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Mechanisms of joint formation throughout semisolid stir welding of AZ91 magnesium alloy

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Abstract: Joining in the semisolid state is considered a possible method to join alloys to each other. The mechanisms taking part in semisolid stir welding of AZ91 alloys were investigated. Two 7.5 mm-thick AZ91 pieces and a 2 mm-thick Mg−25%Zn interlayer piece were placed in a heating plate. After holding for 3 min at a desired temperature, the weld seam was stirred by a rotational tool. The heating plate was travelled on a trolley at a constant speed of 4.6 cm/min. In addition, one sample was welded without interlayer. Evolution of welding as a function of stirring rate, tool shape and temperature was studied throughout this welding process with scanning electron and optical microscopes. Interlayer decreases the joining temperature and assists to investigate the possible semisolid stir welding mechanisms. Increasing temperature and stirring rate, and using round stirrer instead of grooved stirrer increase the stir zone width. The results show that some possible mechanisms are helpful to achieve a proper metallurgical bonding in the welding process, such as oxide layer disruption, liquid phase blending, globule joining, and liquid penetration to the base metal, merging a group of globule into stir zone from the base metal.

Key words: AZ91 magnesium alloy; semisolid joining; Mg−Zn interlayer; mechanical stirring; metallurgical bonding

1 Introduction

Semisolid metal processing is one of the favorable processes due to its great industrial aspects. Its products have greater features than casting from the view of mechanical property, energy consuming, near net shaping, process controlling, etc [1,2]. Considering these excellent features, some researchers have tried to apply its advantages to joinning different alloys. SAINT-ANTONIN et al [3,4] have offered the globular filler metal for aluminium to copper brazing. HU et al [5] have also joined two pieces of Al-based composite to each other in the semisolid state. SUGIYAMA et al [6] have introduced joining of metals and even non-metals by penetrating the solid materials into slurries. The main mechanism to join non-metallic materials to the semisolid metal is mechanical locking. MENDEZ et al [7] have studied joining of two Sn−15%Pb pieces to each other by means of Sn−5%Pb semisolid slurry filler metals produced in a rheocaster and placed between two preheated substrates. In another study, the weld seam of Sn−15%Pb was heated up by AMIRKHIZ et al [8] with a hot gas and then a stirrer was introduced into the seam to produce a globular microstructure and mix two substrates. NARIMANNEHAD et al [9] and ALVANI et al [10] have employed the same procedure to join AG40A die cast zinc alloy and A356 aluminum alloy, respectively. The newest investigation in this field is semisolid stir brazing, in which A356/SiC$_p$ composite plates have been joined to each other by placing a Zn-based filler and stirred in the semisolid state, when the substrates are in solid state. It has been found out that stirring leads to the elimination of oxide layer and formation of diffusion bond [11]. Furthermore, in another distinctive study, removing of oxide layer by applying vibration on semisolid filler metal between two aluminum alloy pieces was investigated [12].

Until now, there is not any reported work to recognize the phenomena occurring during semisolid stir joining. In this work, we try to figure out possible dominating mechanisms in semisolid stir welding.

2 Experimental

The AZ91 (8.88%Al, 0.85%Zn, 0.29%Mn, and Mg balanced; its solidification temperature range: 437−590 °C) piece with dimensions of 25 mm×25 mm×7.5 mm

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was used. First of all, surfaces of pieces were grinded with SiC paper to remove oxide layers. The pieces were put in a stainless steel tray. The tray was put on a heating plate. Then, the fixture was heated up to the joining temperature and held for 3 min. A stirrer was introduced into the weld seam which was traveled at a line speed of 4.6 cm/min on a trolley. Table 1 shows the joining parameters which were used. As may be seen in Table 1, six samples were welded to each other using a 2 mm-thick cast Mg−25%Zn interlayer and also one sample without interlayer.

