DOI: 10.2478/v10172-011-0084-y

A. KIERZEK*, J.ADAMIEC*

EVALUATION OF SUSCEPTIBILITY TO HOT CRACKING OF MAGNESIUM ALLOY JOINTS IN VARIABLE STIFFNESS CONDITION

OCENA SKŁONNOŚCI DO PĘKANIA GORĄCEGO SPOIN NAPRAWCZYCH ODLEWÓW ZE STOPÓW MAGNEZU W WARUNKACH ZMIENNEJ SZTYWNOŚCI

Magnesium alloys, due to their low density and advantageous resistance properties, are being increasingly used in automotive and aircraft industries. It is connected with the desire for vehicles mass lowering and fuel consumption decreasing. One of the development directions of magnesium alloys is the increase of creep resistance, which allows for usage at higher temperatures. The following property is possible to acquire thanks to alloy additions such as: rare-earth elements and zirconium.

Almost 90% of used magnesium alloys are casting alloys: precision castings are most frequently used in automotive industry and gravity ones in aircraft industry. After the process of casting, some defects can be visible in the material, e.g. misruns or microshrinkages, but they are repaired with the use of overlay welding and other welding techniques. The main criteria of magnesium alloys weldability assessment is their susceptibility to hot cracking, which constitute the greatest difficulty during welding, and their overlay welding capacity.

This paper presents the evaluation of the influence of technological factors on magnesium alloys susceptibility to hot cracking. For that purpose, several tests of joint welding in variable stiffness conditions (Houldcroft test) and metallographic examination had been made. The examination was carried out on three magnesium alloys suitable to work at elevated temperatures: ZRE1, WE43 and MSRB and, for comparison, on the most frequently used for gravity castings – AZ91 alloy, in cast state and for two alternatives of heat treatment.

Keywords: weldability of magnesium alloy, brittleness temperature range, hot cracking, repair casting, Houldcroft test

Stopy magnezu, dzięki swojej niskiej gęstości i korzystnym właściwościom wytrzymałościowym znajdują coraz większe zastosowanie w przemyśle motoryzacyjnym i lotniczym. Jest to związane z dążeniem do obniżenia masy pojazdów oraz ze zmniejszeniem zużycia paliwa. Jednym z kierunków rozwoju stopów magnezu jest zwiększenie odporności na pełzanie, co umożliwi stosowanie wyższych temperatur eksploatacji. Właściwość tę uzyskuje się poprzez dodatki stopowe takie jak: pierwiastki ziem rzadkich oraz cyrkon.

Prawie 90% stosowanych stopów magnezu to stopy odlewnicze, po procesie odlewania w materiale mogą pojawić się niedolania i rzadzizny. Wady te naprawiane są z zastosowaniem technik napawania i spawania. W trakcie spawania stopów magnezu wykazują one skłonność do pękania na gorąco. Pęknięcia gorące powstają w zakresie kruchości wysokotemperaturowej. Dlatego też głównym kryterium oceny spawalności stopów magnezu jest ich skłonność do pękania na gorąco.

W pracy przedstawiono ocenę wpływu czynników technologicznych na skłonność do pękania gorącego stopów magnezu. W tym celu przeprowadzono próby spawania w warunkach zmiennej sztywności złącza oraz wykonano badania metalograficzne. Próbę Houldcrofta wykonano na popularnym stopie AZ91 z dodatkiem cynku i aluminium oraz stopach o zwiększonej odporności na pełzanie: ZRE1, WE43 oraz MSRB, dla dwóch wariantów obróbki cieplnej oraz w stanie lanym.

1. Introduction

Magnesium alloys are most frequently used in automotive and aircraft industries. It is due to low density of these alloys at simultaneously advantageous resistance properties. Lowering of vehicles mass is one of the methods of decreasing the emission of gases contributing to greenhouse effect. It is estimated that a car being lighter by 100 kg uses 0,5 liter less fuel per 100 km [1]. In automotive industry, magnesium alloys with the addition of zinc or manganese are commonly used. Development of magnesium alloys allowed for the use of magnesium for elements working at elevated temperatures, such as, among other things, engine casings or a gearbox cas-

* DEPARTMENT OF MATERIALS SCIENCE, FACULTY OF MATERIALS SCIENCE AND METALLURGY, SILESIAN UNIVERSITY OF TECHNOLOGY, 40-019 KATOWICE, 8 KRASIŃSKIEGO STR., POLAND

ings. The addition of rare-earth elements into magnesium alloys caused the increase of creep resistance up to a temperature of 250°C [2].

Almost 90% of used magnesium alloys are casting alloys, which are most often used in gravity casting into sand moulds and pressure casting. Irrespective of a casting method, there are often some defects appearing, e.g. micro-cracks, blisters, misruns and shrinkages. It occurs that almost half of the castings of every batch are defective, therefore, opportunities of repairing them by welding are very important for both producers and customers [3]. The repair welding of castings is also used after operational wear. Fig. 1 presents padding welds in a Porsche gearbox.

