Investigations on Tungsten Inert Gas Welded Magnesium Alloy

I Peter* and M Rosso
Politecnico di Torino, Department of Applied Science and Technology
Corso Duca degli Abruzzi, 24, 10129 Torino- Italia

*Corresponding author: ildiko.peter@polito.it

Abstract. Generally, magnesium alloys show interesting technological characteristics, which make them valuable for many industrial applications. Good mechanical properties, creep resistance and good castability, recyclability are only some of the most important properties remarkable for their employment in different areas. Generally, at industrial level welding technologies, like Tungsten Inert Gas technique, are used to eliminate and/or to repair the casting defects. In the present paper some details on their microstructural behaviour and mechanical performances on welded WE43 magnesium alloy are evaluated and reported. The obtained results have demonstrated that welding do not decrease the mechanical performance of the material and the heat affected zone cannot compromise the overall behaviour of the welded samples. In most of cases, the material’s failure takes place nearly the welding defects.

1. Introduction
Actually, light alloys are more and more employed in different industrial applications. In order to obtain high integrity and improved performance components, the need of new alloy compositions and of innovative production techniques are required. Al-based alloys are ideal light-weighting material for automotive and aeronautical applications [1-6]. In the same time, the lowest density of Mg alloys compared to Al-based ones, allows achieving a further weight saving [7-9]. Magnesium alloys due to their extremely interesting and promising properties like high value of specific strength and stiffness, low density, remarkable damping capacity, excellent castability, high thermal conductivity and for their recyclability, are very attractive for a wide range of applications. Automotive, aerospace and electronics industries [10-12] are the most relevant areas where these alloys are employed. However, due to their hexagonal close-packed (HPC) crystal structure, magnesium alloys are characterized by reduced castability and cold workability at room temperature, which make complicate and extremely expensive the manufacturing process of components, especially with a complex shape and geometry [13]. Extended use of light alloys in automotive industry needs reliable welding technologies, because many of the produced parts need to be joined to one similar or different materials to obtain a more complex geometry. To achieve this goal, welding techniques have received particular attention. Generally, welding of Al alloys can be realized through different welding processes: Arc-welding techniques, such as metal inert gas (MIG), tungsten inert gas (TIG) and manual metal arc (MMA) [14-16]. Actually, in many industrial fields, the development of welding technologies represents a key factor to enlarge the use of Mg-based alloys too for the manufacturing of structural components. Currently, the most important welding procedures used for magnesium alloys are: TIG, Laser Beam Welding (LBW), Electron Beam Welding (EBW) and Friction Stir Welding (FSW) [17-18]. Nowadays, at industrial level, TIG and MIG fusion welding technologies are especially applied for removing and for repairing defects.
in Mg castings [18]. TIG is largely used at industrial scale, due to its advantages of utility and economy. However, Mg-based alloys are characterized by low melting point, high thermal conductivity, strong affinity toward oxygen and nitrogen, and for these reasons during the welding, many defects can be developed. The most relevant defects are related to the presence of porosity and cracks, wide heat affected zone (HAZ), residual stresses and distortions [19-20]. Additionally, application of TIG welding technology presents some restrictions due to its low penetration in single pass welding and its low productivity. According to the literature data, improvement of both the penetration and the quality of Mg alloys weldments can be realized through the addition of TiO2 coating [17] and the application of high frequency vibration, during the solidification of the melt [20]. According to [21-23], the increasing use of Mg-based alloys for cyclically-loaded structural applications has given rise to a growing interest for as concerns fatigue properties of cast magnesium alloys. The presence of defects, developed during the casting operations, as well as of the specific microstructural features of the alloys, such as grain size, second-phase particles and hardening precipitates, represent the elements that mainly affect the fatigue properties of these alloys [24-25]. Porosity, oxide films and intermetallic inclusions are defects that, acting as stress concentration sites, can constitute favorable nucleation sites for cracks with relevant negative consequences, decreasing both the lifetime and the fatigue strength of the alloys, mainly at elevate numbers of cycles [25]. In this paper, the microstructure, the tensile properties and the fatigue strength of ZE41 Mg alloy before and after TIG welding process carried out with double pass, are evaluated, aiming to appreciate how the welding process affects the microstructure and the mechanical strength. Fracture surface analysis completes the study, in order to identify the defects and to correlate their presence to the level of the fatigue strength.

2. Experimental

The chemical composition of the ZE41 magnesium alloy is reported in Table 1.

| Elements      | Zn | Zr | Si  | Mn | Rare earths (Ce,La,Nd,Pr) | Mg  |
|---------------|----|----|-----|----|--------------------------|-----|
| Wt%           | 4  | 0.7| 0.04| 0.03| 1.68                      | Balance |

Some plates have been produced by sand casting technology and have been submitted to a two-step T5 heat treatment. The thermal treatment has been carried out in the following sequence: first step performed at 330°C for 2 hours, which is useful to guarantee a stress relieving. This has been followed by air quenching then a second ageing step carried out at 180°C for 12 hours followed by air cooling. TIG welding process has been used for the joints development, and during this step the plates have been made in contact without a rigorous control of the gap.

