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Investigation of Joining Ability of Different Welding Technologies at Joining Mg Alloy

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Abstract* - This contribution deals with research of metallurgical jointing of Mg alloy AZ 31B by selected jointing technologies. Special technologies of welding (FSW, LBW) and soldering will be primary investigated. Welded and soldered joints has been performed with cooperation of: Welding Research Institute - Industrial Institute Bratislava SR, FS ČVUT Prague CR, and Faculty of Materials Science and Technology in Trnava SR. Nowadays, there is performed intensive research in field of metallurgical jointing of Mg alloys in the whole world. It is caused due their wide versatility in industry.

***Index Terms*-FSW, inter metallic phase, metallurgical jointing, LBW**

I. INTRODUCTION

In lasts years, importance of Mg and its alloys rapidly increase, due increasing of claims on weight of constructions (automotive and aerial industry). Mg represented approx. 3 % of weight of passenger vehicle in year 2005 and there is premise of increasing of this ratio to 10 % in year 2015 [1]. With increasing of usage of Mg and its alloys, seeking of proper method of jointing of this material begins. One of the options is soldering, diffusion welding, FSW process, or LBW. Mechanical properties of alloy AZ 31B are decreasing during soldering at temperature 595 °C, namely 8 % of tensile strength and 35 % of ductility. These above mentioned loss of mechanical properties is main reason of the using of low-melting solders [2, 3, 4, 5]. Early applications of technology FSW has been used on light alloys. Between main welding parameters of FSW method are included: presser force, spindle speed, welding speed and angle of inclination of tool. Welding process is suitable for manufacturing utilized welding robots and for automatic manufacturing. FSW process offer many environmental advantages in comparison with melting methods of welding. During welding, filler material is not necessary [9, 10]. Laser Beam Welding (LBW) is progressive and widely used technology, due its speed, precision and effectiveness. However it presents difficulties, especially when light alloys are welded. During laser welding of Mg alloys, some processing problems and weld defects can occur, such as an unstable weld pool and solidification cracking. Nonetheless, crack-free laser welded joints, with low porosity and good surface quality, can be obtained by using of eligible laser processing conditions [13, 14].

II. CHARACTERISTICS OF JOINTED MATERIAL

In consideration of Mg is the lightest metal, there is possibility to decrease weight of construction currently by application of Mg alloys. Metallurgical jointing of Mg alloys and other metals is an objective of extensive research in the world. Weight of mobile technics is constantly decreasing especially in aerial, automotive and else industry. It is related to decreasing of energy consumption and environmental influences. Commercial utilized Mg alloys have specific weight approx. 1.7 g.cm^{-3}, which is approx. 35 % lower value then density of Al alloys and approx. 75 % lower than case of steels. It preorda in magnesium alloys to increasingly wider application in mentioned area [6]. Mg alloy AZ 31 in form of rolled sheet has been used on experiments. This alloy is not heat-threated, because it is non-hardenable. Weldability is limited to usage of proper protective atmosphere or vacuum (GTAW, EBW, LBW). During soldering, there is recommended to use inert atmosphere (Ar, He). High thermal conductivity of Mg alloys could cause excessive thickening of grains during soldering at elevated temperatures [7, 8]. Chemical composition, physical and mechanical properties are shown in Tab. 1, 2 and 3.

Tab. 1 Chemical composition of Mg alloy AZ 31B [1]

Elements	Al	Mn	Zn	Si	Mg
Wt. %	2.5 - 3.5	0.4	0.6 - 1.4	0.1	Bal.

