ARCHIVES OF METALLURGY AND MATERIALS
Volume 56 2011 Issue 3
DOI: 10.2478/v10172-011-0085-x

J. ADAMIEC*

# THE INFLUENCE OF CONSTRUCTION FACTORS ON THE WELDABILITY OF AZ91E ALLOY

# WPŁYW CZYNNIKÓW KONSTRUKCYJNYCH NA SPAWALNOŚĆ STOPU AZ91E

Magnesium alloys, together with aluminum and titanium alloys, are a member of the group of light alloys that are of the greatest practical importance in construction applications. Magnesium alloys are currently used in mass sand-mould castings, high-pressure castings, and precision castings. Magnesium alloy casting defects (misrun, micro-shrinkage and cracks) are frequently found, particularly in the case of mass castings. These defects can be repaired with surfacing and welding methods that are common practice in foundries. The purpose of this work was to assess the impact of construction factors on the weldability of AZ91E alloy. Various tests were conducted: transvarestraint tests to determine the range of high-temperature brittleness, critical speed of strain and critical temperature intensity of weld strain under the conditions of forced strain; the Fisco test, which simulates welding under the conditions of permanent stiffening of the weld; and the Houldcroft test, which simulates variable strain distribution found in the weld.

One concluded that the strain of castings is characteristic of the process of pad welding and welding. Assessment of susceptibility of AZ91E alloy to cracking under the conditions of forced strain (transvarestraint test) allows to determine the width of the range of high-temperature brittleness HTBR, critical strain speed of the weld CSS and critical temperature strain intensity CST. These parameters are the criteria of hot cracking of welds from AZ91E alloy, therefore, they are indicators of the assessment of the alloy's weldability. Castings from AZ91 E alloys with constant rigidity should be classified as easily weldable. On the other hand, variable rigidity of the casting, resulting from e.g. diverse thickness of the walls, causes significant increase of the alloy's susceptibility to hot cracking.

Thermal treatment of gravity castings affects weldability of AZ91E alloy. Gravity castings from AZ91E alloy should therefore be pad welded or welded by TIG method, filler metal with chemical composition similar to the basic material after supersaturation with linear energy of the arc in the range from 3.0 kJ/cm to 4.0 kJ/cm.

*Keywords*: magnesium alloys, AZ91E, weldability of magnesium alloys, hot cracking, repair of castings

Stopy magnezu, obok stopów aluminium i stopów tytanu, wchodzą w skład grupy stopów lekkich, które mają największe znaczenie praktyczne w zastosowaniach konstrukcyjnych. Stopy magnezu stosowane są obecnie na odlewane do form piaskowych odlewy wielkogabarytowe, odlewy wysokociśnieniowe oraz odlewy precyzyjne. W odlewach ze stopów magnezu często występują wady odlewnicze (niedolania, rzadzizny oraz pęknięcia), szczególnie w odlewach wielkogabarytowych. Wady te naprawiane są metodami napawania i spawania. Jest to praktyka powszechnie stosowana w odlewniach. Celem pracy była ocena wpływu czynników konstrukcyjnych na spawalności stopu AZ91E. Przeprowadzono próbę „transvarestraint", która umożliwiła ocenę skłonności do pękania złączy w warunkach wymuszonego odkształcenia odlewu, próbę Fisco, która symuluje spawanie w warunkach silnego usztywnienia złącza oraz próbę Houldcrofta symulującą zmienne odkształcenie złącza.

Stwierdzono, że odkształcenie odlewów jest charakterystyczne dla procesu napawania i spawania. Ocena skłonności do pękania gorącego stopu AZ91E w warunkach wymuszonego odkształcenia (próba transvarestraint) umożliwia wyznaczenie szerokości zakresu kruchości wysokotemperaturowej ZKW, krytycznej szybkości odkształcenia złącza CSS oraz krytycznej temperaturowej intensywności odkształcenia CST. Parametry te stanowią kryteria pękania gorącego spoin ze stopu AZ91E, a zatem są wskaźnikami oceny spawalności stopu. Odlewy ze stopów AZ91 E o stałej sztywności należy zaliczyć do łatwo spawalnych. Natomiast zmienna sztywność odlewu wynikająca np. ze zróżnicowanej grubości ścianek powoduje znaczny wzrost skłonności stopu do pękania gorącego.

Obróbka cieplna odlewów grawitacyjnych wpływa na spawalność stopu AZ91E. Odlewy grawitacyjne ze stopu AZ91E należy napawać lub spawać metodą TIG, spoiwem o zbliżonym składzie chemicznym do materiału podstawowego, po przesycaniu energią liniową łuku w zakresie od 3,0 kJ/cm do 4,0 kJ/cm.

---

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

## 1. Introduction

The International Institute of Welding (IIW) divides the weldability of a material into three categories [1]:

- local (metallurgical), refers to a part of the welded joint where metallurgical processes and structural transformations take place,
- operative (technological), includes the possibility of making welded joints without analyzing the phenomena occurring during welding, and
- global (constructional), considers the structure as a whole.

In general, magnesium alloys are considered as weldable [2]. However, when welding these alloys, one encounters difficulties associated mainly with their metallurgical properties, e.g., the chemical composition, the high affinity of magnesium to oxygen and the formation of MgO oxide that has a very high melting point of ca. 2500°C, high thermal conductivity, low temperature of vaporization, ca. 1100°C [1,3-5], and a wide range of temperatures between liquidus and solidus temperature.

However, the most frequent reason for unacceptable welded joints in magnesium alloy castings are hot cracks. It is believed that, the main cause of their formation has been attributed to the reduction in metal plasticity due to high-temperature brittleness, as well as metal strain during crystallization, which results in a loss of material cohesion [6,7].

The main assumptions in assessing the susceptibility to hot cracking with regard to high-temperature brittleness were formulated by Prochorow, who assumed that the formation of hot cracks depends on three factors [8]: size of the high-temperature brittleness range *(HTBR)*, plastic strain capacity, as well as the rate at which the strain increases(Fig. 1).

