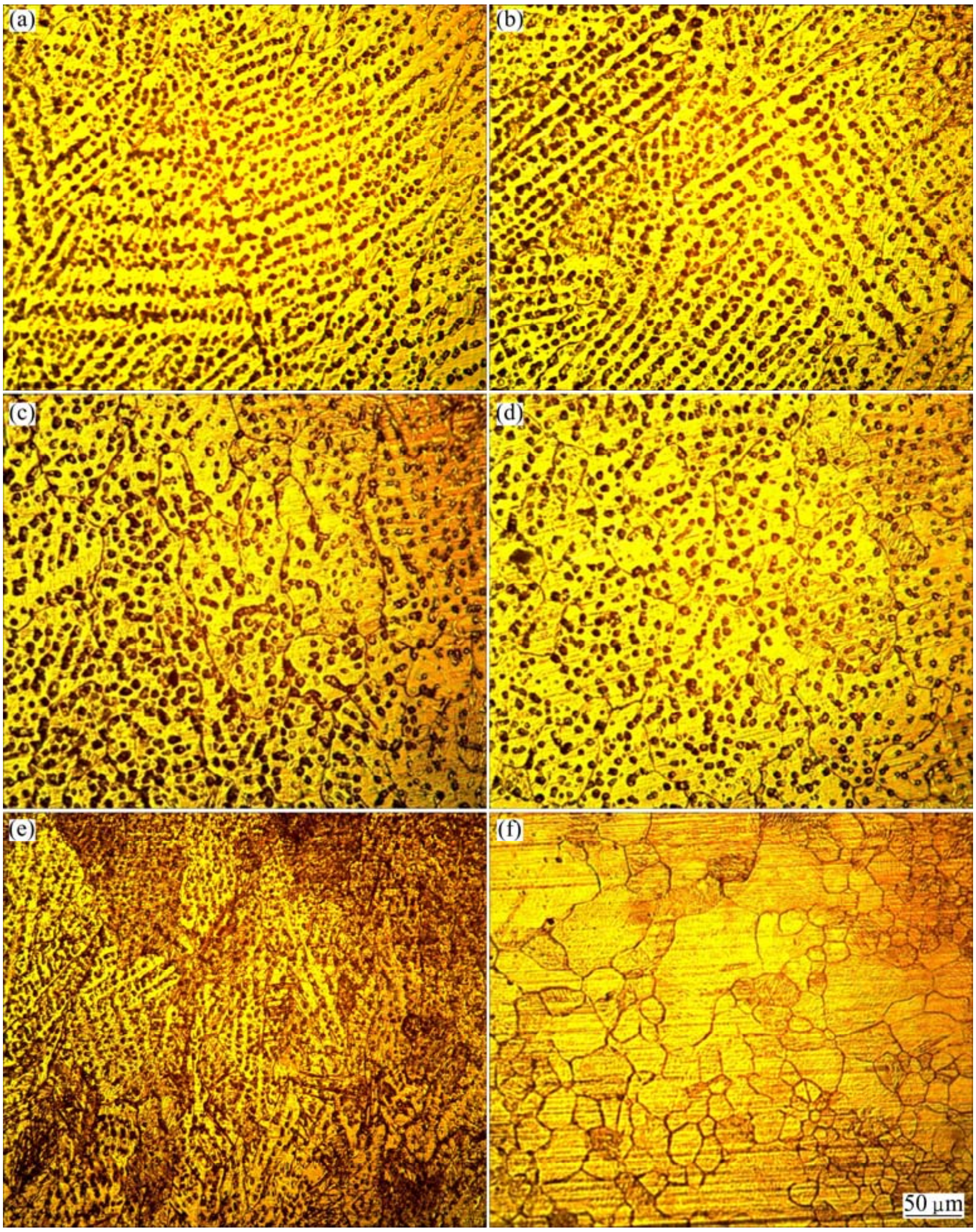

Fig. 6 Microstructures of fusion zone under different welding speeds: (a) 105 mm/min; (b) 115 mm/min; (c) 125 mm/min; (d) 135 mm/min; (e) 145 mm/min; (f) Base metal

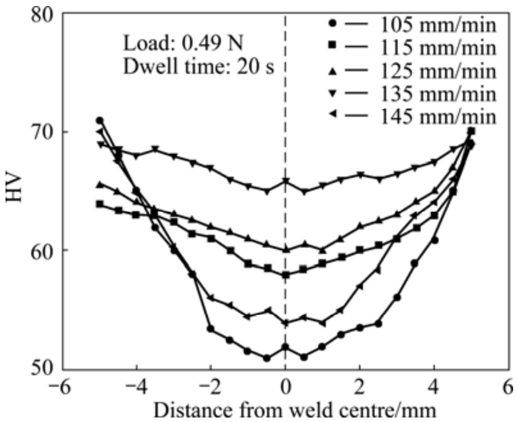

Fig. 7 Effect of welding speed on microhardness of joint across fusion zone

with a welding speed of 105 mm/min recorded lower hardness (HV 59) in the fusion zone.

