ARCHIVES
of
FOUNDRY ENGINEERING
Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences
ISSN (1897-3310)
Volume 10
Issue Special1/2010
339-344
66/1

Influence of design factors on weldability of the AZ91E alloy

J. Adamiec
Department of Materials Science,, Silesian University of Technology University, ul. Krasińskiego 8,
40-019 Katowice, Poland
*Contact: e-mail: janusz.adamiec@polsl.pl

Received 05.03.2010; accepted in revised form 23.03.2010

Abstract
Basic design factors which influence weldability include casting shape, its stiffness and type of welded joint. The influence of casting stiffness on weldability, understood as susceptibility to hot cracking, in conditions of constant joint stiffness has been determined on the basis of the Fisco test results, and in conditions of varying stiffness on the basis of the Houldcroft test

Keywords: casting defects, welding of magnesium alloys, hot cracking, AZ91,Fisco test, Houldcroft test

1. Introduction

In addition to aluminium and titanium alloys, the magnesium alloys comprise the group of lightweight alloys which have the highest practical importance in structural applications. Due to their low density (1.738 g/cm^3), magnesium alloys are 35 % lighter than aluminium alloys, 60 % lighter than titanium alloys, and 75% lighter than steel [1].
Majority of commercially available magnesium alloys are based on double Mg-Al equilibrium system (fig. 1). Microstructure of alloys containing up to 12% Al consists of two phases: crystals of aluminium terminal solid solution in the α-Mg magnesium, and the $Mg_{17}Al_{12}$ phase designated as β [1]. The eutectic mixture consisting of the α-Mg phase and primary crystals of the β phase, being the solid solution on the matrix of the $Mg_{17}Al_{12}$ intermetallic bond, should appear when the aluminium content exceeds 12.7% (fig 2.1.1) [2, 3]. In practice, however, as a result of dendritic microsegregation which causes enrichment of liquid metal with aluminium, the eutectic mixture appears when the aluminium content is mere 2% [3].
In addition to the eutectic mixture partially separated in the microstructure, there are supersaturated areas of the α-Mg solid solution, as well as needle precipitations of the $Mg_{17}Al_{12}$ phase (fig. 2.1.2) [3,4]. They precipitate in the solid state as a result of the fact that as the temperature drops, the solubility of aluminium in magnesium is reduced [5].

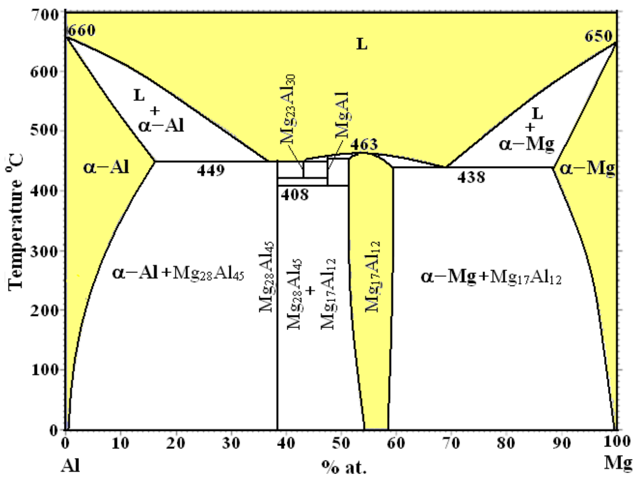


Fig. 1. Al-Mg phase equilibrium [2].

In addition to the $Mg_{17}Al_{12}$ phase, the structure of Mg-Al-Me alloys includes also the precipitations of the Al_8Mn_5 phase, most frequently of globular shape [4]. Appearance of the Al_4Mn or

Mg_2Si phases is also possible [6]. Volumetric content of these phases in the Mg-Al alloys is small, therefore they do not influence their properties. The aluminium content in these alloys is from 3% to 9% by weight. In addition, manganese and zinc are added in concentration not exceeding 1% by weight [7].

