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MECHANICAL PROPERTIES OF WE43 MAGNESIUM ALLOY JOINT AT ELEVATED TEMPERATURE

WŁAŚCIWOŚCI MECHANICZNE ZŁĄCZY ZE STOPU MAGNEZU WE43 W PODWYŻSZONEJ TEMPERATURZE

The WE43 cast magnesium alloy, containing yttrium and rare earth elements, remains stable at temperatures up to 300°C, according to the manufacturer, and therefore it is considered for a possible application in the aerospace and automotive. Usually, it is cast gravitationally into sand moulds and used for large-size castings that find application in the aerospace industry. After the casting process any possible defects that might appear in the casting are repaired with the application of welding techniques. These techniques also find application in renovation of the used cast elements and in the process of joining the cast parts into complex structures. An important factor determining the validity of the application of welding techniques for repairing or joining cast magnesium alloys is the structural stability and the stability of the properties of the joint in operating conditions. In the literature of the subject are information on the properties of the WE43 alloy or an impact of heat treatment on the structure and properties of the alloy, however, there is a lack of information concerning the welded joints produced from this alloy. This paper has been focused on the analysis the microstructure of the welded joints and their mechanical properties at elevated temperatures. To do this, tensile tests at temperatures ranging from 20°C to 300°C were performed. The tests showed, that up to the temperature of 150°C the crack occurred in the base material, whereas above this temperature level the rapture occurred within the weld. The loss of cohesion resulted from the nucleation of voids on grain boundaries and their formation into the main crack. The strength of the joints ranged from 150 MPa to 235 MPa, i.e. around 90 % of strength of the WE43 alloy after heat treatment (T6). Also performed a profilometric examination was to establish the shape of the fracture and to analyze how the temperature affected a contribution of phases in the process of cracking. It was found that the contribution of intermetallic phases in the process of cracking was three times lower for cracks located in the area of the weld.

Keywords: WE43 magnesium alloy joint, tensile test, microstructure, fractography, structure degradation mechanism

Odlewniczy stop magnezu z itrem oraz innymi pierwiastkami ziem rzadkich WE43 może pracować wg producenta do temperatury 300°C, co czyni go stopem o dużej perspektywie rozwoju w zastosowaniach w przemyśle lotniczym i motoryzacyjnym. Najczęściej odlewany jest grawitacyjnie do form piaskowych i przeznaczony jest na odlewy wielkogabarytowe dla lotnictwa. Po procesie odlewania w odlewach mogą pojawić się wady, które naprawia się z zastosowaniem technologii spawalniczych. Technologie spawalnicze stosuję się również do regeneracji zużytych odlewów oraz do łączenia odlewów w konstrukcje. Istotnym czynnikiem decydującym o zasadności stosowania technologii spawalniczych do naprawy lub łączenia odlewów ze stopów magnezu jest stabilność strukturalna i stabilność właściwości złącza w warunkach eksploatacji. W literaturze można znaleźć informacje na temat właściwości stopu WE43, wpływu obróbki cieplnej na strukturę i właściwości, brak jest natomiast tych danych dla złączy spawanych. W pracy zbadano mikrostrukturę złączy oraz ich właściwości mechaniczne w podwyższonych temperaturach. W tym celu wykonano statyczną próbę rozciągania w zakresie temperatur od 20°C do 300°C. Stwierdzono, że zniszczenie do temperatury 150° C następuje w materiale rodzimym, a powyżej tej temperatury w spoinie. Utrata spójności jest wynikiem powstawania pustek w miejscach styku kryształów i ich łączenia się w pęknięcie główne. Wytrzymałość złączy była na poziomie od 150 MPa do 235 MPa, tj. ok. 90 % wytrzymałości stopu WE43 po obróbce cieplnej (T6). Dodatkowo wykonano badania profilometryczne mające na celu ustalenie kształtu przełomu oraz zbadanie wpływu temperatury na udział faz w procesie pękania. Stwierdzono, że udział faz międzymetalicznych w procesie pękania jest trzykrotnie mniejszy dla pęknięć, które są w obszarze spoiny.