Tab. 2 Mechanical properties of Mg alloy AZ 31B [1]

Properties	Value
Elongation	15 %
Hardness	41 HV
Tensile strength	290 MPa
Fatigue strength	97 MPa
Yield strength	221MPa
Young´s modulus of elasticity	45 GPa

Tab. 3 Physical properties of Mg alloy AZ 31B [1]

Properties	Value
Density	1.77 g.cm^{-3}
Melting temperature	605 - 630 °C
Boiling temperature	1090 °C
Thermal conductivity	96 W.m^{-1}.K^{-1}
Electrical resistance	0,274 μΩ.m
Thermal capacity	960 J.kg.K^{-1}

Between advantages of Mg alloys belong high strength-weight ratio, good castability and machinability. In generally, Mg alloys have approximately equal corrosion resistance as mild steels; however, their corrosion resistance is lower than resistance of Al alloys.

III. EXPERIMENTAL METHODS

One of possibility of metallurgical jointing of Mg alloy is solid state welding by FSW method. Principle of this technology is based in rotating tool with specially designed pin of arm, which is pressing to interface of welded materials. Welding tool is lead in direction of weld line. During welding, there occurs transformation of mechanical energy into heat. Heat occurs in consequence of friction and plastic deformation. The highest importance during welding is placed on welding tool [11]. During welding, tool must resist of pressure load. It also has to enough slide strength at elevated temperatures in order to avoid braking and deformation of tool during welding [12]. In our experiment, there has been selected three types of welding tools with different pin geometry (inclination of pin) Fig. 1. Tool steel AISI H13 (4Cr5MoSiV1) has been used as material for tools. Welded joints have been performed in cooperation of VÚZ - PI Bratislava SR, which dispose by welding device type FSW - LM - 060 manufactured in China. Welding material: AZ 31B, material thickness: 6 mm, type of welded joints: edgeless.

Fig.1 Welding tools used for welding AZ 31B with pin inclination a) 20°; b) 15°; c) 6°

Quality welded joint (Fig. 2) has been performed by tool with angle of pin inclination 6° at welding parameters: spindle speed 600 rpm and welding speed 60 mm/min. Welded joint has been evaluated by light microscopy (Fig. 3, 4), by measuring of microhardness (Fig. 5) and by static tensile test (Fig. 6).

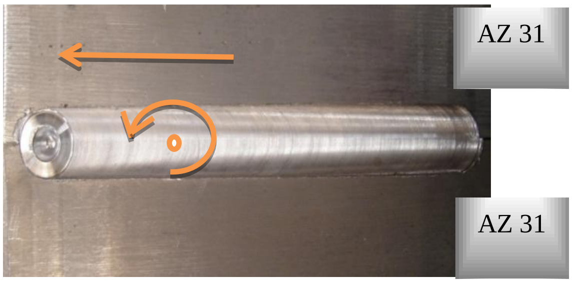


Fig. 2 Welded joint of Mg alloy type AZ 31

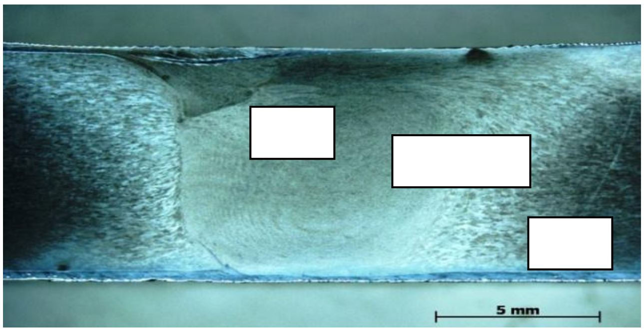


Fig. 3 Macrostructure of welded joint

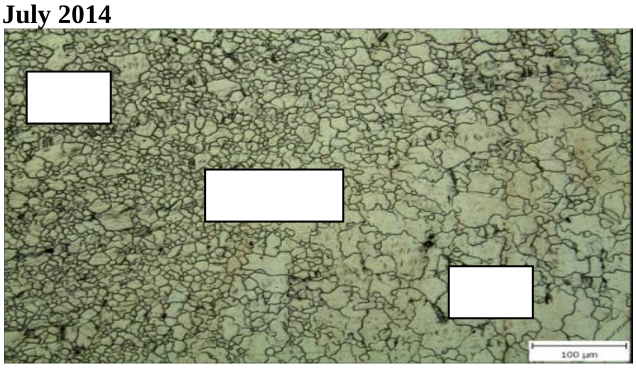


Fig. 4 Microstructure of welded joint (boundaries between the Stirred Zone (SZ), Thermo-Mechanical Affected Zone (TMAZ) and Basic Material (BM).

