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Evaluation of structure and properties of welded joint of magnesium alloy EZ33A-T5

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Abstract

In recent years, improvement of casting magnesium alloys welding technology has resulted in an increase in the number of publications on this topic. The symptom of this trend is to replace traditional construction materials of magnesium alloys. Magnesium alloys of Mg-Zn-RE-Zr group are used in the automotive, aerospace and defense industries, mainly as gravitional casts to sand moulds or die-casting. Casting defects often appear in these casts (misruns, micro-shrinkage, cracks). The welding technologies are most often applicable to repair of casts, mainly nonconsumable electrode welding in the inert gas cover. The premise of this research work was to define structure and mechanical properties of welded joints of magnesium alloy EZ33A-T5. For this purpose, were attempted trails welding and conducted non-destructive testing, metallographic and strength mechanical tests allowing to assess the properties of welded joints. Evaluation of properties of welded joints was possible by carrying out welding trials and execution of non-destructive tests and metallographic. Research of the microstructure was used with the methodology and test procedures for the quantitative evaluation of the structure of welded joints which was developed in the Department of Materials Science of Silesian University of Technology.

Keywords: Mechanical properties, weldability of alloys of magnesium, EZ33, Microstructure, Quantitative procedure

1. Introduction

The dynamic development of the application of magnesium alloys in recent years, has contributed to the increase of interest of modern production technologies and their further processing methods of magnesium alloys, such as casting and welding technologies. The factors that determine the innovative use of magnesium alloys are less density, higher strength, better resistance to high temperatures and corrosion of gas compared to the previously used materials. An annual international conference devoted to technologies of production and processing of magnesium alloys can be evidence for it organized by the American Society of Minerals of Metals and Materials (TMS).

Currently, magnesium and its alloys are finding wider use application in different branches of industry, successfully can compete with much cheaper construction materials. A published US Geological Survey report which the world participation is introducing the production of magnesium is attesting to it (fig.1) [1]. Low density with very great strength properties makes magnesium alloys are of particular interest in modern industry and are a very good alternative for aluminum alloys, titanium alloys or steel. Good resistance to high-temperature corrosion, high damping capacity and low inertia, allow to use the castings magnesium alloys to quickly moving elements in places where there are rapid changes in speed [2, 3].

Cast magnesium alloys with a group of Mg-Zn-Zr-FE are characterized by a good castability, a lack of the microporosity and a little tendency to cracks [4]. These alloys can be considered a good weldability, recommended method for welding nonconsumable electrode welding in the inert gas cover (TIG),

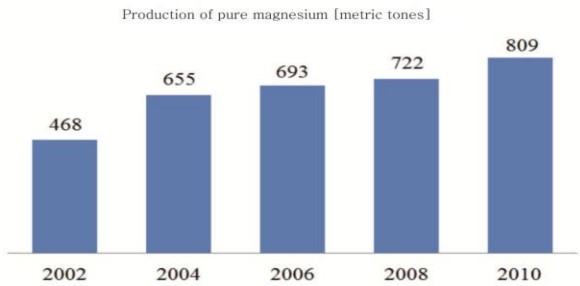

Fig 1. Worldwide production of magnesium at the turn of the last decade [1]

at using additional material about the same chemical composition [6]. After welding, the castings are usually subjected to heat treatment, consisting of solutioning at 345°C / 2 hours / water and aging for 5 hours in temperature 215°C [7,9,10].

Magnesium alloys with a group of Mg-Zn-RE-Zr are finding application to components working at elevated temperatures. The presence of rare earth elements increases the creep resistance of alloys through releasing of the stable phases at grain boundaries, which make it difficult to dislocation glide. The addition of zirconium due to the similar crystal lattice parameters of magnesium, apart from grain refining, also raises corrosion resistance. The main task of the zinc in Mg-Zn-RE-Zr alloys is to increase the endurance properties at room temperature [4,11].
Magnesium alloys of Mg-Zn-RE-Fs can be divided into two groups [7]:

- with high zinc content (EZ33, ZE41, ZE63)
- with increased contents of rare earth elements (MEZ).

