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Hot cracking of ZRE1 alloy in constant joint stiffness condition

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Abstract

ZRE1 alloy with addition of Zn, Zr and rare earth elements is gravity casted to sand casting moulds, and is used mainly in aerospace and automotive industries. Magnesium alloy castings often have defects, such as misruns and micro-shrinkage. This defects are repaired with welding and overlay welding techniques. Main practical difficulty during welding of magnesium alloys is their susceptibility to hot cracking in the crystallization process.
The paper intends to evaluate susceptibility of magnesium alloys to hot cracking and examine influence of heat treatment on cracking of the ZRE1 magnesium alloy with addition of zinc and rare earth elements during welding in conditions of constant stiffness. The results of tests of susceptibility to hot cracking of repair welding joints of ZRE1 alloy castings have been described.
The range of research has included the Fisco test and metallographic tests. It has been observed that heat treatment decreases susceptibility of the ZRE1 alloy to hot cracking.

Keywords: casting defects, welding of magnesium alloys, hot cracking, ZRE 1, Fisco test

1. Introduction

Magnesium alloys, as one of the lightest commercially used structural materials, traditionally have been used in automotive industry, aircraft, spacecraft and military applications. Having densities 36% less than Al and 78% less than steel, Mg alloys have excellent strength/weight ratios. The production of magnesium has doubled during the last years and the tendency of growing is still observed.

As an extremely light metal (density 1,74g/cm^3), magnesium alloys have excellent specific strength, excellent sound damping capabilities, good castability, hot formability, excellent machinability, good electromagnetic interference shielding, and recyclability [1, 2]. Unfortunately, magnesium has a number of undesirable properties including poor corrosion resistance, inferior creep resistance and bad plastic processing ability that have hindered its widespread use in many applications [3,4].

Wrought magnesium alloys can be produced by extruding, rolling or forging in the temperature range of 300–500 ◦C. Since wrought semi-finished products are not available at reasonable costs, approximately 85–90% of all magnesium components are manufactured by casting processes.

Though magnesium alloys can be produced by nearly all casting methods such as sand, shell, plaster, semi-permanent, permanent mould, investment, die cast, squeeze, thixocasting and thixomolding, die casting has been the dominant process, constituting approximately 70% of all magnesium castings [5, 6].

Gas porosity, however, has been a main problem for magnesium die casings as a result of high filling rate and quick cooling. Compared with non-vacuum die-castings, vacuum die cast components have less gas inclusions [7]. While die-casting is the dominant process, sand castings of magnesium alloys are also important, especially for aerospace applications [8]. After process casting appear defects (misruns, micro-shrinkage, cracks) in materials. When producing castings of complicated shapes, the defect rate can exceed 50%. These defects are repaired with welding technique.

1.1. Hot cracking of magnesium alloys

Weldability is understood as an ability of welded material to produce joints of required physical properties, capable of

transmitting loads foreseen for a given type of structure. In case of steel, weldability is expressed as resistance to cold cracking. When evaluating weldability of magnesium alloys, their resistance to hot cracking is considered because hot cracking is the most frequent cause of rejection of welding joints of cast magnesium alloys.

During the welding process, solidifying metal is under tensile stresses. Such stresses are generated as a result of restricted shrinkage of the welded joint and uneven heat diffusion by hot material. Under those stresses, the weld material undergoes strain, and when its ability to strain is limited, it cracks [10]. Development of hot cracking in a welded joint is shown in figure 1.

