ARCHIVES OF METALLURGY AND MATERIALS
Volume 56 2011 Issue 3
DOI: 10.2478/v10172-011-0083-z

D. MIARA*, A. PIETRAS*, K. MROCZKA**

# MICROSTRUCTURE AND PROPERTIES OF FRICTION STIR BUTT-WELDED MAGNESIUM CASTING ALLOYS

# STRUKTURA I WŁAŚCIWOŚCI ODLEWNICZYCH STOPÓW MAGNEZU ZGRZEWANYCH DOCZOŁOWO METODĄ FSW

The article presents results of testing the quality of FSW welded joints made in plates of various magnesium casting alloys, including MCMgAl9Zn1 (AZ91), MCMgRe3Zn2Zr (ZRE1), MCMgRe2Ag2Zr (MSR-B) and MCMgY4Re3Zr (WE43). In this paper, all results for magnesium casting alloy AZ91 are presented, whereas for other alloys (ZRE1, MSR-B and WE43) only selected testing results for best parameters have been chosen and shown. Butt joints were produced on the friction welding machine built on the base of the conventional vertical milling machine. Quality assessment included the visual inspection, temperature measurements in welding region, tensile strength testing, analysis of the weld structure, hardness, weld force and torque measurements. Research aimed at the recognition of the FSW abilities to weld cast magnesium alloys, the influence of the welding conditions on the welds' properties as well as their structures. The research results have revealed that cast magnesium alloys are weldable using FSW process – it is possible to produce joints of very good quality in relatively narrow range of parameters and the strength of the joints is satisfactory. In order to acquire joints of the best quality it is recommended that workpieces should be rigidly clamped and the welding speed should be limited. The best mechanical properties have been obtained for friction with rotation speed of 355 rpm.

*Keywords*: friction stir welding, FSW welding, cast magnesium alloy

W artykule przedstawiono wyniki badań jakości złączy, wykonanych metodą zgrzewania tarciowego z mieszaniem materiału zgrzeiny (FSW), odlewniczych stopów magnezu MCMgAl9Zn1 (AZ91), MCMgRe3Zn2Zr (ZRE1), MCMgRe2Ag2Zr (MSR-B), MCMgY4Re3Zr (WE43). Złącza wykonywano na zgrzewarce zbudowanej na bazie frezarki konwencjonalnej. Ocenę jakości złączy przeprowadzono w oparciu o badania wizualne, pomiary temperatury obszaru zgrzewania, badania szczelności złączy metodą penetracyjną, badania wytrzymałości na rozciąganie, analizę budowy strukturalnej zgrzein, badania twardości. Celem badań było poznanie możliwości zgrzewania FSW odlewniczych stopów magnezu, wpływu warunków zgrzewania na własności złączy oraz budowę strukturalną zgrzein. Wyniki badań wskazują na dobrą zgrzewalność odlewniczych stopów magnezu metodą FSW – poprawne złącza można uzyskać w stosunkowo wąskim zakresie parametrów zgrzewania, a wytrzymałość tych złączy jest zadowalająca. W celu uzyskania złączy o najwyższej jakości elementy muszą być dociśnięte do siebie, a proces zgrzewania nie może być prowadzony z nadmierną prędkością. Najlepsze własności wytrzymałościowe uzyskano prowadząc proces tarcia z prędkością obrotową narzędzia 355 obr/min.

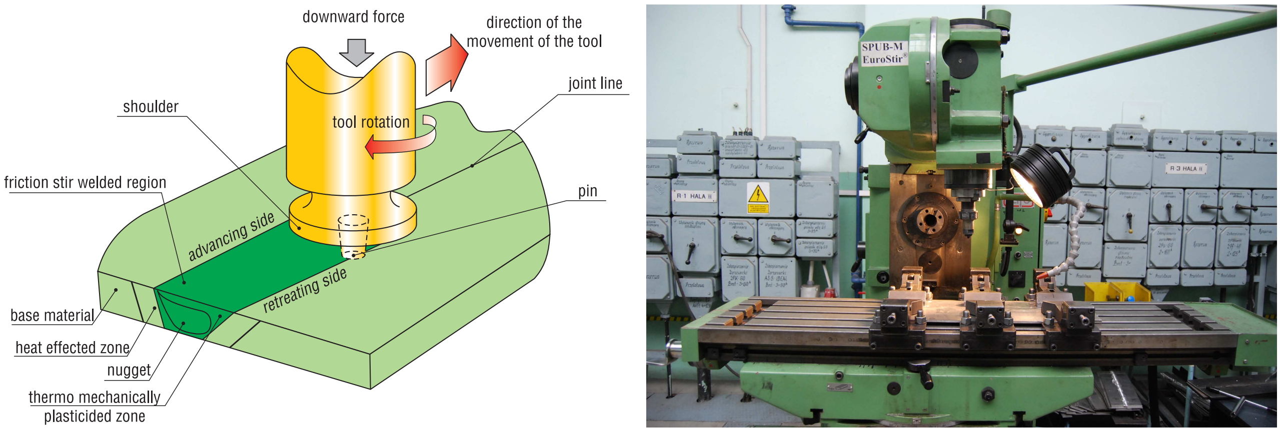
## 1. Introduction

Magnesium alloys have many advantages, such as low density and high specific strength. It is predicted that the application of magnesium alloys will grow rapidly in the near future, especially in the transport industry. With fast development and wide applications, the welding of magnesium alloys becomes a main concern.