The following welding parameters have been adopted: 160-180 (A); 15-17 (V) and an electrode with a diameter of 3.2 mm has been used. The same ZE41 magnesium alloy has been used as filler material; finally, argon has been employed as shielding gas. The welding process has been carried out with double pass. In order to reduce the thermal shocks as much as possible, that is due to the thermal gradient existing between the base metal and the filler, the plates have been preheated to 160°C before welding. After the welding, the samples have been submitted for 12 hours to a stress relieving post heat treatment, performed at a temperature of 185°C. Samples for microstructural, mechanical and fatigue tests have been extracted from the prepared plates.

Microstructure analysis have been carried out on the samples prepared by a standard metallographic technique by mounting and polishing procedures after tensile and fatigue tests using an optical microscope, (OM, MeF4 Reichart-Jung) and Scanning Electron Microscopy (SEM, Leo 1450VP) equipped with Energy X-rays Dispersive Spectroscopy unit (EDS, Oxford microprobe) for compositional analysis. SEM has been employed for fracture surface analysis, after mechanical and fatigue tests, to determine the causes which can be associated to the failure of the samples.
On the polished surfaces Vickers micro-hardness measurements have been performed using a Volpert DU01 tester. A force of 200 gf (1.96 N) has been applied for 15 s for each measurement and a minimum of 5 indentations have been performed on each samples. Micro-hardness has been measured along a line, from the weld centre line to the base metal, with a distance of 1 mm between two consecutive indentations.

3. Results and discussion

3.1. Microstructural analysis

Figure 1 reports the microstructure of base material: as it can be observed, it consists mainly of equiaxed α-Mg matrix grains and an eutectic compounds, distributed along the grain boundaries. The eutectic compound highlighted in Figure 1 and analyzed by the X-rays diffraction, reported in Figure 2 is orthorhombic T-phase (Mg7Zn3RE), which presents the following lattice parameters $a = 0.99$ nm, $b = 1.15$ nm and $c = 0.98$ nm.

![Figure 1. SEM microstructure of ZE41 magnesium alloy](image)

Homogeneously distributed small Zr particles as shown in Figure 3 ($\leq 5\mu m$) that have been individuated in the analysed samples. Zr represents one of the most powerful grain refinement for Mg-based alloys. Its grain refining ability is reduced by the presence of chemical elements such as Al, Mn and Si according to [27]. However, due to their low volume fraction, the Zr-rich phase has not been detected by XRD.
Figure 3. Zr-rich particle which acts as nucleation site for α-Mg grains

The SEM micrograph reported in Figure 4, shows the transition zone between the fusion zone and the heat affected zone. Both zones are mainly composed of primary α-Mg matrix grains and eutectic compounds, T-phase (Mg7Zn3RE), along grain boundaries, as shown in Figure 1. It can be observed in Figure 5 that the three zones, namely FZ, HAZ and BM consisting of equiaxed grains have been individuated. Fine grains appear in the FZ (Figure 5). Due to the high cooling rate of the welding pool, coming from the high thermal conductivity of ZE41 Mg-based alloy, the FZ is finer with respect to the HAZ. As reported in [28], a finer grain size represents a suitable feature to reduce the susceptibility to cracking in welded castings. The conductive heat dissipated toward the side of the welding pool during the TIG welding process mainly causes the grain coarsening occurred in the HAZ. The HAZ shows a coarsened T-phase compared to the BM, as illustrated in the OM micrographs reported in Figure 5.

Figure 4. SEM micrograph of the transition zone between the fusion zone (FZ) and the heat-affected zone (HAZ)
3.2. Vickers Micro-hardness
The TIG welding process causes microstructural variations, which locally influence the material properties, as reveal the Vickers micro-hardness profiles (Figure 6), of both not welded and TIG welded samples. The grain size and the presence of strengthening precipitates represent the two factors that mainly influence the micro-hardness of an alloy. In fact, according to the Hall-Petch equation [29], hardness increases when grain size decreases; however due to the Orowan hardening mechanism [30] the hardness increases if the spacing between the hardening precipitates is reduced. The highest micro-hardness values of the FZ, registered for the TIG welded samples, also compared to that of the not welded samples, are principally due to the grain refinement and the possible re-precipitation of strengthening precipitates. The micro-hardness profile of TIG welded samples shows a significant decrease in correspondence of the HAZ, because these zones are submitted to a softening effect and a grain coarsening [31]. Finally, the micro-hardness of welded samples, in the BM zones, reaches the value of not welded sample (~75 Hv).

4. Conclusions
In this research, the effects of TIG welding process on the microstructure, the tensile properties and the fatigue strength of ZE41(Mg–Zn–RE–Zr) magnesium alloy were investigated. In case of the TIG welded samples, a grain refinement in the fusion zone and a grain coarsening in the heat affected zone takes place. The distributions of the micro-hardness reflect the microstructure variations occurred in the welded samples.

