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FRICTION STIR WELDING OF MAGNESIUM ALLOY TYPE AZ 31

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Abstract

The paper deals with welding of Mg alloy of the type AZ 31 by Friction Stir Welding technology (FSW). The FSW technology is at present predominantly used for welding light metals and alloys, as aluminium, magnesium and their alloys. Experimental part consists of performing the simulation and fabrication of welded joints on a new-installed welding equipment available at the Welding Research Institute - Industrial Institute of SR Bratislava. Welding tools made of tool steel type H 13 were used for welding experiments. Geometry of welding tools was designed on the base of literature knowledge. Suitable welding parameters and conditions were determined using numerical simulation. Main emphasis was laid upon the tool revolutions, welding speed and tool bevel angle. The effect of welding parameters on the quality of welded joints was assessed. Assessment of welded joints was carried out by radiography, light microscopy, hardness measurement and EDX microanalysis. Static tensile test was employed for mechanical testing.

Introduction

As well known, the Friction Stir Welding (FSW) process is defined as solid state welding at heating. The FSW method was invented by Thomas Wayne [1] at TWI (The Welding Institute) Abington in 1991. The first patent describes this technology as: „a way of joining parts, defining a common zone without occurrence of relative motion of parts welded“. Heating at FSW process takes place owing to friction and plastic strain of welded metals. Principle of welding by FSW process consists in the fact that a rotating tool with especially designed tip (in literature called as „pin“) is impressed into the boundary of parts welded [2-4], see Fig. 1. At FSW process, the transfer of mechanical energy to heat occurs.

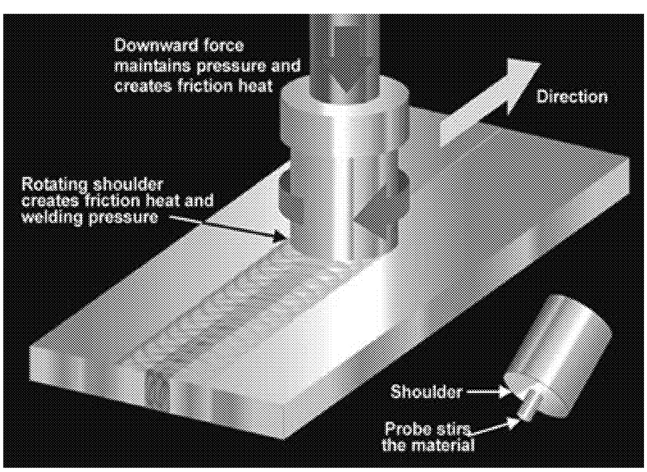

Fig.1 Principle of welding by FSW process [5]

The main welding parameters are as follows: downward force, tool revolutions and welding speed. The tool bevel angle represents also an important parameter.

The FSW process offers a number of metallurgical and environmental merits, when compared to fusion welding technologies. No filler metal is needed for FSW process. Welding of light alloys by FSW process is utilised mainly in the transport technologies (aviation, automotive and other industries) [6]. One of the most efficient ways of utilisation of computer technology for the support in application of advanced technologies consists in simulation.

The purpose of welding process simulation is to shorten the time needed for the determination of welding parameters and conditions without costly fabrication of actual welds. At simulation, the real system is replaced with a computer model.

A number of experiments may be performed via computer model, to assess them, analyse, optimise, repeatedly solve and subsequently apply to a real system [7]. Simulation is a suitable means also from the financial viewpoint: the costs for realisation of individual experiments may be higher than the price of a proper simulation program.

Welded material

The Mg alloy type AZ 31, 6 mm in thickness was selected as welded material. Magnesium alloy type AZ 31 exerts a good plastic properties and toughness and it is suitable for welding. It is typical with increased ductility and fracture toughness. However, this alloy is susceptible to corrosion in a wet environment and in environments containing the chlorides.