Table 1 Applied joining variables

Sample No.	Interlayer	Stirrer type	Stirring rate/ $(r\cdot min^{-1})$	Temperature/ °C
1	Without	Round	1200	575
2	Mg−25%Zn	Grooved	1200	515
3	Mg−25%Zn	Grooved	1600	515
4	Mg−25%Zn	Grooved	800	530
5	Mg−25%Zn	Grooved	1200	530
6	Mg−25%Zn	Round	800	530
7	Mg−25%Zn	Round	2000	530

Interlayer thickness was 2 mm in solidification temperature range of 350−572 °C; Round: 2 mm cylindrical bar; Grooved: 2 mm drill tip

After joining process, joints were cut from their cross section in the center of weld line. After surface preparation with SiC paper and Al_2O_3 suspension, the macro-etch reagent with composition of 60% ethylene glycol, 19% acetic acid, 1% HNO_3 and 20% H_2O was used to reveal the macrostructure of the weld zone. To characterize the microstructure, same procedure with lower etching time was applied. The metallographic photos were taken with high resolution Olympus optical microscope. Microstructural investigation and solute distribution through the different zones of joining were carried out by SEM (VEGA TESCAN model).

3 Results and discussion

To investigate the trend of joint formation, first of all, the specimens were joined to each other without interlayer at 575 °C. After using interlayer, the stirring rate was changed to achieve different shearing rates at the joining temperature of 515 °C. Then, the joining temperature was increased to 530 °C in order to increase the liquid fraction of interlayer and base metal. In addition, at 530 °C, grooved stirrer was changed to round stirrer to obtain different shearing conditions.

Figure 1 indicates the microstructure of specimen joined without any interlayer at 575 °C. It should be considered that the only difference between each zone is the distance from stir zone. This means that the used stirring parameters increased liquid fraction and decreased globule size. In addition, the joint interface is removed completely by stirring. The possible mechanism for joining is that the liquid fraction of each side increases by stirring and liquid in both sides blends with each other due to elimination of oxide layer. Detecting of all joining mechanisms is impossible, since the compositions of base metal and weld metal are same. In addition, joining at this temperature needs to heat the pieces to high temperature which leads to high oxidation rate and even ignition.

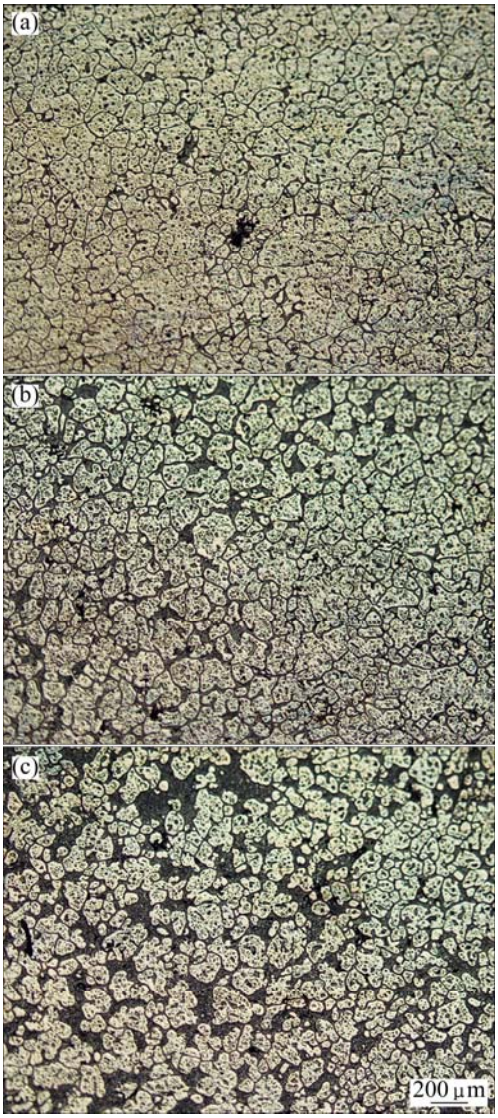

Fig. 1 Joint microstructures of AZ91 alloy (round tool, without interlayer, 575 °C, 1200 r/min): (a) Base metal; (b) Partially stirred affected zone; (c) Stir zone

When the interlayer was used, not only stirring temperature decreased by around 60 °C, but also the zinc content of interlayer assisted to trace bonding behaviors. Figure 2 shows the microstructures of welded specimen at 515 °C with rotational speed of 1200 r/min, in which both interlayer and base metal are in the semisolid state.