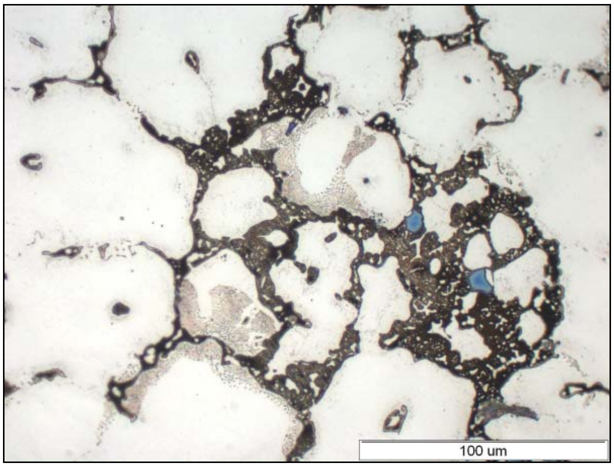


Fig. 2. Microstructure of the AZ-91 (Mg-9Al-1Zn) alloy after casting in a sand mould: a) visible are bright crystals of the α-Mg solid solution, and irregular areas of partially separated eutectic mixture [7]

Among the recognized manufacturers of magnesium alloy castings, ZM WSK Rzeszów manufactures the castings to be used for parts of gear units and aircraft engines, made of the GA8 alloy which chemical composition and properties are similar to those of AZ91. This alloy is also widely used in the USA and the UE [8]. Attempts are planned in the nearest future to cast magnesium alloys with addition of silver and rare earth elements into sand moulds [9]. EuroMag SA Kędzierzyn Koźle, as well as NPT SA and POLMAG SA (also from Kędzierzyn Koźle) manufacture magnesium alloy parts for the automotive and engineering industries and parts to be used in household appliances [10].
Magnesium alloys are now used to make large-size castings in sand moulds, high-pressure castings and precision castings [11]. Magnesium alloy castings, particularly large-size castings, often have defects (misruns, micro-shrinkage, cracks). In castings of complicated shapes, the defect rate may exceed 50% [12].
The possibility of repairing the magnesium alloy castings with welding techniques is determined by the weldability of said magnesium alloys. Weldability is a property of a material which defines its susceptibility to joining. Weldability can be defined as an ability of welded material to produce joints of required properties [14]. The PN-84/M-69005 standard defines weldability as usability of a material, with a given sensitivity to welding, to produce, under specified conditions, a metallically continuous joint of required utility properties.
The main difficulty encountered when welding and pad welding magnesium alloys is their susceptibility to hot cracking during the weld crystallization [15]. Therefore, it can be assumed that the weldability of cast magnesium alloys is determined by the metallurgical, design and technological factors which influence susceptibility of an alloy to hot cracking (fig. 3).

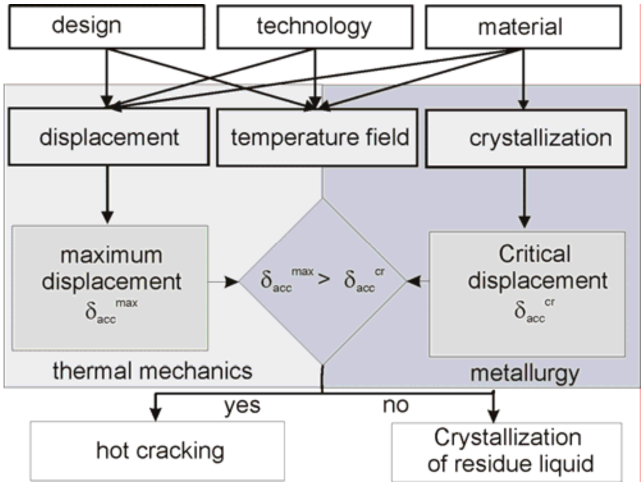


Fig. 3. Phenomenological interrelation between the hot cracking criteria and the factors influencing the susceptibility to hot cracking [15].

The paper presents the results of welding tests of the AZ91E alloy in conditions of constant joint stiffness (Fisco test) and in conditions of varying joint stiffness (Houldcroft test). We have evaluated the influence of design factors on susceptibility of the AZ91E alloy to hot cracking, and hence on its weldability.