FSW process (Friction Stir Welding) is more and more popular method of joining of various structural materials. FSW is a solid state joining technique, developed at TWI in 1991, for which two blanks are joined by inserting a specially designed rotating pin into the adjoining edges of the sheets to be welded and then moving it all along the welding line. The principle of friction stir welding process and the station designed at Instytut Spawalnictwa in Gliwice are shown in Fig. 1. In case of magnesium casting alloys a tool is made of high-speed tool steel. The method is very promising as it makes possible to join efficiently difficult to weld magnesium alloys in any configuration [1, 2, 3]. Due to high cost of a tool for stirring material of the weld, the FSW method application for joining steel, titanium and other materials of high plasticisation temperature is still in the stage of laboratory testing [4].

---

* INSTYTUTE OF WELDING, DEPARTMENT OF RESISTANCE AND FRICTION WELDING AND ENVIRONMENTAL ENGINEERING, 44-100 GLIWICE, 16-18 BL. CZESLAWA STR., POLAND
** PEDAGOGICAL UNIVERSITY OF CRACOW. INSTITUTE OF TECHNOLOGY, 30-084 KRAKÓW, 2 PODCHORĄŻYCH STR., POLAND



a) b)

Fig. 1. General description of FSW method: a) the principle of FSW welding, b) welding station built in Instytut Spawalnictwa in Gliwice

Research presented in this paper is a part of works on the assessment of the impact of welding conditions on a weld quality while welding using conventional milling machines. Issues of the FSW welding are under the development at various research centres [5, 6, 7].

## 2. Research into the conditions of FSW process

### 2.1. Testing station and materials

Testing equipment at Instytut Spawalnictwa in Gliwice has been built on the basis of the conventional FYF32JU2 milling machine. Tests were conducted using a conical tool equipped with a probe feature in a form of screwed pin. This tool is made of tungsten-molybdenum high-speed steel (SW7M).

Research was conducted on following magnesium casting alloys: MCMgAl9Zn1 (AZ91), MCMgRe3Zn2Zr (ZRE1), MCMgRe2Ag2Zr (MSR-B) and MCMgY4Re3Zr (WE43). Aluminium plays the most important role in the chemical constitution of those magnesium alloys as it improves tensile strength of alloys in the room temperature, as well as their hardness and elongation. The increase in the aluminium content then results in the reduction of ductility as a consequence of the growing number of brittle phases $\beta$-$Mg_{17}Al_{12}$or $Al_8Mn_5$. Aluminium also improves casting properties of alloys. Zinc improves the resistance to corrosion caused by Fe and Ni impurities as well as tensile strength of the alloys [8]. It is also used for the enhancement of alloys castability. Manganese and silicon occurrence in magnesium alloys increase their corrosion resistance.

During the investigations 6.0 mm thick plates were rigidly clamped using special fixtures in welding machine and butt welded without cleaning the contact surfaces.

The paper presents results of research into FSW butt welding of various 6 mm thick magnesium alloys plates. Welding parameters applied while testing are shown in Table 1.

TABLE 1
Parameters for welding of AZ91, ZRE1, MSR-B and WE43 magnesium casting alloys plates of 6 mm in thickness

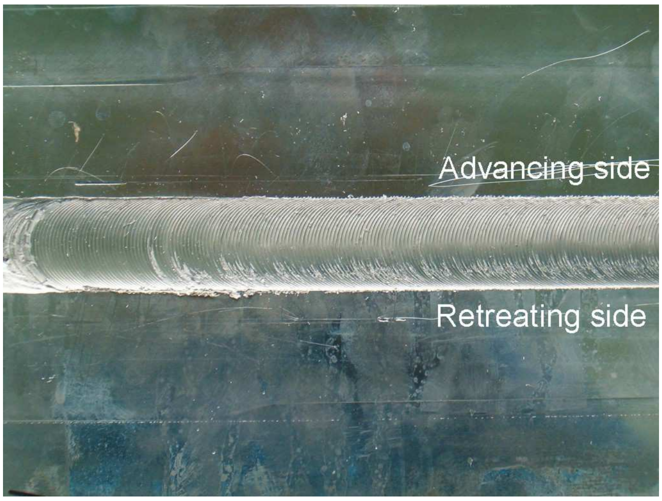
| **No.** | Tool dimensions | **Rotation speed, rpm** | **Travel speed, mm/min** | **Welding type** |
|---|---|---|---|---|
| 1 | – Diameter of the pin: Ø8 mm,<br>– Length of the pin: 5.8 mm,<br>– Diameter of the shoulder: Ø24 mm. | 355 | 180 | one side |
| 2 | | 355 | 224 | one side |
| 3 | | 355 | 280 | one side |
| 4 | | 355 | 355 | one side |

### 2.2. Visual inspection of welds

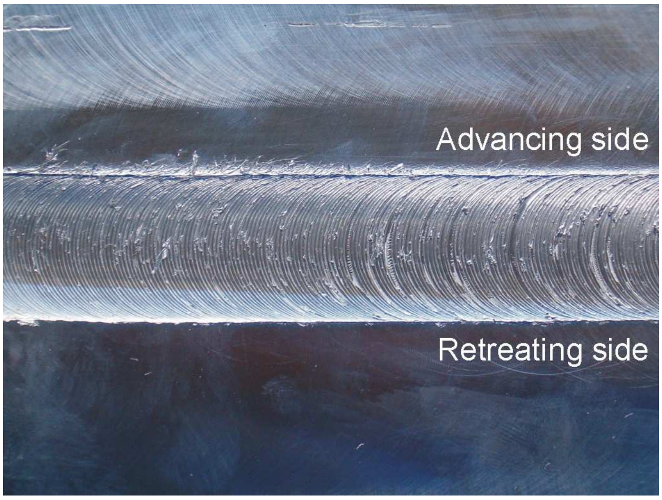
In the initial stage of research, welding speed value that resulted in proper formation of weld face as well as forces and moments acceptable for friction welding machine have been determined for the range of welding rotation speeds being tested. Welds produced at the selected range of parameters were subjected to the routine non-destructive tests, including visual examination.