In Fig. 1 the curve p reflects the change in metal plasticity as a function of temperature with regard to high-temperature brittleness. Close to the liquidus temperature, the mixture of liquid and solid crystals in the microstructure yields high formability. As the crystallization temperature decreases, the plasticity rapidly fell, reaching a critical value $p_{min}$. If the straight line $\varepsilon$, which represents the amount of strain, crosses the curve p within the temperature range of brittle behaviour, cracks form in the weld. Resistance of a welded joint to hot cracking can therefore be expressed by $\Delta\varepsilon_z$, thus denoting potential formability:

$$\Delta\varepsilon_z = p_{\min} - (\Delta\varepsilon_{sk} + \Delta\varepsilon_k)\,, \qquad (1)$$

where $p_{min}$ – minimum capacity of the material for plastic strain, $\Delta\varepsilon_{sk}$ – strain caused by free shrinkage, $\Delta\varepsilon_k$ – strain due to weld shape change.

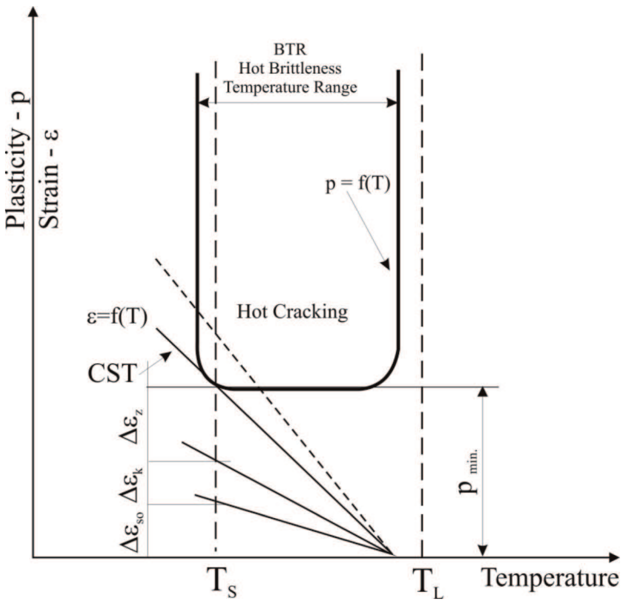

Fig. 1. Scheme of the dependence between alloy plasticity within the HTBR and the intensity of increasing strain, CST–critical temperature intensity of strain determined from the tangent of the slope angle of straight line $\varepsilon$ [8]

The resistance to tearing or hot cracking is also characterized by the so-called plasticity margin ratio A [8]. This quantity is associated with the critical temperature intensity of strain (*CST)* as well as the high-temperature brittleness range and depends mainly on technological, construction and metallurgical factors, i.e., thermal conditions during casting or welding and the rigidity of the casting or connection:

$$A = CST \cdot HTBR, \qquad (2)$$

where A – plasticity reserve [%], CST – critical temperature intensity of strain [%/°C], and HTBR – high-temperature brittleness range [°C].

Therefore, Prochorow assumed that the main measure of susceptibility to hot cracking is alloy plasticity in the liquid-solid condition. A crack will occur if alloy strain in the weld exceeds its plasticity.

The most common magnesium alloy, AZ91E, currently used for gravity as well as pressure castings, is considered easily welded [9]. The manufacturer recommends the TIG welding method with a wire of similar chemical composition. After welding it is necessary to perform either the T4 or T6 thermal treatment, consisting of annealing at temperature of 415°C for 30 min. or a temperature of 415°C for 30 min. and followed by 215°C for 240 min. [9]. However, no independent research work has been performed to confirm this information.

Construction factors affecting the weldability of magnesium alloy AZ91E castings include, among others, the construction solution of the casting, the degree of casting complexity, differences in the thicknesses of the walls, the stiffness of the casting and the presence of notches. The literature does not describe the impact of these factors in determining the weldability of magnesium alloys. However, our own experience found significant problems when repairing AZ91 alloy bulky castings with welding techniques [10-12]. Thus, there is a need for determining the construction factors that affect the weldability of this alloy.

## 2. Materials for tests

The AZ91E alloy, manufactured by Magnesium Elecktron, was used for testing. Factors that influence the structure and thus its weldability–the chemical composition, basic mechanical properties in the as-supplied condition, as well as the heat treatment parameters performed–are shown in Table 1.

AZ91E magnesium alloy with additions of ca. 9% Al and ca. 0.6% Zn in the as-supplied condition is characterized by a structure composed of an aluminum and zinc solid solution in a magnesium Mg ($\alpha$) matrix and $Mg_{17}Al_{12}$ ($\beta$) phase precipitates. The two morphologies for this phase are massive (volume fraction ca. 5.7%) and lamellar (volume fraction ca. 9.4%) in the interdendritic areas (Fig. 2). The addition of manganese causes the formation of small, globular $Al_4Mn$ phase. In the structure one also observes precipitates of the $Mg_2Si$ phase, the volume fraction of which does not exceed 0.1% [13]. The thermal treatment recommended by the manufacturer (supersaturation and ageing) is intended to improve the mechanical properties of ready-made castings. Annealing the alloy at a temperature of 415°C for 24 hours causes the dissolution of the $Mg_{17}Al_{12}$ massive phase (ca. 0.5%) and lamellar phase (2.1%), and ageing after supersaturation leads to the formation of this phase in the lamellar form (8.9%) [14].

TABLE 1

Chemical composition of, properties of and heat treatment options for the AZ91E alloy

<table>
<tr><th rowspan="2">Alloy</th><th colspan="7"><b>Chemical composition</b> [%]</th></tr>
<tr><th><b>Heat</b></th><th>Zn</th><th>Al</th><th>Mn</th><th>Fe</th><th>Ni</th><th>Other</th></tr>
<tr><td rowspan="8"><b>AZ91E</b></td><td>ASTM B80</td><td>0.4–1.0</td><td>8.1–9.3</td><td>0.13–0.35</td><td>–</td><td>–</td><td>–</td></tr>
<tr><td><b>000810</b></td><td>0.56</td><td>8.6</td><td>0.21</td><td>0.003</td><td>0.001</td><td>< 0.01</td></tr>
<tr><td colspan="7"><b>Mechanical properties</b></td></tr>
<tr><td colspan="2">$R_m$, MPa,</td><td colspan="2">$R_e$, MPa,</td><td colspan="2">$A_5$,%</td><td>HV3</td></tr>
<tr><td colspan="2">275</td><td colspan="2">115</td><td colspan="2">1</td><td>66</td></tr>
<tr><td colspan="7"><b>Parameters of heat treatment</b></td></tr>
<tr><td>I</td><td colspan="6">Supersaturation: 24 h/415 °C/air/heating 50°C/h</td></tr>
<tr><td>II</td><td colspan="6">Supersaturation: 24 h/ 415°C/air/heating 50°C/h<br>Ageing: 10 h/200°C/air</td></tr>
</table>