Chemical composition and mechanical properties of magnesium alloy casting is shown in table 1.

Table 1.
Chemical composition and mechanical properties of Mg-Zn-RE-Zr magnesium alloys [5].

Alloy	Chemical composition, [%]			
	Mg	Zn	RE	Zr
EZ33	rest	2,0÷3,0	2,5÷4,0	0,4÷1,0
ZE41	rest	4,2	1,2	0,7
ZE63	rest	5,8	0,7	2,6
MEZ	rest	0,5	2,5	0,7
RE – mixture of rare earth elements containing cerium, lanthanum and neodymium				
Mechanical properties				
	R_m [MPa]	R_e [MPa]	A_5 [%]	
EZ33	140÷155	95÷100	3	
ZE41	200÷215	135	3÷4	
ZE63-T6	300	195	10	

Magnesium alloys type of Mg-Zn-RE-Zr with high zinc content are intended for gravity casting and production of castings by high pressure [12,13].

The microstructure of Mg-Zn-RE-Zr alloys with high contents of rare-earth (MEZ alloys) is characterized by a presence of grains of the α-Mg solid solution and intermetallic phase $Mg_{12}RE$ precipitates at the grain boundaries. In the case of alloys from a group of Mg-Zn-RE-Zr with high content of zinc (ZE and EZ alloys) structure is similar. On account of the higher content of zinc in EZ and ZE alloys at the grain boundaries of the solid solution α-Mg phase is formed $(Mg,Zn)_{12}RE$ (Fig. 2), which is a secondary solid solution based on intermetallic phase $Mg_{12}Ce$ [12,14,15]. Solutioning and aging of these alloys do not bring the desired effect, because it leads to the breakup phase $(Mg,Zn)_{12}RE$, in result a $Mg_{12}RE$ phase and RE_2O_3 oxides are coming into existance. However, the enrichment of a solid solution in the zinc occurs to a level which prevents effective strengthening of the alloy. Therefore the heat processing of these alloys is confining itself to anneal in the 170°C-200°C temperature in order to remove casting stresses (fig. 2b) [13,16].

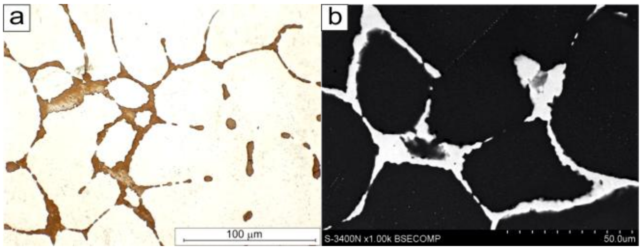

Fig. 2. Microstructure EZ33A-T5 alloy mesh intermetallic precipitates (Mg, Zn)$_{12}$RE at grain boundaries: a) the state after casting (light microscopy), b) annealed condition (scanning electron microscope)

2. Material and research methodology

Premise of the research was to assess the properties of welded joint of EZ33A-T5 alloy. welded joints. For the material tests used a casting magnesium alloy (EZ33A-T5) from the group of Mg-Zn-RE-Zr with addition of zinc and rare earth elements. Evaluation of properties of test welded joints was conducted on magnesium alloys in initial state i.e. after casting into sand moulds and magnesium alloys after heat treatment. The chemical composition and mechanical properties of alloy and parameters of the heat processing are summarized in table 2.

For research works were prepared test sliced sheets that casted by gravity to sand moulds about dimensions 500x320x20mm. The casting sliced sheets were cut for test samples with dimensions 250x50x10mm. After welding trials the test pieces have been heat treated by stress relief annealing (16hours/200°C/atmospheric air).

Test welded joints were subjected to procedures of visual examinations according to the norm. Before taking actions to the visual inspection, surface of welded joints have been cleaned. The visual examinations were carried out with relevant conditions and adequate access to the test welded joint.

Table 2.
Chemical composition and mechanical properties of EZ33A-T5 alloyT5 [8].