Welding process while testing of selected materials had similar run – a stable and proper process of FSW joints formation was performed, with periodically occurring irregularity of surface and without sticking materials to the tool.

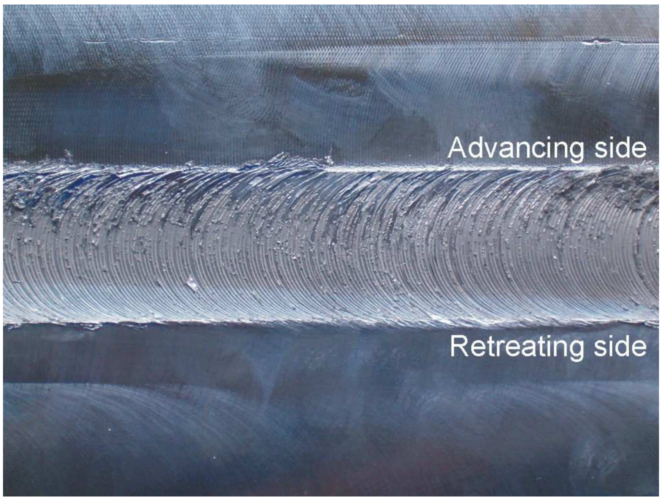
Research has revealed that joints have a proper weld face structure with the slight imprint of a shoulder and without significant discontinuities and deformations of materials. From face side there were no traces of the former contact line. The surface was continuous, smooth and without any discontinuities. Selected homogenous joints of AZ91, ZRE1, MSR-B and WE43 magnesium alloys are shown in Fig. 2.



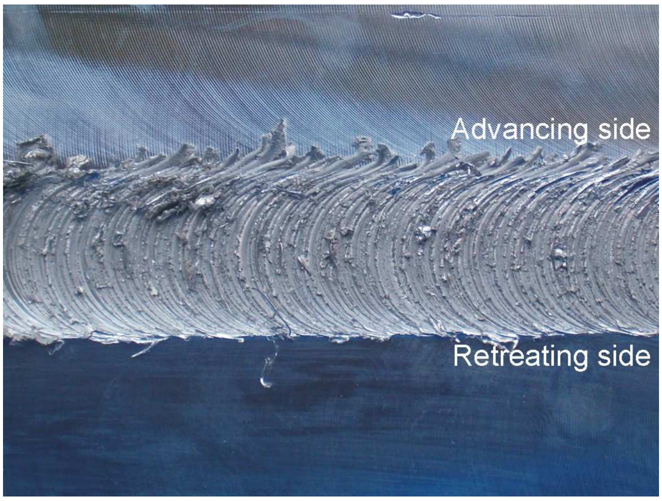
a)



b)



c)



d)

Fig. 2. Joints in magnesium casting alloys – view from the face side: a) AZ91 alloy, b) ZRE1 alloy, c) MSR-B alloy, d) WE43 alloy. Welding parameters – item 2 of Table 1

### 2.3. Temperature measurements in weld area

While welding, measurements of temperature of the upper surface of welding region (just after the tool passage) were conducted using non-contact pyrometer FLUKE 576 (Fig. 3).

Selected results of the plate surface temperature measurement directly after the tool passage are shown in Fig. 4 and Fig. 5.

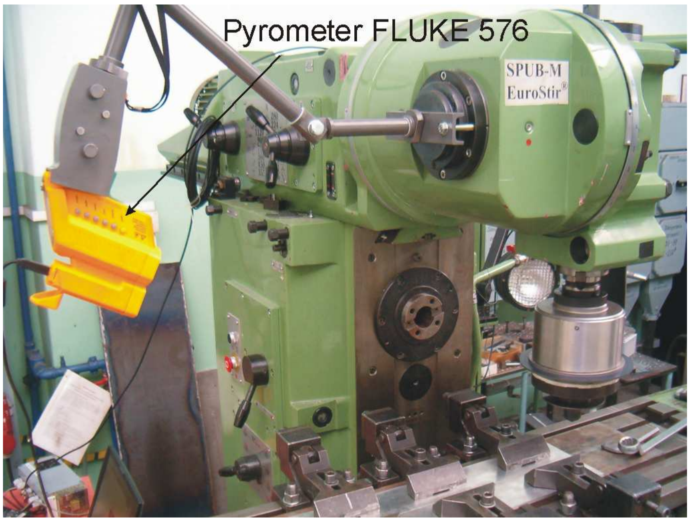


Fig. 3. Station for the temperature measurements of welding region: FLUKE 576 pyrometer used for measuring of temperature of weld face surface

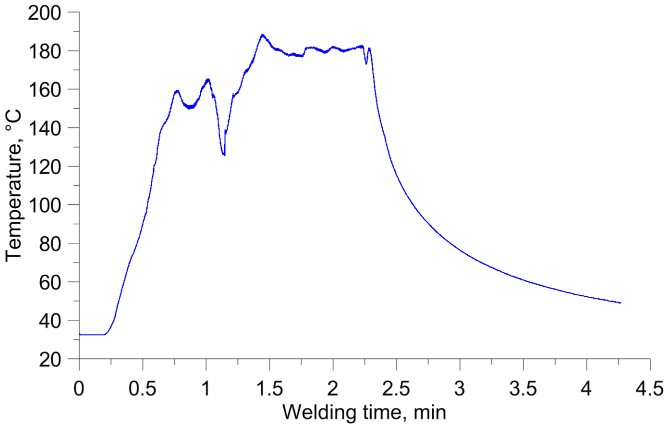


Fig. 4. Temperature curve of welding region in AZ91 magnesium alloy. Welding parameters – item 2 of Table 1