1. Introduction

Magnesium, apart from aluminium and titanium, belongs to a group of light metals (metals of density of up to 4.5 g/cm3), which makes it an attractive constructional material for those branches of industry in which reducing the weight of the construction is more important than the price. Because of its low strength, pure magnesium cannot be used as a structural material. For this reason, various magnesium alloys, which, depending on the various alloying elements, are even 35%

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lighter than the aluminium alloys and 60% lighter than the titanium ones, are applied. The main recipient of the magnesium alloys are the automotive and aerospace industries, in which the application of light magnesium alloys reduces vehicle weight, lowering thus the fuel consumption [1,2].

The elements usually added to magnesium alloys are aluminium, zinc and manganese. These alloys are characterized by good machinability, good mechanical properties in room temperature, good resistance to corrosion and low price. Their disadvantage is low creep resistance, which limits their working temperature to 125°C.Addition of rare earth elements increases the creep resistance of magnesium alloys. It allows for the application of these alloys in the automotive and aerospace industries, where the working temperature of e.g. gearbox housings, engine block or pistons exceeds 125°C (Fig.1) [2,3]. According to the manufacturer, the WE43 cast magnesium alloy containing yttrium, rare earth elements and zirconium remains stable at the temperature of up to 250°C, and during a short exposure at the temperature of even 300°C [4].

Magnesium alloys are mainly used for large-size castings into sand moulds, as well as for pressure and precision castings. In magnesium alloy castings, and especially in large-size ones, various defects like misruns, shrinkage porosities and cracks often occur Such defects are repaired with the use of pad welding and welding. Welding techniques can also be applied for joining magnesium alloy elements and for repairing the casts after their wear and tear (Fig. 2) [6]. A possible application of welding techniques for the repair of a given magnesium alloy is determined by the weldability of that particular alloy. Weldability is a property of material that determines its susceptibility to permanent joining. Weldability might also be considered as ability to form, with the application of welding, joints with required physical properties [7].

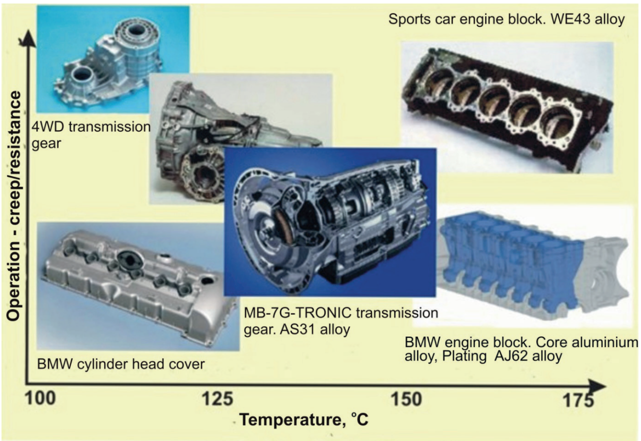


Fig. 1. Working temperature and application of magnesium alloy elements in the automotive industry [5]

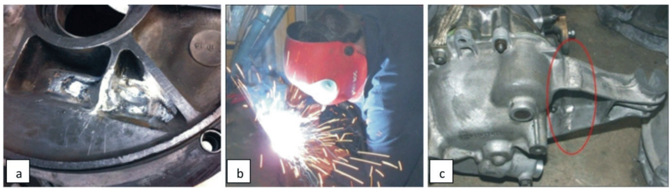


Fig. 2. Application of welding techniques in cast magnesium alloys: a) repairing castings, b) joining castings, c) repairing cast after wear and tear [8,9]

A number of repaired magnesium alloy castings and welded magnesium alloy structures, approved for operation is unsatisfactory. The most frequent reason for rejecting a repaired castings or a welded structure are cracks occurring during the welding process. An important factor determining the validity of application of welding techniques for repairing or joining of cast magnesium alloys is also the structural stability and the stability of the properties of the joint in operating conditions [10].