2. Material for tests

The tests have been performed on the AZ91E alloy: magnesium cast alloy from the group containing aluminium and zinc. Chemical composition and mechanical properties of the tested alloy are given in table 1. Comparing the chemical composition with relevant specifications, it was decided that the tested alloy produced by Magnesium Elektron meets the requirements of the ASTM B80 standard in terms of chemical composition. Welding and pad welding was performed with the dia 2.4 mm wire, also manufactured by Magnesium Elektron, of chemical composition similar to that of the base metal (table 1).
Influence of design factors on weldability of the AZ91E alloy has been evaluated on the alloy in initial state, i.e. after casting in a sand mould and after heat treatment. The heat treatment parameters, specified according to the manufacturers guidelines, are summarized in table 2. Structure and results of quantitative assessment of the alloy AZ91E is presented in table 3.

Table 1. Chemical composition and mechanical properties of magnesium alloys used in the tests

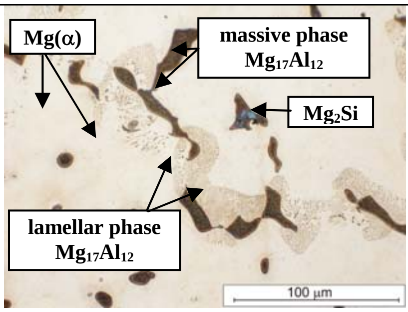
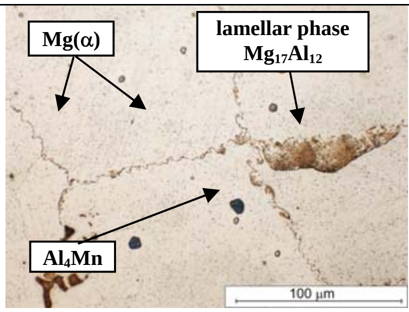
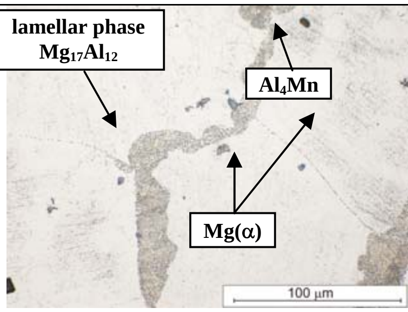
Alloy	Chemical composition [%] – base metal								
	Heat	Zn	Al	Si	Cu	Mn	Fe	Ni	Other
AZ91E	ASTM B80	0.4-1.0	8.1-9.3	-	-	0.13-0.35	-	-	-
	000810	0.56	8.6	0.04	-	0.21	0.003	0.001	<0.01
	Chemical composition [%] – welding wire								
	20099000	0.69	8.6	0.06	0.006	0.18	0.002	<0.001	<0.30

Mechanical properties – base metal			
R_m [MPa]	R_e [MPa]	A_5 [%]	HV3
275	150	1	66

Table 2. Heat treatment parameters for cast magnesium alloys

Alloy	Heat treatment	Heat treatment parameters
AZ91E	OCI	Solution heat treatment: 24h/415°C/air/heating 50°C/h
	OCII	Solution heat treatment: 24h/415°C/ air/heating 50°C/h;Ageing: 10h/200 °C/air

Table 3. Structure and results of quantitative assessment of the alloy AZ91E.

	Delivery state	Heat treatment	
		I	II
AZ91E	 V_v ($Mg_{17}Al_{12}$) massive p. = 5.7 % V_v ($Mg_{17}Al_{12}$) lamellar p. = 9.4 % V_v (Mg_2Si) = 0.1%	 V_v ($Mg_{17}Al_{12}$) massive p.= 0.5% V_v ($Mg_{17}Al_{12}$) lamellar p. = 2.1 % V_v (Mg_2Si) = 0.1%	 V_v ($Mg_{17}Al_{12}$) massive p.= 0.5% V_v ($Mg_{17}Al_{12}$) lamellar p.= 8.9 % V_v (Mg_2Si) = 0.1%

3. Determining susceptibility to hot cracking in conditions of constant joint stiffness – Fisco test

The Fisco test simulates real repair welding of strongly stiffened castings. The test involved stiff fixing of 180x80x5 mm plates with 2 mm welding gap in a special jig (fig. 4). The plates were unbevelled (joint "I"), bevelled to "Y", and bevelled to "V" (fig 4). Three single-bead welds were made with material of similar chemical composition on each specimen. The beads were made from right to left, one directly after the other (fig. 4c). The welding method was TIG, 110 A - 130A alternating current. The criterion of susceptibility of the alloy to hot cracking was ratio of total hot cracks length to the total length of the welded joints, expressed in percent. This ratio was called "F". Graphical representation of the results is given in fig. 4d.