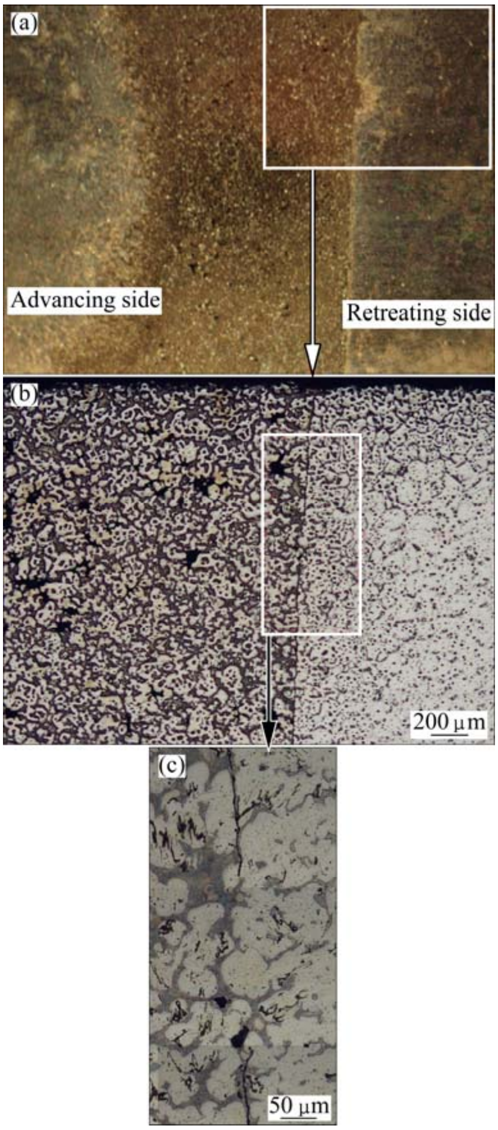

Fig. 2 Joint microstructure of AZ91 alloy (grooved tool, Mg−25Zn interlayer, 515 °C, 1200 r/min)

There are two distinctive sides in the macrostructure of AZ91 joint. The side that bonding is completed is advancing side, in which the work piece has opposite velocity vector with rotational speed vector. Thus, higher crushing force is made between slurry and base metal and it brings about complete oxide elimination. SHI et al [12] reported that the solid particles from slurry disrupted the oxide layer throughout brazing with a semisolid globular interlayer and applying vibration on the weld seam. In the present work, the disruption of oxide layers was more intensive, because not only the base metal contained liquid which led to the more fragile oxide layer, but also the slurry impacted more harshly to the oxide layer than vibration. In addition, some points of interface may have been touched by the stirrer and consequently the oxide layers were broken. In the retreating side, the crushing force is low, yet it renders one of the possible mechanisms presented in this welding method. Liquid from interlayer tries to touch liquid formed in the base metal, if stirring is applied. This phenomenon does not have chance to occur in the most of place in retreating side due to the existence of thick oxide layers.

Bonding proceeds through a narrow gap between base metal and stir zone due to elimination of oxide layers. Under this condition, the liquid of interlayer and base metal are mixed together, and globules grow in the blended liquid from one side to the opposite side of the bonding face, which leads to disappearance of the interface (same as advancing side). As shown in Fig. 3(a), bonding face is removed entirely when rotational speed increases to 1600 r/min (grooved stirrer) and temperature increases to 515°C (grooved stirrer). Same observation is also obtained at 530 °C when rotational speed decreases to 800 r/min (Fig. 3(b)).

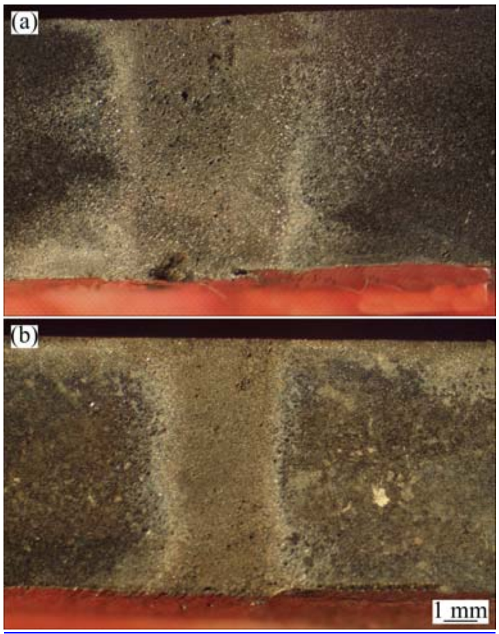

Fig. 3 Joint macrostructure of AZ91 alloy: (a) Grooved tool, Mg−25Zn interlayer, 515 °C, 1600 r/min; (b) Grooved tool, Mg−25Zn interlayer, 530 °C, 800 r/min

Figures 4(a) and (b) indicate the joint interface of samples 3 and 4 in which some globules revealed with joined to each other. The results of EDS and this observation show that the joined globules contain different amount of alloying elements. It seems that the globules are collided and joined to each other at the weld interface. This means that with increasing the stirring rate, temperature, or both of them, not only the liquid was combined to each other (as mentioned above), but solid particles also was joined to each other from stir zone and base metal. It is a significant matter which brought about the disappearance of the original interface line and made a homogenous boundary.