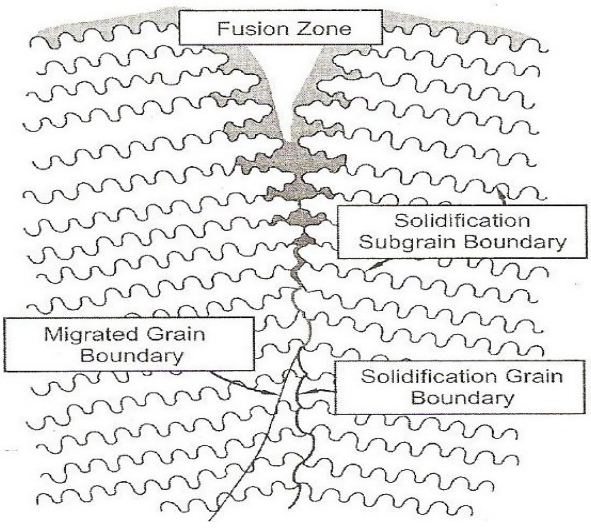


Figure 1. Hot cracking in material [11]

According to the place of occurrence, the hot cracks can be divided into crystallization cracks in the weld joint and segregation cracks in the heat-affected zone and in the welded joint near the fusion line [10].

Susceptibility of material to hot cracking depends on speed of increase of strength and ductility of material in high temperatures and on speed of build-up of stresses [12]. The cracking process during solidification takes place in a so-called range of high-temperature brittleness (ZKW). The upper range corresponds to the NST (Nil Strength Temperature), and the lower range is limited by the DRT, i.e. ductility recovery temperature during cooling [10]. J. F. Lancaster [13] assumes that the upper limit of high-temperature brittleness is coherence temperature, and the lower limit is the NDT (Nil Ductility Temperature). As liquid metal is solidifying, crystals grow and at the coherence temperature they merge creating a not fully solidified mass. E. Tasak [10] called this phenomenon the "bridging" in material. The narrower the high-temperature brittleness range, the lower the material susceptibility to hot cracking.

Hot cracks develop as a result of combined action of: [14]
- significant material shrinkage during solidification,
- low strength and ductility of weld material during solidification,
- presence of low-melt metallic and non-metallic phases and impurities on the border between weld metal and HAZ,
- coarse-grain structure of welded joint and HAZ,
- microsegregation of low-melt phases on the border between weld metal grains and HAZ,
- strong weld stiffness,
- high speed of weld cooling during solidification,
- unfavourable shape of welded joint.

In order to prevent hot cracking, high-purity fillers should be used, welding and strain caused by welding should be limited, low linear energy of welding should be used, and the welding should be performed in narrow beads to limit the growth of grains in weld metal and heat-affected zone [14].

The paper intends to evaluate the susceptibility of the ZRE1 magnesium alloy to hot cracking. In order to provide correct conditions of welding of the magnesium alloy castings, we have used the Fisco test, most frequently used to evaluate the susceptibility of steel welded joints to cold cracking.

2. Research material

We have used the ZRE1 magnesium allow with addition of zinc and rare earth elements. The susceptibility to hot cracking has been evaluated on alloys after casting into sand moulds and after heat treatment. In variant one (OC I), the specimens were preheated to 180 ^{o}C, held for 10 hours, and then cooled in air. Variant two (OC II) involved preheating the specimens to 200 ^{o}C, holding for 16 hours and cooling in air. Chemical composition and properties of the ZRE1 alloy are given in table 1.

Table 1.
Chemical composition and properties of the ZRE1 alloy

Chemical composition, [%]					
	heat	Zn	Zr	RE	other
ZRE1	BS EN 1753	2.0-3.0	0.4-1.0	2.5 - 4.0	-
	20091901	2.8	0.51	2.87	<0.05

Mechanical properties				
ZRE1	R_m [MPa]	R_e [MPa]	A_5 [%]	HV3
	160	110	3	50

Heat treatment		
	OCI	stress relief annealing: 10h/180°C/air
	OCII	stress relief annealing: 16h/200°C/air

Filler metal, chemical composition [%]			
Zn	Zr	RE	Mg
2.5	0.52	3.17	remaining

3. Test methodology and results

The Fisco test involves welding of plates fixed in a special jig (fig. 2). Such arrangement simulates repair welding in the constant stiffness conditions. The tests were performed on the ZRE1 magnesium alloy plates, dimensions 180x90x5 mm, bevelled to "I", "Y", and "V"(fig. 3).

