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Preliminary Investigation on Friction Spot Welding of AZ31 Magnesium Alloy

L.C. Campanelli[1,2,a], U.F.H. Suhuddin[2,b], J.F. dos Santos[2,c], N.G. Alcântara[1,d]

[1]Federal University of Sao Carlos (UFSCar), Department of Materials Engineering (DEMa), Rodovia Washington Luiz km 235, 13565-905 Sao Carlos-SP, Brazil

[2]Helmholtz-Zentrum Geesthacht GmbH, Institute of Materials Research, Materials Mechanics, Solid State Joining Processes (WMP), Max-Planck-St. 1, D-21502 Geesthacht, Germany

[a]leoccampa@hotmail.com, [b]uceu.suhuddin@hzg.de, [c]jorge.dos.santos@hzg.de, [d]nelsong@ufscar.br

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Abstract. Friction spot welding (FSpW) is a recent solid state welding process developed and patented by GKSS Forschungszentrum (now Helmholtz-Zentrum Geesthacht), Germany. A spot-like connection is produced by means of an especially designed non-consumable tool consisting of pin, sleeve and clamping ring that creates a joint between sheets in overlap configuration through frictional heat and plastic deformation. FSpW offers many advantages over conventional spot joining techniques including high energy efficiency, surface quality and environmental compatibility. Comparing with friction stir spot welding, FSpW produces a weld without keyhole on the surface at the end of the joining process. In the present study, the possibility of joining AZ31 magnesium alloy by FSpW technique was evaluated by using different welding parameters (rotational speed, plunge depth and dwell time), aiming to produce high quality connections. Microstructural features were analyzed by light optical microscope and mechanical performance was investigated by microhardness test and lap shear test. Microstructure analysis revealed that defects free welds could be produced. A slight decrease in grain size of the stir zone was observed causing a slight increase in the microhardness of this region. The preliminary lap shear data demonstrated that the weld strength is comparable to other welding process.

Introduction

Friction spot welding (FSpW) is a spot solid state process to join two or more sheets in lap configuration that was developed and patented by GKSS Forschungszentrum (now Helmholtz-Zentrum Geesthacht), Germany [1]. FSpW is performed using a non-consumable tool, which consists of three independently moving parts: pin, sleeve and clamping ring, arranged as shown in Fig. 1. Clamping ring is responsible for keeping the plates to be joined held tightly and avoiding the loss of material while the pin and sleeve rotate and have the ability to plunge into the plates.

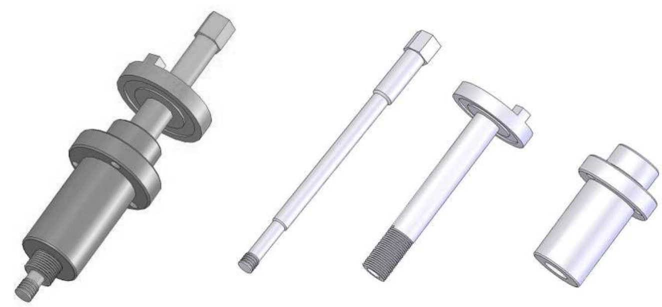
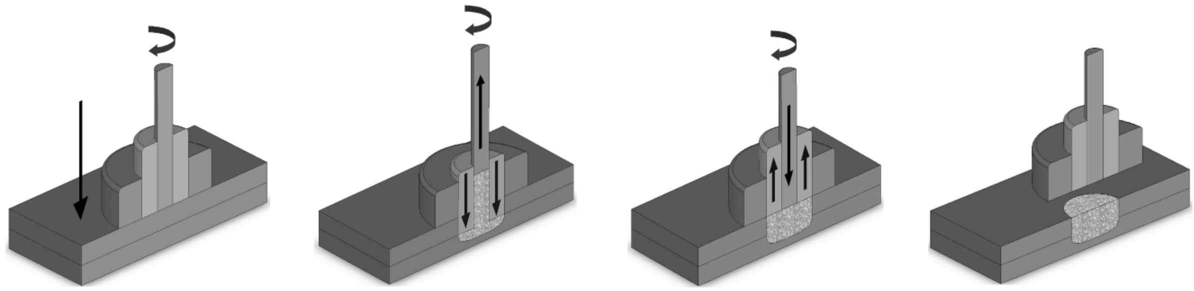


Figure 1: Schematic illustration of the FSpW tool system and its three parts (pin, sleeve and clamping ring).