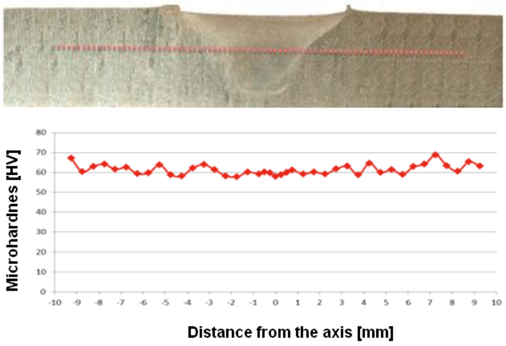


Fig. 5 Microhardness course across the welded joint

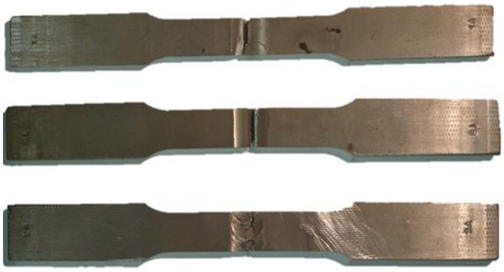


Fig. 6 Specimens after destruction of welded joint

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 specimen is failing in stir zone.

Tab. 4 Values of static tensile strength of welded joint

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

A sound welded joint was fabricated with welding tool designated 6° at the following parameters: downward force 38kN, spindle speed 600 RPM, welding speed 60 mm/min., tool slope angle 3˚. The measured microhardness values varied in the range from 59 to 70 HV. Approximately similar microhardness values were measured in (TMAZ) and in (BM). The strength of welded joints achieved 55 to 60% value of the base metal.

Other option of metallurgical jointing of Mg alloys is welding by concentrated source of energy (such as laser beam welding - LBW). To creation of recasts, disc laser TruDisk 4001 has been used, which possess MTF in Trnava with max. Performance 2 kW and wave length $\lambda = 1.03$ µm. There has been used beam with radius $\omega_0 = 0.2$ mm. Disc lasers are characterized by high quality of beam. Absorption of laser beam by material can be increased for example by treatment, by roughening of surface, by creation of cover layer, by double crossing of beam, etc. By elimination or reduction of oxidic layer on surface of welded material, marginal intensity of radiation has been decreased, which is required to welding by laser beam. Higher quality of weld has been achieved, as well as spray minimalize. However, this do not applies to Nd: YAG and disc lasers. Minimal absorption of laser beam by oxidic layer on surface of magnesium alloys at disc laser TruDisk 4001 has to result, that there do not occur to sublimation of oxide at impact of beam on surface and nor to purification of melted welded metal. At the Fig. 7 we can observe dependence of depth of recast on type of surface modification.

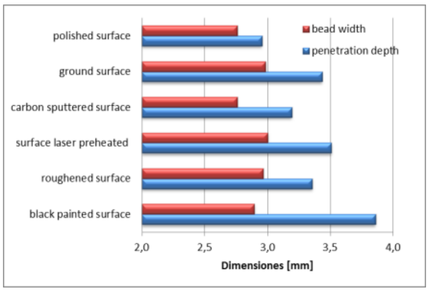


Fig. 7 Weld width and penetration depth; disc laser, P = 2 kW, v = 20 mm.s^{-1}, dif. surface pretreatments

Accordingly on this figure is obvious, that surface modification has influence on depth and width of recast. In experiment, some surface modifications has been performed, which are commonly used in practice at LBW. At welding on disc laser at performance P = 2 kW, there has been the highest difference between polished surface and black painted – 0.91 mm. Position of focus has equal significant influence on process and welding quality. Position of focus should be adjusted in place of achieving of maximum depth of recast, or the best tolerance of process. By proper adjusting of focal position is possible to affect width and depth of weld. Fig. 8 shown depth of recast in dependence of position of focus at performance 1.5 kW at disc laser.