The welding tests were performed on specimens in all states of the material, i.e. as-delivered, after OCI, and after OCII; three specimens for each type of joint. Three single-bead welds were made on each specimen, length 50 mm, gap about 10 mm. The

beads were made from right to left, one directly after the other. Crater pipes were not filled. We used an inverter welder Invertec V270 TP AC/DC. We welded with the 120A alternating current, voltage 13V, TIG method in argon shield. The filler was dia 2.0 mm wire, with chemical composition similar to base metal (table 1). After the welding, the specimens were left in the jig until completely cooled. The criterion for the test was ratio of the hot cracks length to the total length of the weld, expressed in percent. This ratio was called F. The presence of cracks was determined by means of visual inspection, and then after the final breaking of specimens by means of observation of the fractures. Typical welded joints after the Fisco test are shown in figure 4a. The Fisco test results are presented in table 2, and figure 5 shows the values of calculated F ratio.

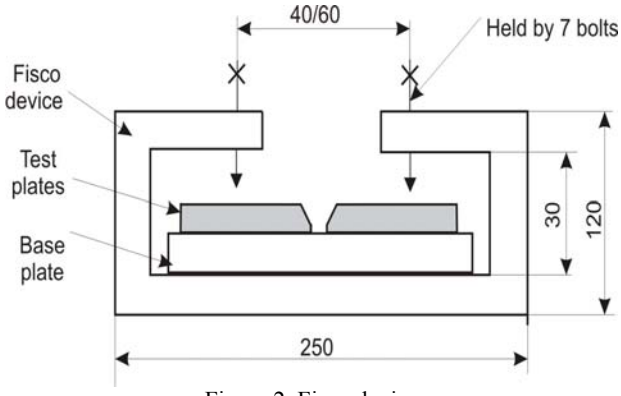


Figure 2. Fisco device

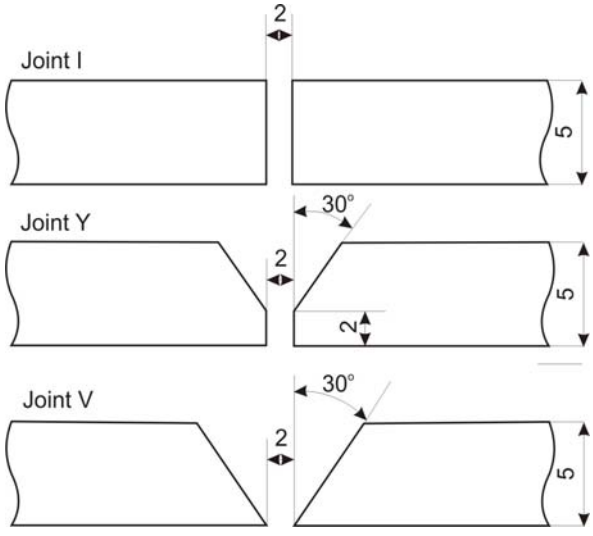


Figure 3. Preparation of plates to the welding

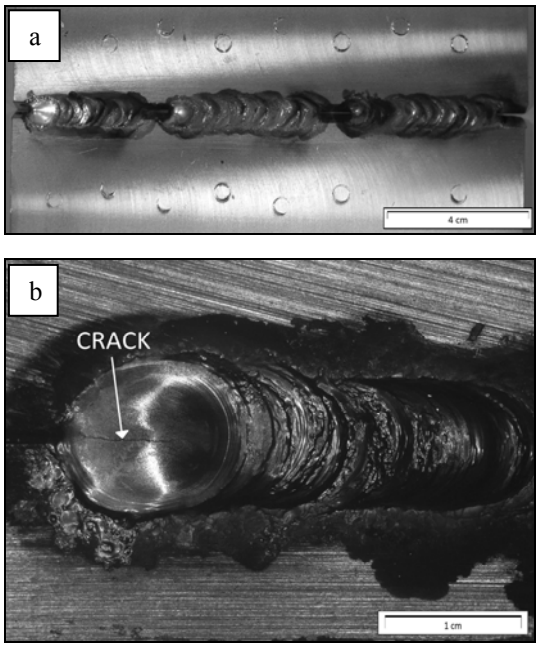


Figure 4. Test specimen after the Fisco test, base metal, TIG welding, welding current 120 A: a) general view, b) crater pipe with visible crack .

