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EVALUATION OF SUSCEPTIBILITY TO HOT CRACKING OF WE43 MAGNESIUM ALLOY WELDS IN TRANSVARESTRAINT TEST

OCENA SKŁONNOŚCI DO PĘKANIA GORĄCEGO SPOIN ZE STOPU MAGNEZU WE43 W PRÓBIE TRANSVARESTRAINT

In castings of magnesium alloys defects or inconsistencies often appear (like casting misrun, porosities and cracks) particularly in the huge dimensional castings. Such defects are mended with the use of padding and welding. The welding techniques can be applied by using weld material consisting of magnesium alloy, as well as for regeneration of alloys after excessive wear. Nevertheless, the number of the repaired castings, which were permitted for use, is not satisfactory for a profitable production. The main reasons for wear are the cracks appearing during welding in brittleness high-temperature range.

This work in combination with industrial tests of casting welding shows that the causes of high-temperature brittleness are the partial tears of the structure and the hot cracks of both the castings and the welded and padded joints. Such phenomena should be treated as irreversible failures caused by the process of crystallisation that is in the area of co-existence of the solid and liquid structural constituent. The assessment of the resistance to hot fractures was conducted on the basis of the transvarestriant trial. The transvarestriant trial consists of changing the strain during welding. It was stated that the range of the high-temperature brittleness is very broad, which significantly limits the application of the welding techniques to join or mend the elements made of alloy WE43. The brittleness is caused mainly by metallurgical factors, i.e., precipitation of inter-metal phases from the solid solution.

Keywords: magnesium, WE43 magnesium alloy, hot cracking, transvarestraint test

W odlewnictwie stopów magnezu często występują wady oraz niezgodności odlewnicze (np.: niedolewy, porowatość oraz pęknięcia), szczególnie przy odlewaniu elementów wielkogabarytowych. Takie wadą są naprawiane poprzez napawanie oraz spawanie. Technologie te można zastosować zarówno do naprawy nowych odlewów, jak i do regeneracji nadmiernie zużytych elementów. Niemniej jednak liczba naprawionych odlewów, które zostały dopuszczone do użytku nie jest satysfakcjonująca dla opłacalnej produkcji. Główną przyczyna zużycia są pęknięcia powstające podczas spawania w zakresie kruchości wysokotemperaturowej.

Niniejsza praca, w połączeniu z próbami technologicznymi spawanych odlewów pokazuje, że przyczyną pęknięć w zakresie kruchości wysokotemperaturowej jest częściowe rozerwanie struktury i pęknięcia gorące w odlewach oraz złączach spawanych i napawanych. Takie zjawisko powinno być traktowane jako nieodwracalne uszkodzenie spowodowane procesem krystalizacji obszarów współistnienia fazy stałej i ciekłej.

Do oceny odporności na pękanie gorące wykorzystano próbę transvarestraint. Polega ona na zmianie odkształcenia podczas spawania. Stwierdzone zostało, że szerokość zakresu kruchości wysokotemperaturowej jest bardzo duża, co znacząco ogranicza zastosowanie technik spawalniczych do łączenia oraz naprawy elementów wykonanych ze stopu magnezu WE43. Kruchość jest spowodowana gównie przez czynniki metalurgiczne, np.: wydzielanie się fazy międzymetalicznej z roztworu stałego.

1. Introduction

Hot cracks are the final effect of the high-temperature brittleness phenomenon and should be treated as irreversible failures caused during crystallisation process, which is co-existence of the liquid and solid phase. Such cracks can appear in casts, in weld and in the heat affected zone (HAZ) of the welded joint in some temperature range called brittleness temperature range (BTR)[1-4].

Hot cracks most often have intercrystalline character and the decrease in metal plasticity in brittleness temperature range is considered the basic reason of their formation. It may be caused by the decrease of the resistance of the grain boundaries areas as a result of the presence of a fusible film of liquid or concentration of

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big amount of crystalline network defects in those areas. Thin liquid film is present in the grain boundaries areas of the solid stage in the last phase of solidification or, as a result of partial melting of those areas in the metal heating process, in solid state. In both of those cases the temperature of the liquid state is lower than the temperature of the solidus of the alloy. The deformations by which the metal is affected in BTR are considered the second reason of hot cracks formation [1-4].

It was stated in paper [1] that the upper limit of the brittleness temperature range is near the liquidus temperature (T_l), where the mutual interactions between crystals begin. In tests conducted by Eskin [2] and Tasak [4], however, the nil-strength temperature (NST) is considered the upper limit of BTR. It is a temperature marked during heating in which the material resistance drops to zero. When close to that temperature and above it, the material is not able to transfer load [1,4,5]. Lower limit of BTR is near the solidus temperature (T_s). The material ductility recovery temperature DRT is considered the lower limit of BTR [4,5]. In technological transvarestriant trial the temperature of the end of crack (T_k) is assumed as the lower limit of the BTR [1,4,5].

Hot cracks can be divided into three types [1,4]:

- crystallizing – forming in the process of material solidification as the effect of the residual liquid film separation in the area of grain boundaries,
- segregating – forming as a result of partial melting of the grain boundaries in the solid stage. They form in the heat affected zone (HAZ) of the base material or in the multi-layer welds as the effect of putting on the next layers,
- polygonisation type – forming in solid phase as a result of material ductility decrease in solid state, which is caused by the accumulation of significant amount of crystalline network defects (vacancies and dislocations) in the solidification process of metal in weld and the later movement and accumulation of those defects in positions of higher energetic stability. As a result of condensation of those defects micro-pores, which with the presence of stresses and lost motion on the grain boundaries grow in size and thus become the nucleuses of cracks in solid phase.