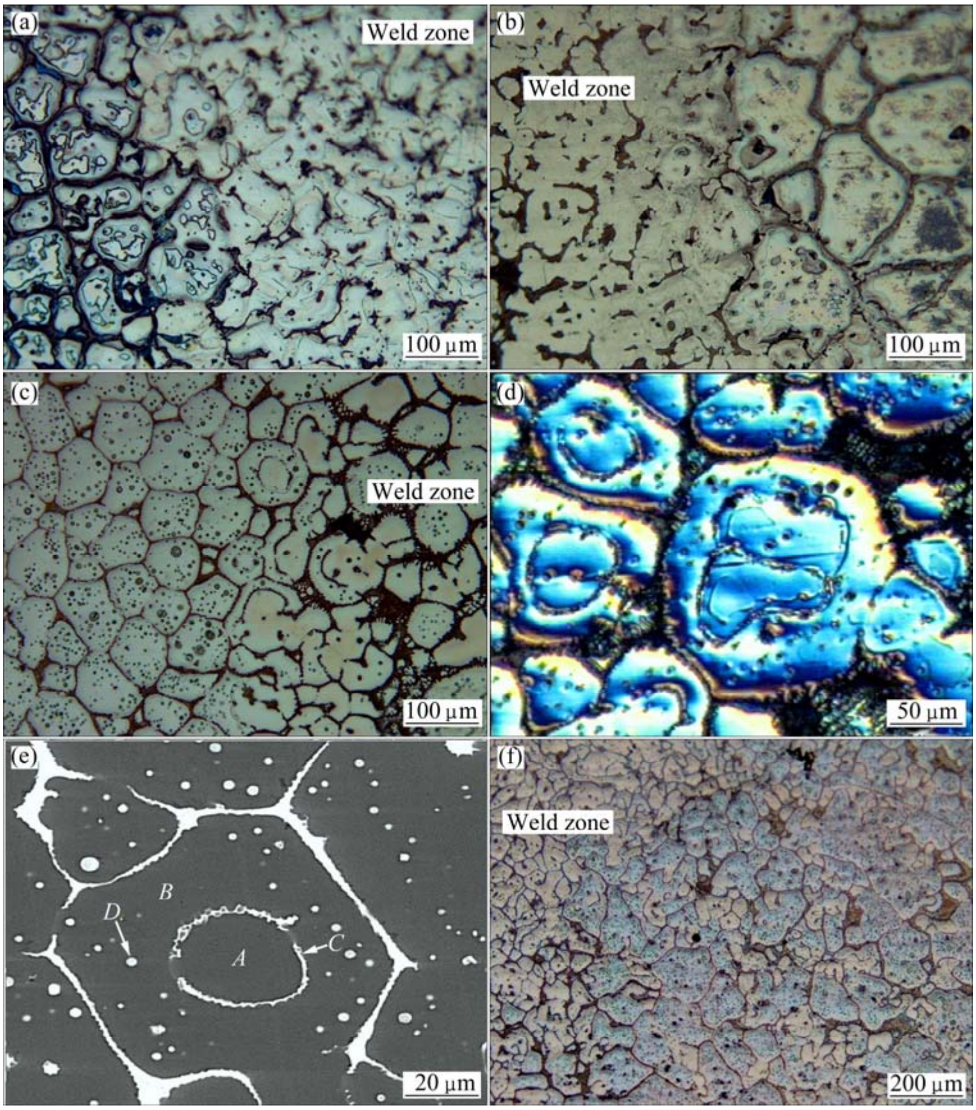

Fig. 4 Joint microstructure of AZ91 alloy with Mg−25Zn interlayer: (a) Grooved tool, 515 °C, 1600 r/min, interface; (b) Grooved tool, 530 °C, 800 r/min, interface; (c) Round tool, 530 °C, 800 r/min, interface; (d) Round tool, 530 °C, 800 r/min, weld zone; (e) SEM, round tool, 530 °C, 800 r/min, interface; (f) Round tool, 530 °C, 2000 r/min

Figure 4(c) shows the interface when a round stirrer was used. It can be seen that some dissimilar globules are collided with each other not only perpendicular to the welding direction (grooved tool), but also other directions. This observation indicates that shear rate increases when stirring tool is changed to a round shape. Furthermore, same collision takes place in the weld zone (Fig. 4(d)). The EDS analysis from two collided globules confirmed the above claim (Fig. 4(e) and Table 2).