Macro- and micrographic tests were performed. The test specimens were cut perpendicularly to the welding direction from the area of discovered hot crack. Metallographic microsections were prepared according to the recommendations of the Struers expert system. After mounting in conductive resins, the specimens were grinded with abrasive papers, and then polished with diamond pastes. Thus prepared metallographic microsections were etched in 3% Nital for 10 s. The macroscopic observations were performed on the Olympus SZX9 stereoscopic microscope, at 20x magnification, using the dark field technique. Figure 4b presents a typical welded joint with visible hot crack in the crater pipe.

Table 2.
Results of the Fisco test to evaluate susceptibility to hot cracking

State of material	Bevelling	Hot crack length, mm		
		Weld 1	Weld 2	Weld
MR	Y	2.3	2.4	0.0.
	V	0.0	0.0	2.7
	II	4.6	0.0.	2.8
OC1	Y	0.0	0.0	2.1
	V	0.0	0.0	0.0
	II	0.0	0.0.	2.7
OC2	Y	0.0	0.0.	3.1
	V	0.0	0.0	0.0
	II	0.0	0.9	0.0

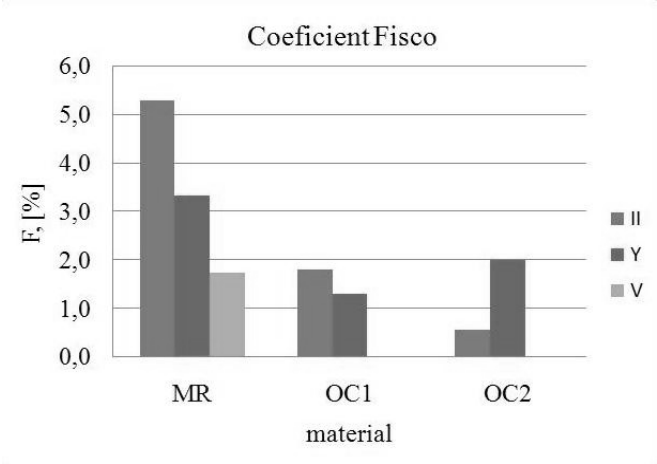


Figure 5. Results of the Fisco test to evaluate susceptibility to hot cracking

The microstructure tests were performed on the Olympus GX-71 optical microscope, in the bright field, magnification from 50 to 500x. The results of the joint structure observations for the material in as-delivered state are presented in figure 6.