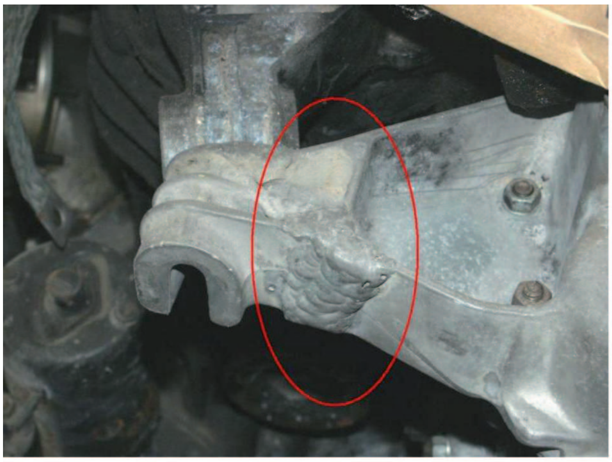


Fig. 1. Magnesium weld sample of a 914 Porsche gearbox

Weldability of magnesium alloys, i.e. the ability to form joints by welding, which would meet their demands and requirements, is defined as a good one only by alloys producers. However, there is lack of weldability research results made by independent centers. Magnesium alloys are most frequently welded by TIG and MIG methods in argon protection, where the TIG method is more advantageous for the sake of more precise adjustment of the applied heat level and the welding puddle shape.

One of the crucial factors influencing magnesium alloys welding and, at the same time, the main difficulty with welding and overlay welding of them, is the susceptibility to hot cracking of magnesium alloys. Those cracks are the results of phenomena present in so-called period of brittleness temperature range (BTR) during crystallization [4]. The upper limit of that range corresponds to nil strength temperature (NST) and the lower limit is ductility recovery temperature (DTR) during cooling. Range of BTR was schematically shown in Fig. 2.

During welding, welding joint area melts, but the process of crystallization starts as a result of cooling. After cooling until NST temperature, grains start to contact with each other, making so-called bridges. These bridges produce liquid responsible for plasticity to flow free with difficulties. Below the NST temperature the fusion weld metal has certain resistance, but the rest of the bridges are not able yet to transfer plastic strain. As a result of further cooling, interdendritic layers solidify, and their resistance increases, enabling the crystals to take over the plastic strain, which occurs in DRT temperature.

Within the BTR during welding, as a result of tearing apart the liquid layer and bridges connecting crystals, some hot cracks may appear. It takes place as a result of shrinkage stresses present on the crystals borders, on which the process of crystallization has not finished so far. Mechanism of hot cracking was shown in Fig. 3.

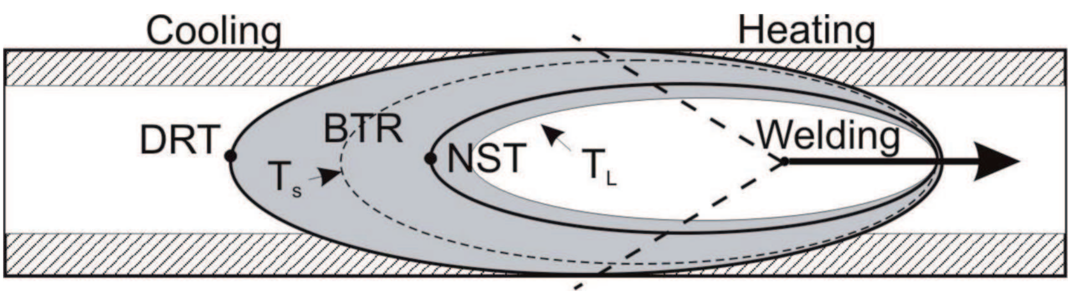


Fig. 2. Model of the scope of high temperature brittleness (BTR) in a welding puddle; NST – nil strength temperature, DRT – ductility recovery temperature [5]