The structure of the WE43 alloy after casting and heat treatment, its physical, chemical and mechanical properties as well the impact of the casting technologies on the structure and properties have been recently described [11,12]. Also the weldability of the alloy and influence of metallurgical, technical and constructional factors on its susceptibility to hot cracking were determined [13,14]. However one lacks information about the structure and properties of magnesium alloy welded joints. This information is necessary to determine the conditions under which the welded joints can operate. Obtaining this information will enable one to develop guidelines for the safe use of magnesium alloy welded joints.

The aim of this paper was to investigate the impact of temperature on the properties of the welded joint. To achieve this, a tensile test in room and elevated temperatures was carried out. Metallographic examinations allowed for the determination of changes occurring in the microstructure due to tensile stresses, whereas profilometric examinations helped to identify the shape of the fracture and to determine the effect of temperature on the mechanism of joint degradation.

2. Research material

A WE43 cast magnesium alloy joint was used in the research. The chemical composition and mechanical properties of the alloy are presented in table 1. The joints were produced with the TIG method, using test plates cut out of castings. Before the welding, each plate was x-rays in order to detect any casting defects. The process of welding was performed with the Lincoln Invertec V 205AC/DC inverter welder, using alternating current. The time of increasing the value of the current was set at 2 s to the given value, and the time of quenching of the welding arc was set at 4 s. An infusible tungsten electrode of 3.2 mm in diameter - WT20 (according to PN-EN ISO 6848:2008) was applied. Technical argon of purity of 99.995 and flow of 12 l/min was used as a shielding gas. Free gas outflow was set at 3 s at the beginning of the welding and at 4 s after the completion of the joining process. Plates of 250 mm x 50 mm x 10 mm were ‘’Y’’-beveled at an angle of 30°, leaving a 2 mm weld threshold. Before welding, the plates were heated up to the temperature of 100°C. The filler material was a wire with a diameter of 2.4 mm and the chemical composition similar to the welded material (Tab. 1). The technical parameters of the welding process are shown in Table 1.

TABLE 1
Chemical composition, mechanical properties and parameters of welding processes

<table>
<tr><td colspan="12">Chemical composition %</td></tr>
<tr><td colspan="2"></td><td colspan="2">Y</td><td colspan="2">Nd</td><td colspan="2">RE</td><td colspan="2">Zr</td><td colspan="2">Mg</td></tr>
<tr><td colspan="2">WE43</td><td colspan="2">3.7</td><td colspan="2">2.2</td><td colspan="2">0.96</td><td colspan="2">0.51</td><td colspan="2">rest</td></tr>
<tr><td colspan="2">wire</td><td colspan="2">3.7</td><td colspan="2">2.2</td><td colspan="2">0.84</td><td colspan="2">0.44</td><td colspan="2">rest</td></tr>
<tr><td colspan="12">Properties of the WE43 alloy – T6 [4]</td></tr>
<tr><td colspan="2">T</td><td colspan="4">Rm, MPa</td><td colspan="4">$Re_{0,2}$, MPa</td><td colspan="2">A, %</td></tr>
<tr><td colspan="2">20°C</td><td colspan="4">200-293</td><td colspan="4">149-215</td><td colspan="2">2-7</td></tr>
<tr><td colspan="2">250°C</td><td colspan="4">187-235</td><td colspan="4">134-193</td><td colspan="2">2-36</td></tr>
<tr><td colspan="12">Welding parameters</td></tr>
<tr><td colspan="4">Welding current, A</td><td colspan="4">Voltage of the arc , V</td><td colspan="4">Linear energy of the arc, kJ/cm</td></tr>
<tr><td colspan="4">120</td><td colspan="4">14</td><td colspan="4">3.0</td></tr>
</table>

The test joints were assessed by the visual tests (VT), penetration tests (PT) and X-ray photography (X-ray). The visual tests were performed in accordance with PN-EN 970:1999. It was found that both the face and the root of the weld were correct. No welding inconsistencies according to PN EN 30042:1998 were detected (Fig. 3a). The penetration tests performed in accordance with PN-EN 1289:2001 did not reveal any discontinuities on the surface of the joint, either. Analysis of the X-ray photographs, carried out in accordance with the PN-EN 1435:2001 standard, showed a presence of few bubbles in the joint, which are, however, acceptable for the B category according to PN EN 30042:1998 (Fig.3b).