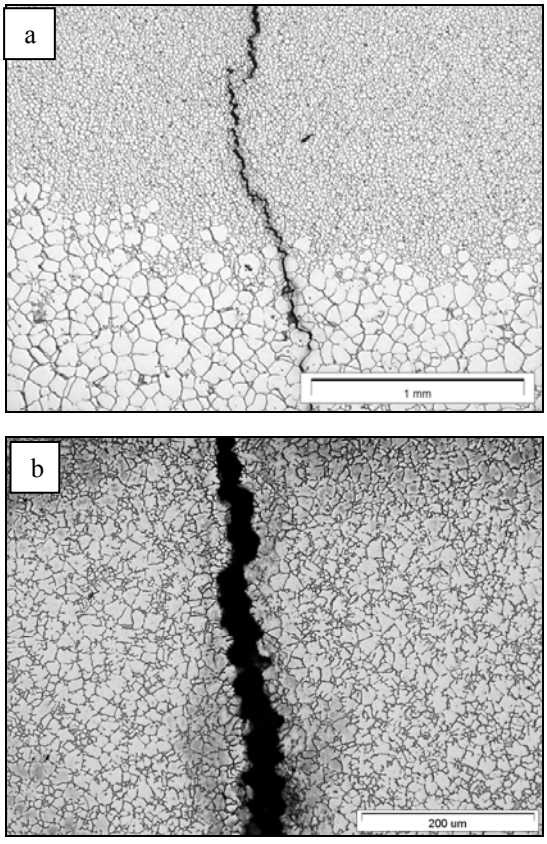


Figure 6. Hot cracks in the weld made on the material in as-delivered state

The analysis of fractures was made on the Hitachi S-3600N electronic scanning microscope, equipped with the system for microanalysis of chemical composition by the EDS method from Noran SYSTEM SIX. The fractures were observed in the technique of recording of secondary electrons (SE) and backscattered electrons (BSE). The SE technique allows observation of the fracture, and the BSE technique allows recording the changes of chemical composition on the surface. Typical images of the fracture surface in the BSE technique are shown in figure 7

Microanalysis of chemical composition was made with the EDS method, at the 15 kV electron acceleration voltage from the areas marked. Results are showed on figure 8.

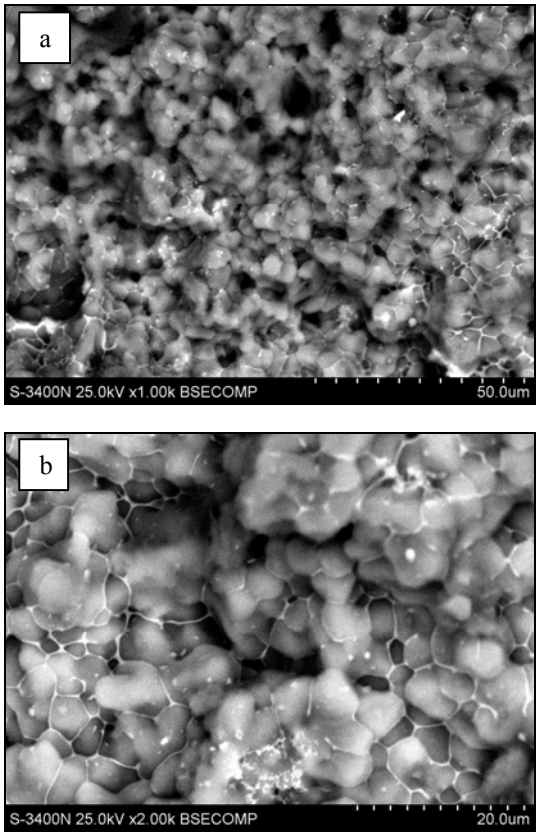
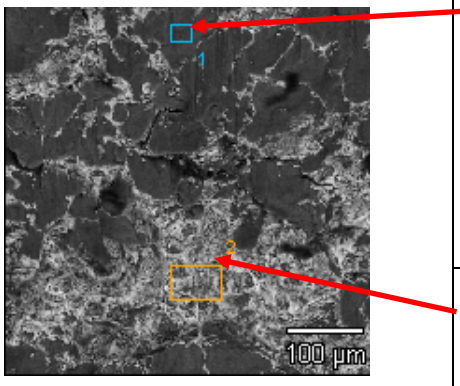
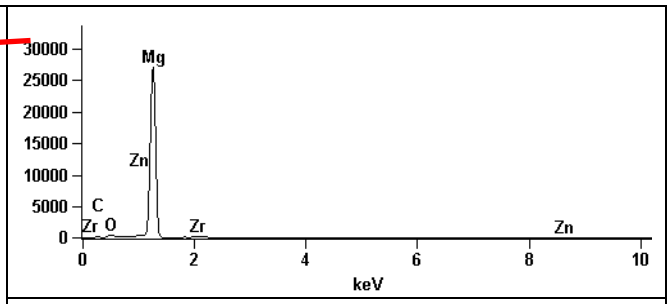
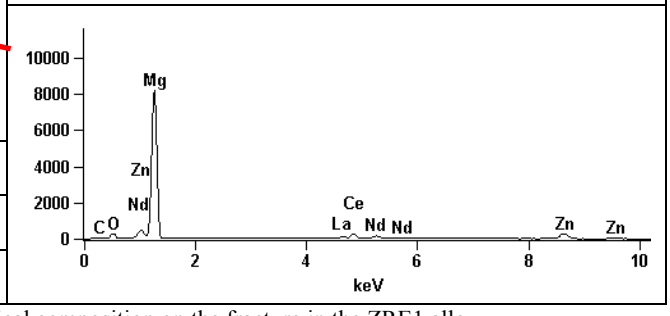