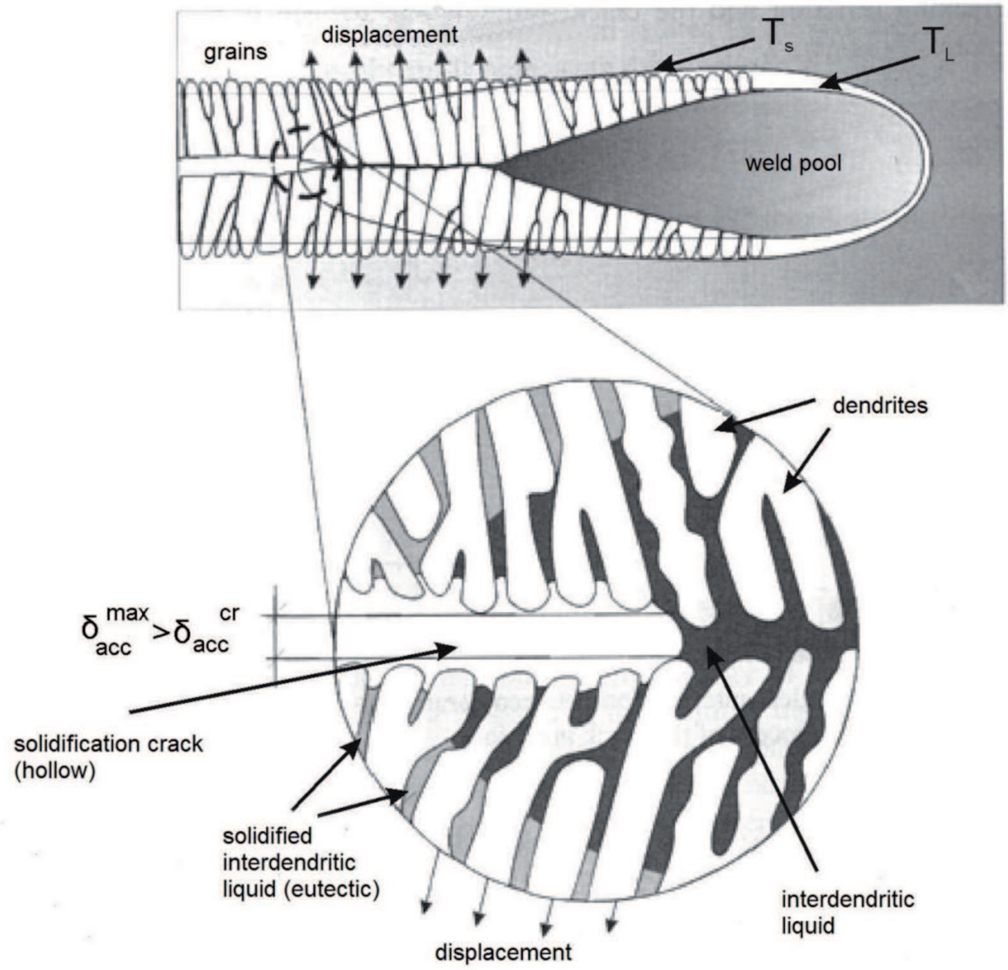


Fig. 3. Mechanism of hot crack formation in a weld; δ_{acc}^{max} – maximum interdendritic fluid displacement, δ_{acc}^{cr} – critical interdendritic fluid displacement without losing cohesion [6]

This paper presents an evaluation of technological factors influencing the susceptibility to hot cracking of magnesium alloys. For that purpose, several tests of joint welding in variable stiffness conditions and metallographic examination had been made. Houldcroft test was carried out on casting magnesium alloys with increased creep resistance: ZRE1,WE43 and MSRB and, for comparison, on the most frequently used for gravity castings – AZ91 alloy, in cast state and for two alternatives of heat treatment.

2. Research material

For the research, magnesium alloys including rare-earth elements were used: ZRE1, WE43 and MSRB, as well as an alloy with the addition of aluminium AZ91. For the assessment of metallurgical, technological and constructional factors influence, alloys in initial state were used, that is after casting into sand moulds in shape of pig and alloys after heat treatment. The chemical composition and mechanical properties of the alloys is compiled in Table 1, while parameters of the heat treatment are shown in Table 2.

TABLE 1

Chemical composition and properties of magnesium alloys

Chemical composition, %											
Alloy	Melt	Al	Zn	Mn	Zr	Y	Nd	RE	Ag	Other	Mg
AZ91	ASTM B80	8.1-9.3	0.4-1.0	0.13-0.35	–	–	–	–	–	–	–
	000810	8.6	0.56	0.21	–	–	–	–	–	< 0.01	Rest
ZRE1	BS EN 1753	2.0-3.0	–	–	0.4-1.0	–	–	2.5-4.5	–	–	–
	20091901	–	2.8	–	0.51	–	–	2.87	–	< 0.05	Rest
WE43	ASTM B80	–	–	–	min. 0.4	3.7-4.3	–	2.4-4.4	–	–	–
	20091842	–	–	–	0.5	3.7	2.-2	–	–	< 0.01	Rest
MSRB	BS EN 1753	–	–	–	0.4-1.0	–	–	2.0-3.0	2.0-3.0	–	–
	4377	–	–	–	0.46	–	–	2.52	2.4	< 0.05	Rest

Mechanical properties				
Alloy	R_m, MPa	R_e, MPa	A_5,%	HV3
AZ91	275	150	1	66
ZRE1	160	110	3	50
WE43	230	178	7	85
MSRB	240	185	2	80

TABLE 2

Heat treatment parameters of magnesium alloy

Alloy	**Alternative**	**Heat treatment**
AZ91E	I	Solid solution: 24h/415°C/air
	II	Solid solution: 24h/415°C/air Ageing: 10h/200°C/air
ZRE1	I	Stress relief annealing: 10h/180°C/air
	II	Stress relief annealing: 16h/200°C/air
WE43	I	Solid solution: 8h/525°C/air
	II	Solid solution: 8h/525°C/air Ageing: 16h/250°C/air
MSR-B	I	Solid solution: 8h/525°C/water 60°C
	II	Solid solution: 8h/525°C/water 60°C Ageing: 16h/250°C/air

AZ91 alloy microstructure consists of a solid solution of aluminum and zinc in α-Mg magnesium and precipitations of $Mg_{17}Al_{12}$ intermetallic phase (Fig.4a). In the ZRE1 alloy, precipitations of the $(Mg,Zn)_{12}RE$ phase are visible at the borders of crystals of solid solution of zinc and rare-earth elements in the α-Mg magnesium (Fig. 4b). During the research of the WE43 alloy with a light microscope there are visible in its structure: the α-Mg solid solution and the [α-Mg + β-$Mg_{12}NdY$] compound eutectic (Fig. 4c). The [α-Mg + β-$(Mg,Ag)_{12}Nd$] eutectic exists at borders of crystals of the α-Mg solid solution in the MSRB alloy (Fig. 4d).