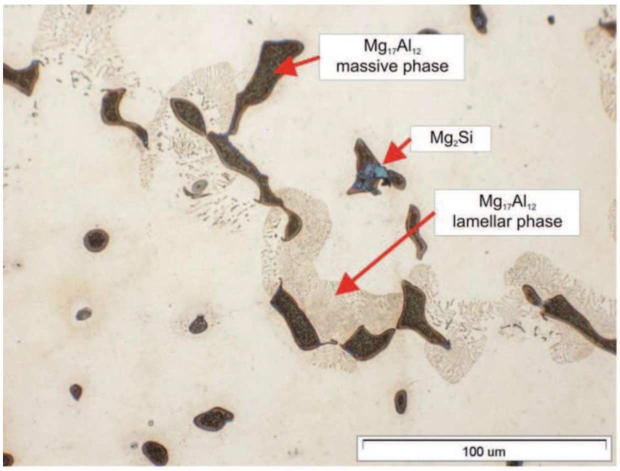

Fig. 2. Microstructure of the AZ91E alloy gravity casting

## 3. Determination of susceptibility to hot cracking under the conditions of forced strain on the weld – Transvarestraint test

The transvarestraint test, which simulates the welding process with forced strain is based on fast bending flat samples on a cylindrical die block (Fig. 3). Bending takes place perpendicular to the direction of the electrical arc remelting in an argon shield – the TIG method (Fig. 3). The amount of strain depends on the thickness of the bent sample and the radius of curvature of the die block. Tests were conducted on magnesium alloy plates with the following dimensions: 120×90×5 mm. These plates were in the as-supplied condition as well as the after heat treatment condition. Remelting of the material was conducted with an AC current intensity of 130 A. The speed of remelting was 1.2 mm/s. Welding parameters were selected to obtain full weld penetration. The amount of strain was determined according to the following relation:

$$\varepsilon = \frac{g}{2R} \cdot 100\%, \tag{3}$$

where $\varepsilon$ – amount of strain [%], g – thickness of the bent sample [mm], and R – radius of die block curvature [mm].

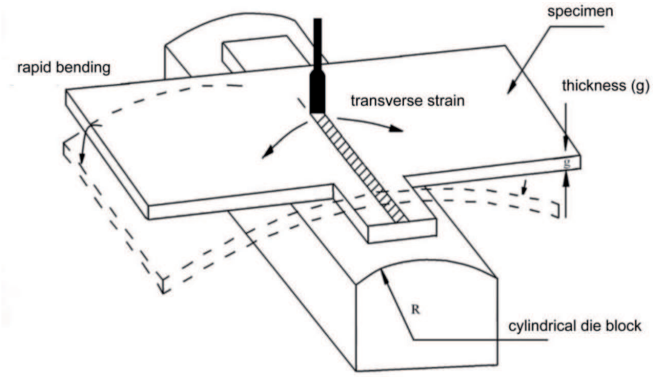

Fig. 3. Schematic of the specimen position during the transvarestraint test

Subsequently the length of the longest crack along the weld axis ($L_{\max}$) and the sum of all cracks ($L_{i\,\max}$) were determined. Knowing the length of the crack that formed in the weld axis ($L_{\max}$) and corresponding strain as well as the welding speed ($v_s$), one could calculate the time for crack formation ($t_{\max}$) based on the following relationship:

$$t_{\max} = \frac{L_{\max}}{v_s}, \tag{4}$$

where $t_{\max}$ – crack formation time [s], $L_{\max}$ – longest crack [mm], and $v_s$ – welding speed [mm/s].

Based on the obtained results for the examined alloys, one could determine hot temperature britleness range (*HTBR)*. The range of high-temperature brittleness is the difference between the nil-strength temperature (*NST=476*) [15] and the temperature at the end of the longest crack ($T_k$) (Fig. 4 and 5). The methodology of determining *HTBR* under the forced strain conditions for the specimen and assessing the susceptibility to hot cracking in the magnesium alloys during transvarestraint testing is schematically shown in Fig. 4. From the obtained results, it is possible to determine the logarithmic curve of the dependence of crack formation time on the strain $t_{\max}$ = f ($\varepsilon$) (Fig. 6a) and the exponential curve of plasticity $\varepsilon$ = f (T) (Fig. 6b). Based on regression analysis and correlation of the function of one variable