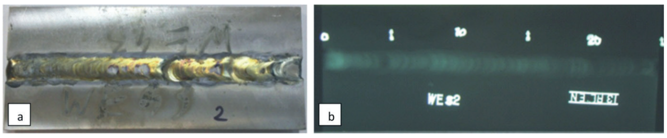


Fig. 3. Welded joint of the WE43 cast magnesium alloy: a) welded test plate, b) X-ray photograph of the plate used for tensile tests

After non-destructive tests of the welded joints, the test plate was subjected to heat treatment according to the recommendations of the manufacturer (T6) (solution heat treatment 8 h/525°C/air and ageing 16 h/250°C/ air). The samples used in the examination of the macro-and microstructure were excised perpendicular to the welding direction. Macro- and microstructure of the joint after heat treatment is shown in Figure 4.

The macroscopic examinations proved that the welded joint was performed properly and no welding inconsistencies were revealed (Fig. 4a). After solution heat treatment and ageing, the joint consist of three areas: base material (Fig.4b), heat affected zone, characterized by the growth of the grain, (Fig.4c) and the weld (Fig 4d). The solution heat treatment resulted in the phases of dissolution and in the growth of the grain in the joint. The process of ageing resulted in the precipitation of the secondary intermetallic phases including yttrium and neodymium.

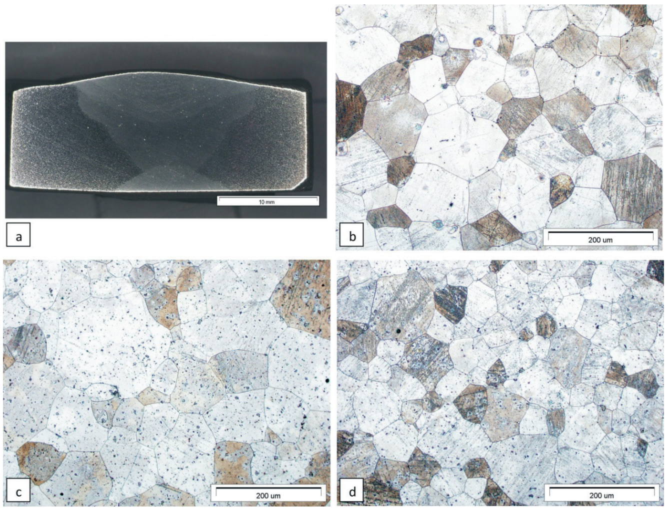


Fig. 4. Research material - welded joint of the WE43 alloy after solution heat treatment (8 h/525°C/air) and ageing (16 h/250°C/air): a) macrostructure of the joint, b) microstructure of the base material, c) growth of the grain in the heat affected zone, d) grain refinement in the area of the weld

3. Tensile test

The tensile test of the heat-treated welded joints of the WE43 alloy was performed with the use of the Kappa 50 DS electromechanical tensile-testing machine, equipped with a three-zone heating chamber of the inside diameter of 100 mm. The temperature was measured with the accuracy of 1°C. The tests were performed at the temperature range of 20 °C - 300 °C on samples with a diameter of 6 mm and gauge length of 42 mm. The weld area was located in the centre of the sample. The strain rate during the tests was set at 4 mm/min (Fig. 5.).