Hot cracks may be prevented in a metallurgical, technological and constructional way. Metallurgic methods consist of changes in chemical composition of the base material and the filler in order to limit the amount of alloy elements and impurities which influence the formulation of the fusible eutectics and, also, in order to achieve the maximally refinemented primary structure of the solidifying alloy.

Technological methods consist of: the proper shaping of the edges of the joined elements and steering the welding parameters in order to get the right shape of the weld pool and the weld, introducing the limited amount of heat and hence the beneficial distribution of the deformation in the metal solidification area in the weld pool, limiting the time the metal of the weld and the heat affected zone HAZ stays in BTR. Constructional methods consist of the right configuration of the construction and elements in order to limit the inner stresses size generated by the welding process [1-4].

2. Test material

Alloy WE43 including yttrium, rare earth elements and zirconium was used in tests. Chemical composition and mechanical properties of WE43 alloy are presented in table 1.

TABLE 1
Chemical composition and the mechanical properties of the WE43 alloy

Chemical composition (%)				
Mg	Y	Nd	Zr	Other
residue	3,7	2,2	0,5	< 0,01
Mechanical properties				
R_e (MPa)		R_m (MPa)	A_5 (%)	HV3
178		250	7	85 - 105

3. Methodology and results of tests

3.1. Marking the characteristic temperatures for crystallisation and melting of WE43 alloy

Temperatures characteristic for crystallisation and melting of the tested alloy, which are the temperatures of the beginning and the end of crystallisation and melting of the eutectics, intermetallic phases and the solid solution of Mg (α), were defined with the use of differential thermal analysis (DTA). The tests were executed using a thermal analysis device SETSYS manufactured by Setaram company with the use of TG-DTA head. The system enables the measurement of the heat flow by phase transitions connected with melting and crystallisation of the tested alloy. Temperature measurements of the beginning and end of the transition were conducted with the use of one set point method. The results of the experiment and measurement results were confronted in table 2, and the DTA curves by heating and cooling are presented in fig. 1.

TABLE 2

Heating and cooling conditions during differential thermal analysis for WE43 alloy

	Heating temperature (°C)	heating speed/cooling speed (°C/min)	Atmosphere (%)	Gas flow speed (l/h)	Type of thermoelement in furnace
	750	10	Ar 99,999	1,45	type S (Pt-Rh 10%)
Heating	Temperature of the melting beginning of the intermetallic phase (°C)	Temperature of the melting end of the intermetallic phase (°C)	Temperature of the melting beginning of solid solution Mg(α) (°C)	Temperature of liquidus (°C)	
	573	589	603	699	
Cooling	Temperature of the crystallisation beginning of solid solution Mg(α) (°C)	Temperature of the crystallisation end of solid solution Mg(α) (°C)	Temperature of the crystallisation beginning of intermetallic phase Mg(α) (°C)	Temperature of solidus (°C)	
	661	596	552	535	

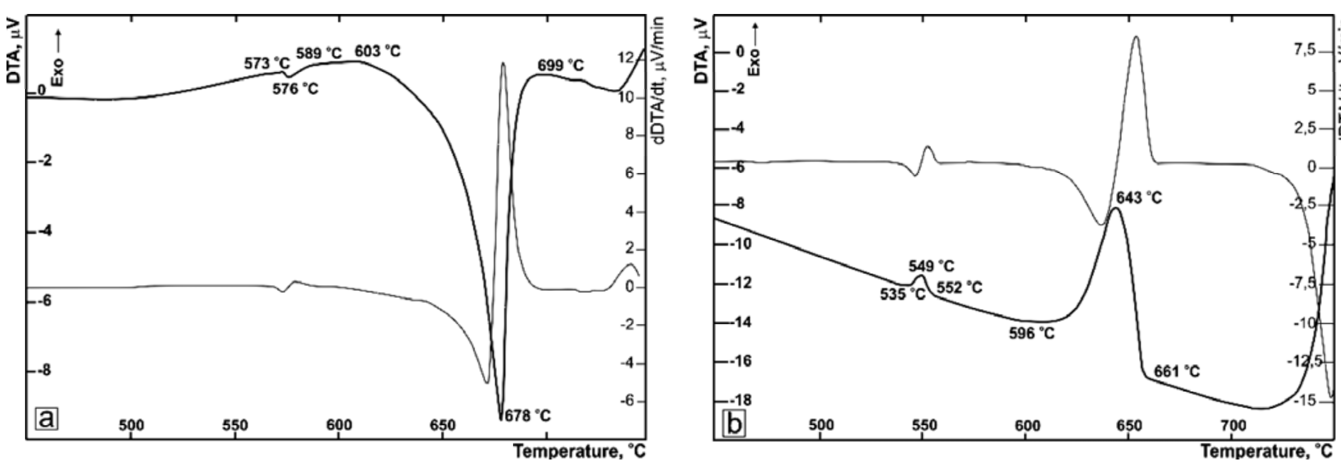


Fig. 1. DTA curves during heating (a) and cooling (b) for WE43 alloy

During heating of WE43 alloy the eutectic [Mg(α) + β($Mg_{12}NdY$)] melts in temperature range from 573 °C to 589 °C. The dendrites of the solid solution begin to melt partially in temperature of 603 °C. Liquidus temperature equals 699 °oC (fig. 1a). During cooling the dendrites of the solid solution begin to crystallise in temperature of 661 °C and grow to the temperature of 596 °C. Liquid between dendrites crystallises in the eutectic form in temperature range from 552 °C to 535 °C (Fig 1b).