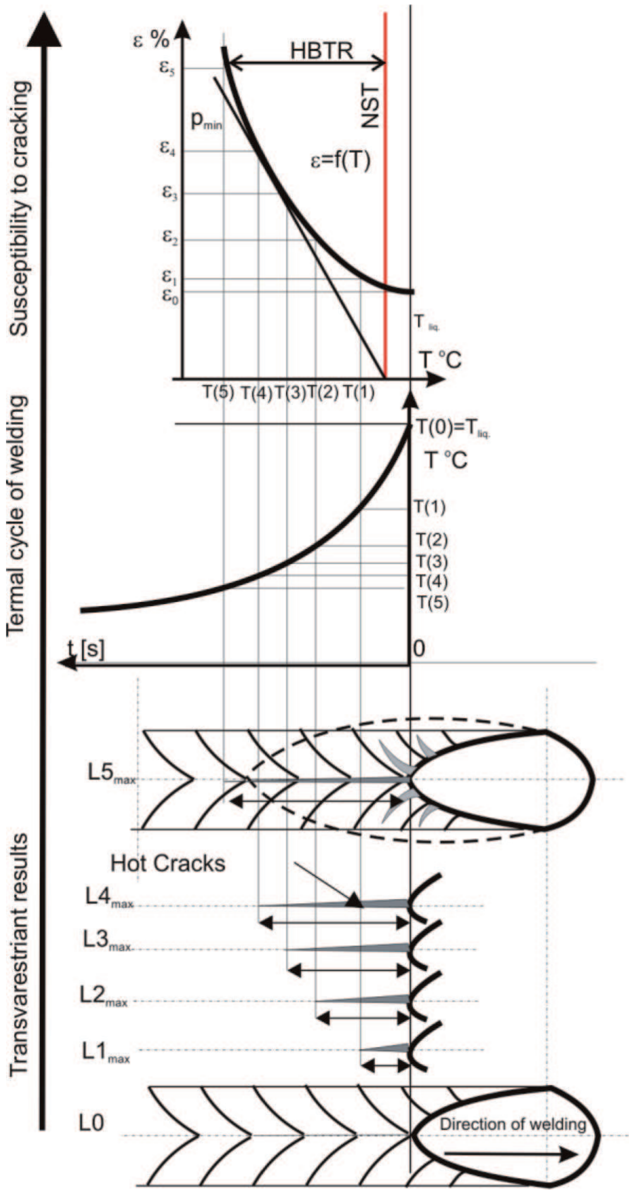

Fig. 4. Assessment of susceptibility to hot cracking in the transvarestraint test – procedure of determining HTBR [15]

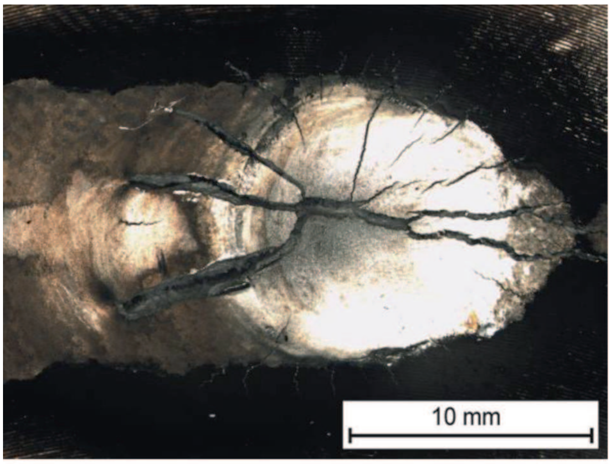

Fig. 5. Weld penetration face with cracks in the crater

(non-linear), one can state that the designated dependencies are important. The critical strain speed (*CSS*) can also be calculated and is given as the value of the tangent of the slope angle between the tangent to the crack formation curve and the crack formation time axis. In addition, the critical temperature intensity of strains (*CST*), which is the tangent of the angle between the tangent to the plasticity curve, $\varepsilon$ = f (T), and the temperature axis can also be calculated. The results are collected in Table 2. Structure of the weld penetration area in AZ91E alloy and fracture surface are presented in Fig. 7.

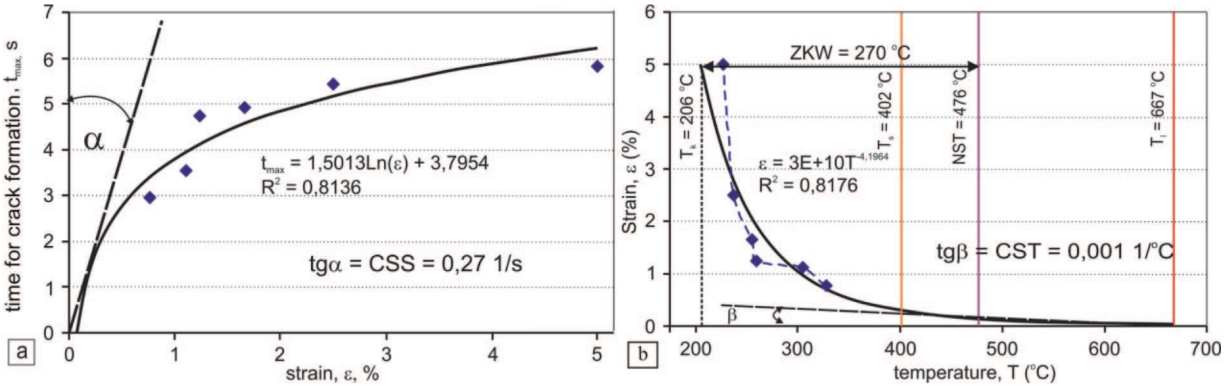

Fig. 6. The dependence of crack formation time on the (a) strain and (b) the plasticity curve for the AZ91E alloy in the as-supplied condition

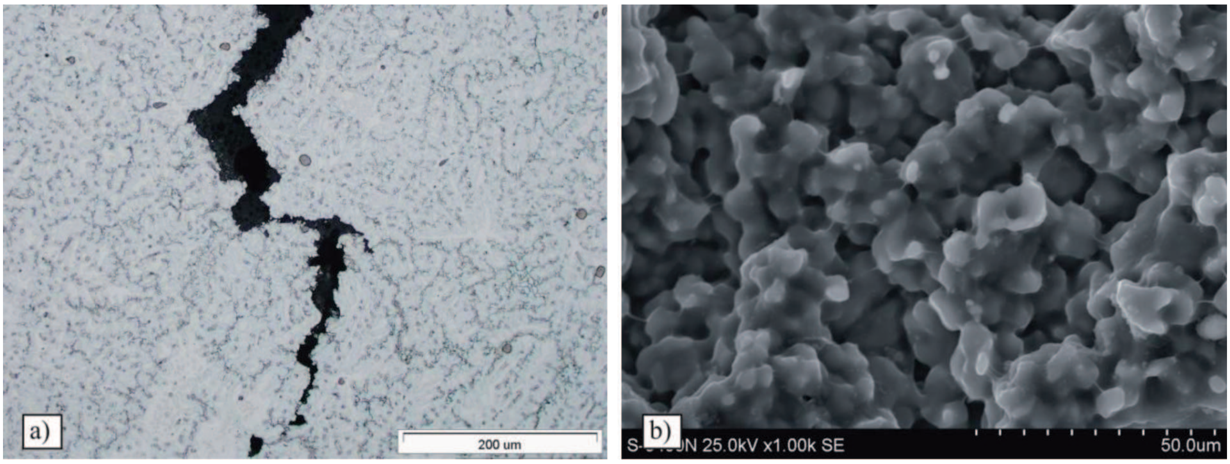

Fig. 7. Structure of the weld penetration area in AZ91E alloy: a) hot crack and b) fracture surface with visible dendrites composed of Mg ($\alpha$) solid solution