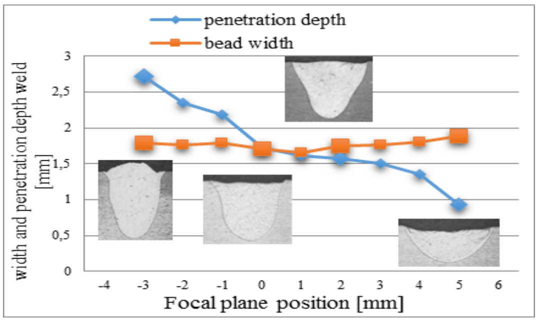


Fig. 8 Influence of focal spot position on penetration depth and width; power 1.5 kW, speed 80 mm.s^{-1}

On the basis of recasts shown in Fig. 8 results, that by changing of focal position from negative position (-3 mm under material surface) to positive position (+5 mm above surface) occur decreasing of camber of weld caterpillar up to moderate overflow of weld caterpillar. The best quality has been achieved at focusing 2 mm above surface. There we can also obtain that moving position of focus from negative to positive values cause reduction of recast depth and moderate increasing of weld width.

In Fig. 9 is shown influence of welding speed on recast geometry at performance 1.5 kW at disc laser on Mg alloy AZ 31B. Temperature input at welding can be also affected by proper choosing of welding speed. In comparison with initial structure, high welding speed leads to significant refinement of grains in BM.

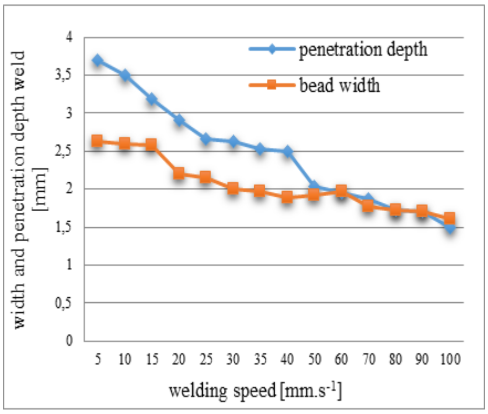


Fig. 9 Influence of welding speed on depth and width of recast at performance 1.5 kW

Last, but not least, economic aspects have influence on welding speed, when goal in each manufacturing is maximize of production and maximize usage of device, may return of investment is as fast as possible. In present, GMAW and GTAW are main welding methods for Mg alloys, especially for repair of defects after casting [6]. However, low welding speed, low area density of energy and the resulting wide HAZ and BM cause decreasing of alloying elements by sublimation [13]. Mainly Zn, with lower boiling point by 183 °C in comparison with Mg, is susceptible to vaporization. Loss of Zn from welded metal cause decreasing of strength and castability of material and also it has negative influence to creation of fine-grained structure. For this reason, EDX analysis of welded joint has been performed, thanks to which is possible to determine chemical composition of different materials, and thus there is also possible to observe composition of welded metal and basic material. In the Fig. 10 is shown course of elements, measured at line EDX analysis in direction from basic material to welded metal.

Measured values from EDX analysis of welded metal and basic material are recorded in Tab. 5.