3.2. Simulation of the heat affected zone – defining the heat cycle

In order to evaluate the behaviour of the alloy in brittleness temperature range during welding the heat cycle was defined, which are the temperature changes of particular points during cooling of the alloy from the temperature close to solidus temperature. Test was conducted on cylindrical samples size Ø 10 x 120mm, on Gleeble 3800 simulator, in Institute for Ferrous Metallurgy in Gliwice. Four thermocouples type S were bonded with the samples: in the weld axis (TC1) and in the distance of 2 (TC2), 5 (TC3) and 8 mm (TC4) from the weld axis. Samples, after fixing them in copper fixtures, keeping the constant distance of 33 mm, were being heated in argon atmosphere with the speed of 20 °C/s up to the temperature when the liquid stage appeared and then they were freely cooled. During the experiment the temperature changes were being registered in particular points of HAZ. On the basis of the results the equation was created, describing the temperature change during cooling of samples. Results for thermocouple on fusion line and equation of temperature change in time function are presented in fig.2. Conducted test, simulating temperature distribution in WE43 alloy during cooling, show that this distribution is the polynomial of second degree (Fig.2).

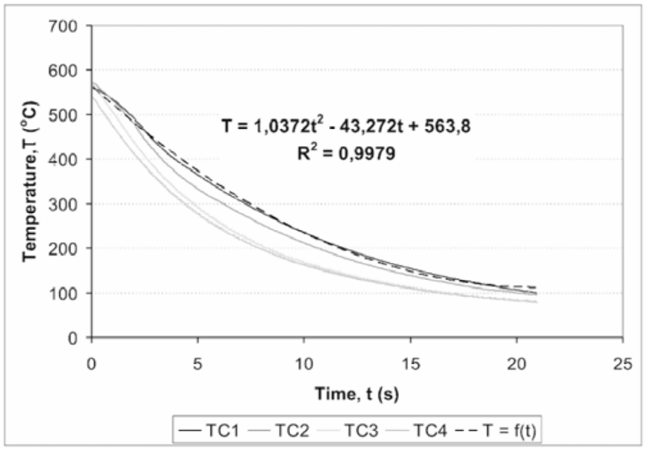


Fig. 2. Heat cycle marked for point on the line of fusion for WE43 alloy (TC1, TC2, TC3, TC4 – marking of thermocouple)

4. Marking the nil-strength temperature NST

In order to define the nil-strength temperature of the alloy during heating, the test was conducted on cylindrical samples size Ø 6 x 90 mm on Gleeble 3800 simulator. Thermocouples of type S were bonded with the samples, and next these were fixed with the use of copper fixtures in the chamber of the device. The constant distance of 52,4 mm between the fixtures was maintained. The chamber, after removal of air, was filled with argon (to 0,14 hPa). Next, a minimum preload of 0,6-0,7 kN was applied, which was maintained through the whole test. Next, the test samples were heated to 400 °C at the rate of 20 °C/s, and then at the rate of 1 °C/s. The NST was determined as the temperature, at which cracks appeared. The temperature for WE43 alloy is 568 °C. The microstructure of the crack area found on perpendicular microsection to the surface of fracture and the fracture surface are shown in figures 3.

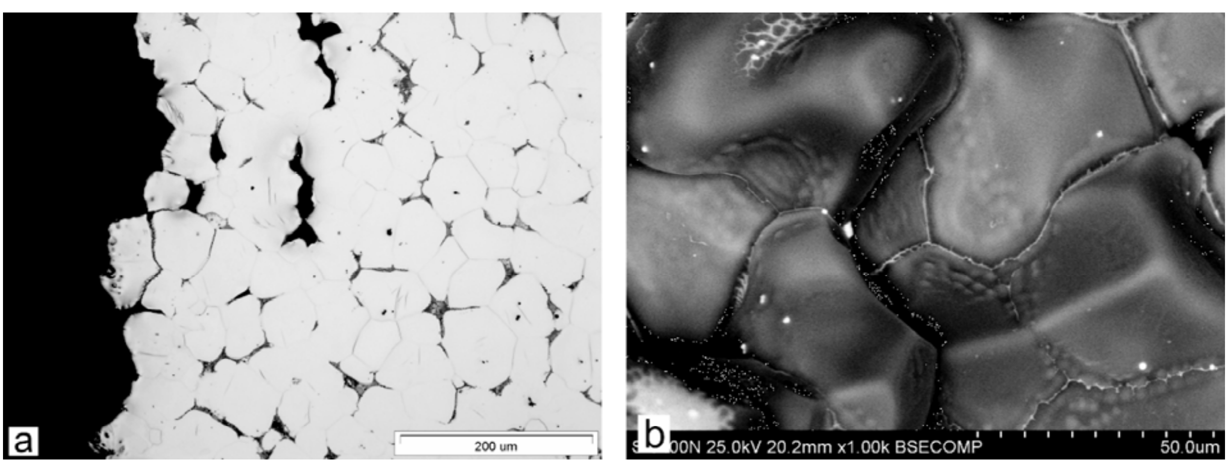


Fig. 3. Structure of the crack area for WE43 alloy after NST test: a) microstructure of perpendicular area to the alloy fracture with micro-cracks in the area of eutectic, b) alloy fracture surface with visible areas enriched in Nd and Y

It was found that the crack runs in the form of a network on the boundaries of the solid solution crystals (*alpha*) in melted eutectic [Mg(α) + β(Mg12NdY)] (fig. 3a). The topography of the fracture, on which the intercrystalline cracks appear, serves as a confirmation of that statement (Fig.3b).

4.1. Marking the nil-ductility temperature (NDT), ductility recovery temperature (DRT), brittleness temperature range (BTR) and coefficient of crack resistance R_f

In order to assess the size of BTR and to define the structure influence on the mechanism of hot cracks the nil-ductility temperature during heating was marked (NDT) and the ductility recovery temperature during cooling (DRT) was found. NDT temperature was assumed as temperature for which the necking of the sample is less than 3%, whereas the DRT temperature is the temperature for the necking above 3%.