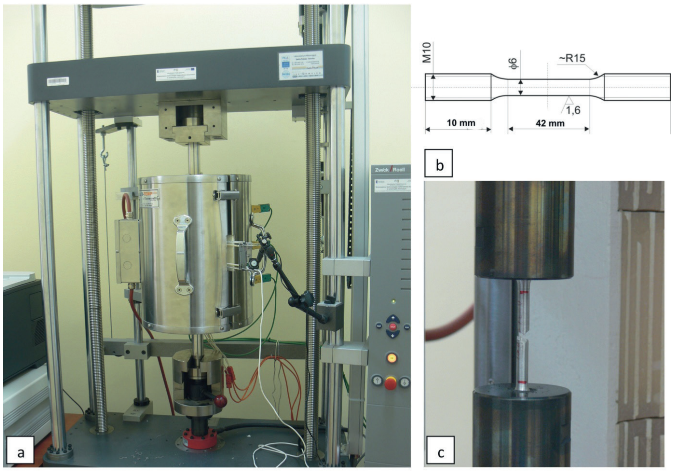


Fig. 5. Tensile test: a) Kappa 50 DS tensile-testing machine, b) sample for tensile tests, c) view of the tensile-testing machine chamber with a broken sample

Examplary tensile curves for the joints are presented in figure 6. The results of the tensile test for the average of three measurements are presented in table 2.

TABLE 2

Results of the tensile test for the WE43 alloy joints

Tensile test temperature	Rm, MPa	Crack
20°C	235	in the material
100°C	209	in the material
150°C	195	in the material
200°C	183	in the joint
250°C	204	in the joint
300°C	150	in the joint

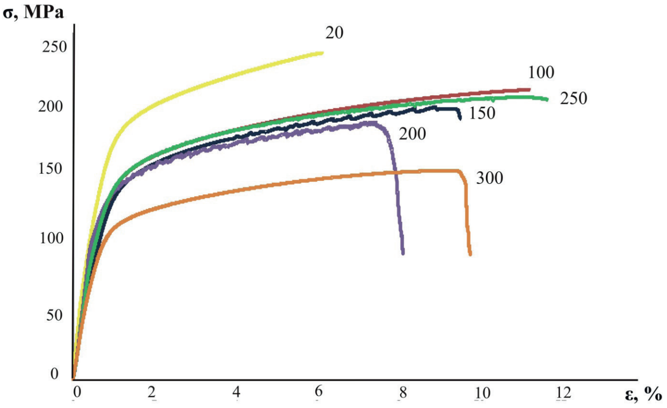


Fig. 6. Tensile curves for various testing temperatures for the WE43 alloy joints

4. Microstructure

Metallographic investigations were performed on specimens, excised perpendicular to the crack surface. The macroscopic examinations were performed with the use of the Olympus SZX9 stereoscopic microscope (Fig. 7a) with the dark field technique. The images of microstructure were recorded with the use of the Olympus GX71 optical microscope, with the bright field technique (Fig.7b). The fracture surfaces tests were examined on a scanning electron microscope with the application of the secondary electron (SE) and backscattered electron (BSE) techniques (Fig. 8). Chemical microanalysis of the phases occurring close to the fracture surface of the welded joint was carried out with the application of the EDS method, using the Hitachi S-3400 N scanning electron microscope, equipped with the Noran SYSTEM SIX system. The tests were performed at an accelerating voltage of 15 kV. The results are shown in Figure 9.