Microstructure of the base metal is formed of solid solution δ (solid solution of Al in Mg) and intermediary phase γ ($Mg_{17}Al_{12}$) [8]. The chemical composition, mechanical and physical properties of Mg alloy type AZ 31 are given in Tables 1, 2 and 3.

Table 1 Chemical composition of Mg alloy type AZ 31 [9]

Elements	Al	Zn	Mn	Si	Fe	Mg
wt.%	2.5 to 3.5	0.6 to 0.4	0.4	0.1	0.005	Bal.

Tab. 2 Mechanical properties of Mg alloy type AZ 31 [10]

Ultimate tensile strength	244 MPa
Elongation	15 %
Hardness	41 HV
Tensile strength	290 MPa
Fatigue strength	97 MPa
Yield point	221MPa
Young's modulus	45 GPa

Tab. 3 Physical properties of Mg alloy of the type AZ 31 [10]

Density	1.77 $g.cm^{-3}$
Melting point	605 - 630 °C
Boiling point	1090 °C
Thermal conductivity	96 $W.m^{-1}.K^{-1}$
Electrical resistance	0.274 μΩ.m
Heat capacity	960 $J.kg^{-1}.K^{-1}$

Welding equipment

Experimental works were performed on experimental equipment type FSW - LM - 060 constructed by CFSW company from China, installed at the Welding Research Institute – Industrial Institute of Slovakia, (VUZ - PI SR) Bratislava. The equipment proper consists of the basic carrying structures, welding head, working table and control panel, see Fig. 2.

Fig. 2 Welding equipment of the type FSW – LM - 060

Welding tools

The welded joints were fabricated by use of welding tools made of tool steel type H 13 (EN ISO X40CrMoV5-1). This tool steel is wear resistant, showing high strength and increased toughness. It is also fatigue resistant. Three welding tools were used for fabrication of welds with pin bevel angles 20°, 15° and 6°. The tools used for welding Mg alloy type AZ 31 are shown in Fig. 3.

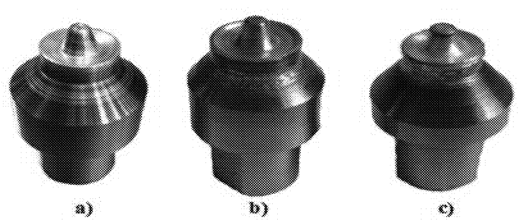

Fig. 3 Welding tools with different pin geometry
a) 20˚, b) 15˚, c) 6˚

Numerical simulation

In the first step of numerical simulation, the simulation model was developed including geometrical model, material properties, loading, boundary and initial conditions. For the model creation, three program codes were applied: Solid Works [11] for preparing CAD models of tools, ANSYS [12] and DEFORM 3D [13] for modelling and FEM analysis of the process of welding. Welding tools were scanned, CAD models generated by Solid Works program and imported to the FE codes. Geometrical model of welded materials consists of two plates with dimensions of 300x150x6 mm. Due to the symmetry of welded plates, only one half of the model was taken into account in numerical simulation with the symmetry plane xz in the middle of the weld joint. Finite element mesh was generated in the program code ANSYS. The mesh density was governed by applied loading, contact conditions and supposed temperature and stress-strain distribution. Mechanical and thermal properties of H13 tool steel and Mg alloy of the type AZ 31 were considered to be temperature dependent. Material models were developed based on the computation of material properties using the software JMatPro [14]. The applied loading corresponds to the suggested parameters of welding, i.e. welding speed, rotations and downward force. The plates were fixed according to real fixation of plates during welding (Fig. 2). The heat transfer from the welded plates to the surroundings by the mechanisms of convection and radiation was taken into account.

The initial computations were performed by the program code DEFORM 3D which is more suitable for modelling of contact and deformation processes. However, according to the complexity of the simulation model the in the DEFORM 3D code was extremely time demanding. In this reason, after the reaching the quasi-stationary regime the computed loadings were imported to the program code ANSYS to analyse in detail the transient stress-strain and temperature fields during friction stir welding.