Tests were conducted on Gleeble 3800 device. Samples of cylindrical shape size Ø 10 x 120 mm were placed in the protective argon atmosphere and fixed in copper fixtures. In order to mark the NDT of a sample, it was heated to given temperature in brittleness temperature range but below the NST temperature and soaked for 5 s, and next stretched with fixed, constant speed of 20 mm/s (fig. 4a). Ductility recovery temperature DRT was marked during cooling of samples from temperature close to NST to a given temperature value and next strained with constant speed of 20 mm/s (fig. 4b). Experiment results and the calculations are presented in table 3.

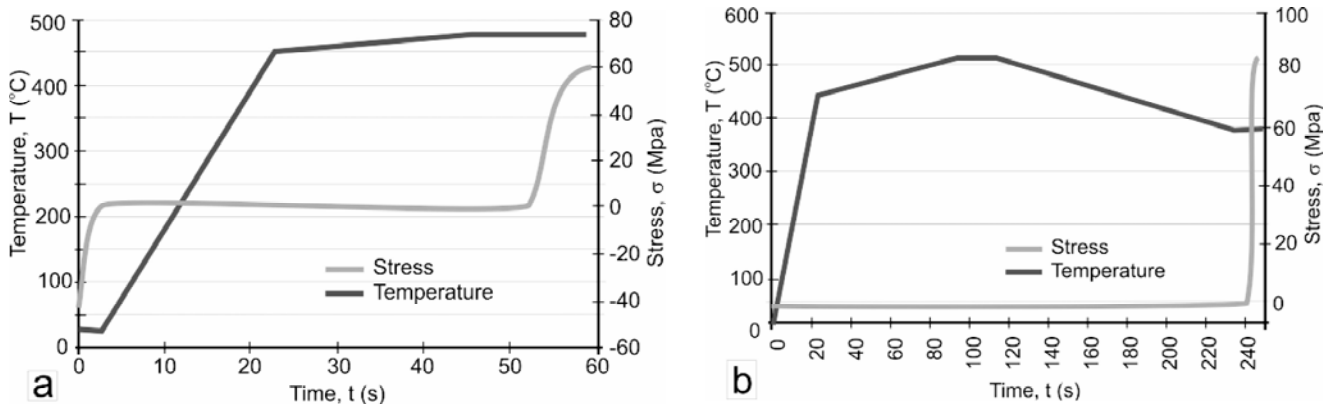


Fig. 4. Change of temperature and stress in a sample for alloy MSRB: a) NDT test, b) DRT test

TABLE 3
Results of NDT and DRT tests for WE43 alloy in delivery state

Alloy	NDT (°C)	DRT (°C)	R_f	BTR (°C)	ΔBTR (°C)
WE43	530	515	0,32	568-515	53

where: NDT - nil-ductility temperature, Rf - coefficient of resistance to hot cracking, DRT - ductility recovery temperature, BTR - brittleness temperature range understood as the diffe- temperature range

4.2. Technological transvarestriant trial

In order to assess the susceptibility of welds of WE43 alloy to hot cracking the technological transvarestriant trial was conducted. It consists of fast bending of the tested samples on a cylindrical die block during weld penetration with the use of electric arc in inactive gas shroud (TIG method). The size of the strain is dependent on the thickness of the bended sample (g) and on the radius of the die block curvature (R) (bending arbor). The schematic representation of the trial is presented in fig. 5.

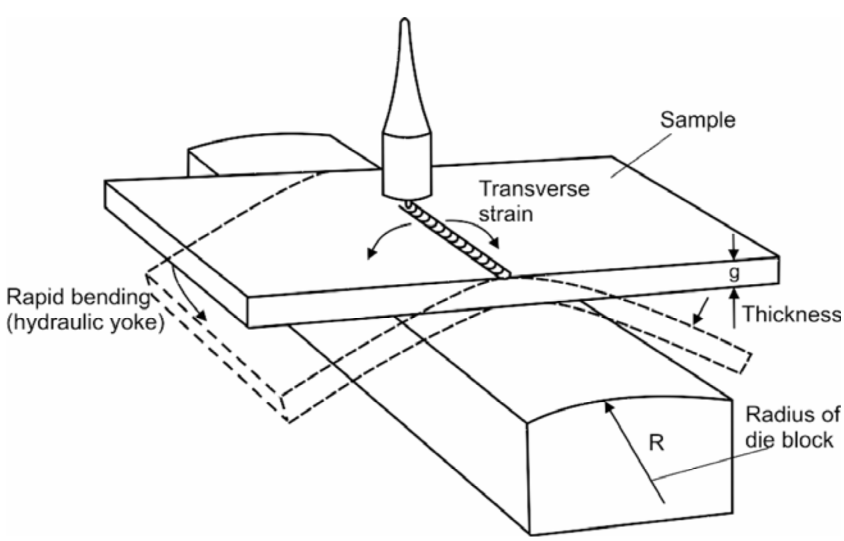


Fig. 5. Schematic representation of the transvarestriant trial [1]

Transvarestriant trial was conducted on a stand designed and built in Faculty of Materials Science of Silesian University of Technology. It is equipped with the hydraulic strain system and welding machine Lincoln V205 AC/DC. The stand also has a set of bending arbors with the following radii of curvature: 50, 100, 150, 200, 224 and 324 mm. Test was conducted on plates size 120 mm x 90 mm x 5 mm. Parameters of the process of weld penetration were chosen in such a way, so that full weld penetration was possible. The weld penetration was conducted in argon shroud with the use of alternating current with intensity of 150 A. The weld penetration speed was 1,2 mm/s. During weld penetration, welding with changeable rigidity of welding joint was simulated. In the trial the following were marked: the length of the longest crack in weld axis (L_{max}), sum of lengths of all cracks (L_{imax}) and the threshold of cracking (εp) as the strain, by which the hot cracking does not appear. The results of the measurements and the calculations are presented in table 4.