Alloy	Chemical composition, [%]				
	Number of melt	Mg	Zn	RE	Zr
EZ33A-T5	ASTM B80	rest	2,0÷3,0	2,5÷4,0	0,4÷1,0
	20091901	rest	2,8	2,87	0,51
Mechanical properties					
	R_m [MPa]	R_e [MPa]		A_5 [%]	HV3
EZ33A-T5	140÷155	95÷100		3	50
Heat treatment	Stress relief annealing: 16 hours / 200°C / free air				

Test sample for macro and microstructure were cut out according to the test procedure, which is perpendicular to the direction of welding. This arrangement provides an analysis of all typical welded joint areas such as base material, heat affected zone and weld [16].

To prepare for the test surfaces a Phoenix 4000 device was used. Tested sample surfaces were polished on abrasive papers of decreasing granularity and then on canvas polishing about 9μm granulation and 3μm in diamond suspension, and then on neoprene polishing wheel in the oxide suspension.

Prepared in this way metallographic specimen surfaces were etched in following reagents: 19ml water, 60ml of ethylene glycol, 20ml of acetic acid, 1ml HNO_3.

Metallographic macroscopic examinations of microsections were conducted on the stereoscopic microscope SZX-9 Olympus at enlarging 5÷50. The aim of the research was developed of welding defects structure.

Microscopic examinations were conducted on the optical microscope GX-71 Olympus at blow-ups 100x and 500x, a technique in the polarized light.Microstructure of the images were recorded using a digital camera OLYMPUS DP-70.

Structures on the light microscope were supplementing observation above examining at blow-ups 500x on the scanning electron microscope. Research works were carried out in the technique of the recording of secondary electrons and backwards dispersed electrons. The recording of secondary electrons enables surface topography mapping, however the detection of backwards dispersed electrons allows for the registration of differences of the chemical composition on the surface of the sample.

In order to identification phase was performed a X-ray phase analysis by diffraction of roentgen rays method (XRD) on X-ray diffractometer JDX-7S of JEOL company with used a copper anode tube ($\lambda_{CuK\alpha}$=1,54178Å) powered current of 20mA at a voltage of 40kV and a graphite monochromator.

In order to determine the mechanical properties was performed the static tensile test at temperatures from 20°C to 300°C. Tests were carried out on cylindrical samples cut perpendicular to direction of welding, the fusion weld was in the middle of measurement. Static tensile test was conducted on an electromechanical endurance machine Kappa 50DS. The samples after fasted in jaws of machine were heated to trial temperature, then heated by 30 minutes and stretched with speed of 4 mm/min.

Examinations were conducted with using methodology and test procedures for the quantitative evaluation of the structure of welded joints, for that purpose a METilo software which was developed at the Department of Materials Science of Silesian University of Technology [16,17].

3. Implementation technology of welded joints

In order to conduct the research on welded joints, for welding test joints used sliced sheets about dimension 250x50x10mm, which beveled on ,,Y" under 30° angle and left 2mm welding threshold (fig. 3a). Before welding test sheet were heated to a temperature of 100°C. The welding was conducted with string beads, takes into account a double sided weld - shown in fig. 3b.

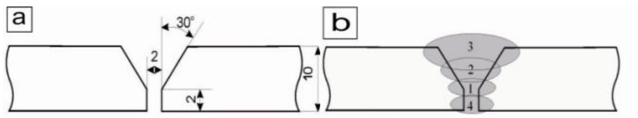

Fig. 3. The schema preparation of test sheets for welding: a) preparing sheets, b) arranging weld beads

To the welding additional material was used in the form of electrode WT20 wire about the diameter 3.2mm, with a similar chemical composition to welded material that includes: 2,5%Zn, 0,52%Zr, 3,17%RE, Mg rest.

Welding trials of butt joints made with non-consumable electrode in the cover of inert gas (TIG), used inverter welding machine Lincoln V 205AC/DC, alternating current. Current rise time was set for 2sec. to set the values, and the time of the welding arc blanking for 4sec. As protective gas it used technical argon about the cleanness of the 99.995% and flow of 12l/min. Free gas outlet at the start of the welding was established at 3sec., 4sec. at the end of the welding process..