TABLE 2

Transvarestraint test results from the *HTBR* assessment of AZ91E

| Alloy | Status | *CSS* [1/s] | *CST* [1/°C] | Δ*ZKW* [°C] | *HTBR* [°C] |
|---|---|---|---|---|---|
| AZ91E | as-supplied | 0.27 | 0.001 | 270 | 206–476 |
| | OCI | 0.40 | 0.002 | 318 | 166–484 |
| | OCII | 0.11 | 0.004 | 324 | 157–481 |

## 4. Determination of susceptibility to hot cracking assuming a permanently rigid weld – Fisco test

The Fisco test provides conditions that simulate the actual repair welding process of strongly stiffened castings. For this test, the test pieces in the form of plates with the dimensions of 180×80×5 mm were rigidly fitted in a special instrument with a welding spacing of 2 mm (Fig. 8a). The plates were prepared without beveling (weld I), with ”Y” beveling and with ”V” beveling (Fig. 8b). Three beads were placed from right to left, one directly after another; the filler material was of similar chemical composition (Fig. 8c). The TIG welding was performed with an AC current intensity value ranging from 110 A to 130 A (Fig. 8d). For the alloy’s susceptibility to cracking under the conditions of permanent rigidity, the ratio of the length of all hot cracks to the length of all welds was assumed as a percentage relation. This ratio was designated as ”F”. The results are shown in graphic form in Fig. 9.

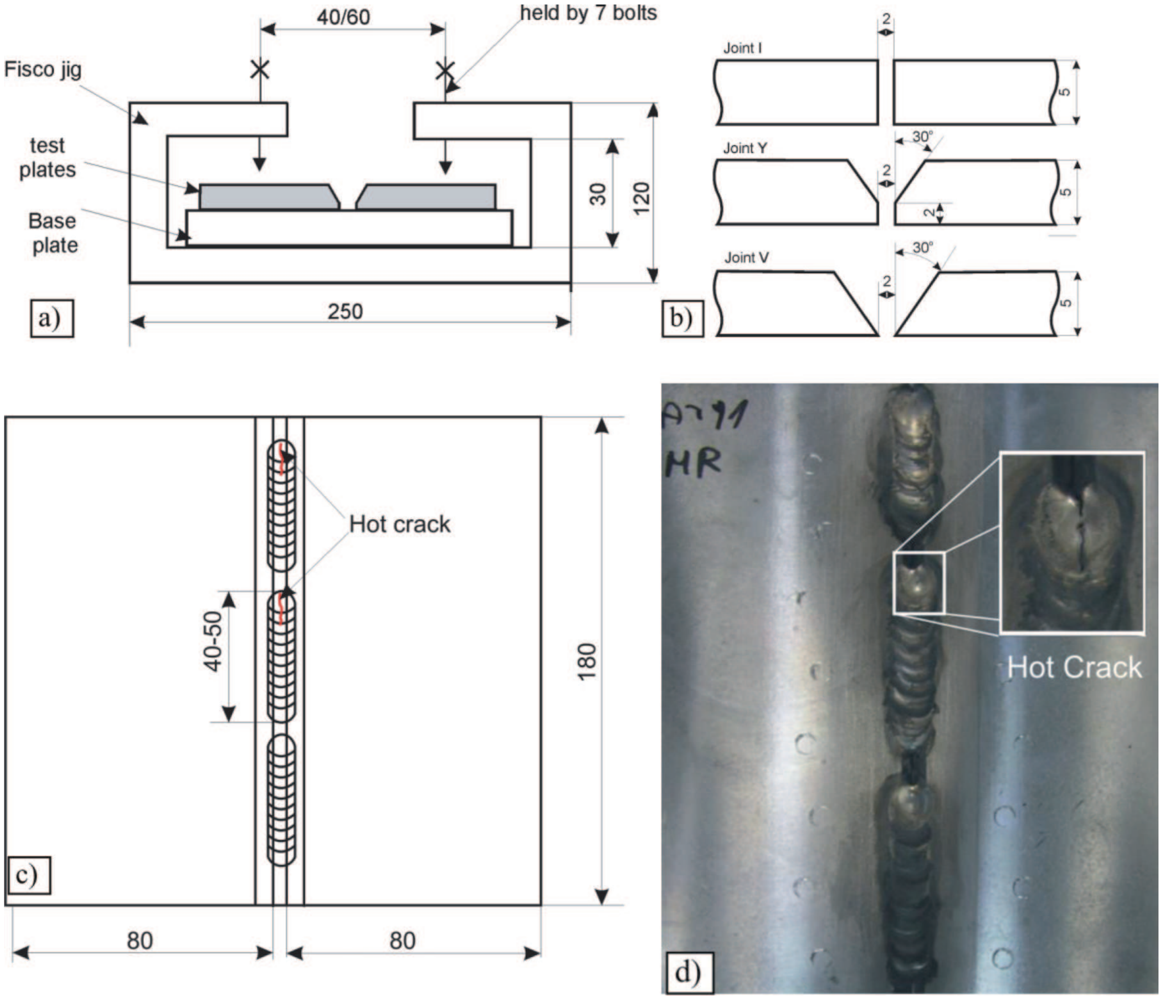

Fig. 8. Fisco test scheme and results: a) basic dimensions of the instrument, b) beveling of test plates, c) position of beads and d) hot cracks of AZ91E alloy after casting