Tab. 5 Comparison of chemical composition of BM and WM

Elements	Mg [wt. %]	Al [wt. %]	Mn [wt. %]	Zn [wt. %]
Basic material	96.33	2.95	0.07	0.66
Welded metal	94.65	4.49	0.20	0.65

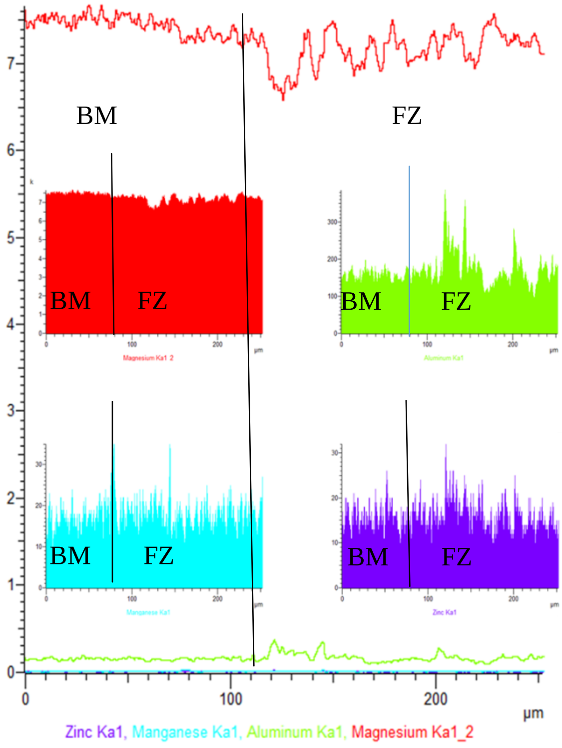


Fig. 10 Line EDX analysis of elements across interface basic material - welded metal

As follows from measured values at EDX analysis, there is not observed any decrease of alloying elements at laser welding. It is caused by very high surface density of laser radiation, narrow welded metal and very low HAZ, in comparison with conventional technologies of welding. Many factors affect weld quality at laser beam welding, such as laser type, kind of welded material, welding parameters, or used protective atmosphere. There are presented results of influence of surface modification and welding speed on depth of recast. Significant influence on recast geometry has position of focus at welding, which results are also published in contribution. The issue at welding of magnesium alloys by conventional technologies is decrease of alloying elements. This unwonted effect was not observed at laser beam welding of magnesium alloy AZ 31.

At soldering, Zn based solder alloyed by Al has been designed. Just a few increasing of amount of Zn increase interfere of oxidic layer on surface of soldered material by accelerating of soldering time, decrease number of mistakes in soldered joint and increase strength [2, 3]. Melting temperature of suggested solder is 382 °C according to phase diagram. Due this temperature, suggested solder ZnAl5 belongs to solders for low-temperature applications. In phase diagrams, there can be seen creation of two low-melting eutectics at temperatures 340 and 364 °C. At these temperatures, there still do not occur local melting of Mg alloys, which in combination with Zn makes interesting alloying element for Mg alloys with high amount of Al [2]. Resultant microstructure of solder (Fig. 2a) has been consisted by primal solid solution reach by β-Zn. The most effective flux to soldering Mg alloys AZ 31B is on base of chlorides $CaCl_2$, KCL, LiCl, NaCl with different ratios. There has been assumed two-compound flux with composition LiCl + KCl in ratio adapted to melting temperature of suggested solder. According to diagram LiCl – KCl there has been assumed eutectic composition of flux with melting temperature 353 °C, which should by proper to soldering by eutectic solder ZnAl5. DSC analysis (Fig. 11) confirm, that solder has eutectic composition with melting 380.5 °C.