TABLE 4

Specification of the measurements and calculations results for cracks appearing in transvarestraint trial, the measuring error did not exceed 5%

Sample	Arbor radius R (mm)	Welding speed v_s (mm/s)	Longest crack Li_{max} (mm)	Sum of all cracks lengths ΣLi (mm)	Time of crack development t_{max} (s)	Size of strain ε (%)	Remarks
E0	0	1,20	lack	lack	lack	lack	no crack
E1	324	1,20	1,18	1,18	0,98	0,77 (> ε_p)	cracks
E2	224	1,20	2,35	3,24	1,96	1,12	cracks
E3	200	1,20	4,15	11,40	3,46	1,25	cracks
E4	150	1,20	4,35	8,27	3,63	1,67	cracks
E5	100	1,20	4,56	14,43	3,80	2,50	cracks
E6	50	1,20	4,84	13,11	4,03	5,00	cracks

4.3. Metallographic research

External visual examination and macro-graphic tests were conducted on stereoscopic microscope Olympus SZX9 with magnifications up to 10x. Example results of observations are shown in fig. 6. To test microstructure, the observations in bright field of the light microscope Olympus GX71 were used, with magnifications up to 500x (Fig. 7a,b). Fractures tests were conducted on electron scanning microscope Hitachi S-3400 with the use of secondary electrons SE detection technique and back-scattered electrons BSE detection technique. The SE pictures show the topography of the fracture clearly, whereas BSE pictures show the differences in chemical composition. Observation results are shown in fig. 7 c,d. The microanalysis of the chemical composition of the extractions in weld with the use of EDS evolution was conducted to supplement the research (Fig.8).

5. Analysis of results

In this paper the temperatures characteristic for WE43 alloy were marked during cooling and heating with the use of differential thermal analysis DTA (Fig.1). Real solidus temperature equals 535 °C, and liquidus 699 °C (table 2, Fig. 1). Heat cycle, marked to supplement the characteristics of alloy in high temperatures, becomes square polynomial (Fig. 2).

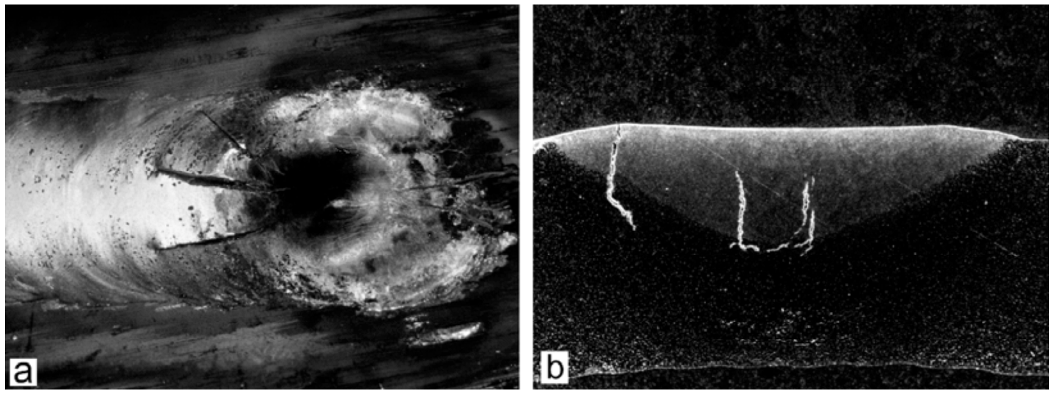


Fig. 6. Results of macroscopic tests: a) cracked face of weld penetration after transvarestraint test, sample E6, magnification 4x, b) macrostructure of weld penetration after transvarestraint test with visible cracks, magnification 6x