Pin plunge and sleeve plunge are the two possible variants of the processes: while in the former pin is plunged into the material and sleeve is retracted, in the latter the opposite is observed [2].A schematic representation of the FSpW process is presented in Fig. 2. Initially, clamping ring is pressed against the material in order to hold the sheets while pin and sleeve are rotated in the same direction (Fig. 2a). Then rotating pin and sleeve are moved in opposite direction to each other (one is plunged into the material while the other moves upwards, depending on the process variant), creating a cavity. At the same time, frictional heat is generated during the process and plasticizes the material, which is squeezed into the cavity (Fig. 2b). Pin and sleeve move back towards the surface of the plate pushing the squeezed material back into the plate, tool rotation is stopped and tool is retracted from the joint, as shown in Fig. 2c and 2d respectively [3].



(a) (b) (c) (d)

Figure 2: Schematic illustration of the FSpW sleeve plunge variant: (a) clamping and tool rotation, (b) sleeve plunging and pin retraction, (c) tool back to surface level and (d) tool removal.

A defect-free joint with high strength is associated with FSpW technique and unlike friction stir spot welding (FSSW) process no keyhole is left on the surface at the end of the joining operation. FSpW also presents many advantages over conventional spot joining techniques including high energy efficiency, surface quality and environmental compatibility. Therefore the potential for the use of FSpW in several structural components is extremely large and the benefits of replacing mechanical fastening or fusion welding techniques are significant. Thus FSpW techniques have recently received a great deal of interest from automotive and aircraft industries [4].

Magnesium (Mg) and its alloys have a major potential with a wide range of applications, especially in the electronics and automotive industry. This attraction is mainly attributed to its low density and high specific strength, besides the good castability and suitability for high pressure die casting and possibility of recycling. Some of the reasons for the limited use of the material are related to its low elastic modulus, low corrosion resistance in some applications, poor cold workability and toughness [5].

Although spot friction welding has focused primarily on aluminum alloys, several studies on magnesium have been reported lately. A research on AZ31 friction spot welds [6] revealed that the strength of the joints depends on the size of the weld zone and hook defect geometry, as well as the texture in the hook region. It was reported that higher weld strength is related to the removal of surface oxide due to improvements on metallurgical bonding. The assessment of tool design influence [7,8] showed that the lap shear strength of AZ31 friction stir spot welds was improved when a three-flat/threaded tool was employed instead of a threaded tool, even though the energy output and microstructural features were similar in both cases. It was suggested that the failure load properties are related to the bonded zone width and hook features. In the present study, the possibility of joining AZ31 Mg alloy by FSpW technique is evaluated, including characterization of the microstructural and mechanical features of the welds.

Experimental Procedure

AZ31B-H24 Mg alloy sheets 2 mm thick have been used in the present study. Sheets were cut to 138 mm long and 60 mm wide coupons. According to ISO 14273:2000 standard, the specimens were prepared in lap-shear configuration with 46 mm overlap. The sleeve plunge variant of the FSpW process is carried out using a RPS 100 machine, which tool consists of a clamping ring, 9 mm diameter threaded sleeve and 6 mm diameter threaded pin.