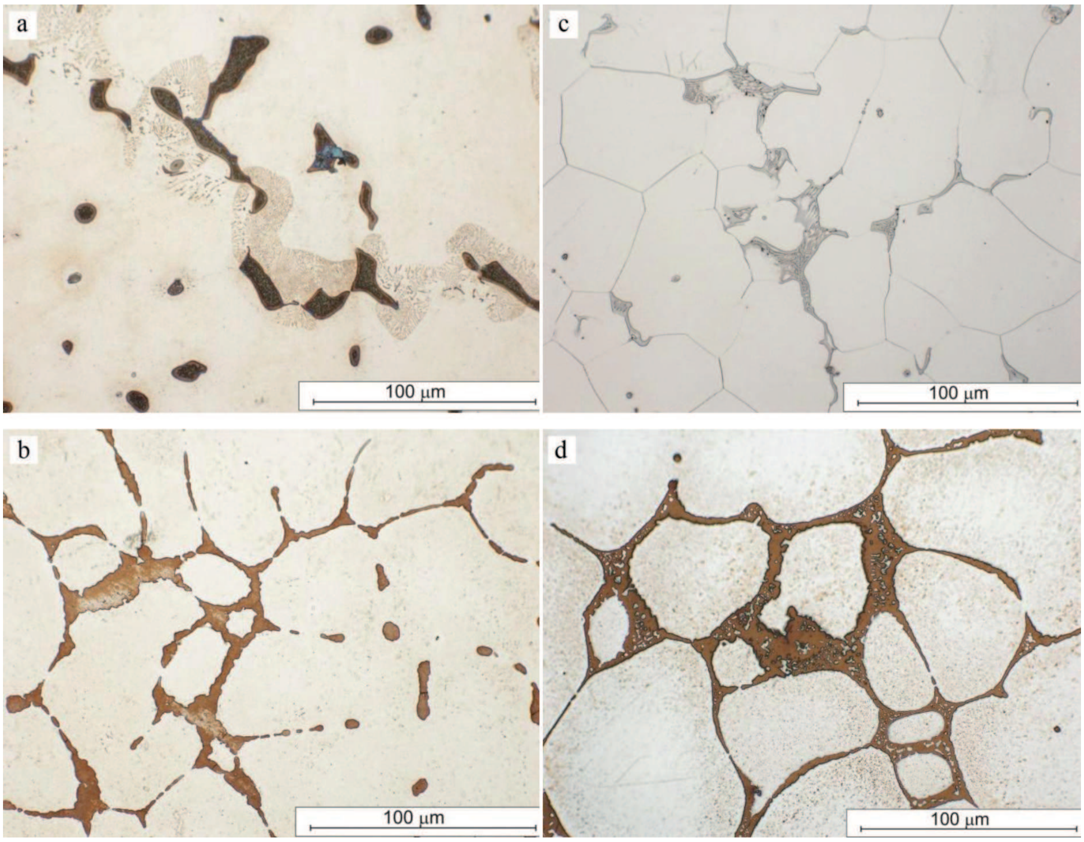
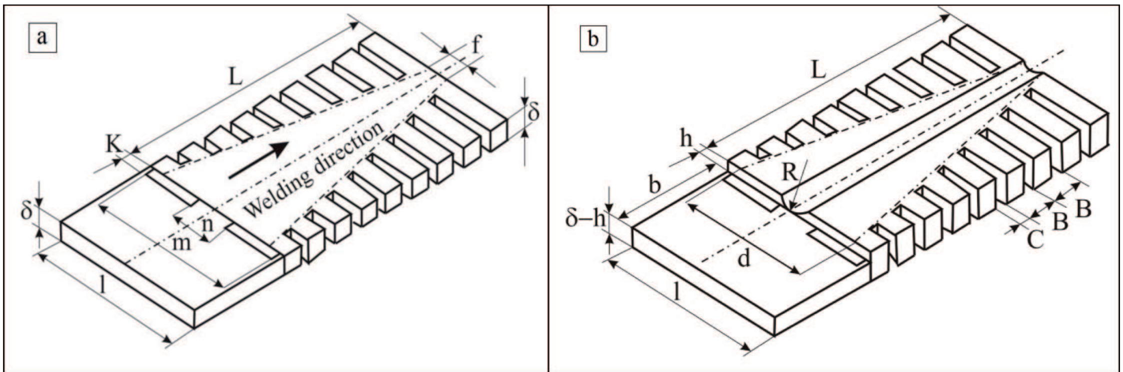


Fig. 4. Microstructure of magnesium alloy in cast state: a) AZ91 alloy, b) ZRE1 alloy, c) WE43 alloy, d) MSRB alloy

3. Evaluation of susceptibility to cracking in variable stiffness conditions – the Houldcroft test

The Houldcroft test was used for an evaluation of susceptibility to hot cracking of magnesium alloys. This test assures welding conditions typical for gravity castings. It also consists in remelting or overlay welding of a sheet metal plate, with indentation at the both sides (Fig. 5). Shrinkage freedom limitation degree decreases from the beginning until the end of the fusion weld due to growing indentations depth . The susceptibility to hot cracking is measured by the length of the fusion weld being cracked.