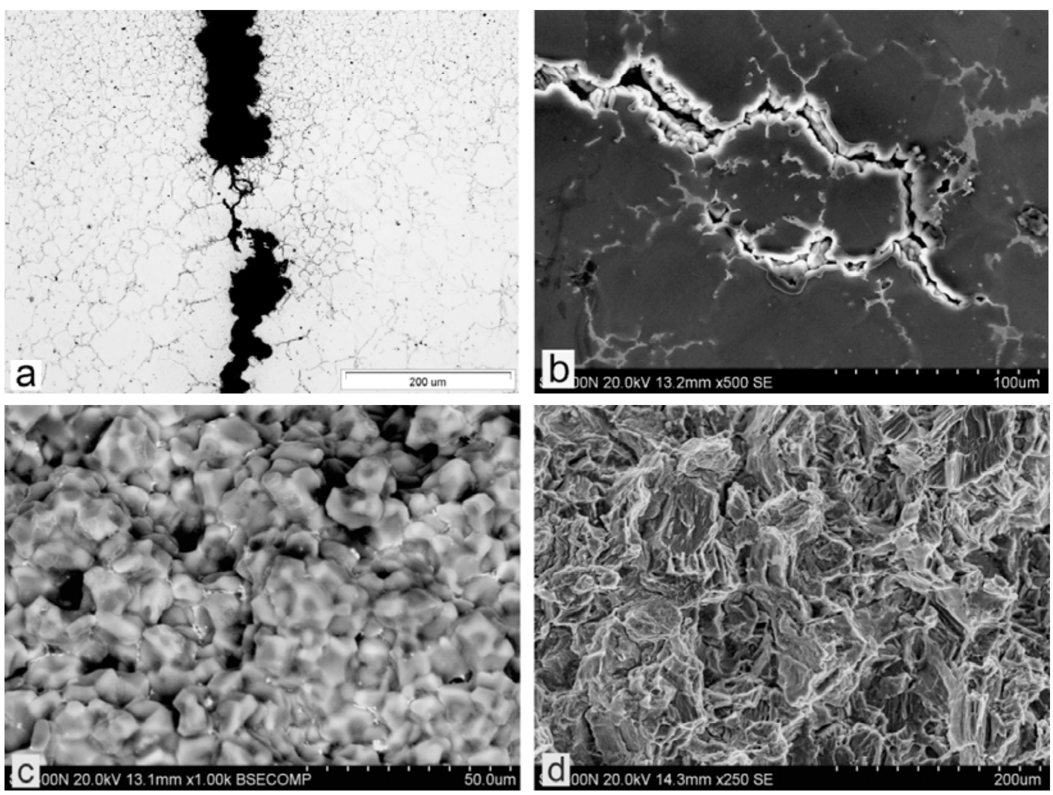
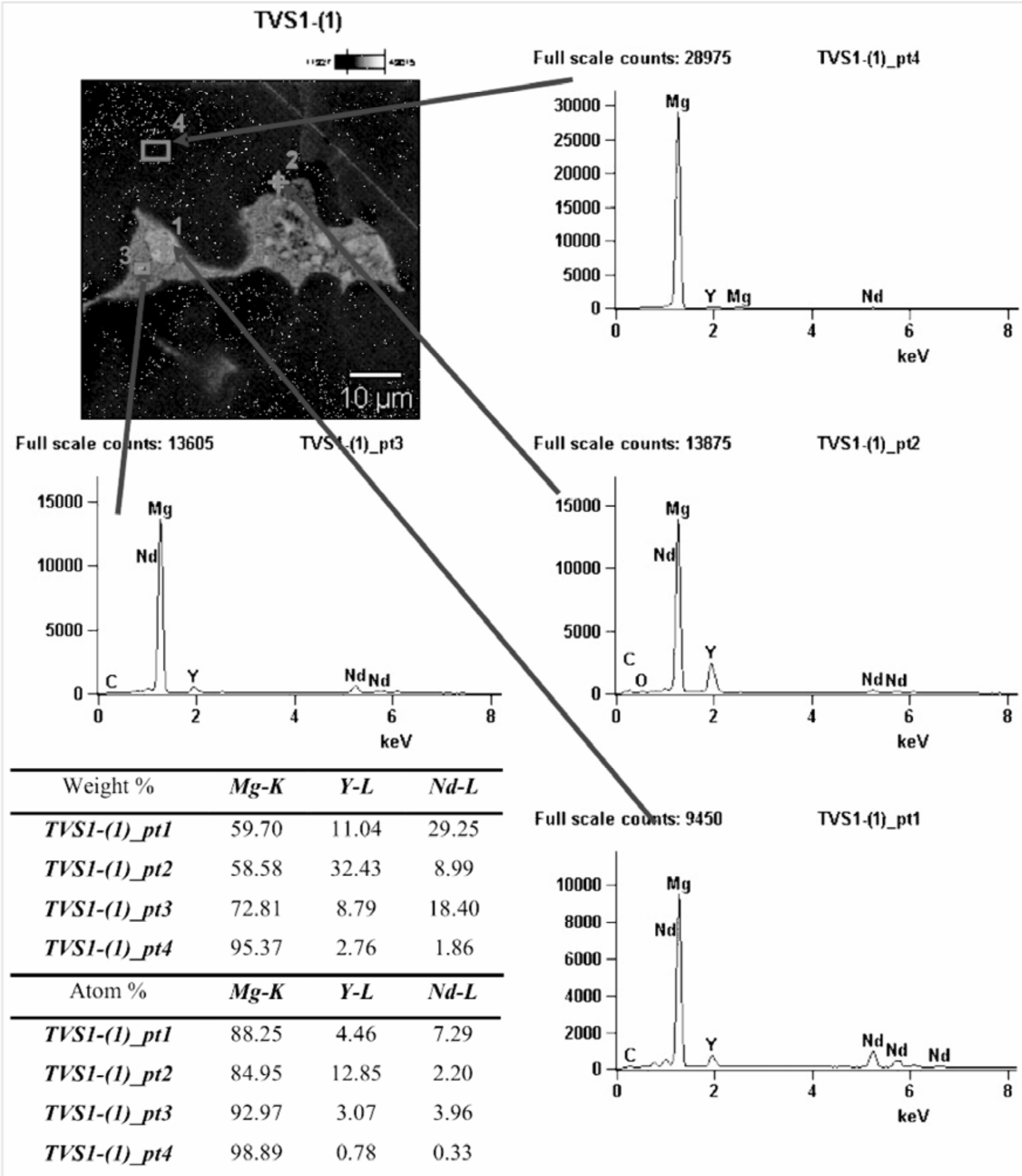


Fig. 7. Microstructure of the weld penetration area after strain in transvarestraint test: a) hot crack going from the weld to the heat affected zone with visible bridge on the line of fusion b) intercrystalline hot crack in the weld c) surface of hot crack with extractions of eutectic on the grain boundaries d) surface of the brittle crack in heat affected zone



Weight %	Mg-K	Y-L	Nd-L
TVS1-(1)_pt1	59.70	11.04	29.25
TVS1-(1)_pt2	58.58	32.43	8.99
TVS1-(1)_pt3	72.81	8.79	18.40
TVS1-(1)_pt4	95.37	2.76	1.86
Atom %	*Mg-K*	*Y-L*	*Nd-L*
TVS1-(1)_pt1	88.25	4.46	7.29
TVS1-(1)_pt2	84.95	12.85	2.20
TVS1-(1)_pt3	92.97	3.07	3.96
TVS1-(1)_pt4	98.89	0.78	0.33

Fig. 8. Microanalysis results of chemical composition of EDS extractions in weld of WE43 alloy

Tests of WE43 alloy in high temperatures simulating the welding process were conducted on Gleeble 3800 simulator. The aim of the conducted tests was to determine the characteristic temperature values in brittleness temperature range of the alloy.