To illustrate the temperature fields computed by the program code DEFORM 3D, the temperature distribution in the plate after tool immersion to the plate material is shown in Fig. 4.

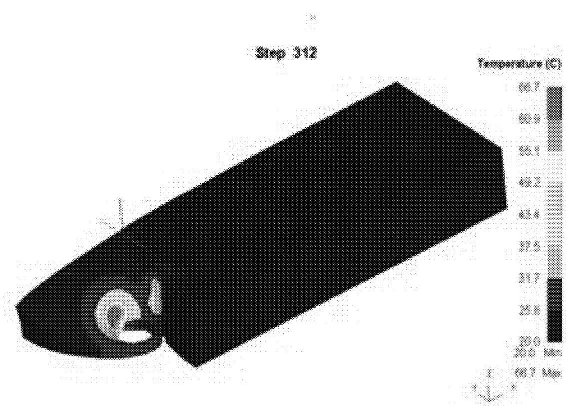

Fig. 4 Thermal field in welded plate illustrating the preferential heat generation on the recede side of creating weld joint

The results from numerical simulation of FSW process by the program code ANSYS in the form of thermal fields after tool immersion in the time of 184 s, 300 s and after finishing of the welding process in the time of 422 s are shown in Figs. 5, 6 and 7, respectively. The maximum temperatures were computed on the recede side of the weld joint at the level of 505 ˚C (Fig. 5-7).

The simulations in DEFORM 3D revealed that the welding tool gradually displaces the material under the tool shoulder. Subsequently, the material is pressed under the tool shoulder. The generated heat is concentrated on the recede side of the weld joint (Fig. 4) resulting in the temperature distribution in the welded material during the process.

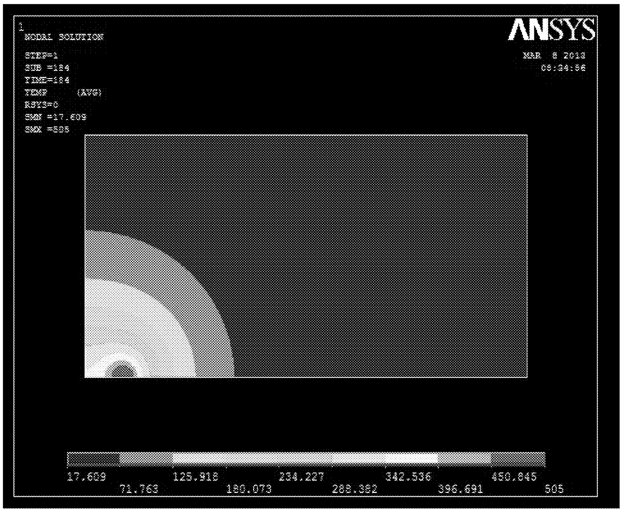

Fig. 5 Thermal field after tool immersion

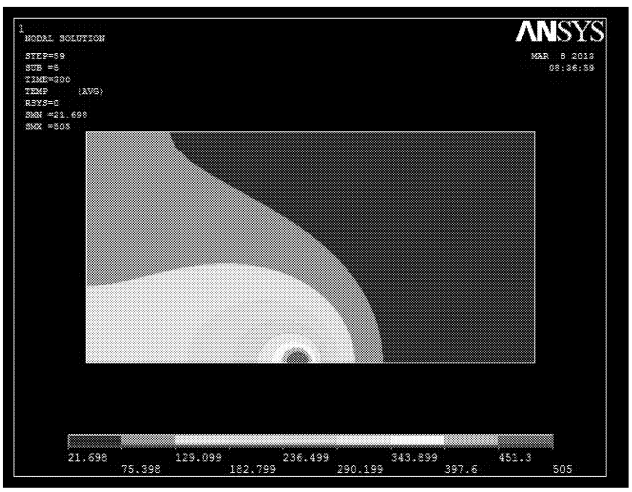

Fig. 6 Thermal field in time 300 s.