Analysis of the Fisco test results indicates that the AZ91E alloy is susceptible to hot cracking in conditions of constat joint stiffness in the as-delivered state ("F" ratio from 1.9% to 3.3%), and after solution heat treatment and ageing ("F" ratio from 0.9 % to 4.3%), irrespective of the type of welded joint. Consequently, this alloy should best be welded or pad welded after the solution heat treatment ("F" ratio does not exceed 1%) (fig. 4d).

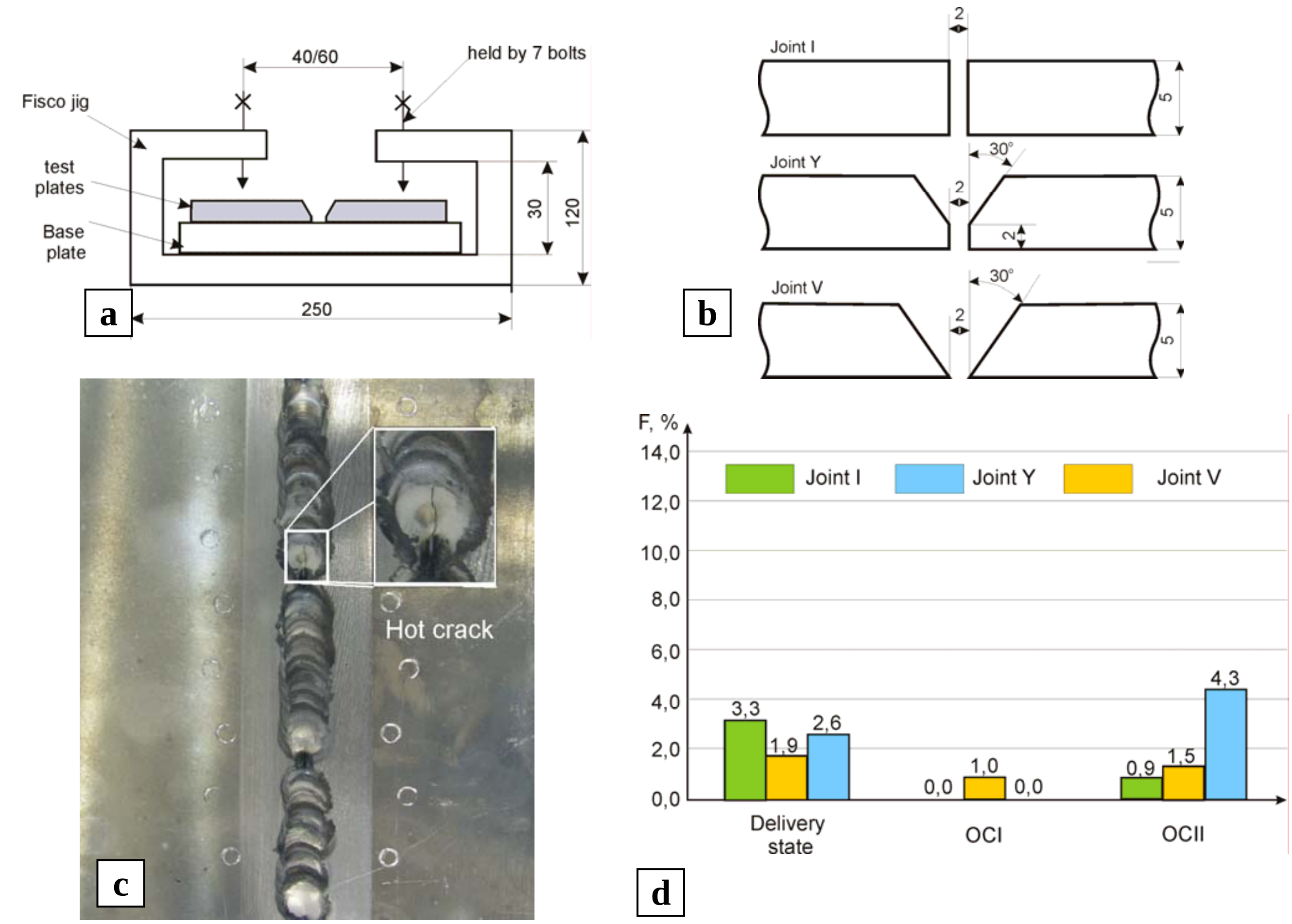


Fig. 4. Fisco test: a) basic dimensions of test jig, b) bevelling of test plates, c) hot cracking of the AZ91 alloy after casting during the Fisco test, d) evaluation of susceptibility of AZ91E allot to hot cracking in conditions of constant joint stiffness – Fisco test

4. Determining susceptibility to hot cracking in conditions of varying joint stiffness – Houldcroft test

Susceptibility of cast magnesium alloys to hot cracking in conditions of varying joint stiffness has been evaluated during the Houldcroft test. The Houldcroft test involves welding of the plates with a non-consumable electrode (TIG) with or without the filler. The measure of the alloy resistance was the ratio “A”, defined as the ratio of the crack length to the specimen length, expressed in percent [17].