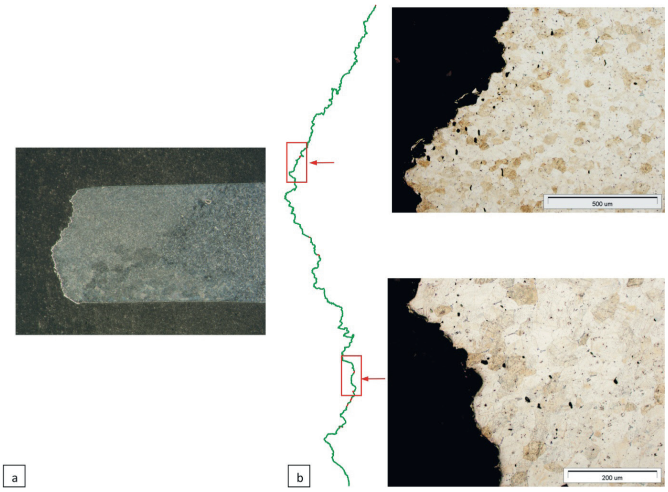


Fig. 7. Structure of the crack area of the WE43-T6 alloy joint after the static tensile test at the temperature of 300°C: a) macrostructure of the joint fracture area – crack in the weld, b) joint profile line and microstructure of the fracture area

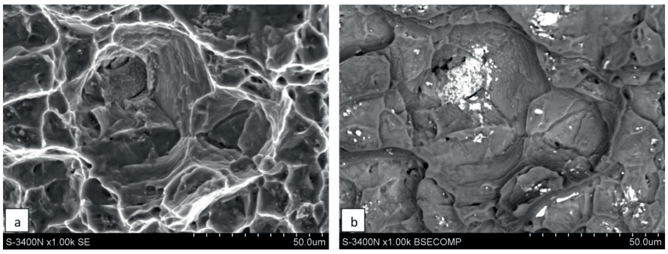
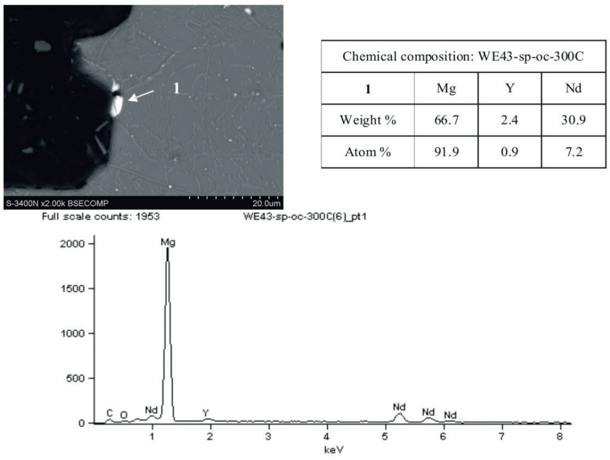


Fig. 8. Fracture surface of the WE43-T6 alloy joint after the tensile test at the temperature of 300°C: a) cracks inside the Mg(α) solid solution grains, SE, b) intermetallic phase on the surface of the fracture, BSE



Chemical composition: WE43-sp-oc-300C

1	Mg	Y	Nd
Weight %	66.7	2.4	30.9
Atom %	91.9	0.9	7.2

Fig. 9. Results of chemical microanalysis of phase on the surface of the WE43-T6 alloy joint fracture after the tensile test at the temperature of 300°C

5. Profilometric examinations

Examination of the fracture surface of the WE43 magnesium alloy joint after the tensile test was performed with the application of the profilometric method. The measured profile lines were oriented perpendicular to the line of the fracture. The minimum length of the analyzed profile line for each sample was 9 mm. An Olympus GX71 optical microscope was the image source. The profile lines were observed at a total magnification of 200 times, with the bright field technique (Fig.7b). Conversion of grey and binary images, detection of the profile and record of its coordinates (taking into account the phases in the profile line) were performed with the application of *Zapis profilu [Profile record]* program developed by the Department of Materials Science of the Silesian University of Technology. The profile line fragments of diversified morphology of the fracture were presented in figure7b.

The parameters of profile lines: profile length, profile expansion rate (R_L), fractal dimension, linear share of the main and secondary phase, and the dominance index of the secondary phase were determined by the *Profil* software. The results are presented in table 3.