Sample dimension, mm												
δ	L	l	m	n	K	f	d	B	C	h	R	b
4	131	78	72	26	1	7	64	15	1.6	2	4	44

Fig. 5. Plates for the Houldcroft test: a) remelting, b) padding

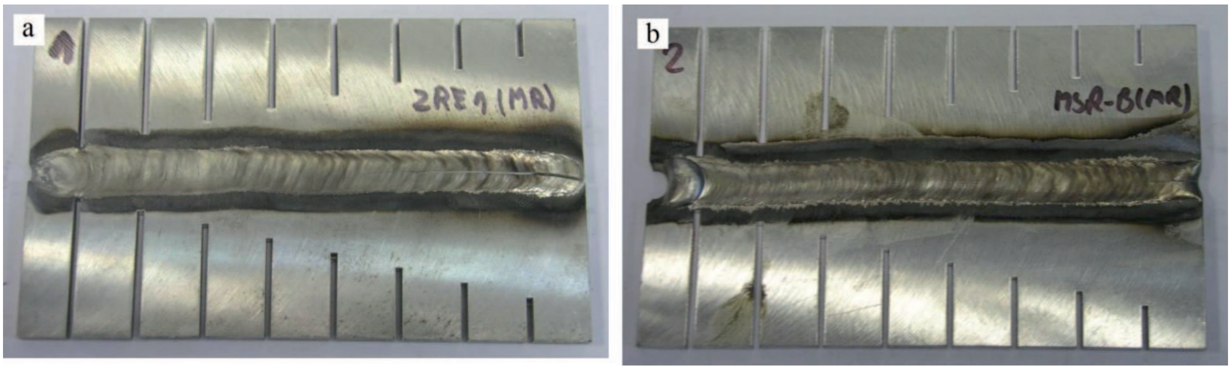


Fig. 6. Plates after Houldcroft test: a) ZRE1 alloy, b) MSRB alloy

The tests of overlay welding and remelting were carried out on sheet metal plates from the AZ91,ZRE1, WE43 and MSRB alloys, with dimensions shown in Fig. 5. Three joint penetrations and three padding welds took place in each alloy, for three stages. The welding was carried out on the V270 TP AC/DC Invertec inverter welding machine, with alternating current of 120 A intensity and voltage of 13 V, by TIG method in argon protection. Additional material were wires of 2,0 mm dimension with chemical compound close to native material. Some sample fusion welds after the Houldcroft test are shown in Fig. 6.

A ratio of fusion weld crack length to the total sample length, expressed in percentage and marked as H, was taken as a criterion of hot crack resistance in the Houldcroft test. An average cracks length of particular joint penetrations and padding welds is shown in Table 3, and Fig. 7 graphically shows the average values of the Houldcroft index.

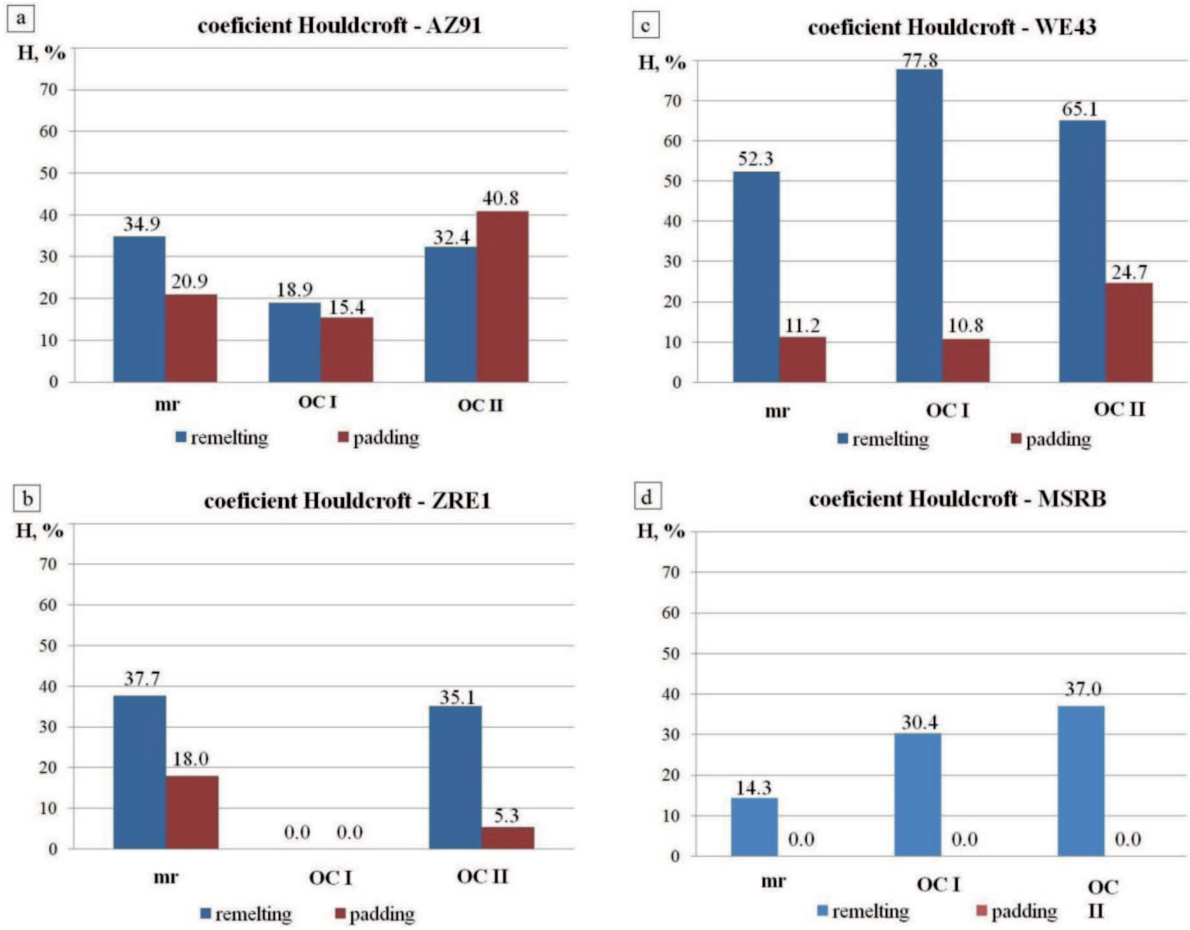


Fig. 7. Results of the Houldcroft test: a) AZ91 alloy, b) ZRE1 alloy, c) WE43 alloy, d) MSRB alloy