The test used three AZ91E alloy specimens, in the as-delivered state and after heat treatment. The preparation of specimens to welding without filler (hereinafter referred to as welding) is shown in fig. 5a. Fig. 5b shows the preparation of specimens to welding with filler (hereinafter referred to as pad welding). The dimensions of specimens are given in figure 4. Dimensions of samples and welding parameters are shown in table 4. Typical plates after the Houldcroft test with visible cracks are shown in figure 6. The results, in the bar chart format, are given in fig. 7.

Table 4. Dimensions of samples and welding parameters

Sample dimensions, mm												
δ	L	l	d	f	B	C	H	R	b	M	n	K
4.0	131.0	78.0	64.0	7.0	15.0	1.6	2.0	4.0	44.0	72.0	26.0	1.0

Welding parameters					
Current, A	Arc voltage, V	Welding speed, cm/min	Gas flow speed, l/min	Gas nozzle diameter, mm	Type and diameter of tungsten electrode
110	15	18	12	12	WT10, 3.2

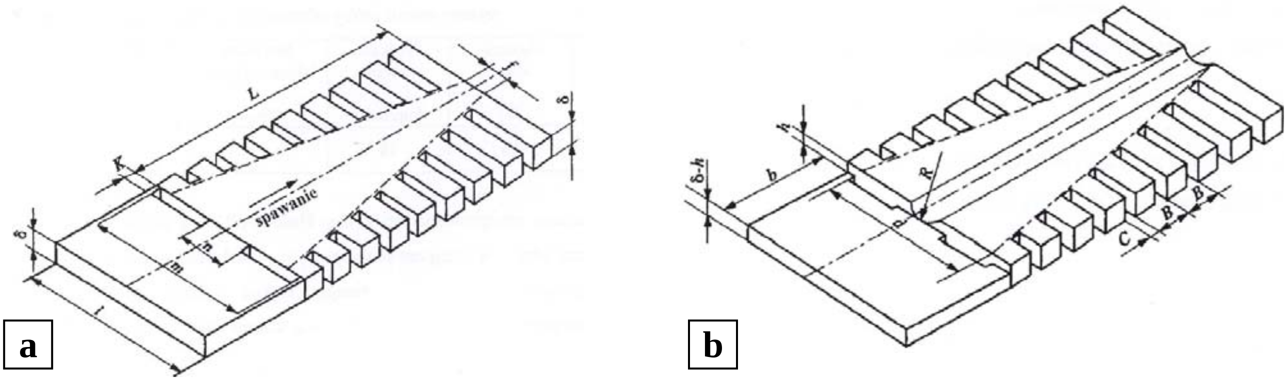


Fig. 5. Houldcroft test plates: a) welding without filler, b) welding with filler [17]