One of the main properties of the material, defining its inclination to cracking during welding is the nil-strenght temperature. That temperature was marked during NST test (fig.3) and for WE43 alloy it is 568 °C. It means that below this temperature the material (welded joint) is not able to transfer load.

Nil-ductility temperature (NDT – 530 °C) during heating and ductility recovery temperature (DRT 515 °C) during cooling are important in determination of the brittleness temperature range of the material (table 3). Thus, the range between the NST temperature (568 °C) and ductility recovery temperature (DRT 515 °C) is considered the brittleness temperature range. Analysis of simulation results on Gleeble 3800 device allows to state that BTR for WE43 alloy is 53 °C (table 3). It is the temperature range where the alloy is prone to hot cracking.

Welding of materials is connected with the necessity to use the concentrated sources of heat of high power, which besides the positive influence of melting the edges of the joined elements, introduce also the non-uniformity of the temperature distribution in the material. Such non-uniformity and too big temperature gradient during welding is the reason of the stains and stresses in the welded material. The strains which influence the metal heated to high temperatures can be the reason of cracks formulation of an intercrystalline character, both in the weld and in the heat affected zone. The size of BTR is also dependent on technological factors, for example the welding parameters, the heat cycle, the stresses and welding strains.

To assess the resistance to hot cracking of WE43 alloy welds the transvarestriant trial was conducted (fig. 5). On the basis of results, the following factors were marked: sample strain stage, the longest crack in the sample axis, the sum of lengths of all cracks and on the basis of welding speed the time of cracks development was calculated (table 4). The cracking threshold was defined as the minimum strain by which the crack do not appear ε_p. This value equals 0,77%. The size of the strain was marked according to dependence:

$$\varepsilon = \frac{g}{2R} \times 100\% \qquad (1)$$

where: ε – strain size (%), g – thickness of the bended sample (mm), R – radius of die block curvature (mm)

Knowing the length of the crack formed in the weld axis (L_{max}) and the corresponding strain and welding speed (v_s) (table 4) the time of crack development (t_{max}) can be calculated according to dependence:

$$t_{max} = \frac{L_{max}}{v_s} \qquad (2)$$

where: t_{max} – time of crack development (s), L_{max} – longest crack (mm), v_s – welding speed (mm/s)

The achieved calculation results enabled to draw the dependence of time of crack development in strain function $t_{max}=f(\varepsilon)$ (fig. 9).

Critical strain rate to time required to cause cracking CSS was marked as the value of the tangent to a curve of cracks development and the strain axis. The CSS value can be estimated as one of the criteria in assessment of the material inclination to hot cracking during welding. For WE43 magnesium alloy the value of CSS equals 1,6 1/s.

Using the results achieved in the transvarestraint test, the heat cycle equation (fig.2) and knowing the liquidus temperature T_l = 699 °C (table 1) and NST temperature = 568 °C, the course of the ductility changes of the tested material in the temperature function $\varepsilon = f(T)$ can be marked. Also the brittleness temperature range for welds or padding welds from WE43 alloy can be marked according to the methodology presented in fig. 10. For the upper limit of BTR the NST temperature was assumed, whereas for the lower limit the temperature of the crack end (T_k) was assumed, which equals 352 °C. So, the BTR was marked according to a dependence:

$$\mathrm{BTR} = \mathrm{NST} - T_k \qquad (3)$$

Brittleness temperature range marked in transvarestraint test for WE43 alloy equals 216,5 °C.

Ductility curve presented in fig.11 is the basis to mark the critical strain rate to temperature drop (CST). CST is a tangent of the angle of tangent to a ductility curve $\varepsilon = f(T)$ and the temperature axis. For magnesium alloy WE43 the value of CST equals 0,14 1/°C.

The microstructure analysis of the samples on light microscope shows the presence of cracks in weld and in the heat affected zone running on the grain boundaries (fig. 6b, 7a,b). The tests show also the presence of so-called bridges in cracks (fig. 7a). Such bridges form in brittleness temperature range of the material during co-existence of liquid and solid stage. They are the result of crystallisation of the liquid residue, which did not separate during the sample strain. Their formulation increases the ductility of the material in BTR [1]. Based on the results of the microanalysis of the chemical composition EDS of extractions and matrix (fig. 8) it was found, that the chemical composition of the extractions corresponds to the phase $\beta(Mg_{12}NdY)$. So, the hot cracks appear as a result of melting the eutectic [Mg(α) + $\beta(Mg_{12}NdY)$] ,which covers the crystals of the solid solution Mg(α) with a thin layer of liquid. The strains of the weld during crystallisation cause the separation of the liquid film composed of eutectic $\alpha + \beta$, which initiates the hot cracking of the weld and HAZ in WE43 alloy.

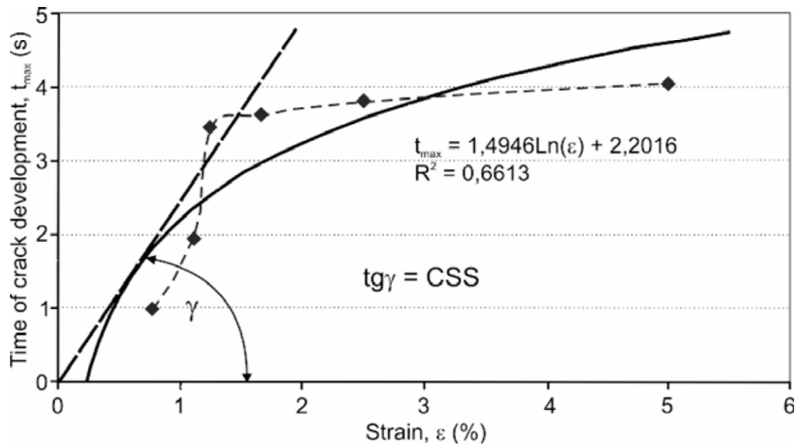


Fig. 9. Dependence of time of crack development in strain function $t_{max} = f(\varepsilon)$