The welds were successfully produced within the following ranges of parameters: rotational speed of 1000-2000 rpm, plunge depth of 2.25-3.00 mm and dwell time of 0-2 s. Weld strength has been characterized using lap shear testing on a screw-driven Zwick testing machine with a constant cross head speed of 2 mm/min. Microstructural examination was performed on cross-sections of the joints. After grinding and polishing stages, the specimens were chemically etched by a picric acid based solution and analyzed in a Leica DM IRM optical microscope. Vickers microhardness profiles were measured on the specimen in a Zwick/Roell ZHV machine.

Results and Discussion

The average lap shear strength (LSS) of certain welding conditions is plotted against rotational speed (RS), plunge depth (PD) and dwell time (DT) in Fig. 3. The results suggest that welding parameter of RS of 1500 rpm combined with a PD of 2.75 mm and DT of 1 s produces good welds in terms of joint strength.

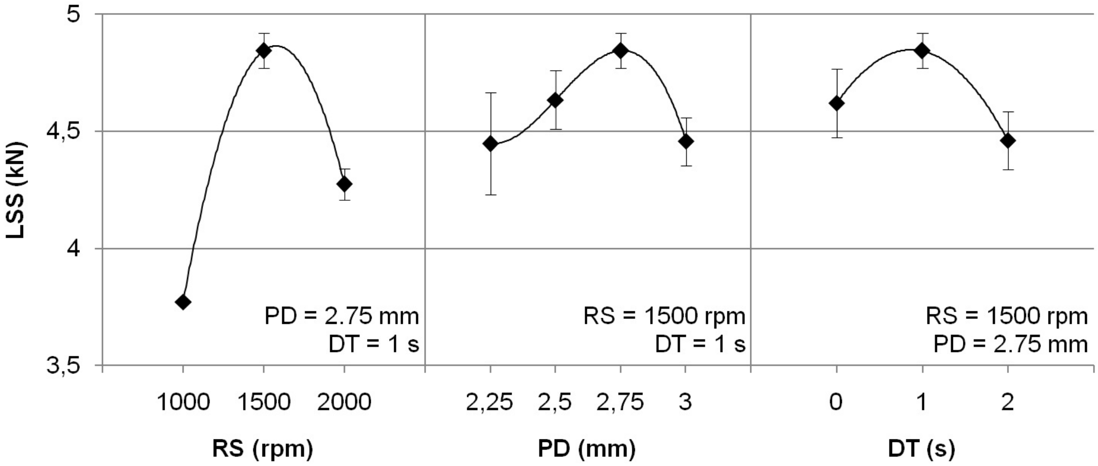


Figure 3: Effect of RS, PD and DT on the LSS under lap shear loading.

In order to compare the values achieved in this study with the values obtained in others spot welding techniques, although there is not a standard way of obtaining the stress of the spot joint from the load, the lap shear stress (LSSt) is considered. The LSSt is defined as the ratio between the LSS and the circular area of the joint. Maximum LSSt of AZ31 joints produced by FSSW [6], FSpW and resistance spot welding (RSW) [9] are summarized in Fig. 4.

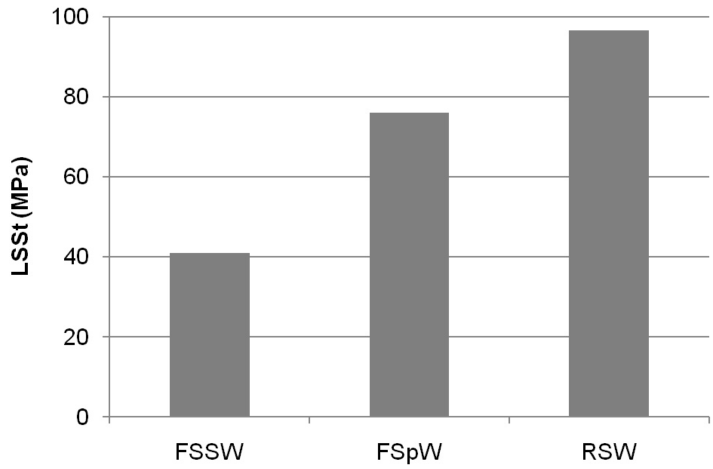


Figure 4: Maximum weld strengths of AZ31 joints produced by different welding techniques.