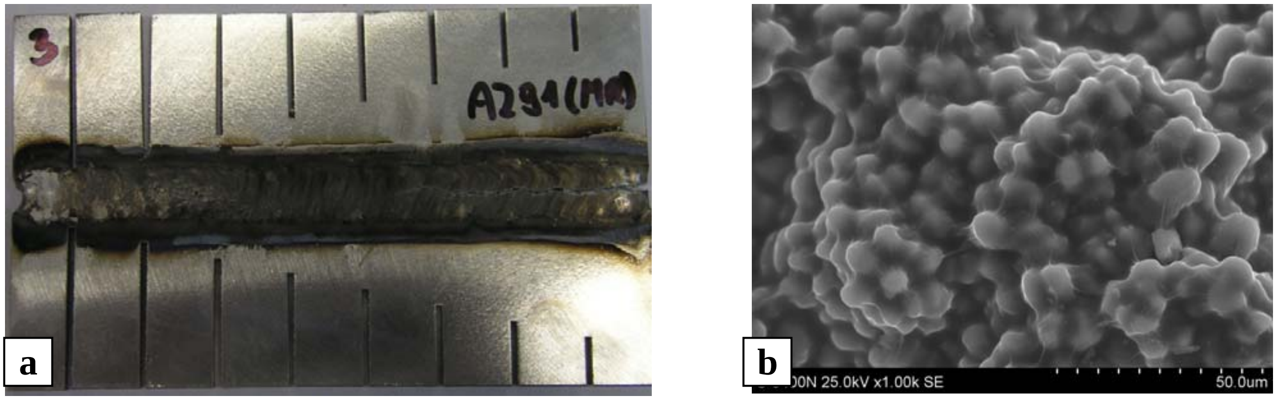


Fig. 6. Plates after the welding test with filler (Houldcroft test): a) face of welded joint on the AZ91E alloy, b) crack surface in the AZ91E alloy, SE,

Fig. 7. Houldcroft test results: a) AZ91E alloy, b) ZRE1 alloy, c) WE43 alloy, d) MSRB alloy

Analysis of the Houldcroft test results for the AZ91E alloy in as-delivered state indicates that this material is by about 40% less susceptible to hot cracking during pad welding than during welding (fig. 6,7). It has been determined that the AZ91E has the least susceptibility to hot cracking after solution heat treatment (OCI). The susceptibility of the alloy to hot cracking results from the solution of the $Mg_{17}Al_{12}$ massive phase – after the OCI process, it is reduced in both, the welding process (A= 18.9%), and the pad welding process (A=15.4%) (fig. 7). Ageing (OCII), which is intended to strengthen the AZ91E alloy, causes however a significant increase of susceptibility to hot cracking. The susceptibility to hot cracking during welding after OCII increases about 1.7 times in comparison to the corresponding value after solution heat treatment. On the other hand, during the pad welding, susceptibility to hot cracking after ageing increases almost 2.7 times (fig. 7). This fact is due to precipitation of the lamellar morphology $Mg_{17}Al_{12}$ phase along the borders of the Mg(α) solid solution (fig. 6b). Therefore, in conditions of varying stiffness, the AZ91E alloy castings should be weld repaired after solution heat treatment.

5. Welding of a cast from alloy AZ91E

On the basis of padding and welding tests the parameters of welding of huge dimensions casts made of alloy AZ91E were determined. Verifying tests of welding were conducted on a cast of oil sump of a gear of aviation engine made of AZ91E alloy. In order to simulate the area after removal of the casting defects, holes of size 50 x 10mm were milled in samples. The welding area was mechanically cleaned through milling of the surface in distance of about 2cm from the edge of the defect. Those holes were welded with current source FALTIG 400 AC/DC, with the use of alternating current. A time of current accretion was set for 2s to a given value and the time of quenching the welding arc for 4s. A wolfram electrode with diameter of 2.4mm was used. Technical argon 99,995 was used as shroud gas with flow intensity of 10 l/min. Slow gas flow at the beginning of welding was set at 3s and 4s at the end of welding process. An additional wire was used in welding with chemical composition similar to native material created with a diameter of 2.4mm. Welding was performed with string beads without weave beads. In order to avoid the welding discrepancies in the form of cracking in HAZ, the samples of casts were under influence of solution heat treatment in temperature of 415^{o}C for 24 hours. After welding an annealing was conducted in temperature 200 ^{o}C / 10 hours. Results of the tests are shown in fig. 8. Macrographic tests conducted on a cut out cast fragment confirmed the correctness of the applied technique and welding technology. No cracks, sticking or blisters were found. Fusion of the weld was correct and no impurities or oxidized surfaces were found in places of pre-welding of the welded joint.