Figure 7. Structure of the crack area in the ZRE1 alloy after the Fisco test a) fracture topography, b) precipitation of phase $(Mg,Zn)_{12}RE$ along the crystals boundaries Mg (α)







% mas.	Mg	Zr	Zn	Ce	La	Nd
1	95.2	1.8	3.0			
2	78.3	11.9		2.5	5.9	1.5

Figure 8. Results of microanalysis of chemical composition on the fracture in the ZRE1 alloy

4. Analysis of results

Susceptibility of the ZRE1 alloy to hot cracking in conditions of constant joint stiffness is one of the indicators of the alloy weldability. The results of Fisco test simulating welding of a strongly stiffened casting indicate that the "I" butt joint of the alloy directly after casting is the most susceptible to hot cracking (F > 5%). Change of the bevelling shape causes reduction of susceptibility to hot cracking (figure 6). The "V" joint is the most resistant to hot cracking in the as-delivered state (F = 1.8%).

Analysis of influence of heat treatment on susceptibility to hot cracking indicates that after stress relief annealing, the ZRE1 alloy is less susceptible to hot cracking than the alloy in the as-delivered state. No hot cracks were found on the "I" welded joints. On the other hand, in case of the "Y" joints, susceptibility to hot cracking is higher after OCI (F=1.8%) in comparison with the joint after OC II (F=0.5%). In case of "V" joints, susceptibility to hot cracking is similar. After OCI the susceptibility to hot cracking ratio is F=1.4%, and after OC II it equals 2.0% (table 5).

Analysis of the structure indicates that the hot cracks found on the microsections are intercrystalline which suggests that they develop in the range of high-temperature brittleness (figure 5). The cracks originate in the welded joint and propagate along the axis towards the heat-affected zone. The Mg(α) solid solution crystals with precipitation of intermetallic phase in interdendritic areas were found on the fracture surface (figure 7). This indicates that the cracks develop as a result of loss of cohesion of the liquid film of chemical composition corresponding to the intermetallic phase in the range of the liquid-solid state of the welded joint (figures 7b and 8)

5. Conclusions

The performed tests and analysis of results allow formulation of the following conclusions:

- Hot cracking of the welds of the ZRE1 alloy develop in the range of coexistence of liquid and solid phases, by tear of the liquid film of chemical composition corresponding the intermetallic phase.
- Heat treatment has an influence on susceptibility of the ZRE1 magnesium alloy to hot cracking. The ZRE1 should be welded after stress relief annealing at 180 ^{o}C for 16 hours. The "I" but joints are the least susceptible to hot cracking in conditions of constant stiffness.
- Determined ratios of susceptibility to hot cracking in conditions of constant stiffness (F) can become a basis for design and welding engineers to develop guidelines for repair of gravity castings of the ZRE1 alloy.

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