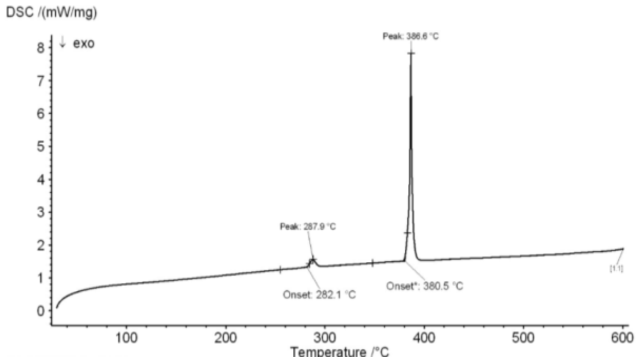
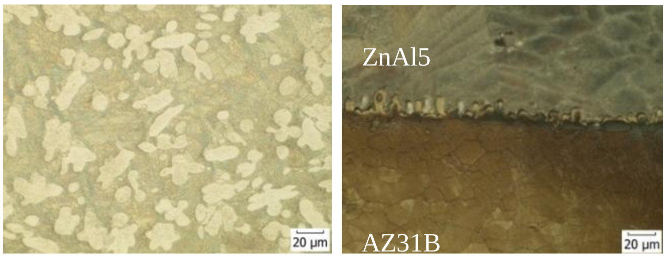


Fig. 11 DSC analysis of eutectic solder ZnAl5

Light microscopy confirm, that Mg alloy AZ 31B keeps polyhedrosis character. Width of diffusion zone has been approx. 7 µm. At interface solder with basic material (Fig. 12b), there has been observed creation and growing of intermetallic phases. Intermetallic phases grow in direction into the solder. Accordingly to phase diagrams, they are phases $Mg_{17}Al_{12}$ and Mg_7Zn_3, which create by eutectic reaction at cooling from melt. Growing of intermetallic phases (approx. 15µm) along interface cause brittleness of joint. Soldered joint has been formed by ternary eutectic structure Mg_{32} $(Zn,Al)_{49}$ and by saturated solid solution α - Mg containing Zn a Al.



a) b)

Fig. 12 Microstructure a) suggested eutectic solder ZnAl5; b) interface solder - substrate

By EDX microanalysis (Fig. 13) has been determined, that chemical composition in area of soldered joint interface is in ratio Mg 81.8 %, Al 2.47 %, Zn 15.73 %. In comparison with origin solder Zn 95 % and Al 5 % is seen, that during soldering, AZ 31B was strongly dissolve into melted solder. Result of this is increased content of Mg in soldered area.

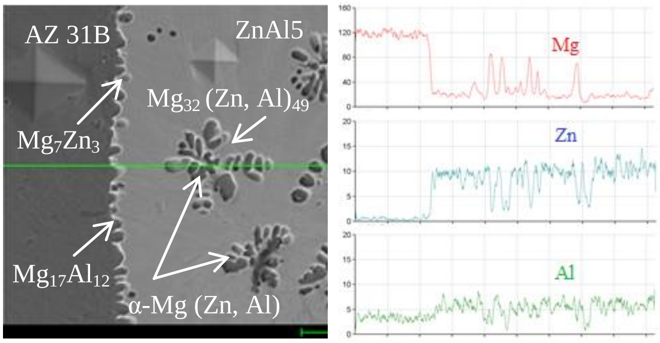


Fig. 13 Line analysis and profiles of Mg, Zn, Al across interface solder - substrate

Solder has in contrast with basic material increased microhardness. In graph can be seen obvious difference in microhardness between basic material, intermetallic phase and solder, which could be reason of joint brittleness. Intermetallic phase $Mg_{17}Al_{12}$ reach value 272 HV and in solder has been measured 160 HV. By frac to graphical analysis fracture areas of soldered joints has been evaluated. Cracks have been present in solder and porosity was observed in majority of fracture area. There has been confirmed, that fracture area has been formed by oxides. Percentage content of oxides on observed area has been in ratio 39 % O_2 and 25 % Mg, which pointed to oxide MgO. At detailed enlarging, there has been observed grown of dendrites β-Zn (Fig. 14) at wall of cavity. High content of MgO oxides, presence of flux on fracture area, porosity of solder and grown of intermetallic phase $Mg_{17}Al_{12}$ significantly influenced mechanical properties of joint.