TABLE 3
Results of profilometric examinations of the WE43 alloy joint fracture surfaces after the tensile test

Parameters of the quantitative profilometry		Test temperature					
		20°C	**100°C**	**150°C**	**200°C**	**250°C**	**300°C**
Length of the profile / mm		11.15	10.55	13.95	10.19	9.86	9.21
RL	profile	2.06	1.65	1.80	1.87	1.53	1,95
	main phase	2.07	1.64	1.77	1.88	1.53	1,96
	secondary phase	1.85	1.88	3.25	1.69	1.59	1,75
Fractal dimension		1.090	1.07	1.08	1.08	1.07	1.10
Linear share,%	main phase	95.27	95.07	96.76	98.40	98.24	97.29
secondary phase	4.73	4.93	3.23	1.59	1.75	2.71	
Dominance index of the secondary phase		11.44	11.92	7.82	9.89	10.88	16.78

6. Hardness tests

Hardness of the joints was tested on metallographic specimens transverse to the direction of the joint cracks, after the tensile test, in the area of the weld and the base material. The test was conducted with the Duramin A300 hardness tester, with the application of the Vickers method and 3 kG load (HV3). The results are presented in figure 10.

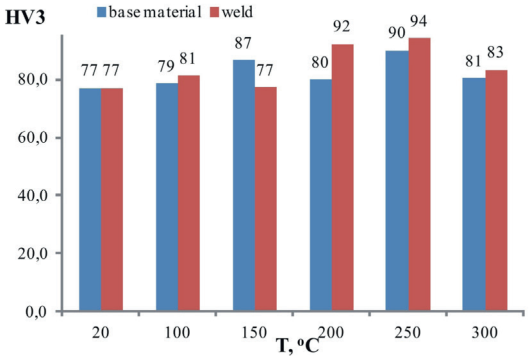


Fig. 10. Results of the joint hardness tests after the tensile test: 20°C, 100°C, 150°C – crack in the base material, 200°C, 250°C, 300°C – crack in the weld

7. Analysis of results

The WE43 alloy joints produced with the TIG method, in accordance with the parameters presented in table 1 were characterized by a full joint penetration and showed no welding inconsistencies (Fig. 3, 4a). After the process of solution heat treatment and ageing, the microstructure of the base material of the joint consisted of the Mg(α) solid solution polygonal grains of the average diameter of 150 μm with finely dispersed intermetallic phases (Fig.4b). In the heat affected zone grain growth was observed (grain diameter of around 200 μm) (Fig. 4c), whereas grain refinement was detected in the area of the weld (grain diameter of around 50 μm) (Fig. 4d).

The tensile test conducted at the temperature range of 20°C – 3000°C allowed for the determination how the temperature affected the mechanical properties of the joints.

With the increase in temperature, the tensile strength of the joints decreased from 235 MPa (200°C) to 183MPa (2000°C). At the temperature of 2500°C was observed an increase of the joint strength (204MPa), whereas at the temperature of 3000°C (150MPa) a sudden drop of the joint strength was observed (table2). Below the temperature of 1500°C the cracks appeared in the base material, whereas above this temperature the loss of cohesion occurred within the weld (Fig. 7a).

The tensile curves for the joints examined at the temperature range of 1500°C and 2000°C, revealed the Portevin-Le Chatelier (PLC) effect, in the form of characteristic of "jerky flow". This effect consists in the fluctuation of the flow stress on the work hardening curve and results in heterogeneous strain of the elongated sample. It results from the formation of the Cottrell atmospheres around dislocations at an early stage of strain and blocking dislocation movement. With the increase of the strain, the dislocations are released and the cycle begins anew. Because after each cycle the number of dislocations increases, the strain curve rises up smoothly, proving the existence of the work hardening of the material [15].

Examinations of the fracture surface allowed to understanding the cracking mechanisms in the joints. As a result of joint strain, voids (the number of which increases with the increase of the strain) appear on the grain boundaries. The voids join together and a short neck in the material is formed. The neck is a place where the material is broken (Fig. 7b). This cracking mechanism is confirmed by the results of fractography tests of the fracture surface. A typical fracture surface of a sample tensile tested at 300°C exhibits an intercrystalline character with a dimples typical forlarge plastic strain (Fig 8a). On the fracture surface one can see precipitations of phases containing yttrium and neodymium (Fig. 8b, Fig.9), which proves that the crack is also initiated in the phase and that the forming voids lead to the loss of cohesion of the joint.