3.5 Temperature profile

The heating and cooling rate under various welding speeds are shown in Fig. 8. The cooling rate for the joint made with the welding speeds of 105, 135, and 145 mm/min was determined and it is presented in Table 4. From Fig. 8, it is observed that the highest temperature of 529 °C was recorded for the joint made with welding speed of 105 mm/min, and the lowest temperature of 360 °C was recorded for the joint made with welding speed of 145 mm/min. From Table 4, it is also observed that the slow cooling rate of 2.8 °C/s was recorded for the joint made with welding speed of 105 mm/min, and the fast cooling rate of 5.1 °C/s was recorded for the joint made with welding speed of 145 mm/min.

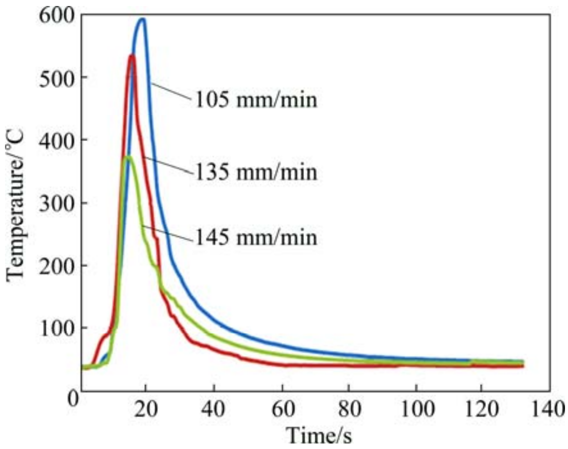

Fig. 8 Effect of welding speeds on temperature profile at 10 mm from fusion zone

Table 4 Measured peak temperature values

Experiment No.	Welding speed/ $(mm\cdot min^{-1})$	Heat input/ $(J\cdot mm^{-1})$	Temperature at 10 mm from weld centre/°C	Cooling rate/ $(°C\cdot s^{-1})$
1	105	415	589	2.8
2	135	369	528	4.5
3	145	323	360	5.1

3.6 SEM fractograph

Figure 9 shows the SEM fractographs of the smooth tensile specimens after tensile test. It is observed that the fractured surface of the specimen at optimum welding speed (135 mm/min) contained a large population of fine and shallow dimples, which is an indication of relatively higher tensile strength and ductility. The other specimens failed in quasi cleavage mode.

3.7 EDS and XRD analysis

The EDS results presented in Fig. 10 confirmed that the matrix composition in the fusion zone is mostly concentrated by Al and Mg elements. The EDS results also confirmed that the PCGTAW joint contained less Zn in the matrix (due to evaporation caused by high peak temperature) than the base metal. This may be one of the reasons for the reduction in tensile properties of the PCGTAW joint compared to the base metal. The XRD results presented in Fig. 11 confirmed the presence of $Al_{12}Mg_{17}$ precipitates in the fusion zone along with the traces of $A_{l2}Mg_3$.

4 Discussion

Welding speed is one of the main factors that control the heat input and weld bead geometry. The heat input is inversely proportional to the welding speed. Due to the above factors, the depth of penetration decreased