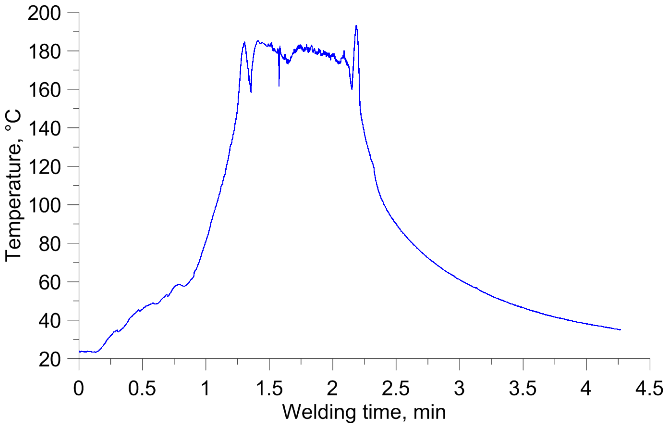


Fig. 5. Temperature curve of welding region in ZRE1 magnesium alloy. Welding parameters – item 2 of Table 1

The results of temperature measurements of welds face surface with pyrometer method have revealed that, for all four examined magnesium alloys, high and repeatable quality of joints can be achieved only if the temperature at the beginning of the process achieves the values of range of 150-160°C. Higher temperature in this stage of welding has negative impact on the quality of welds being produced as voids and discontinuities can be observed. Lower temperature means that welded pieces are heated and plasticised insufficiently which leads to machine cutting of materials with a tool in the line of welding. Moreover in the solid phase, i.e. after process stabilisation, in case of good quality of the joints for each examined alloys temperature of the surface of the welding area is in the range of 160-220°C. The highest stable temperature of 200-220°C of the face surface of a weld has been reached for WE43 alloy.

## 2.4. Strength of welded joints

AZ91 magnesium alloy was subjected to tensile strength testing. Due to the brittleness of the material, samples in the tensile strength testing conducted in accordance with a standard PN-EN ISO 6892-1:2010 [9] cracked in jaws of a testing machine or if the forces values were highly scattered, test pieces cracked outside the weld. Therefore in order to determine mechanical properties of thermo-mechanically plasticised material along a weld axis, samples of material, 12,5 mm wide (Fig. 6) were cut out and subjected to tension to failure on INSTRON 4210 testing machine.

Results of mechanical testing of welds in AZ91 alloy are shown in Table 2, where for the comparison purposes, medium values of tensile strength of AZ91 parent alloys are presented.

Tensile strength tests of a thermo-mechanically deformed weld material conducted only for AZ91 magnesium alloy have revealed that initially the tensile strength grows with the increased tool travel speed. Next as the speed increases the tensile strength declines because the tool fails to stir material masses. This situation happens when during the welding process temperature on the surface welding area exceeds 200°C. Too high temperature causes excessive heating and plasticisation of materials with the decrease of its mechanical properties.

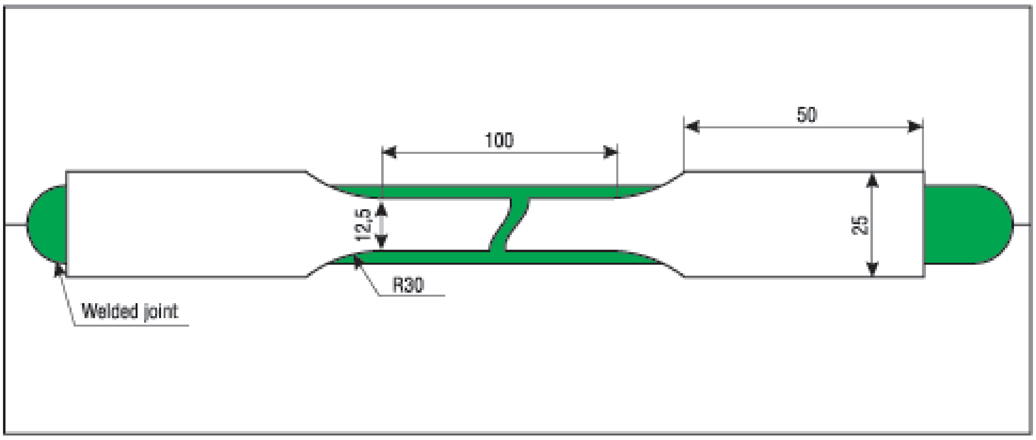
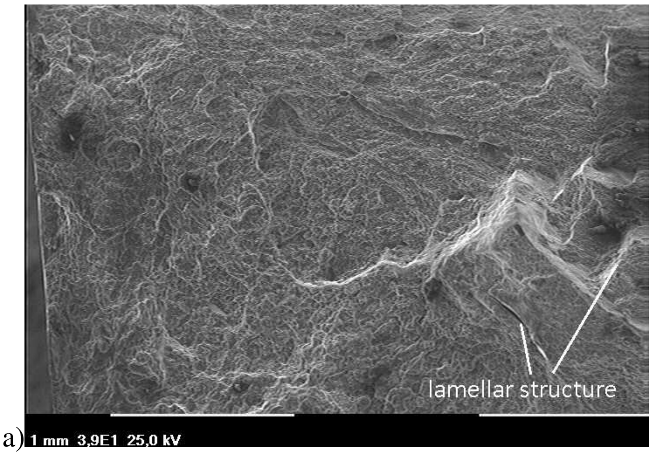


Fig. 6. Preparation (cutting out) of samples for mechanical testing: test pieces cut out along the weld axis – a part of a weld material plasticised thermo-mechanically