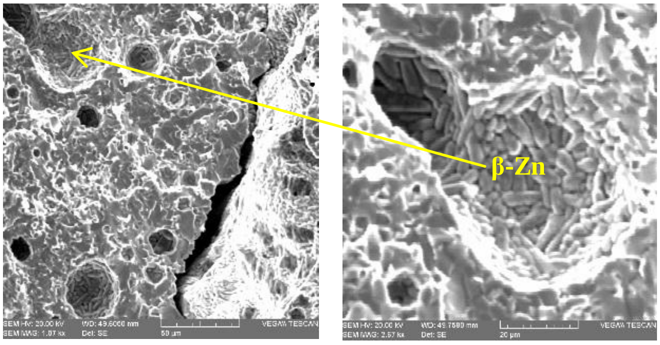


Fig. 14 Dendrites β-Zn in eutectic solder ZnAl5

Eutectic solder ZnAl5 is manufactured by inductive heating in protective atmosphere of Ar. Resultant microstructure of solder has been formed by primal solid solution reach on β-Zn phase with dendritic structure. According diagram LiCl–KCl, there has been proposed eutectic composition of flux with melting temperature 353 °C, which is suitable to soldering by eutectic solder ZnAl5. Soldering properties of solder and flux have been tested in muffle furnace. Quality metallurgical joints have been performed at temperature 430 °C after term 5 minutes. Resultant structure of soldered joint is consists of eutectic ternary structure $Mg_{32}(Zn,Al)_{49}$ and solid solution α-Mg containing elements Zn and Al. On interface solder – substrate are present intermetallic phases $Mg_{17}Al_{12}$ and Mg_7Zn_3. Intermetallic phase $Mg_{17}Al_{12}$ reach value of hardness 272 HV and phase Mg_7Zn_3 value 311.4 HV. Fracture area of soldered joint has been created by oxides.

IV. CONCLUSION

The top quality welded joint of Mg alloy, created by FSW process, was fabricated with welding tool with pin inclination 6° at the following parameters: downward force 38 kN, spindle speed 600 RPM, welding speed 60 mm/min., tool slope angle 3˚. The measured of microhardness values in SZ varied in the range from 59 to 70 HV. Similar microhardness values were measured in TMAZ and in BM. The strength of welded joints achieved 55 to 60% value of the strength of the base metal. Decrease of alloying elements was not observed at LBW. It is caused by very high concentration of focused laser radiation, narrow welded metal and very low HAZ, in comparison with conventional welding technologies. Many factors affect weld quality at LBM, such as type of laser, kind of welded material, welding parameters, used protective atmosphere, etc. There were presented results of influence of surface modification and welding speed on depth of recast. Position of focus at welding has also high influence on recast geometry. The issue at welding of Mg alloys by conventional technologies is decreasing of alloying elements. This unwonted effect was not observed at LBW of Mg alloy. The best metallurgical joints of Mg alloy, created by soldering, have been performed at temperature 430 °C after term 5 minutes. Resultant structure of soldered joint consists of eutectic ternary structure $Mg_{32}(Zn,Al)_{49}$ and solid solution α-Mg containing Zn and Al elements. On interface solder – substrate are present intermetallic phases $Mg_{17}Al_{12}$ and Mg_7Zn_3. Intermetallic phase $Mg_{17}Al_{12}$ reach value of hardness 272 HV and phase Mg_7Zn_3 value 311.4 HV. Fracture area of soldered joint has been created by oxides. Other option, how jointing Mg alloys is ultrasonic welding. At these method, ultrasonic energy is transformed into heat and plastic deformation, which are used to accelerate diffusion and cause jointing of different materials. Advantages of this method are: short welding time, low temperature and no flux or filler material. This process does not require electrical conductive materials, nor additional processing, and process is easy to automatize. This welding method will be detailed elaborated in further contribution.

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