Table 2 EDS results of Fig. 4(e)

Point	*w*(Mg)/%	*w*(Al)/%	*w*(Zn)/%
A	93.37	2.88	3.51
B	93.45	3.11	3.44
C	59.31	6.74	33.95
D	56.78	13.93	29.29

It is clear in Table 2 and Fig. 4(e) that, point *A* contains a higher amount of zinc and a lower amount of aluminum than point *B*. Globule *A* and globule *B* may be from stir zone and base metal respectively due to their composition. The composition of the remained liquid between these two globules indicates that this liquid belongs to the weld zone (point *C*). Liquid entrapped pool in point *D* contains more aluminum than point *C*. This means that although at this point zinc content is more than aluminum due to the diffusion of zinc atoms into the globules, the liquid pool is originally from base metal.

Figure 4(f) shows displacing of globules from the weld zone to base metal or formation of new globules from blended liquid at higher stirring rates (round tool). At this situation, interface of base metal became a band instead of a line.

Figure 5 shows long distance penetration of zinc-rich liquid to the globule boundaries of base metal abutting the stir zone, which brings about a proper metallurgical bonding. While a few zinc atoms diffuse into the solid globules, zinc-rich liquid is mixed with interglobular liquid formed due to the semisolid holding of base metal. Consequently, being in semisolid range of base metal is so essential to achieve a sound metallurgical bonding.

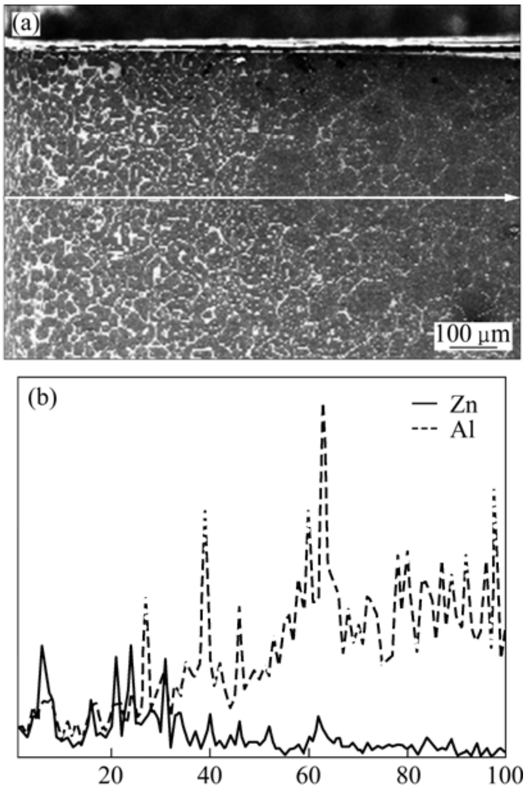

Fig. 5 SEM image (a) and elemental line scan (b) of weld metal to base metal (round tool, 530 °C, 800 r/min)

Figure 6 shows that a bunch of globules are separated from the base metal and attached to the weld zone at high rotational speeds using round tool, because of zinc penetration to base metal. This bunch of globules is merged with new area and a reasonable metallurgical bonding is formed.

Figure 7 shows the stir zone width (SZW) of different samples. If sample 2 with 3, sample 4 with 5, and sample 6 with 7 are compared in which couple the variable is stirring rate, SZW increases with increasing the stirring rate due to higher shearing rates. Increasing temperature also increases SWZ due to severer mixing condition and softer base metal and interlayer with a higher content of liquid phase (samples 2 and 5). In addition, improving the shear effect with changing the tool shape from grooved shape to round shape also brings about severer mixing condition and increases SWZ (samples 4 and 6).