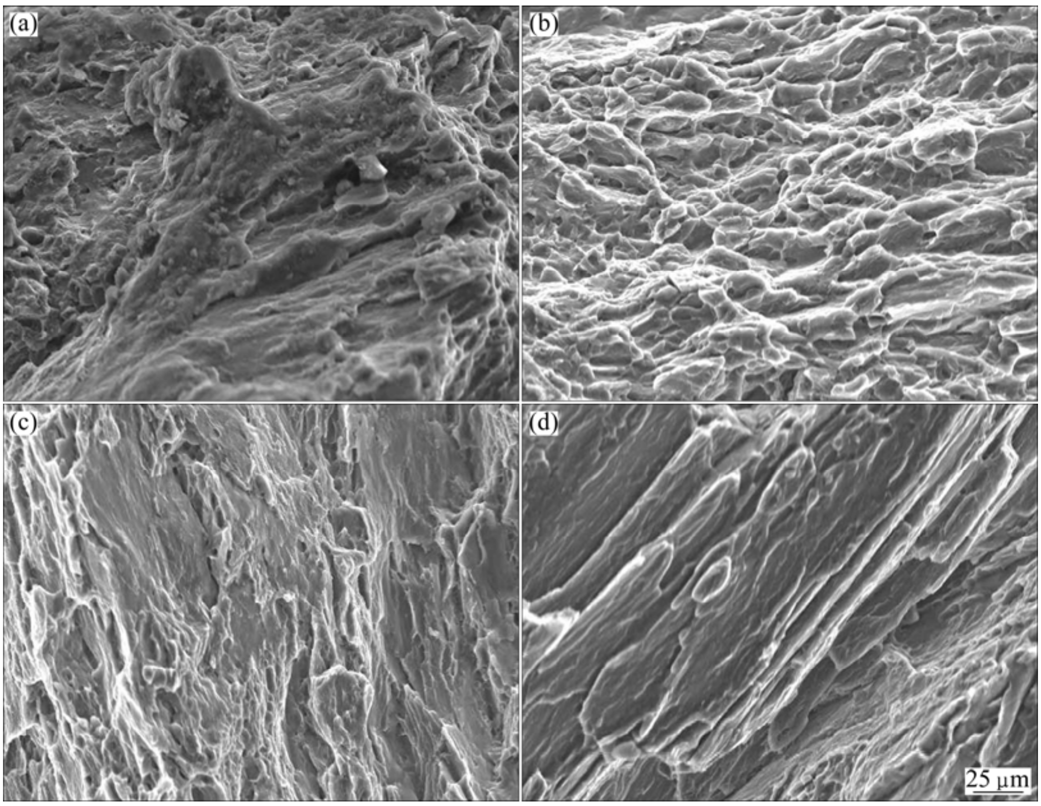

Fig. 9 SEM fractographs of unnotched tensile specimen: (a) 105 mm/min; (b) 135 mm/min; (c) 145 mm/min; (d) Base metal

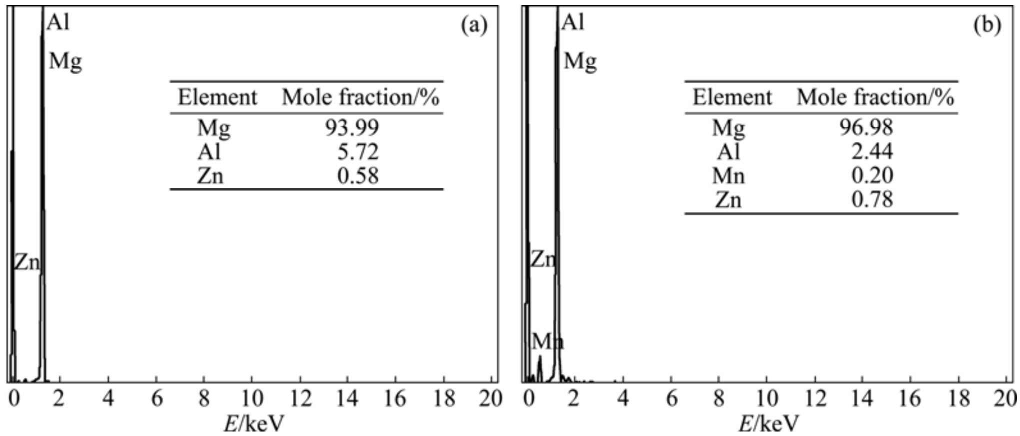

Fig. 10 EDS results of AZ31B magnesium alloy: (a) Joint fabricated at 125 mm/min; (b) Base metal

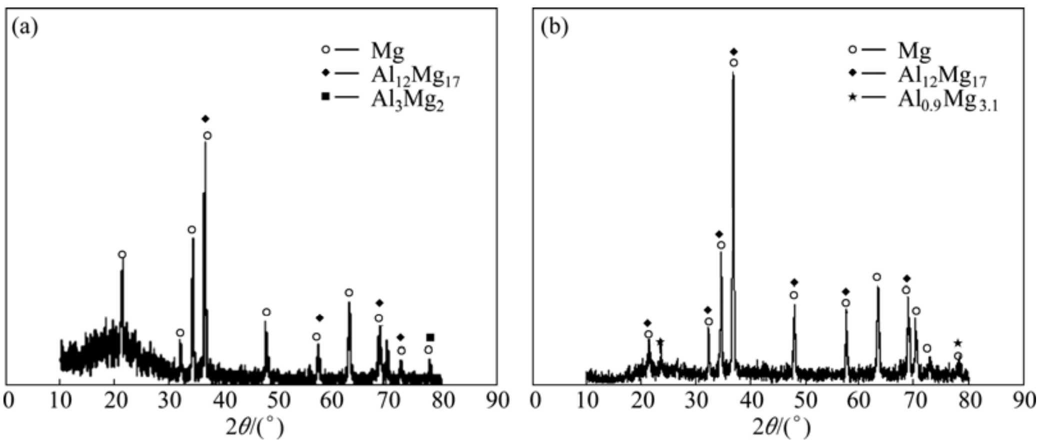

Fig. 11 XRD patterns of AZ31B magnesium alloy: (a) Joint fabricated at 125 mm/min; (b) Base metal