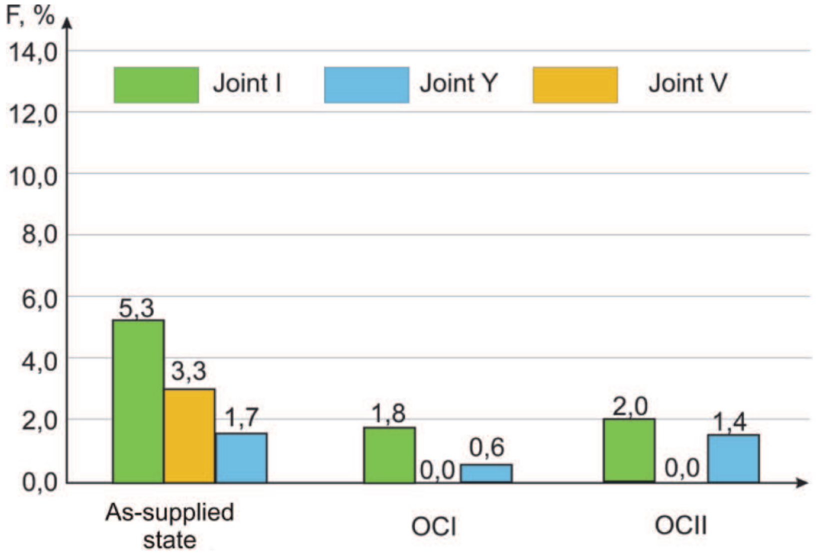

Fig. 9. Assessment of susceptibility of AZ91E alloy to hot cracking under the conditions of permanent rigidity – Fisco test

The analysis of the Fisco test results indicates that the AZ91E alloy is susceptible to hot cracking under permanent stiffening of the casting in the as-supplied condition (F ratio ranges from 1.9% to 3.3%), as well as after supersaturation and ageing (F ratio ranges from 0.9% to 4.3%), regardless of the weld type. Therefore, it is best to pad or weld this alloy after supersaturation (F ratio does not exceed 1%) (Fig. 9).

## 5. Determination of susceptibility to hot cracking with variable rigidity of the weld – Houldcroft test

Testing the susceptibility to hot cracking of magnesium alloy castings, assuming variable rigidity of the weld, was performed by means of the Houldcroft test. The Houldcroft test involves the remelting of plates with a nonconsumable electrode in a neutral gas shield (TIG method) with or without an additional material. One characteristic feature is cut on the plates, which simulates variable rigidity of the element during welding. As a measure of the alloy's resistance to cracking the value the ratio of the crack length to the length of sample (A), and expressed in percentage, was taken.

For the tests three plates of AZ91E alloy in the as-supplied and after heat treatment conditions were used. The sample preparation methods involved remelting without additional material, hereinafter referred to as remelting, as shown in Fig. 10a, and remelting with additional material, hereinafter referred to as pad welding, as shown in Fig. 10b. Dimensions of samples and parameters for the remelting process are shown in table 3. After the Houldcroft test, sample plates had visible cracks, shown in Fig. 11. The results in the form of bar graphs are presented in Fig. 12.

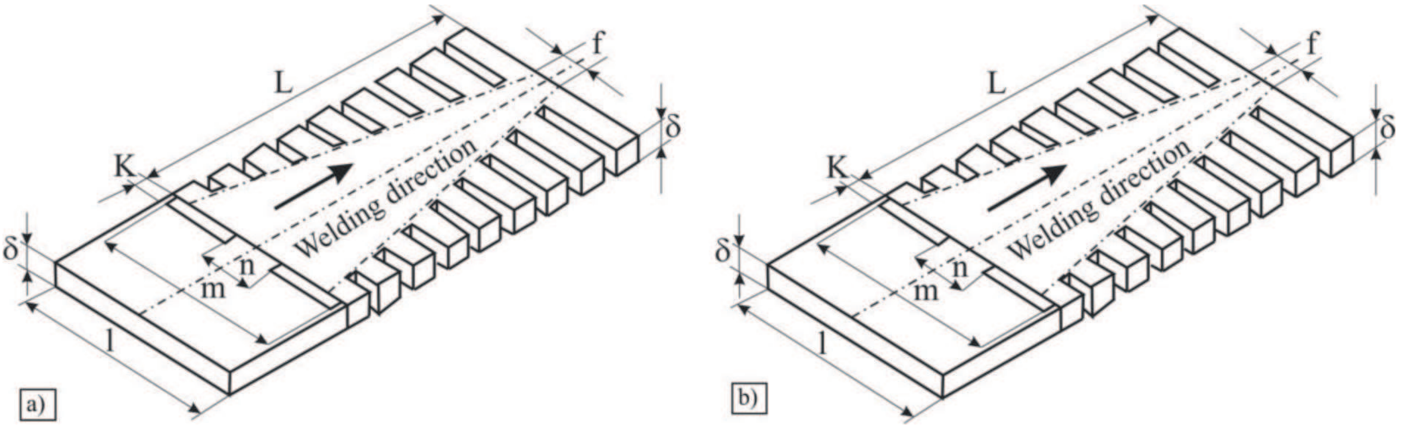

Fig. 10. Plates for the Houldcroft test: a) remelting without additional material and b) remelting with additional material [15]

TABLE 3

Dimensions of samples and parameters for the remelting process

<table>
<tr><th colspan="13">Sample dimensions, mm</th></tr>
<tr><td>$\delta$</td><td>L</td><td>L</td><td>d</td><td>f</td><td>B</td><td>C</td><td>H</td><td>R</td><td>b</td><td>M</td><td>N</td><td>K</td></tr>
<tr><td>4.0</td><td>131.0</td><td>78.0</td><td>64.0</td><td>7.0</td><td>15.0</td><td>1.6</td><td>2.0</td><td>4.0</td><td>44.0</td><td>72.0</td><td>26.0</td><td>1.0</td></tr>
<tr><th colspan="13">Parameters of remelting process</th></tr>
<tr><td colspan="2">Current intensity, A</td><td colspan="2">Arc voltage, V</td><td colspan="2">Welding speed, cm/min</td><td colspan="2">Stream of gas volume, l/min</td><td colspan="2">Gas nozzle diameter, mm</td><td colspan="3">Type and diameter of tungsten electrode</td></tr>
<tr><td colspan="2">110</td><td colspan="2">15</td><td colspan="2">18</td><td colspan="2">12</td><td colspan="2">12</td><td colspan="3">WT10, 3.2</td></tr>
</table>