5. References
[1] Guo MX, Zhang Y, Zhang XK, Zhang JS, Zhuang LZ 2016 Non-isothermal precipitation behaviours of Al-Mg-Si-Cu alloys with different Zn contents, J. Material Science Engineering A 669 20
[2] Cavazzoni L, Miscia G, Rotondella V, Baldini 2015 Procedia Eng 109 17
[3] Grosselle F, Timelli G, Bonollo F 2010 J. Material Science Engineering A 527: 3536–3545.
[4] Peter I, Rosso M, Bivol C 2009 Microstructure and mechanical behaviour of Al-based alloy obtained by liquid forging technique, Metal Int 2 15
[5] Huang Y, Ye X, Hu B, Chen L 2016 Equivalent crack size model for pre-corrosion fatigue life prediction of aluminum alloy 7075-T6, Int J Fatigue 88 217
[6] Tavares SMO, Dos Santos J, De Castro PMST 2013 Friction stir welded joints of Al–Li Alloys for aeronautical applications: butt-joints and tailor welded blanks, Theor Appl Fract Mech 65 8
[7] Hirsch J, Al-Samman T 2013 Superior light metals by texture engineering: Optimized aluminum and magnesium alloys for automotive applications, Acta Mater 61 818
[8] Park GH, Kim JT, Park HJ et al 2016 Development of lightweight Mg-Li-Al alloys with high specific strength, J. Alloys Compd 680 116
[9] Zhang W, Xiao W, Wang F, Ma C (2016) Development of heat resistant Mg-Zn-Al-based magnesium alloys by addition of La and Ca: Microstructure and tensile properties, J Alloys Compd 684:8-14
[10] Chen XH, Huang XW, Pan FS, Tang AT, Wang JF, Zhang DF (2011) Effects of heat treatment on microstructure and mechanical properties of ZK60 Mg alloy, Trans Nonferrous Met Soc China 21:754-760.
[11] Huang ML, Li HX, Bao L, Ma XB, Hao SM (2012) Partial phase relationships of Mg-Zn-Ce system at 350 °C, Trans. Nonferrous Met. Soc. China 22 681-685.
[12] Ratna Sunil B, Pradeep Kumar Reddy G, Mounika ASN, Navya Sree P, Rama Pineswari P, Ambica I, Ajay Babu R, Amarnadh P (2015) Joining of AZ31 and AZ91 Mg alloys by friction stir welding, J. Magnes Alloy 3:330–334.
[13] Coelho R, Kostka A, Pinto H, Riekehr S, Kocak M, Pyzalla AR 2008 Mater Sci Eng A 485:20–30.
[14] Zhang L, Li X, Nie Z, Huang H, Niu L (2016) Comparison of microstructure andmechanical properties of TIG and laser welding joints of a new Al–Zn–Mg–Cu alloy, Mater Des 92:880–887.
[15] Yi J, Cao SF, Li LX, Guo PC, Liu KY (2015) Effect of welding current on morphology and microstructure of Al alloy T-joint in double-pulsed MIG welding, Trans Nonferrous Met Soc China 25 3204−3211.
[16] Peter I, Rosso M (2011) Effect of the filler metals on aluminium alloy joints, Metal Int 16:157-160.
[17] Wang L, Shen J, Xu N (2011) Mater Sci Eng A 528:7276–7284.
[18] Min D, Shen J, Lai S, Chen J, Xu N, Liu H (2011) Effects of heat input on the low power Nd:YAG pulse laser conduction weldability of magnesium alloy AZ61, Opt Lasers Eng 49:89–96.
[19] Carlone P, Palazzo GS (2015) Characterization of TIG and FSW weldings in cast ZE41A magnesium alloy, J Mater Process Technol 215:87–94.
[20] Wen T, Liu SY, Chen S, Liu LT, Yang C (2015) Influence of high frequency vibration on microstructure and mechanical properties of TIG welding joints of AZ31 magnesium alloy, Trans Nonferrous Met Soc China 25:397−404.
[21] Li Z, Wang Q, Luo AA, Peng L, Zhang P (2015) Fatigue behavior and life prediction of cast magnesium alloys, Mater Sci Eng A 647:113–126.
[22] Luo AA, Fu PH, Peng LM, Kang XY, Li ZZ, Zhu TY (2012) Metall Mater Trans A 43:360–368.
[23] Yang F, Lv F, Yang XM, Li SX, Zhang ZF, Wang QD (2011) Enhanced very high cycle fatigue performance of extruded Mg–12Gd–3Y–0.5Zr magnesium alloy, Mater Sci Eng A 528: 2231–2238.
[24] Xu DK, Liu L, Xu YB, Han EH (2008) The fatigue behavior of I-phase containing as-cast Mg–Zn–Y–Zr alloy, Acta Mater 56:985–994.
[25] Mayer H, Papakyriacou M, Zettl B, Stanzl-Tschegg SE (2003) Influence of porosity on the fatigue limit of die cast magnesium and aluminium alloys, Int J Fatigue 25:245–256.