The technological parameters of the welding process are summarized in table 3. Welded joints were assessed base on visual inspection, roentgenographic, structural examinations and strength tests.

Table 3.
Welding parameters of tested sheets.

No.	Welding current[A]	Arc voltage [V]	Linear energy arc [kJ/cm]
1	100	12	2,4
2	120	14	3,0
3	140	16	4,0

4. Results

4.1. Visual inspection

Trial boards made from magnesium alloy EZ33A-T5 have been marked depending on the linear energy arc during welding. For energy 2.4 kJ/cm marked board as Z1 (fig. 4), for linear energy arc 3.0 kJ/cm indicated Z2 (fig. 5) and Z3 for energy 4.0 kJ/cm (fig. 6).

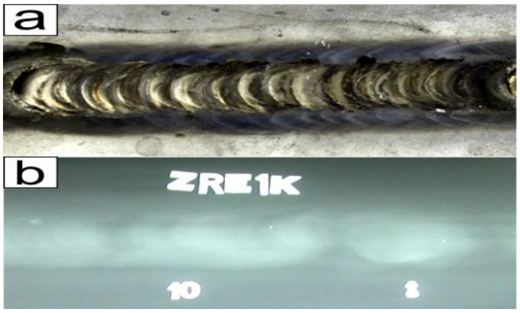

Fig. 4. Results of visual inspections of welded joint marked as Z1:
a) face of welded joint (2,4 kJ/cm)
b) radiograph of welded joint

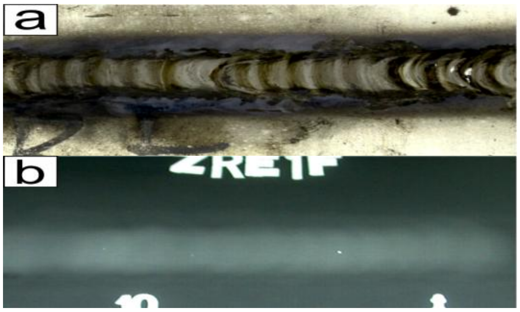

Fig. 5. Results of visual inspections of welded joint marked as Z2:
a) face of welded joint (3,0 kJ/cm)
b) radiograph of welded joint

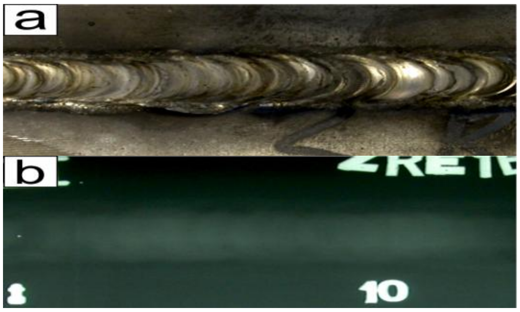

Fig. 6. Results of visual inspections of welded joint marked as Z3:
a) face of welded joint (4,0 kJ/cm)
b) radiograph of welded joint

The results of visual inspection of faces and backs welds made during test welding, revealed no surface imperfections or other imperfections welding. Trial welded joints have been classified as correct (fig. 4a, 5a, 6a).

Analysis of radiographs of the indicated welded joint as Z1 revealed a few minor non-metallic inclusions in the joint about diameter 1 mm (fig. 4b). Similar inclusions were observed in the joints Z2 and Z3 (fig. 5b, 6b).

Analysis of results welding of EZ33A-T5 alloy indicates that this alloy is weldable. The completed welded joints revealed a few gas pocket which were on acceptable level.

4.2. Metallographic

4.2.1. Macrostructure

The results of macrographic structure of welded joints before stress relief annealing and after annealing (stress relief annealing: 16hours/200°C/atmospheric air) is shown in Figure 7.

Fig. 7. Macrostructure of trial welded joints: a) state before annealing, b) annealed condition

From conducted analysis macrostructures were stated, that test welded joints of EZ33A-T5 alloy are devoid of internal imperfection welding. The visible line of fusion in base material and heat affected zone is continuous and there is no lack a local interrupts on its length.