Performing Houldcroft test revealed that heat treatment of alloys influences the susceptibility to hot cracking of magnesium alloys (Fig. 7). The highest value of the H index was for the WE43 alloy, remelted after solid solution (H=77.8%), and the lowest one for the ZRE alloy after annealing (10h/180°C/air), where no cracks were stated (H=0%).

4. Metallographic research

Samples for test were cut perpendicularly to welding direction from the area of hot crack being revealed. Metallographic microsections were prepared according to the recommendations of the expert system from the Struers company. The samples were grinded on an abrasive paper after previous mounting in conductive resins, and then were polished with diamond pastes. The metallographic microsections having been prepared this way were etched in 3% Nital (ZRE1) or solution of $15mlHNO_3$+85ml glycol (AZ91,WE43,MSRB) for 10s. The microstructure research was carried out with the Olympys GX-71 light microscope in a light field technology, at a magnification of 50-500x. Results of the joint structure observation for material in delivery state are shown in Fig. 8.

The cracks arisen in the material have an intercrystalline run. They are formed in the fusion weld and they develop in the direction of heat affected zone. Figure 8a and 8b show so-called bridges, characteristic of hot cracks.

The Hitachi S-3600N scanning electron microscope was used for analysis of fractures. Observations of fractures were made in a technology of secondary electrons registration (SE) allowing for observations of the fracture topography. Some pictures of the fracture surface in the BSE technology are shown in Fig. 9.

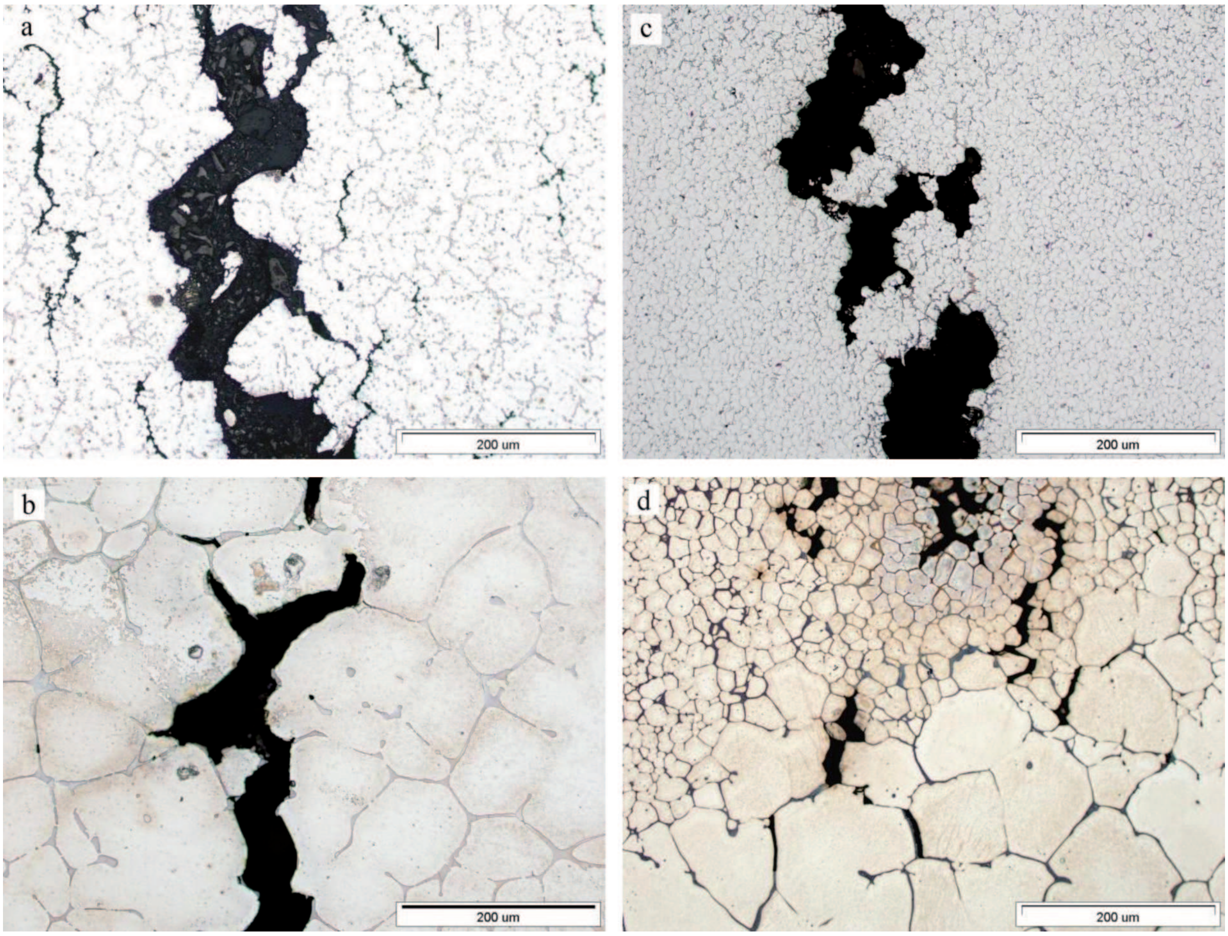


Fig. 8. Hot cracks in magnesium alloy after Huoldcoft test, delivery state: a) a hot crack with visible bridges in AZ91, b) the crack with precipitations of $(Mg,Zn)_{12}RE$ phase in ZRE1, c) a hot crack with visible bridges in WE43, d) a net of hot cracks on the melt-down line in MSRB