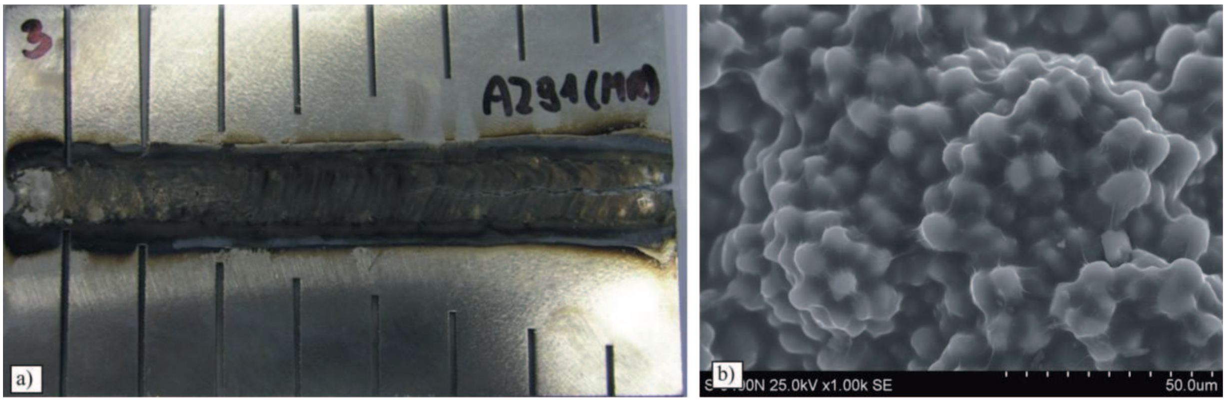

Fig. 11. AZ91E plates after remelting test with additional material (Houldcroft test): a) remelting face and b) fracture surface, SE

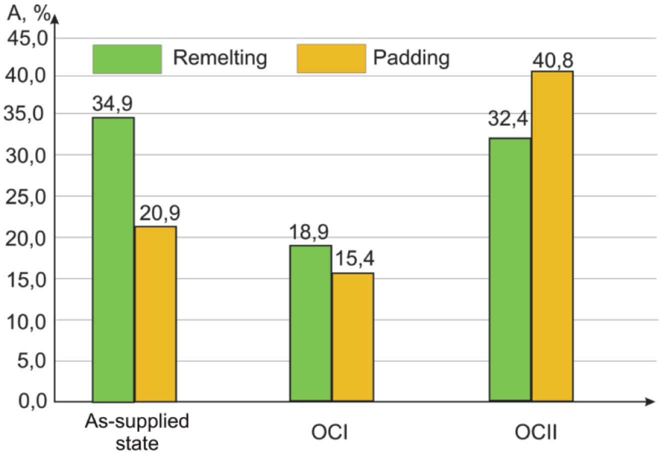

Fig. 12. Results of the Houldcroft test

The analysis of the Houldcroft test results for the AZ91E alloy in the as-supplied condition indicates that during pad welding, this material is less susceptible to hot cracking by approximately 40% versus remelting (Fig. 11, 12). The alloy's slight tendency for breaking occured after supersaturation (OCI) condition. The alloy's susceptibility to hot cracking is the result of dissolution of the massive $Mg_{17}Al_{12}$ phase, and for the alloy that underwent OCI, the susceptibility drops for both the remelting (A=18.9%) and pad welding (A=15.4%) processes (Fig. 12). Ageing (OCII), which is supposed to strengthen the AZ91E alloy, causes, however, a significant increase in susceptibility to cracking. The alloy's susceptibility to cracking during remelting after the OCII increases approximately 1.7 times that of the alloy after supersaturation. On the other hand, the aged alloy's susceptibility to hot cracking during pad welding increases almost 2.7 times (Fig. 12). This is due to precipitation of the lamellar $Mg_{17}Al_{12}$ phase on the boundaries of the Mg ($\alpha$) solid solution (Fig. 11b). Therefore, AZ91E alloy castings under the conditions of variable rigidity should be repaired with welding techniques after supersaturation.

## 6. Analysis of the results

Based on the literature data, one can assume that construction factors affecting the resistance to hot cracking are the casting shape and its rigidity.

Transvarestraint tests for susceptibility to hot cracking of magnesium AZ91E alloy castings during remelting and subjected to a forced strain were conducted (Fig. 3). This test allows the determination of *HTBR* under the conditions of forced strain (Fig. 4). This type of strain is typical when castings are repaired by welding techniques. An analysis of the literature as well as the phenomena taking place during weld crystallization indicates that *HTBR* should be defined as the difference between the nil-strength temperature (*NST*) of the alloy and the temperature at the end of the longest hot crack ($T_k$). From the test one can also calculate the critical strain speed *CSS* and the critical strain intensity *CST* (Table 2). During welding, the critical strain speed is the value, which if exceeded, the alloy cracks hot. Also, too fast an increase in strain during the welding process causes cracking of the alloy. The criterion is the critical strain intensity *CST*.

The analysis of the dependence of crack formation time on the strain ($t_{\max} = \mathrm{f}\ (\varepsilon)$) for the AZ91E alloy helped with calculating the alloy's critical strain speed in the as-supplied condition (*CSS* = 0.27 1/s, Fig. 6a), after supersaturation (*CSS* = 0.40 1/s) and after ageing (*CSS* = 0.11 1/s) (Table 2). Therefore, the AZ91E alloy after supersaturation (OCI) is characterized by the greatest acceptable strain speed during remelting. The plasticity curves of AZ91E alloy in each heat treatment condition are exponential (Fig. 6b). The range of high-temperature brittleness for the alloy in the as-supplied condition is 270°C (from 206°C to 476°C) (Fig. 6b). After supersaturation the *HTBR* range increases to 310°C (from 166°C to 484°C), and after ageing it still increases by 6°C (from 157°C to 481°C) (Table 2). Therefore, heat treating the alloy during remelting under forced strain conditions has a significant impact on the *HTBR* range. However, an analysis of the critical temperature intensity of strain (*CST*) – which is 0.12 1/°C for the as-supplied condition, 0.11 1/°C after supersaturation (OC I) and 0.04 1/°C after ageing (OC II) – indicates that AZ91E alloy is particularly difficult to weld after precipitation hardening (Table 2).