4.2.2. Microstructure – quantitative procedure

Below there are results of microstructure examinations of base material (fig. 8) and fusion weld (fig. 9), with using a developed quantitative procedure for evaluation of structure of welded joints. The results of parameters that define structure of welded joints presented on fig. 12.

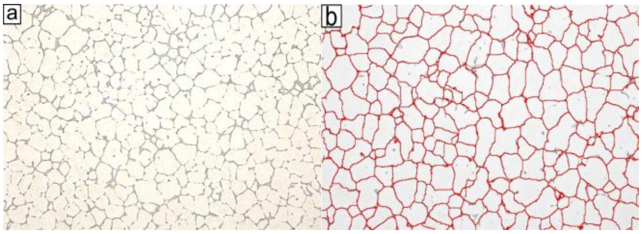

Fig. 8. Microstructure of base material of trail welded joints after heat treatment:
a) base image, b) result measurement image

Conducted examinations of the microstructure of trial welded joints of magnesium alloy EZ33-T5 confirmed that selected technology of welding was correct. There was no significant effect of heat treatment on the structural changes and the geometrical complete joint penetration.

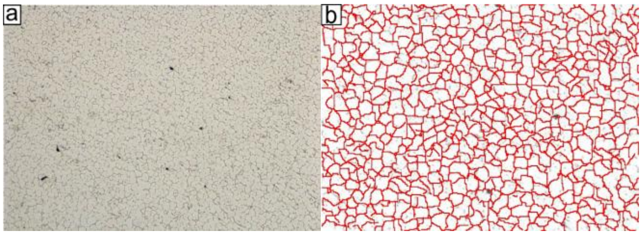

Fig. 9. Microstructure of fusion weld of trail welded joints after heat treatment:
a) base image, b) result measurement image

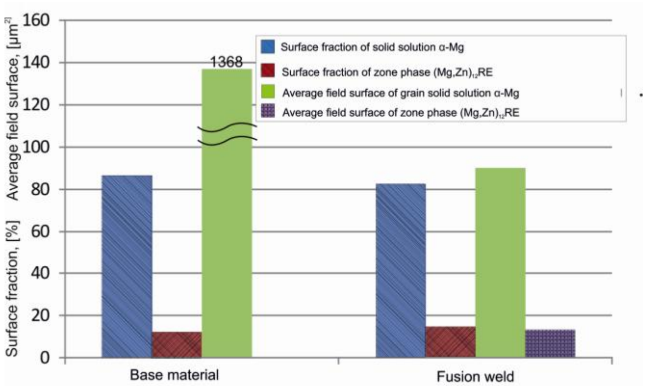

Fig. 10. Results of the quantitative analysis of evaluation structure of test welded joints of EZ33A-T5 alloy after heat treatment

Quantitative evaluation of structure joint allowed to statement that average field of flat crystal section α-Mg in material is on level 1368μm^2, while crystals in the fusion weld are much smaller (average field of flat crystal section α-Mg amounts to 90μm^2). The intermetallic phase in fusion weld is also characterized by a smaller average surface area of flat section of grain (13,3μm^2). Surface fraction of phase $(Mg,Zn)_{12}RE$ in base material is at 12%, while in case of fusion weld this fraction rises slightly to 14,6%. The results of parameters describing the structure of welded joint presented on fig. 10.

Supplemented by observations on light microscopy were researched in a scanning electron microscope. Exemplary structures are shown in figure 11.