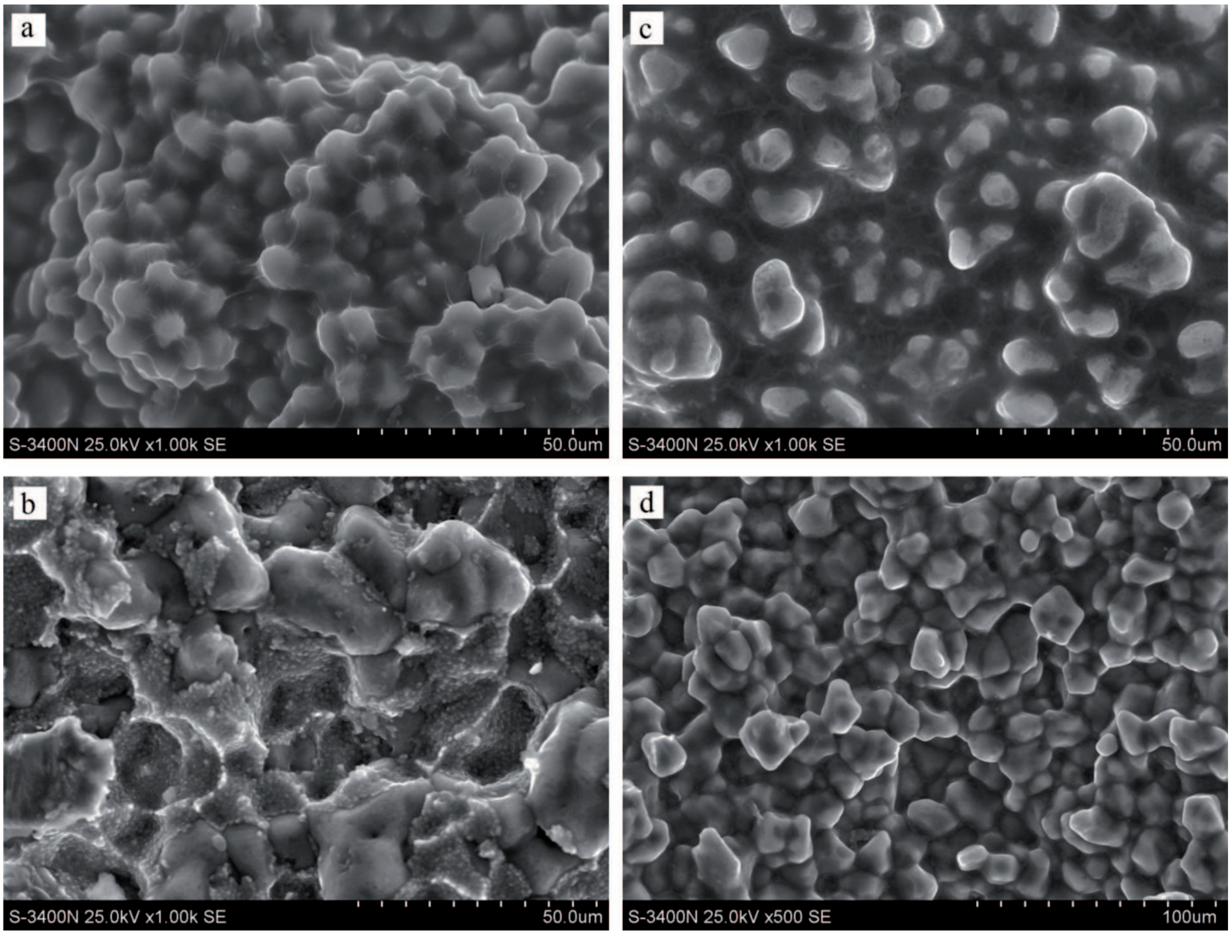


Fig. 9. Structure of the crack area after Houldcroft test: a) surface of AZ91 alloy crack, SE, b) surface of ZRE1 alloy crack, SE, c) surface of WE43 alloy crack, SE, d) surface of MSRB alloy crack, SE

The analysis of fractures of the tested alloys indicates that the alloys reveal their susceptibility to hot cracking. Fig. 9 shows partially melted crystals of solid solution. It is also visible that the fracture has an intercrystalline character.

5. Analysis of results

The Houldcroft test simulating welding in variable stiffness condition joint was carried out for an evaluation of susceptibility to hot cracking of the AZ91, ZRE1, WE43 and MSRB magnesium alloys. Remelting and overlay welding were carried out on material in delivery state and in two variants of heat treatment (Table 2). The H index of hot crack resistance was calculated based on the results achieved in the Houldcroft test. It was stated that the heat treatment of the magnesium alloys influences their susceptibility to hot cracking.