Fig. 8. Fragments of repair of side wall of huge-dimensions cast of sump gear of aviation engine - face of weld, b) macrostructure of the padded area.

6. Summary

Based on the literature data, it has been assumed that the design factors which determine susceptibility to hot cracking comprise the shape and stiffness of a casting.

Evaluation of susceptibility to hot cracking in conditions of constant stiffness (Fisco test) has proved that the AZ91E alloy is susceptible to hot cracking irrespective of the type of welded joint (fig. 6). The AZ91E alloy has the least susceptibility to hot cracking after the solution heat treatment (fig. 6). In conditions of strong stiffness, the repair works using the welding technique should be carried out after solution heat treatment of the casting.

Analysis of results of the Houldcroft test, which simulates the conditions of varying casting stiffness, indicate that the AZ91E alloy is susceptible to hot cracking both during welding and pad welding (fig. 7, fig. 8). The AZ91E alloy castings should be weld repaired after solution heat treatment, due to the least volumetric content of the $Mg_{17}Al_{12}$ phase. This is a dominating phase in the cracking process, as evidenced by its presence on the surface of welded joint crystals (fig. 8).

Acknowledgements

This paper is financed by the Minister of Science and Higher Education as a part of project: PBR-7/RM-7/2008 (N R15-0015-04/2008) "Phenomena occurring during crystallisation of casted magnesium alloys, deciding upon high-temperature brittleness range".

References

[1] Avedesian M., Baker H., Magnesium and Magnesium Alloys. ASM Speciality Handbook, 1999

[2] Dahle A.K., and others: Development of the as-cast microstructure in magnesium-aluminum alloys, Journal of Light Metals 1 (2001) p. 61.

[3] Roskosz S., Adamiec J. Quantitative description of Mg-Al alloy structure, Acta Metallurgica Slovacia 1/2007,

[4] Kiełbus A. Adamiec J. Hetmańczyk M.: Microstructure of die casting alloy of magnesium GA8, Archiwum odlewnictwa nr 18, rok 2006, p 203-208, (in polish)

[5] Friedrich H.E., Mordike B.L. (Eds), Magnesium Technology. Metallurgy, Design Data, Applications, Springer-Verlag Berlin Heidelberg, 2006

[6] Adamiec J. , Chabko T. : Problems by welding and overlay welding casting of magnesium alloy AZ91D, Spajanie 2/4/2009, 2009, p. 20-23, (in polish)

[7] Roskosz S. Adamiec J., Błonicki M.: Influence of delivery state quality on microstructure and mechanical properties of as cast AZ91 Mg alloy, Archives of foundry Engineering, Vol. 7, 1/2007, 2007 p 143-146

[8] Magnesium alloys and processing technologies for lightweight transport applications – a mission to Europe, Global Watch Mission Report, MAG TECH 1,2004

[9] Friedrich H.E., Mordike B.L. (Eds), Magnesium Technology. Metallurgy, Design Data, Applications, Springer-Verlag Berlin Heidelberg, 2006

[10] Mordike B.L. Wiesner P.: Fugen von Magnesium Werkstoffen, DVS Verlag 2005

[11] Kiełbus. A, Kuc D., Rzychoń T.: Magnesium alloys – microstructure,properties and applications in Szkliniarz W: Modern metalllic materials, Wyd. Politechnika Śląska 2009, p.61-102, (in polish)

[12] Adamiec J., Roskosz S., Jarosz R. : Repair of Magnesium Alloy Castings By Means of Welding and Pad Welding, Journal of Achievements in Materials and Manufacturing Engineering, vol. 22, issue 1, 2007, p:21-24,

[13] Pilarczyk J.: Handbook of Welding, Vol 1, WNT, Warszawa 2003

[14] Bollinghaus T., Herold H., Cross C., Lippold J.: Hot cracking phenomena in welds II, rozdz. Katgerman L., Eskin D.G.: In search of the prediction of hot cracking in aluminum alloys, Springer 2008.

[15] Herold H. Pchennikov A., Steitenberger: Influence of deformation rate of different test on hot cracking formation, Bollinghaus T., Herold H. Hot cracking phenomena in welds, Springer 2005, p 328-346