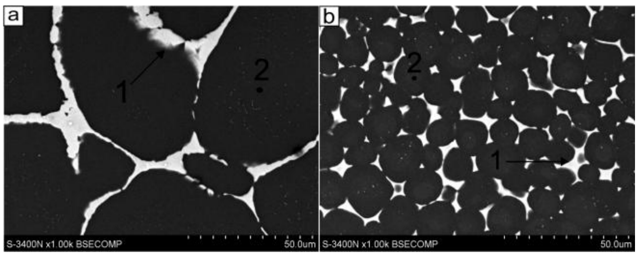

Fig. 11. Microanalysis results of the chemical composition of welded joint after heat treatment:
a) the zone of base material, b) the zone of fusion weld

In the zone of base material conducted microanalysis of chemical composition of welded joint made of trial boards EZ33A-T5 alloy conducted in the zone of base material confirmed presence of two phase, grains of solid solution α-Mg and intermetallic phase in the form of grid on crystals boundaries, identified as $(Mg,Zn)_{12}RE$. In the zone of fusion weld, where the biggest gradients of temperatures, was observed a degradation of intermetallic phase matrix $(Mg,Zn)_{12}RE$, in the consequence of degradation arises a phase $Mg_{12}RE$ and oxides RE_2O_3.

Table 4.
Microanalysis results of chemical composition (EDS) – the zone of base material

Point	Chemical composition [% at.]			
	Mg-K	Zn-K	La-L	Ce-L
1	84,8	9,4	1,4	4,4
2	99,2	0,8	-	-

Table 5.
Microanalysis results of chemical composition (EDS) – the zone of fusion weld

Point	Chemical composition [% at.]			
	Mg-K	Zn-K	La-L	Ce-L
1	85,4	8,5	1,8	4,2
2	99,4	0,6	-	-

Analysis of metallographic results revealed no signification changes in structure of fusion weld occur during heat treatment. It was found that the intermetallic precipitates on grains boundaries of both fusion weld (table 4) and base material (table 5) are enriched in zinc and rare-earth elements. Phase analysis performed by XRD method confirmed that this is phase $(Mg,Zn)_{12}RE$ (fig. 12).

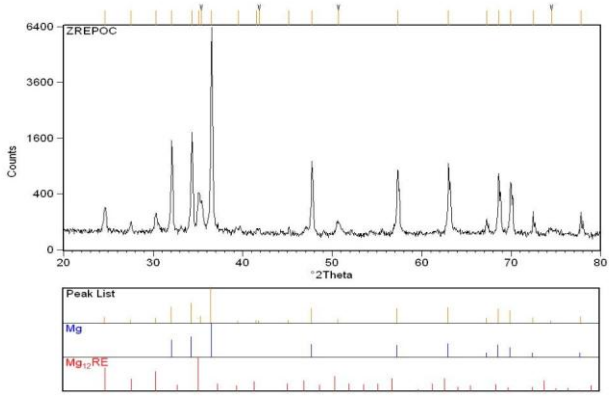

Fig. 12. The results of phase composition analysis of welded joint made of EZ33A-T5 trail boards after heat treatment – the zone of fusion weld

4.3. Static tensile test at high temperature

The objective of assessment of mechanical properties of welded joints at elevated temperatures shows the results of tests carried out a static stretching in the temperature range from 20-200°C for welded joints EZ33A-T5 alloy. Results of static tensile test as shown in table 6, whereas the examples of test pieces after stretching and work-hardening curves are shown on fig. 13-15.

Table 6.
The results of static tensile test of welded joints of EZ33A-T5 alloy

Temp. test [°C]	R_m [MPa]	Attention
20	122	Breaking out of the welded joint
100	127	Breaking out of the welded joint
150	130	Breaking out of the welded joint
200	92	Breaking out of the welded joint
250	99	Breaking out of the welded joint

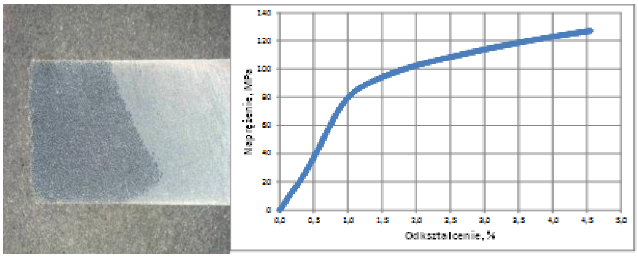

Fig. 13. The test piece after static tensile test and work-hardering curve in temperature 100°C