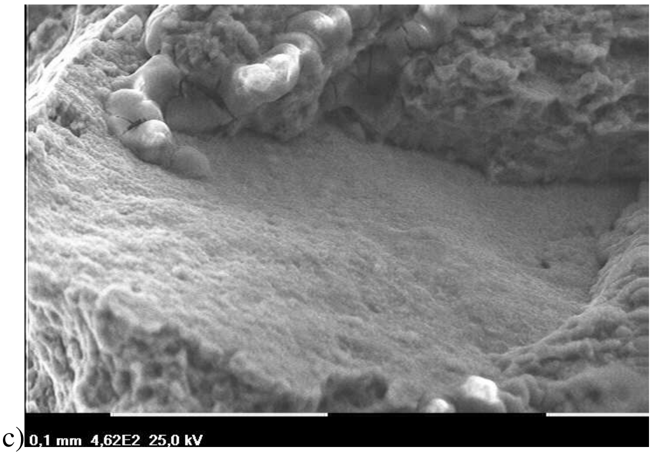
TABLE 2

Parameters of welding and mechanical properties of thermo-mechanically deformed AZ91 magnesium alloy

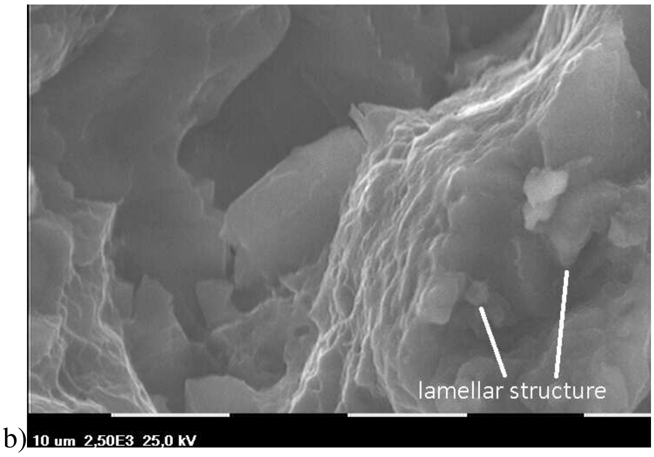
| No. | Process parameters Rotation, rpm / travel, mm/min | Average value of tensile strength Rm, MPa | Standard deviation $\sigma$ | Confidence interval |
|---|---|---|---|---|
| 1 | 355/180 | 133.4 | 12.25 | 119.54 < m < 147.26 |
| 2 | 355/224 | 228.8 | 2.08 | 226.45 < m < 231.15 |
| 3 | 355/280 | 184.5 | 3.67 | 180.35 < m < 188.65 |
| 4 | 355/355 | 189.0 | 8.88 | 178.96 < m < 199.04 |



a)



c)



b)

Fig. 7. SEM microstructures of the fracture in base material, HAZ and weld nugget (a, b, c respectively) obtained for AZ91 magnesium casting alloy

Topography of the fracture of test pieces, which were destroyed during technological tensile strength test was analysed using fractographic method. A fracture often shows the course of the destruction which helps to select the direction and scope of testing necessary to determine the reasons and kind of the failure. The fracture runs through the weakest area and therefore may reveal discontinuities in the material, such as: remains of shrinkage porosity, cavities, non-metallic inclusions, etc.

Results of examination conducted for points from base material, HAZ and weld nugget are shown as SEM microstructures in Fig. 7. These results have been obtained for fractures after tensile test of samples produced at rotation speed 355 rpm and travel speed 224 mm/min.

While analyzing sample fractures both alloy and HAZ brittle and lamellar structures can be observed (Fig. 7a and 7b). Crack along the plane of moving particular parts of metal in strongly mixed nugget is shown in Figure 7c. Bright areas illustrate $Mg_{17}Al_{12}$ phase particles, which improve casting and mechanical properties of alloy.