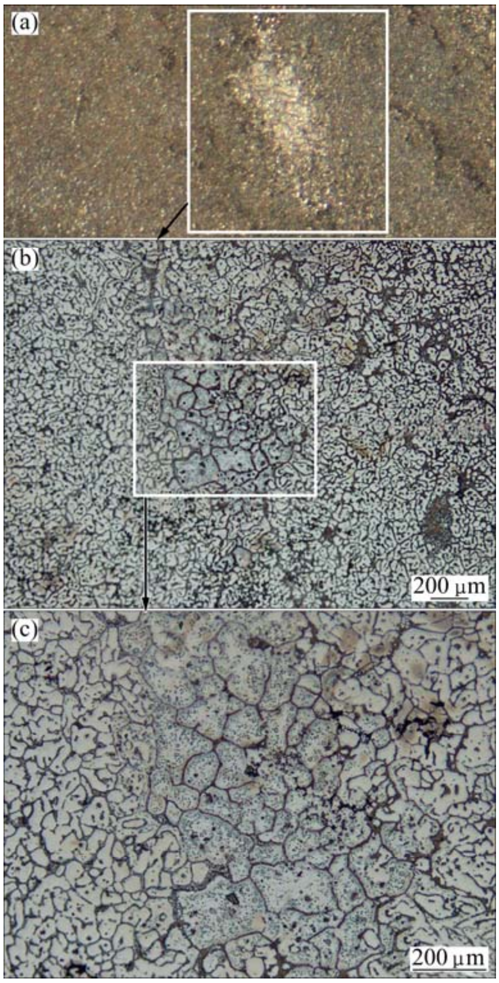

Fig. 6 Separation of bunched globules from base metal to weld metal (round tool, 530 °C, 1200 r/min)

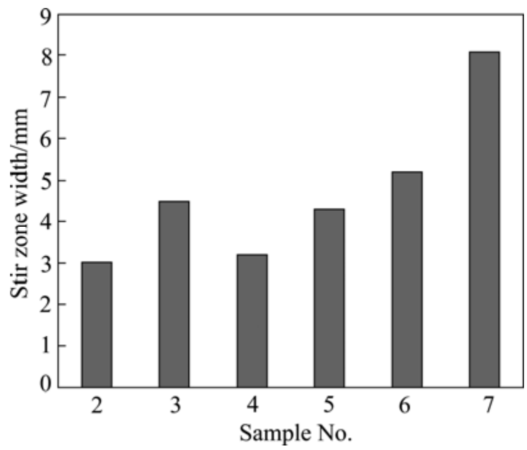

Fig. 7 Stir zone width of different samples

4 Conclusions

Joining mechanisms of semisolid stir welded AZ91 magnesium alloy with or without the Mg−25%Zn interlayer were investigated. Although the pieces were joined to each other without interlayer at 575 °C, the interlayer not only reduced the joining temperature by around 60 °C, but also allowed that possible joining phenomena were detected. The most important point to form a bond was elimination of oxide layer which did not occur at low temperatures and stirring rates in advancing side due to lower crushing forces. Then, liquid phase of base metal and interlayer were blended with each other. With increasing the stirring rate, rising the temperature, or using the round tool, other events were also added to the above mentioned mechanisms: collision and joining of globules, long distance liquid migration to the base metal from the weld zone, and detaching a bunch of globules from the base metal to rest in the weld zone. This experiment design permitted us to understand the joint formation from a ineffective situation in which the base metal was not affected in one side to a severe situation in which a bunch of globules from base metal were joined to stir zone by having own shape and character.

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AZ91 镁合金的半固态搅拌摩擦焊接连接形成机理

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摘　要：半固态连接被认为是一种连接合金的可能的方法。研究了 AZ91 镁合金半固态搅拌摩擦焊接的机理。将 2 块 7.5 mm 厚的 AZ91 镁合金试件和 1 块 2 mm 厚的 Mg−25%Zn 中间层放在加热板上，加热到所需温度并保温 3 min 后，采用旋转搅拌头搅拌焊缝。 将加热板在台车上以 4.6 cm/min 的恒定速度运动。同时，对一个样品进行无中间层焊接。使用扫描电子显微镜和光学显微镜研究焊接过程中搅拌速度、搅拌头形状和温度的影响。结果表明，中间层降低了焊接温度；升高温度、加快搅拌速度、采用圆形搅拌头代替槽形搅拌头都能增大搅拌区的宽度。在焊接过程中，可能存在某些机理，从而有助于获得良好的的冶金结合，例如氧化层消失、液相混合、液球连接、液体渗入基体、从大量液球基体金属进入焊缝区。

关键词：AZ91 镁合金；半固态连接；镁锌中间层；机械搅拌；冶金结合

(Edited by Xiang-qun LI)