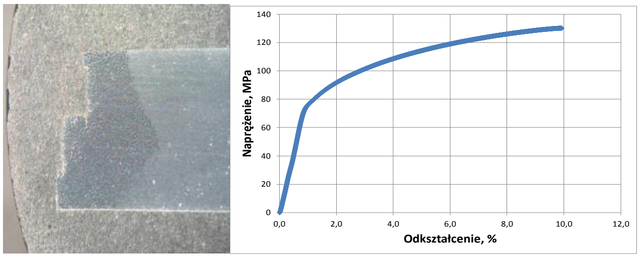

Fig. 14. The test piece after static tensile test and work-hardering curve in temperature 150°C

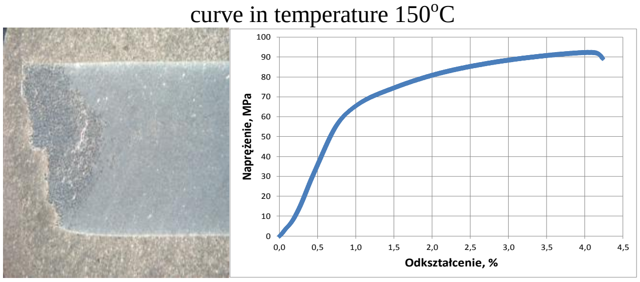

Fig. 15. The test piece after static tensile test and work-hardering curve in temperature 200°C

Breakdown of test pieces sampled from welded joints of magnesium alloy trial boards in all cases occurred outside the fusion weld, it indicates a higher strength fusion weld than base material alloy. The strength of EZ33A-T5 for welded joints to temperature 150°C is on constant level, in the range of 122-130MPa. Above this temperature the strength properties of welded joints are falling about 25%.

6. Summary

The research work has been working with casting magnesium alloy EZ33A-T5 with high zinc content and additive of rare earth elements. The conducted technological trials to made a welded joints, visual inspection, metallographic examinations with using procedures and quantitative evaluation of structure and tensile tests, allowed for evaluation of structural and mechanical properties of magnesium alloy EZ33A-T5.

It was found that alloy EZ33A-T5 reveals a good weldability, and the best method of bonding magnesium alloys is gas tungsten-arc welding. This method allows to precisely regulate quantity of heat inserted to zone of welded joint, what is contribute maintenance to correct temperatures field and stresses. For welding should be use an added metal about possibly similar chemical composition to base metal. After welding it is recommended to carry out a heat treatment (stress relieving).

The results of visual inspection of welded joints made of magnesium alloy EZ33A-T5 revealed no surface imperfections or other imperfections welding and the roentgen tests revealed only a few minor non-metallic inclusions and gases pocket. It was found that welded joints were at an acceptable level of quality.

The conducted analysis of macrostructures were stated, that test welded joints made of EZ33A-T5 alloy are devoid of internal imperfection welding. The visible line of fusion in base material and heat affected zone is continuous and there is no lack a local interrupts on its length.

The conducted microstructure examinations and microanalysis of chemical composition and phase, revealed no signification changes in structure of fusion weld occur during heat treatment. However confirmed that the structure of this alloy is built with zinc solid solution and rare earth elements in magnesium phase (α-Mg) and precipitates of intermetallic phase $(Mg,Zn)_{12}RE$ at crystals boundaries.

The tests of strength properties indicated that the fusion weld after heat treatment featuring the strength on base material level at throughout range of tests temperatures i.e. to 250°C. Mechanism of cracking of welded joint during static tensile test at high temperature is formation of microcracks in phase $(Mg,Zn)_{12}RE$ at grain boundaries of solid solution α-Mg. At a temperature of 250°C, the main role in cracking process make a formation of neck, in which are formed microcracks and mechanism of cutting. During further deforming of grain boundaries of solid solution, are formed more and more pores which connect into main crack.

The results resented in this research work allow for conclusion that castings of EZ33A-T5 alloy reveal a good susceptibility to long-lasting join. Conducted assessment of structure and mechanical properties at high temperatures allows to declare that these welded joints can work in the same conditions as base material in temperatures to 150°C.

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