The LSSt value obtained from the welds produced by FSSW is about 41 MPa in a 1.3 mm thick specimen [6]. The result could be found due to removal of surface oxide, which enhanced the partially metallurgical bonding. This result is inferior when compared with the value of joints produced by FSpW at 1500 rpm, 2.75 mm and 1 s, which is about 76 MPa. However, the LSSt of friction spot weld is lower than that of the weld produced by RSW, which is about 97 MPa in Mg alloys 2 mm thick [9].

In an attempt to understand the microstructural feature, the weld produced at 1500 rpm, 2.75 mm and 1 s was characterized. A low-magnification overview of the weld is presented in Fig. 5. Based on microstructure analysis, welded zone could be characterized as base material (BM), thermo-mechanically affected zone (TMAZ) and stir zone (SZ). It is also observed the formation of a geometrical pattern at the interface of overlapped sheets, which is called hook. It is important to note that the dotted lines between the welding zones are only an approximation.

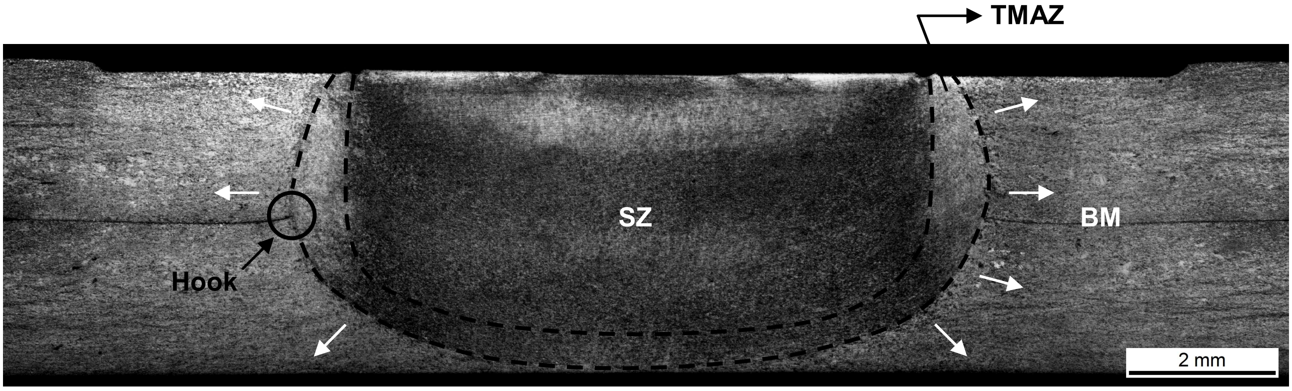
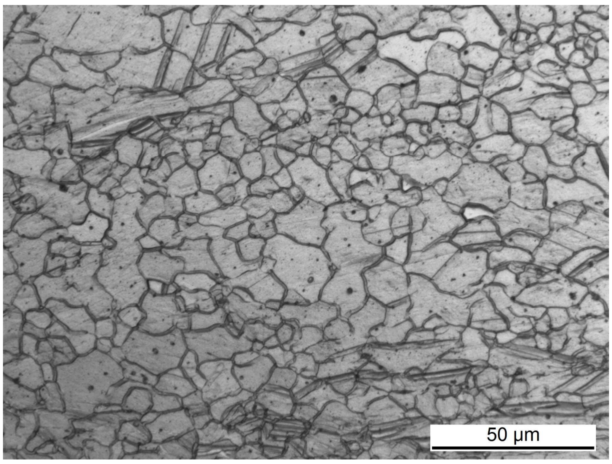