Metallographic examinations revealed that hot cracks, formed during remelting in the transvarestraint test, developed in an intercrystalline manner throughout the melted $Mg_{17}Al_{12}$ phase (Fig. 7a). The alloy in the as-supplied condition cracked in areas containing the massive $Mg_{17}Al_{12}$ phase (Fig. 7a). After supersaturation, the cracking initiated in areas with the undissolved $Mg_{17}Al_{12}$ phase and formed small cracks that eventually joined the main crack. A similar mechanism of cracking occurred in the material after precipitation hardening (OC II). Fractographic testing of the crack surface in all cases revealed a small dendritic system with the crystallized phase $Mg_{17}Al_{12}$ visible (Fig. 7b).

An assessment of the susceptibility to hot cracking under permanent rigidity conditions (Fisco test) showed that the AZ91E alloy is susceptible to cracking in the as-supplied condition, regardless of the type of weld (Fig. 9). The slightest susceptibility to hot cracking under such conditions is characteristic for the AZ91E alloy that was supersaturated (Fig. 9). Under the strong stiffening conditions (gravity castings), repair work with welding techniques should be conducted after supersaturation of the casting.

Analysis of the results from the Houldcroft test, which simulates the variable rigidity conditions the casting undergoes, indicates that the AZ91E alloy is susceptible to hot cracking during both pad welding and welding (Fig. 11, 12). Castings of the AZ91E alloy should be repaired after supersaturation using welding techniques, due to the presence of even the smallest volume fraction of the $Mg_{17}Al_{12}$ phase. This stage dominates the cracking process, which is proven by its presence on the surface of the weld's crystals (Fig. 12).

Therefore, the AZ91E alloy is most resistant to hot cracking after supersaturation. This is mainly due to the single-phase Mg ($\alpha$) structure that has a few precipitates, undissolved massive $Mg_{12}Al_{17}$ phase. Based on the results from the transvarestraint, the Fisco and Houldcroft tests and under the forced strain conditions, AZ91E alloy should be welded or pad welded after OCI (24h/415°C/air/heating 50°C/h).

## 7. Conclusions

Based on the test results and their analyses, the following conclusions can be formulated:

- Casting strains are characteristic of the pad welding and welding processes. An assessment of the AZ91E alloy's susceptibility to hot cracking under the conditions of forced strain (transvarestraint test) allows the determination of the range of high-temperature brittleness (HTBR), critical strain speed of the weld (CSS) and critical temperature strain intensity (CST).

These parameters specify the hot cracking criteria for the AZ91E alloy welds; therefore, they are indicators of the alloy's weldability.

- AZ91E alloy castings with constant rigidity should be classified as easily weldable. On the other hand, castings with variable rigidity, resulting from, e.g., diverse wall thicknesses, cause a significant increase in the alloy's susceptibility to hot cracking.
- The loss of cohesion in the repaired joints of the AZ91E alloy castings occurs as a result of treating the melted thin layer of the massive $Mg_{17}Al_{12}$ phase and the consequent breaking of the initially melted dendrites in the magnesium $Mg(\alpha)$ solid solution.
- Thermal treatment of gravity castings affects the weldability of the AZ91E alloy. Gravity castings should therefore be pad welded or welded by the TIG method, and the filler metal should have a chemical composition similar to the supersaturated basic material. A linear arc energy in the range from 3.0 kJ/cm to 4.0 kJ/cm should be used.

**Acknowledgements**

The study has been financed by the Ministry of Science and Higher Education within the project PBR N R15-0015-04/2008 "Phenomena Accompanying Crystallization of Cast Magnesium Alloys Determining the High-temperature Brittleness".

## REFERENCES

[1] J. Pilarczyk, Welding Handbook **1**, Wydawnictwo Naukowo-Techniczne, Warszawa (2003).

[2] Joining of magnesium alloys, Data sheet 250, Magnesium Elektron, Wielka Brytania, (2006).

[3] A. Ambroziak, K. Zin, Joining of magnesium and their alloys. Joining, HMR–Trans, 13-17 (2007).

[4] M. Rethmeier, B. Kleinpeter, H. Wohlfarht, MIG welding of magnesium alloys—metallographic aspects, document MIS IX-2083-03, 1-7 (2003).

[5] L.M. Liu, D.H. Cai, D.H. Zahng, Gas tungsten arc welding of magnesium alloy using activated flux-coated wire, Scr. Mater. **57**, 695-698 (2007).

[6] B. Ścibisz, J. Adamiec, Evaluation of susceptibility to hot cracking of WE43 magnesium alloy welds in transvarestraint test, Archives of metallurgy and materials, **55**, 1, 131-141 (2010).

[7] J. Adamiec, S. Mucha, Investigation of susceptibility to hot cracking of MSR-B magnesium alloy. IOP Conf. Series: Materials Science and Engineering **7**, 1-11 (2010).

[8] N.N. Prokhorov, The problem of the strength of metals while solidifying during welding, Svar Proiz **6**, 5-11 (1960).

[9] Elektron AZ91E, Data sheet 456, Magnesium Elektron, (2006).

[10] T. Chabko, J. Adamiec, The structures and properties of repairing welds of the AZ91 magnesium alloy, 16th ISDM Proceedings, 6, (2009).

[11] J. Adamiec, T. Chabko, Influence of parameters of the FSW (Friction Stir Welding) process on structure and properties of Mg-alloys joints, 15 th ISDM Proceedings, (2008).

[12] J. Adamiec, T. Chabko, Problems during welding and padding of magnesium alloy AZ91D, Joining, HMR—Trans, 20-23 (2007, 2009).

[13] S. Roskosz, J. Adamiec, Quantitative description of Mg-Al alloy structure, Acta Metallurgica Slovaca **13**, 102-107 (2007).

[14] Wang Yeshuang, Sun Baode, Wang Qudong, Zhu Yanping, Ding Wenjiang, An Understanding of solidification of AZ91, Mater. Lett. **53**, 1-2, 35-39 (2002).

[15] J. Adamiec, Weldability of casting magnesium alloys, published by Silesian University of Technology, Gliwice, Poland (2010).

*Received: 10 February 2011.*