with the increase in welding speed. From the result, it was observed that the welding speed had predominant effect on the tensile properties of PCGTAW joints of magnesium alloy. The highest temperature (529 °C) was recorded for the joint made with the welding speed of 105 mm/min. Further, it was also observed that for higher heat input (415 J/mm) the slow cooling rate (2.8 ºC/s) was observed, which led to the formation of coarser grains in the fusion zone. The average grain size of fusion zone was about 45 µm. It is known that an increase in heat input will result in slow cooling rate. Moreover, the slower the cooling rate during solidification, the longer the time available for grain coarsening. The microhardness value recorded in the joint made with 105 mm/min was lower than that of the joint made with 135 mm/min in the fusion zone. The higher heat input produces coarse and elongated grains in fusion zone, which is one of the reasons for lower hardness values. Moreover, the tensile strength of the joint was lower than that of the joint made using the welding speed of 135 mm/min. During tensile test, all the specimens invariably failed at fusion zone. This is consistent with the hardness profile (Fig. 7). If the welding speed was lower than 135 mm/min, due to higher heat input (415 J/mm), the surface breaking defects were also observed. These are the reasons for the lower hardness and lower tensile properties of these joints.

The lowest peak temperature (360 °C) was recorded for the joint made with the welding speed of 145 mm/min. Further, it was also observed that for lower heat input (323 J/mm), the cooling rate was higher (5.1 °C/s), which led to the formation of finer grains in the fusion zone. The increase in welding speed led to the decrease in heat input. This led to faster cooling rate and subsequently led to the formation of finer grains in fusion zone. Over the solidification range for AZ31B magnesium alloy with an increased cooling rate, the solidification time was suppressed and a finer weld metal microstructure was produced [7,8]. If the welding speed was greater than 135 mm/min, the lack of penetration was achieved (Fig. 5). This may be due to the lower heat input. The heat is not sufficient to melt all the metals in the fusion zone. This is one of the reasons for lower tensile strength (193 MPa) of these joints.

The joint fabricated with a welding speed of

135 mm/min (Fig. 6(c)) contained finer grains in the fusion zone (average grain size of about 30 μm) and recorded higher hardness (HV 66) in the fusion zone compared to other joints. Also the heat input of 369 J/mm produced defect-free joint with full penetration [9,10]. The formation of finer grains in the fusion zone and uniformly distributed precipitates in this joint are the main reasons for the higher hardness compared to other joints [11,12]. The moderately higher hardness of welds close to the fusion boundary is possibly due to a large fraction of alloying elements in solid solution at the end of the weld thermal cycle, thereby giving conditions for extensive age hardening. This can be explained as follows: at the fusion boundary, precipitate dissolution occurs as the particles are exposed to temperatures higher than 400 °C during heating and cooling as a result of welding [13,14]. The reason for this trend of microhardness in the fusion zone is relatively faster cooling rate due to steeper thermal gradients and consequently has fine grained microstructure [15,16]. Grain refinement leads to an improvement of tensile properties in fusion zone. The maximum tensile strength was achieved for the joint made with a welding speed of 135 mm/min. The distribution of higher hardness in the weld metal is also the reason for the higher tensile strength of the joint [17,18]. Very fine grains were observed at the centre of the weld, which is attributed to the higher cooling rates at the weld centre compared to those at the fusion boundary [19].

5 Conclusions

1) The welding speed has significant influence on the grain size and hardness in the fusion zone and subsequently on the tensile properties of PCGTAW joints of AZ31B magnesium alloy.

2) Of the five welded joints, the joint fabricated using a welding speed of 135 mm/min shows superior tensile properties than their counterparts. The formation of finer grains, higher hardness, and uniformly distributed precipitates in the fusion zone are the main reasons for the superior tensile properties of the joint.

3) A heat input level of 369 J/mm is found to be optimum for joining 3 mm-thick rolled sheets of AZ31B magnesium alloy. This optimum level of heat input is achieved when the welding speed is maintained at 135 mm/min.

Acknowledgments

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焊接速度对 GTA 焊接 AZ31B 镁合金接头组织和拉伸性能的影响

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摘　要：研究焊接速度对脉冲电流钨极惰性气体保护焊接(PCGTAW)AZ31B 镁合金接头组织和拉伸性能的影响。实验中焊接速度为 105~145 mm/min。结果表明，焊接速度为 135 mm/min 时，所得接头具有最好的拉伸性能。在熔合区生成的细小晶粒组织和均匀分布的析出相是导致较好的拉伸性能的主要原因。

关键词：AZ31B 镁合金；钨极惰性气体保护焊；焊接速度；拉伸性能；显微组织

(Edited by Sai-qian YUAN)