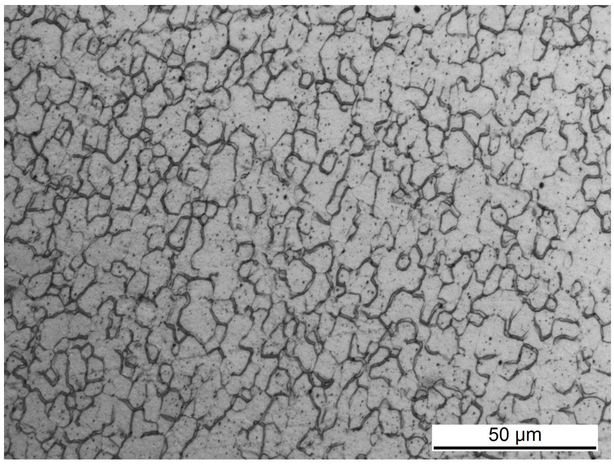
Fig. 5: Cross-section of a connection showing the main joint zones.

Higher magnification micrographs of each welding regions are shown in Fig. 6. Microstructure of BM (Fig. 6a) is considerably heterogeneous and mainly composed of small equiaxed grains with an average size of about 9 µm. Twins can be easily found throughout the microstructure, which has been formed during the previous wrought working process.

TMAZ (Fig. 6b) is characterized by an elongated structure pointing upwards due to plastic deformation with an average grain size of 6 µm. It is believed that this region experiences plastic deformation and is exposed to high temperature [10,11]. SZ (Fig. 6c) is characterized by equiaxed and somewhat refined grains with an average size of 3 µm. This microstructure feature might be related to dynamic recrystallization caused by the high strain rate during the sleeve plunging/retracting stage and the thermal cycle imposed by the process [10,11].



(a)



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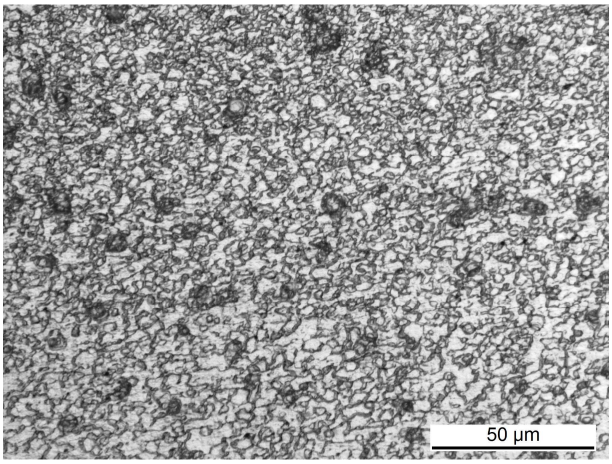
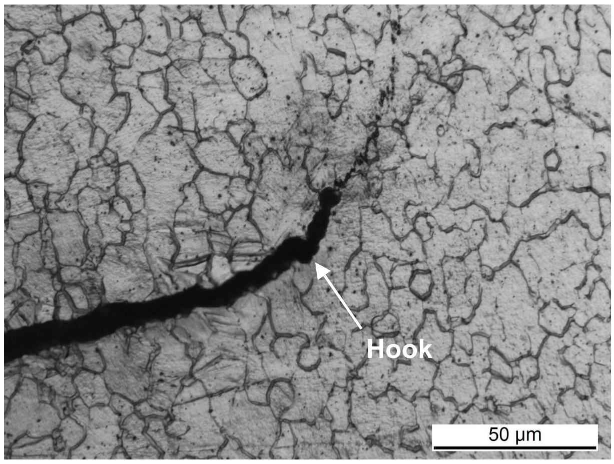


(c)



(d)

Figure 6: Microstructures of cross sections of (a) BM, (b) TMAZ, (c) SZ and (d) transition between BM and TMAZ.

As outlined in Fig. 5, it is noticed at the interface of overlapped sheets the formation of a hook, which basically consists of a geometrical defect formed because of the upward bending of the sheet interface during the sleeve penetration into the bottom sheet [6]. Fig. 6d shows a higher magnification of the hook. In current study, the width of the welding zone measured corresponds approximately to the distance between the tips of both hooks and is about 9.8 mm, somewhat larger than the diameter of the sleeve used to produce the welds.