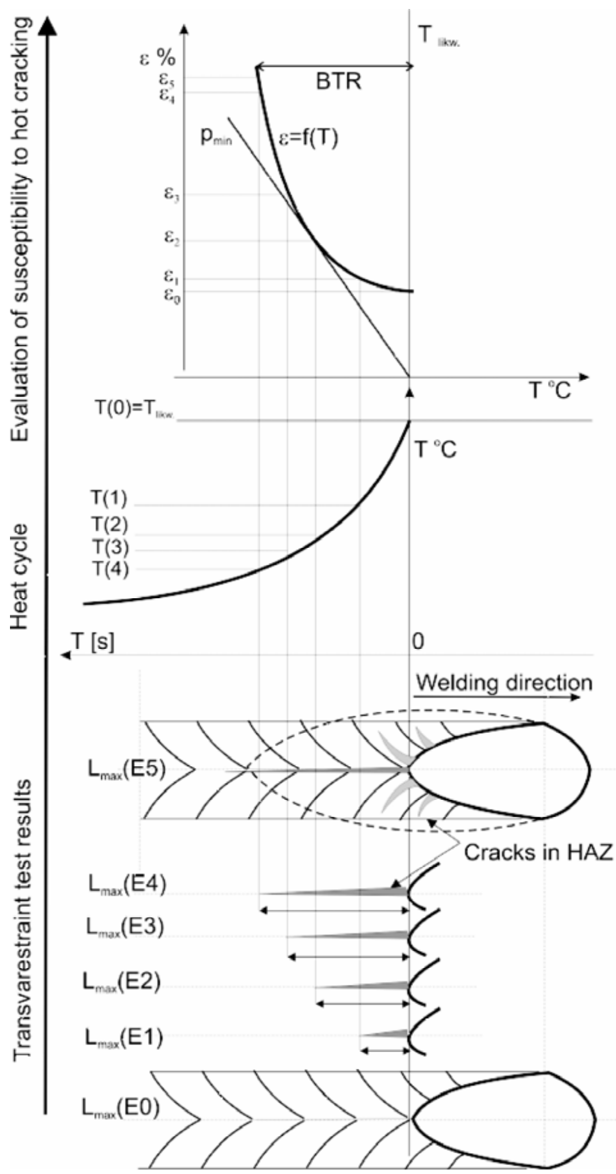


Fig. 10. Methodology of the inclination to hot cracking assessment for welds of WE43 alloy in transvarestriant test

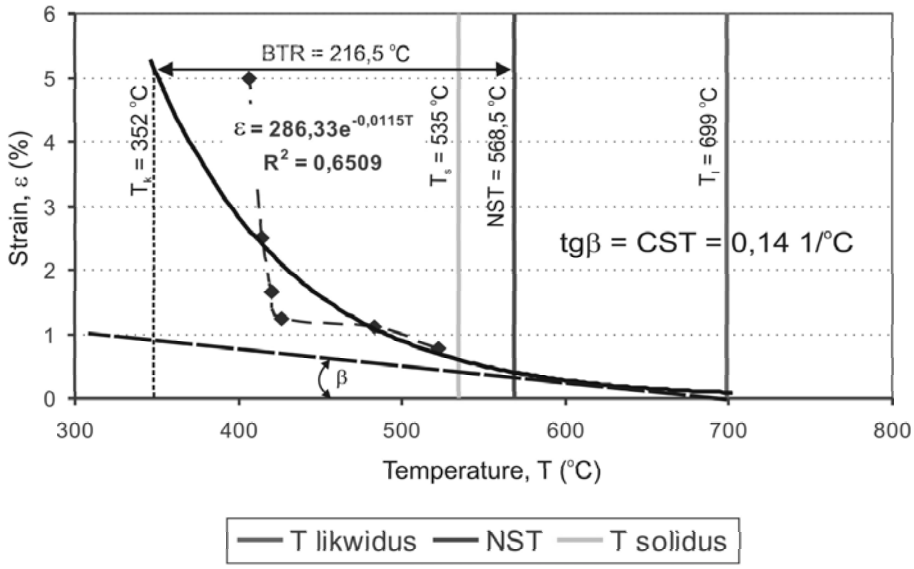


Fig. 11. Ductility curve of the weld of WE43 alloy marked in transvarestriant test

6. Conclusions

The following conclusions were derived on the basis of conducted tests and results analysis:

- The formulated methodology of the inclination to hot cracking assessment in transvarestraint trial for magnesium alloys enables to define the resistance of the alloy to hot cracking during welding. The trial can be also applied to assess the weldability of the magnesium alloys.
- To assess the inclination of welds of WE43 alloy to hot cracking the following indicators marked in transvarestraint trial may be applied: length of crack in weld axis (Li_{max} = 4,84mm), cracking threshold (ε_p < 0,77%), brittleness temperature range (BTR = 216,5 °C), critical strain rate to time required to cause cracking (CSS = 1,6 1/s) and criticalstrain rate to temperature drop (CST = 0,14 1/°C).
- Hot cracks appear in the areas of grain boundaries as a result of melting the fusible eutectics of intermetallic phase β enriched in yttrium and neodymium [6]. Melted eutectic covers the crystals of solid solution Mg(α) with a thin film of liquid. The stresses in operation during crystallisation and welding generate the strains, which causes the separation of the liquid film and, as a result, formulation of a crack and material damage.
- The characteristic feature of the hot cracks in WE43 alloy is formulation of the so-called bridges, which form as a result of co-existence of liquid and solid stage in metal pool during welding.

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