The analysis of the Houldcroft test results of the AZ91 alloy indicates that this alloy is the most susceptible to hot cracking in a state after solid solution and ageing. The H indexes for that state were the highest: H=32.4% for remelting and H=40.8% for overlay by welding. This material is also more inclined to hot cracking during remelting than during welding (Fig. 7a).

Carrying out of the stress relief annealing (10h/180°C/air) of the ZRE1 alloy revealed that it does not show any susceptibility to cracking in the Houldcroft test (H=0%), both in the remelted samples and in those being surfaced by welding. The same operation of the heat treatment was carried out in a temperature of 200°C for 16h, however, it had no significant influence on the ZRE1 alloy test result towards the material being in the delivery state (Fig. 7b).

The lengths of cracks of the WE43 alloy in delivery state are considerably different; the Houldcroft index for the remelted sample was more than 50%, while for the sample being overlay welded, it was at a low level of H=11,18%. Samples after heat treatment revealed some cracks as well, while the samples after solid solution being welded without any additional material indicated the highest susceptibility to cracks: H=77.8% (Fig. 7c).

After overlay welding of the MSRB alloy, both during delivery and in the state after heat treatment, the material did not reveal any cracks (H=0%). The MSRB alloy indicates the greatest susceptibility to hot cracking during remelting after solid solution and ageing, the H index = 37% (Fig. 7d).

Microanalysis of the AZ91 alloy structure on the light microscope revealed that cracks in the fusion weld and heat affected zone run across the grains borders, propagating along the occurrence of $Mg_{17}Al_{12}$ phase (Fig. 8a). The fracture has an intercrystalline character (Fig.9b). Development of hot cracks in the ZRE1 alloy takes place along borders of the α-Mg solid solution along with partial melting of the intermetallic phase $(MgZn)_{12}RE$ (Fig. 8b). In Figure 9b there are visible precipitations of that phase on the fracture surface. So-called bridges (Fig. 8c) are indicative of hot cracking of the WE43 alloy. Those bridges are formed in brittleness temperature range of the material during the coexistence of liquid phase and solid phase and they are a result of crystallization of the residues of the liquid which did not separate itself during the sample strain. Research of the fracture surface of the WE43 alloy with scanning microscope revealed partial meltings of α-Mg crystals on grain borders surface and melting of the intermetallic phase enriched with yttrium and neodymium (Fig. 9c). Observations of the MSRB alloy microstructure revealed hot cracking with visible bridges of a partially separated eutectic α+$(Mg,Ag)_{12}Nd$ (Fig. 8d). The partially melted grains of the solid solution prove that the loss of coherence took place as a result of tearing of a thin layer of the intercrystalline liquid (Fig. 9d). Heat treatment of the magnesium alloys had no influence on the character of cracking of these alloys.

6. Conclusions

Based on the research performance and analysis of the results the following conclusions were formulated:

- The indexes determined in the Houldcroft test allowed to assess the susceptibility to hot cracks of the magnesium alloys being tested. In the AZ91 alloy the lowest H index = 15.4% was determined for the material surfaced by welding in solid solution state. No cracks were stated (H=0.0%) in the ZRE1 alloy after annealing in 180°C for remelted materials surfaced by welding. The H index = 0.0% was also stated for the MSRB alloy being surfaced by welding in delivery state and after heat treatment (Fig. 7). In WE43 alloy, the lowest H index was determined for the material in delivery state.
- Hot cracks of fusion welds from the magnesium alloy are formed in range of coexistence of the liquid phase and the solid phase by tearing of a liquid layer with chemical composition corresponding to intermetallic phase. The loss of coherence is caused by joint strain as a result of shrinkage during crystallization. The cracks are formed in the fusion weld and develop towards the heat–affected zone. The analysis of the surface fractures of the tested alloys indicates that the cracks have an intercrystalline run. It proves that they are hot cracks (Fig. 8 and 9).
- The influence of heat treatment on susceptibility to hot cracking of the magnesium alloys was determined. The AZ91 alloy should be welded after solid solution, the ZRE1 alloy after stress relief annealing, the WE43 alloy after solid solution and ageing and the MSRB alloy during delivery.

Received: 10 February 2011.

Acknowledgements

This paper was financed by the Ministry of Science and Higher Education as the 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] E. Aghion, B. Bronfin, D. Eliezer, The role of magnesium industry in protecting the environment, Journal of Materials Processing Technology **117**, 381-385 (2001).

[2] H.E. Friedrich, B.L. Mordike, Magnesium Technology: metallurgy, design, data, applications, Springer-Verlag Berlin Heidelberg, 2006.

[3] J. Adamiec, A. Kierzek, Influence of heat treatment on susceptibility to hot cracking of magnesium alloy EN-MCMgRE3Zn2Zr, Archives of Metallurgy and Materials **55**, 1 (2010).

[4] J. Tasak, A. Ziewiec, Spawalność materiałów konstrukcyjnych, tom1 Spawalność stali, Wydawnictwo JAK, 2009.

[5] H. Herold, A. Pchenikov, M. Steitenberger, Influence of deformation rate of different test on hot cracking formation, Bollinghaus T., Herold H. Hot cracking phenomena in welds II, Springer, 328-346 (2005).

[6] Ploshikhin V., Prikhodovsky i in.: Integrated mechanical-metallurgical approach to modeling of solidification cracking in welds, Bollinghaus T., Herold H. Hot cracking phenomena in welds, Springer, 223-244 (2005).