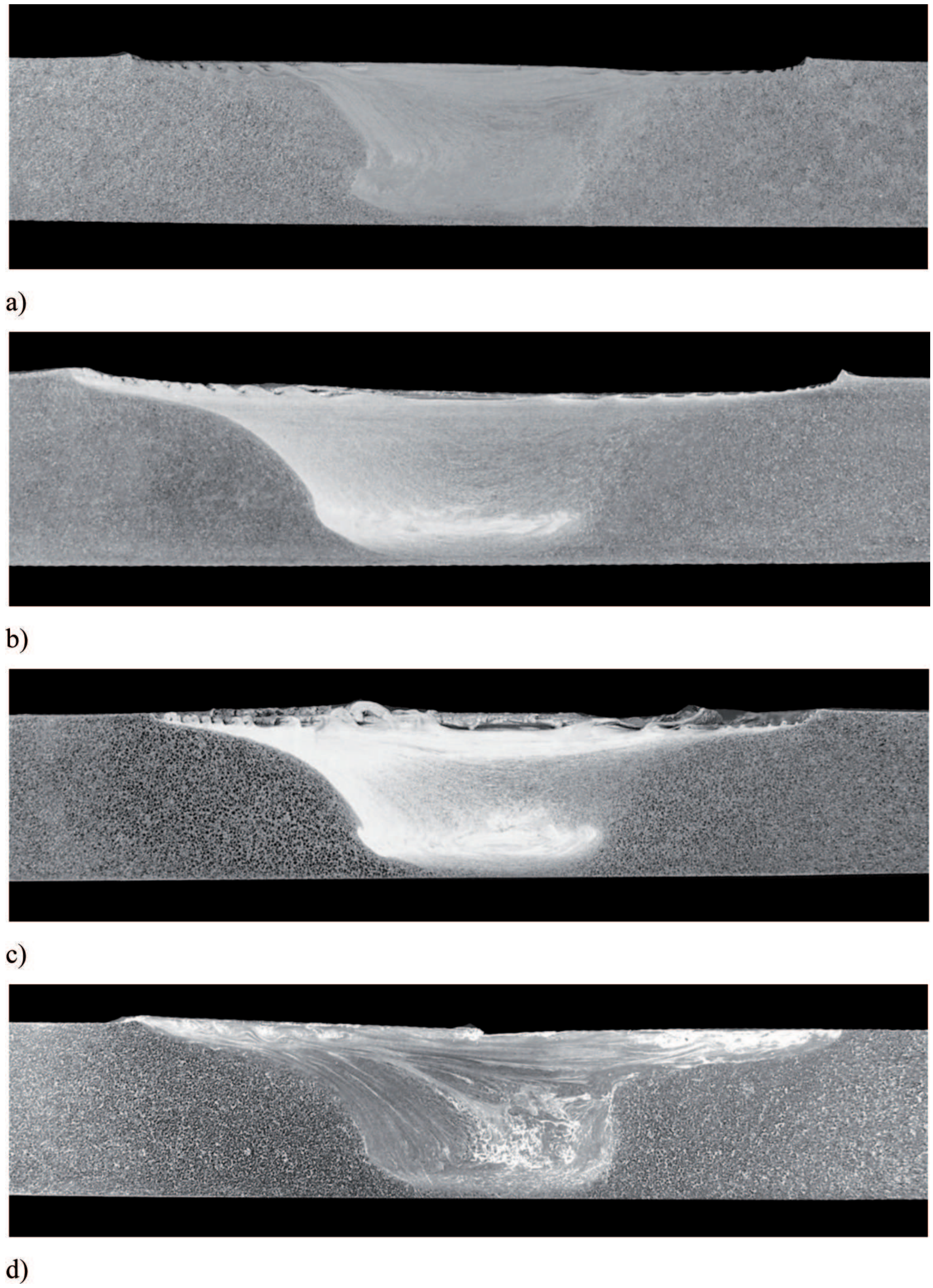


Fig. 8. Macrostructures of welds in magnesium casting alloys: a) AZ91 alloy, b) ZRE1 alloy, c) MSR-B alloy, d) WE43 alloy. Welding parameters – item 3 of Table 1. (Etching: Keller, Magn. 6x)

## 2.5. Structure of welds

Metallographic examination was conducted on LEICA MeF4M type optical microscope in accordance with a standard PN-EN 1321:2000 [10]. Samples were prepared so as to the examination area covered weld region, including heat affected zone, parent metal, weld nugget and the area affected by the shoulder.

The impact of a shoulder and a probe on the process of heating and forming of a weld depends on the welding speed. Each time a weld is of trapezoid shape. In Fig. 8 selected structures of welds produced using conical tool in similar welding conditions, i.e. for tool rotation speed of 355 rpm and travel speed of 280 mm/min are shown.

## 2.6. Hardness measurements using Vickers method

Hardness measurements using Vickers method were performed for AZ91 magnesium alloy for parent metal, weld region and heat affected zone. Point of measurements are marked in the Figures. The results are shown in the Fig. 9 and 10 and reveal that the characteristic is typical of FSW process – hardness increases in central regions of weld (nugget) and decreases in heat affected zone.

| Measuring line | HV5 hardness in separate measuring points | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| A - ■ | 58.5 | 64.4 | 59.0 | 69.4 | 70.0 | 74.0 | 72.1 | 74.0 | 72.4 | 77.8 | 75.5 | 66.9 | 65.5 | 69.4 | 67.4 |
| B - ● | | | | 69.4 | 70.5 | 73.3 | 75.2 | 72.6 | 72.5 | 67.8 | 63.3 | 59.5 | | | |

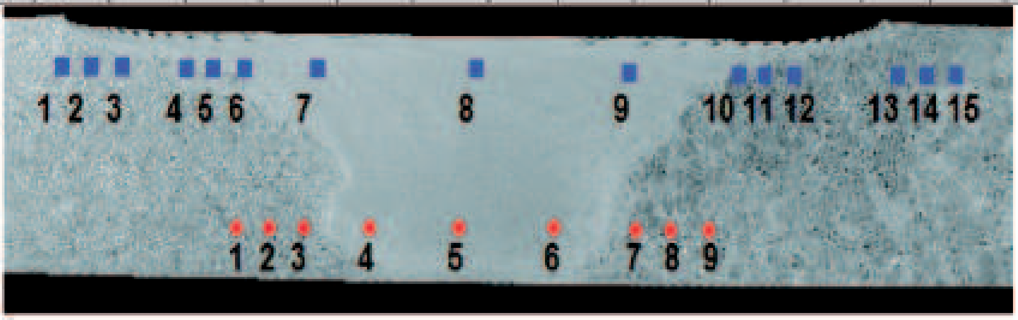


Fig. 9. Hardness measurement in sections of FSW joint. Conical tool. Welding parameters – item 2 of Table 1

| Measuring line | HV5 hardness in selected measuring points | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| A - ■ | 60.0 | 52.8 | 61.2 | 72.3 | 73.1 | 73.7 | 72.5 | 72.6 | 79.0 | 74.5 | 76.4 | 76.2 | 63.6 | 62.3 | 64.0 |
| B - ● | | | | 71.5 | 75.7 | 74.1 | 77.3 | 78.2 | 82.0 | 67.1 | 67.2 | 53.8 | | | |