Assessment of the shape of the fracture with the application of the *Profil* software made it possible to determine the dominance index of the secondary phase in the fracture and the impact of the area of cracking and the impact of temperature on the share of secondary phases in the process of cracking. It was found that in the case of joints where the cracks occurred in the base material, the dominance index of the secondary phase in the fracture decreased with the increase of the temperature. In the case of joints that were broken within the weld, the share of the phases in the process of cracking increases with the increase of the temperature (table 4). The phase dominance indexes in the fracture for the joints fluctuated around 7.82 (150°C) – 16.78 (300°C). This suggests that the phase is a preferential site in the process of cracking for the WE43 magnesium alloy joints. The linear share of the secondary phase in the fracture is 2 times higher in case of cracks in the base material than in the case of cracks in the weld.

The hardness of the weld and of the base material of the joints in the cracking surface after the tensile test was on a similar level (77-94 HV). The largest difference in hardness between these joint areas was observed at the tensile test temperature of 150°C. Regardless of whether the crack occurred in the base material or within the weld, the hardness increased near the cracking line. The material was the hardest at the temperature of 250°C. A tensile test for the WE43 alloy after solution heat treatment and ageing at the temperature of 20°C was conducted too. The results are shown in fig.11.

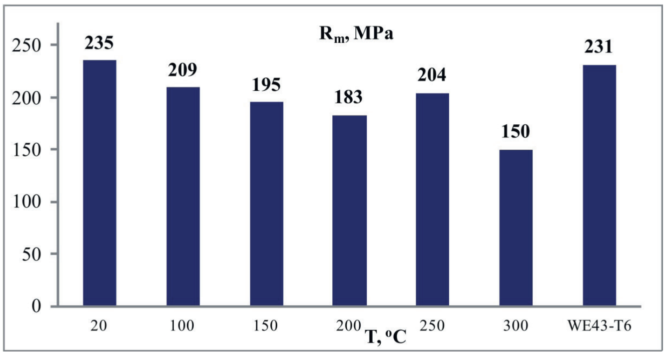


Fig. 11. The results of the tensile test for welded joints of the WE43 alloy, elongated at the temperatures from 20oC to 300°C, and results of the tensile test for the WE43-T6 alloy conducted at the temperature of 20°C

Comparing the results obtained for the WE43-T6 alloy with the results obtained for the WE43 alloy welded joints at the temperature of 20°C, one can observe that the strength of the joints at the temperature of 20°C is on a similar level as the strength of the alloy (Fig.11). With the increase of the temperature, the strength of the joints declines. At the temperature of 250°C the strength increases and its value fluctuates within the limits specified by the manufacturer for the WE43-T6 alloy (table 1). This might suggest that the welded joint displays properties similar to those of the WE43-T6 alloy.

8. Summary

Based on the performed tests and analysis of their results, the following conclusions have been drawn:

1. welded joints of the WE43 cast magnesium alloy, produced with the application of the TIG method, after solution heat treatment and ageing were subject to the tensile test at the temperatures from 20°C to 300°C. The following results were obtained Rm = 235 MPa at the temperature of 20°C and Rm = 150 MPa at the temperature of 300°C. Within the temperatures 150 -200°C the Portevin – Le Chatelier (PLC) effect was observed,
2. loss of cohesion of the joint welded with application of the TIG method results from the appearance of voids on the grain boundaries and on intermetallic phases, forming the main inter-crystalline crack,
3. intermetallic phases is a preferences sites in the process of fracturing(phase dominance index in the fracture fluctuates around 7.82 – 16.78),
4. hardness of the joints after the tensile test fell in to the range of 77 – 94HV,
5. the welded joints meet the requirements, i.e. they might be used for elements operating in the same working conditions as the working conditions of the casts which do not require any repairs

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