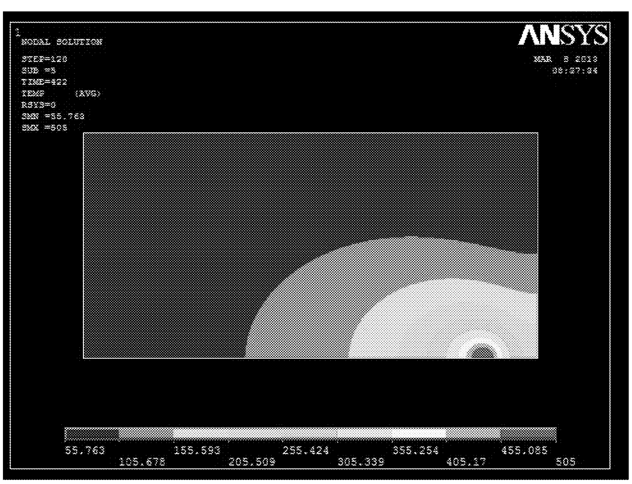

Fig. 7 Thermal field after end of welding in time 422 s.

The results of numerical simulations were verified by temperature measurement during the FSW process. Very good agreement was observed comparing the calculated and measured temperatures.

To determine suitable parameters for FSW welding process, the following simulations and analyses of thermal and stress-strain fields were performed using different parameters of welding. Based on the results of numerical simulation the following welding parameters were suggested for the experimental friction stir welding of plates from Mg alloy of the type AZ 31: tool revolutions from 400 rpm to 600 rpm and welding speed from 40 mm/min to 120 mm/min by the loading force of 35 kN and the bevel angle of 3°.

Experimental

Different welding parameters according to the results of numerical simulation were used for experimental welding. A sound welded joint was fabricated with the following parameters: tool revolutions of 600 rpm and welding speed of 60 mm/min.
The produced weld joints were assessed by light microscopy, microhardness measurement, EDX microanalysis and static tensile test.
The weld joint fabricated by the above mentioned welding parameters is shown in Fig. 8. The macrostructure of the weld joint is illustrated in Fig. 9. The weld joint consists of stir zone (SZ) and thermo-mechanically affected zone (TMAZ) surrounded by the based material (BM). Fig. 10 documents the gradual microstructure refinement from the based material through the thermo-mechanically affected zone the stirred zone. The measured microhardness values varied from 59 HV to 65 HV. Lower microhardness values were measured in the stirred zone, when compared to values in the zone of base metal. Approximately similar microhardness values were measured in TMAZ zone.
EDX microanalysis has shown several compounds in TMAZ, which were introduced to structure during casting. They were subsequently mixed with the base metal.