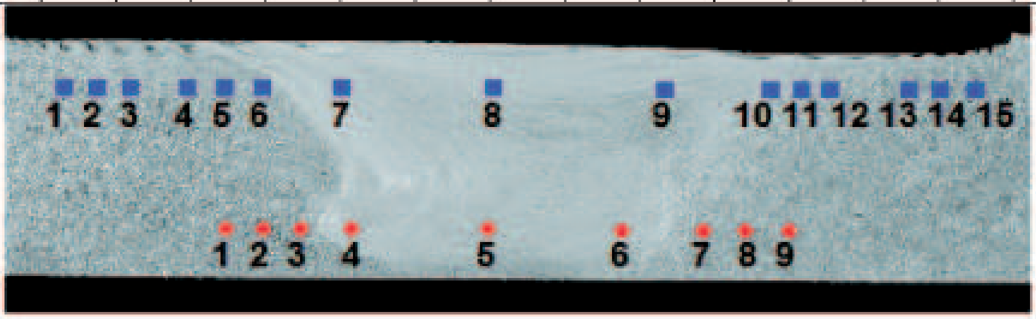


Fig. 10. Hardness measurement in sections of FSW joint. Conical tool. Welding parameters – item 3 of Table 1

### 2.7. Weld force and torque

During the welding process of AZ91, ZRE1, MSR-B and WE43 magnesium casting alloys weld force and torque measurements were made using LOWSTIR head. Measurements were performed for the whole length of joint with frequency of 100 Hz. Exemplary courses of the weld force and torque, which were registered during welding process of AZ91 and ZRE1 magnesium alloys are shown in Figures 11 and 12. These courses were registered during welding of plates with a thickness of 6.0 mm, tool rotation speed of 355 rpm and a travel speed in the weld direction of 224 mm/min.

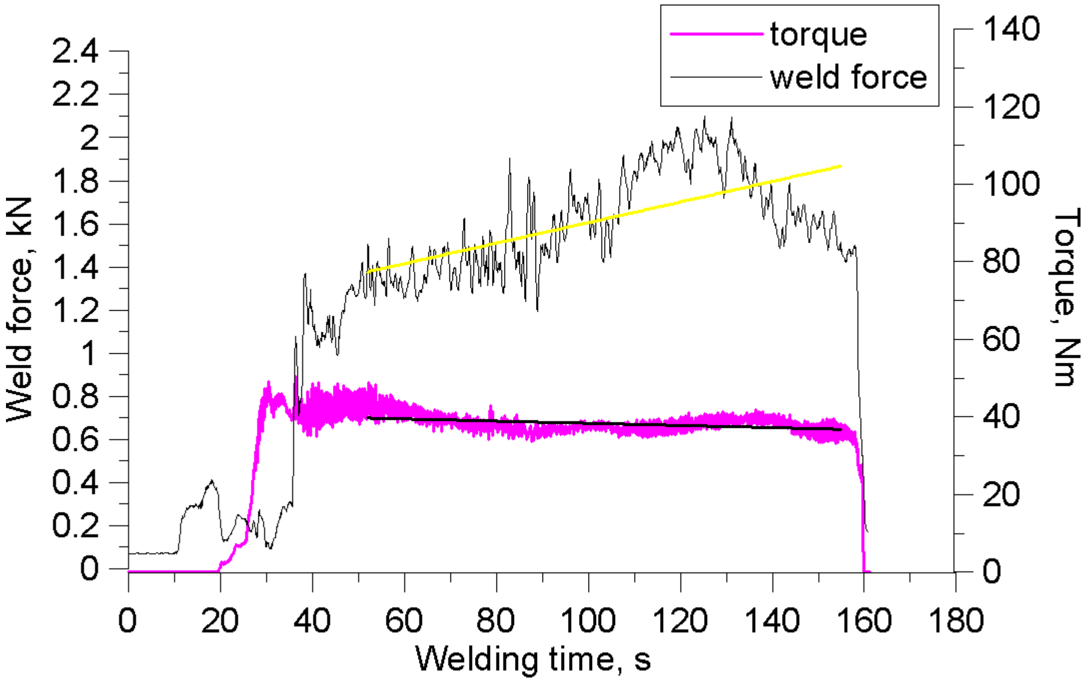


Fig. 11. Course of the weld force and torque, registered during welding process of AZ91 magnesium alloy using conical tool. Tool rotation speed: 355 rpm, travel speed in the weld direction: 224 mm/min

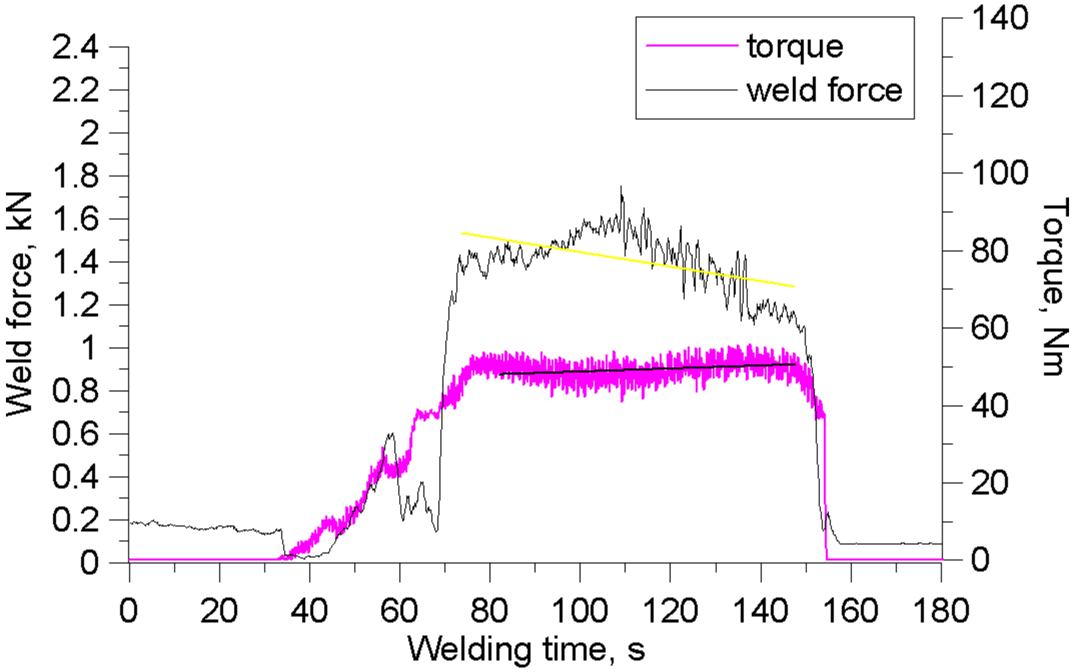


Fig. 12. Course of weld force and torque, registered during welding process of ZRE1 magnesium alloy using conical tool. Tool rotation speed: 355 rpm, travel speed in the weld direction: 224 mm/min