Hardness profile for the joint processed at 1500 rpm, 2.75 mm and 1 s is presented in Fig. 7. The hardness profile was measured along the mid-thickness of the top sheet.

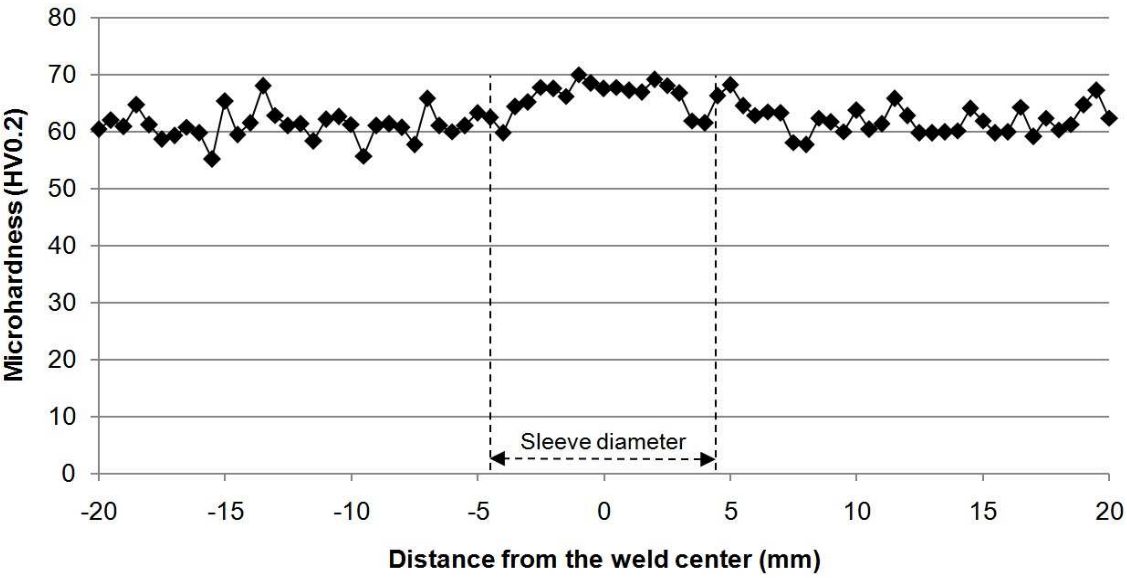


Figure 7: Microhardness profile measured in the middle of the upper sheet at the cross section of a joint.

The only noticeable difference is a small increase in hardness in the SZ region, which can be attributed to the slightly reduction in the grain size in that region in comparison to the other regions. According to the Hall-Petch equation, hardness should increase as the grain size decreases. Although there is a scattering between 55 and 70 HV, hardness tends to be almost uniformly distributed along the other zones, making it difficult to detect and delimitate each of the regions. This result is very interesting from a technological view since there is no loss of material properties after the welding process.

Conclusions

In order to develop the FSpW process for AZ31 magnesium alloy, a preliminary matrix of process parameters was investigated in this study. The welds were successfully produced within the following ranges of parameters: rotational speed of 1000-2000 rpm, plunge depth of 2.25-3.00 mm and dwell time of 0-2 s. It was found that the best result of joint resistance under lap shear loading was associated with the weld produced at 1500 rpm, 2.75 mm and 1 s, which shows to be considerably superior to the values associated with FSSW technique. However, the friction spot weld has lower joint resistance than that of weld produced by RSW technique. Microstructure observations showed that the joint is characterized as base material, thermomechanically affected zone and stir zone, besides the presence of hook defect at the interface of overlapped sheets. A very slight difference in grain size among these regions was observed, which explained the Vickers hardness profile of the weld.

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