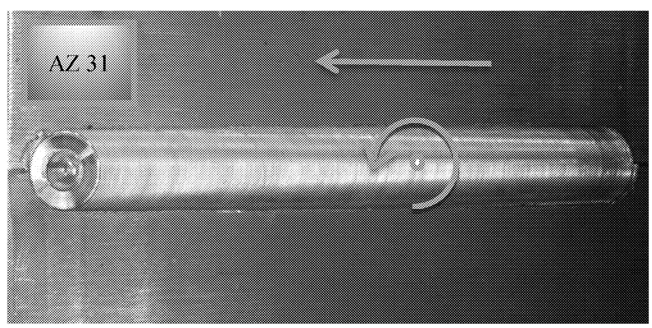

Fig. 8 Welded joint of Mg alloy type AZ 31

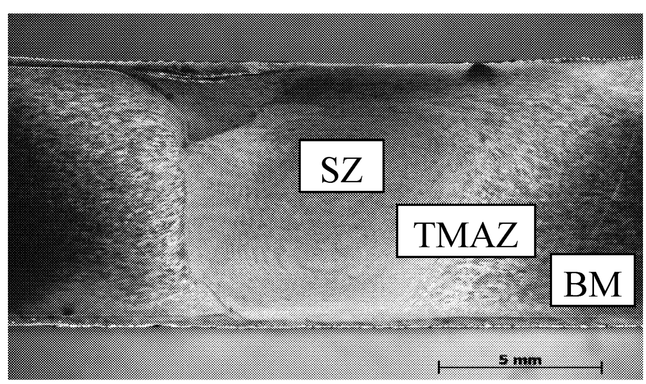

Fig. 9 Macrostructure of weld joint

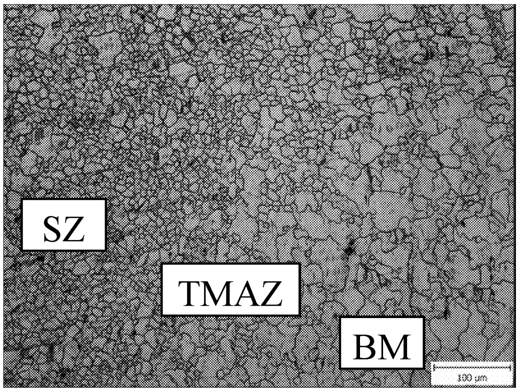

Fig. 10 Microstructure of weld joint (boundaries between the stirred zone, TMA zone and based material)

For evaluation of the mechanical properties of the weld joint, the static tensile test was performed. The test specimens used for testing are shown in Fig. 11.

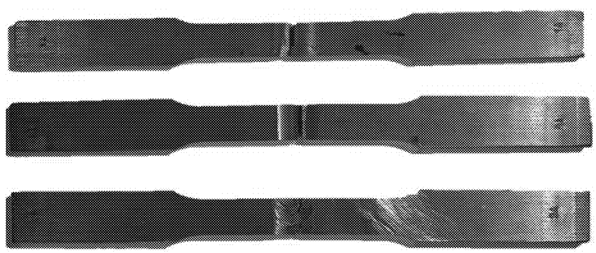

Fig. 11 Specimens after welded joint destruction

The results of static tensile test are given in the table 4. Values of ultimate tensile strength of welded joints vary from 125 to 155 MPa. The mean value of ultimate tensile strength attains the value of 265 MPa. Each tensile specimens are failing in stir zone.

Tab. 4 Values of static tensile strength of welded joint

Des.	T [°C]	t_s [mm]	b_0 [mm]	S_0 [mm^2]	F_m [kN]	R_m [MPa]	A [%]
1	20	6.2	17.9	111.0	15.54	140	4.1
2	20	6.2	18	111.6	13.95	125	3.7
3	20	6.2	18	111.6	17.30	155	4.5

T- temperature, S_0- considered cross section of specimens (b_0 x t_s),
F_m- axial force, R_m– tensile strength, A- elongation

Conclusions

The contribution deals with welding of the Mg alloy of the type AZ 31 by FSW. The main aim was to suggest the parameters and conditions of welding allowing the fabrication as good as possible welded joints. To determine suitable parameters for welding by FSW process, the numerical simulation of thermal fields was performed. High quality welded joint was fabricated by use of welding tool with pin bevel angle 6° at the following parameters: downward force 35 kN, tool revolutions 600 rpm and welding speed 60 mm/min. The quality of welded joints was assessed by radiography. Selected high-quality joint was then investigated by light microscopy, where analysis of individual zones across the cross section was performed. Light microscopy has revealed a fine-grained structure in weld metal. The measured microhardness values varied from 59 to 65 HV. EDX microanalysis has shown several compounds in TMAZ, which were introduced to structure during casting. Strength of welded joint attained the values from 55 to 60% of the base metal strength.

Acknowledgment

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