Weld force and torque values are close to zero in the initial area of the diagrams, which is connected with inserting tool into joining plates (Fig. 11 and 12). Growth of weld force and torque can be observed after starting of the tool travelling. Afterwards, the process is stabilised after appropriate plasticisation of welded material. Weld force and torque slightly decrease and from this moment their values are more or less on the same, constant level. This tendency occurs for all welding alloys, whereas values of weld force and torque depend on type of welding alloy. It can be seen that with the growth of travel speed, weld force also increase, which is connected with higher tool resistance during welding process. At the same time, in each case, growth of rotation moment can be observed and it is connected with higher plasticisation of masses of alloy being joined and consequently larger contact surface between tool and welding material.

## 3. Summary

Results of the investigation into FSW conducted at set welding speed but for various rotation speeds of a tool have revealed that good weld quality, that is reflected in the weld strength and structure, can be obtained for relatively large range of process parameters. For low rotation speed, heating and plasticising of material in weld region are influenced by the shoulder action and a weld takes on a trapezoid shape.

The results of temperature measurements using pyrometer have shown that the maximum temperature of a weld face surface, just behind the tool, vary between 160-220°C and mainly depends on rotation speed of a tool and speed of its plunging between welded edges.

Mechanical testing of thermo-mechanically deformed weld material show that the tensile strength of weld metal is higher than that of parent material. The elongation of thermo-mechanically deformed material during tensile test is 4-12 mm, while the strength increases by 45% when comparing to that of the parent metal.

Fractography examination has revealed that the AZ91 magnesium alloy structure is brittle with locally occurring areas of higher ductility.

The hardness survey of the welds have shown typical behaviour of FSW joints – hardness increases in central region of a weld (nugget) and decreases in HAZ. On the weld face side, hardness is slightly higher than on the root side. This is the result of the action of the tool shoulder which exerts an impact on the weld from the face side.

Research has revealed that magnesium casting alloys can be successfully welded with FSW method at relatively narrow range of welding parameters. Good quality of joints can be obtained if basic conditions of correct welding process are maintained.

Weld force and torque measurements which were made during welding process using LOWSTIR head have shown that while plunging a tool into the line between plates being joined both parameters are initially close to zero. Then, their growth can be observed and after stabilisation of welding process, these parameters are more or less on the same, constant level.

## 4. Conclusions

The results of this investigation have revealed that:

1. the FSW process successfully plasticises materials in the weld region of magnesium alloys being tested,
2. thermo-mechanically deformed weld material shows higher tensile strength than parent metal. Thermo-mechanical deformation of the material in the weld region and formation of a weld are proper at the relatively narrow range of FSW temperatures,
3. minimum temperature of weld surface behind the shoulder, which ensures welds of proper structure and face of a weld is 150°C,
4. in case of properly selected conditions for process performance, the weld has characteristic trapezoid structure,
5. selection of adequate parameters of FSW welding process ensures high quality of welds (high strength and compact weld structure).

Article was formed on base of results of research work no Bb-104 done in Instytut Spawalnictwa in Gliwice, which was financed by Ministry of Science and Higher Education.

REFERENCES

[1] M.St. Węglowski, A. Pietras, A. Węglowska, Effect of Welding parameters on mechanical and macrostructural properties of al. 2024 joints produced by friction stir welding. Journal of KONES and Transport **16**, 1 (2009).

[2] M.J. Rusell, S.A. Lockyer, Mechanical Properties of Friction Stir Welds in Magnesium Alloys. TWI, Cambridge UK, (2000).

[3] J. Adamiec, L. Zadroga, T. Chabko, Structure and properties of the AZ91 magnesium alloy welds created with the use of Friction Stir Welding (FSW). Inżynieria Materiałowa nr 4/2008, Warszawa (2008).

[4] C. Hamilton, S. Dymek, M. Blicharski, Friction Stir Welding of Aluminum 7136-T76511 Extrusions, Archives of Metallurgy and Materials **53**, 1047 (2008).

[5] H.K. D.H. Bhadeshia, Friction Stir Welding. Cambridge, (2002).

[6] G.J. Fernandez, L.E. Murr, Characterization of tool wear and weld optimization in the friction-stir welding of cast aluminum 359+20% SiC metal-matrix composite, Materials Characterization **52**, 1 (2004).

[7] Y.G. Kim, H. Fujii, T. Tsumura, T. Komazaki, K. Nakata, Effect of welding parameters on microstructure in the stir zone of FSW joints of aluminum die casting alloy, Materials Letters **60**, 29-30 (2006).

[8] L.A. Dobrzański, Metaloznawstwo opisowe stopów metali nieżelaznych. Wydawnictwo Politechniki Śląskiej. Gliwice (2008).

[9] PN-EN ISO 6892-1:2010. Metallic materials – Tensile testing – Part 1: Method of test at room temperature (ISO 6892-1:2009).

[10] PN-EN 1321:2000. Destructive tests on welds in metallic materials – Macroscopic and microscopic examination of welds.

*Received: 10 February 2011.*