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ORIGINAL ARTICLE

A novel severe plastic deformation method for manufacturing Al/Mg bimetallic tube

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Abstract

A new severe plastic deformation for manufacturing Al/Mg bimetallic tube called the TES (tube extrusion shearing) process, which combines direct extrusion with two-step shearing, has been developed to manufacture Al/Mg bimetallic tube. Load evolution with stroke at different temperatures has been simulated by establishing three-dimensional finite element simulation of the TES process of Al/Mg bimetallic tubes. To explore the deformation mechanisms of the Al/Mg bimetallic tube during the TES process, the microstructures and phase compositions and microhardnesses of the bonded layer have been observed and analyzed. A higher extrusion temperature would decrease the extrusion loads. Defects of bonding layer appear less if the extrusion temperature is higher, and the bonding layer of the bi-metal tube has better quality. Three eutectic compounds, Mg_2Al_3, MgAl, and $Mg_{17}Al_{12}$, can be formed in the interface transition zone. The average hardness of the bonding layer is very high. The results indicate that the TES process can produce large plastic deformation and manufacture Al/Mg bimetallic tube and improve the bonding layer.

Keywords Al/Mg bimetallic tube · TES process · Bonding layer · Numerical simulation

1 Introduction

Magnesium alloys have characteristics of low density, high specific strength, excellent machinability, etc., which are known as a green material for sustainable development of resource and environment in the twenty-first century [1–4]. Therefore, it is widely used in aerospace, automobile, 3C electronics, and precision instrument industries [5]. Unfortunately, the crystal structure of magnesium alloy is inherent hexagonal close-packed (HCP), which have few slip systems and poor plastic deformation ability, which hinders its wide application in various fields at room temperature. Magnesium alloys have a poor corrosion resistance because second phases or impurity elements could cause galvanic corrosion and oxidation films on the surface of magnesium alloys, which are porous structures and cannot protect magnesium alloys from corrosion effectively when compared to other alloys [6–8].

In contrast to magnesium alloys, the aluminum is light metal alloy also, and aluminum alloy is the most widely used material besides steel. Aluminum alloy will form an oxide film to further prevent corrosion when it was exposed to the air. Al and Al alloys usually own good plastic forming ability and corrosion resistance. The double-layer composite tube is a kind of composite material which is composed of two kinds of metals with different properties, which are difficult to achieve by the individual constituents [9]. The bimetallic tube has high strength, corrosion resistance and excellent conductivity, heat conduction, and other comprehensive properties. Therefore, the bimetallic tube is more and more used in various fields. With the development of materials, the trend of lightweight materials is increasing, and the use of light alloy and composite materials has become a new trend. Magnesium alloy is lightweight and non-corrosion resistant, while aluminum alloy is the opposite. Both metals have their own advantages. The aluminum alloy and magnesium alloy were extruded to

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produce a bimetallic composite with magnesium alloy as the inner layer and aluminum alloy as the outer layer by TES process.

Plastic forming technology is widely used in the composite process of bimetallic composite tube at home and abroad. Bimetallic composite material is a new kind of material. Its manufacturing principle is to make two or more metal compounds by using specific composite manufacturing technology and process on the contact interface. Compared with the matrix, the composite metal generally has different physical, chemical, and mechanical properties [10]. There are many production methods of double clad tube, such as drawing, extrusion, explosion, hot rolling, centrifugal casting, continuous casting explosion, and welding complex method [11]. These methods have been applied in production, but there are still some shortcomings such as high energy consumption, high cost, poor quality, and serious environmental pollution. Some methods also have some shortcomings as follows: process is complex, and the position and thickness of the bonding interface are inaccurate, and wall thicknesses are uneven, etc. In view of the above shortcomings, a novel severe plastic deformation method for manufacturing Al/Mg bimetallic tube has been proposed.

In the present research, an attempt is made to combine direct extrusion process and successive shearing to manufacture Al/Mg bimetallic tube, which is shortened as TES (tube extrusion shearing) in this paper. Both experiments and numerical finite element modelings of TES process have been carried out. To illustrate the potential industrial application of the TES process of manufacturing Al/Mg bimetallic tube, a complex extrusion die is designed and manufactured. Bonding layers of Al/Mg bimetallic tube have been observed and analyzed with different extrusion temperatures. Microstructural analysis and hardness testings have been performed on the deformed tube.

2 Experimental procedure

2.1 Materials

The properties of the selected matrix and coated tubes play an important role in the forming quality of the bimetallic composite tubes. The comprehensive properties need to be considered when two kinds of materials are selected [12]. In the experiment, commercial AZ31 magnesium alloy tube was used as the intermediate matrix tube and 6063 aluminum alloy was used as the cladding layer tube and Table 1 shows the chemical composition of AZ31 and 6063.

Table 1 Chemical composition of AZ31 and AA6063 (wt %)

Material	Mg	Si	Cu	Zn	Mn	Fe	Al
AZ31	Balance	0.05	0.01	0.63	0.7	0.05	3.2
AA6063	0.58	0.43	<0.01	0.016	<0.01	0.06	Balance

The magnesium material was cut into specimens with 80-mm length and inner diameter φ20.2 mm and outer diameter φ24.8 mm, respectively. The aluminum was cut into specimens with 80-mm length, and inner diameter φ24.9 mm and outer diameter φ39.7 mm, respectively. The samples are then polished. Then, ultrasonic cleaning is carried out to remove surface impurities. Magnesium alloy tube was put into aluminum alloy tube. The die and billets were heated to 360°C, 390°C, and 420°C, respectively. Then, the extrusion experiment is performed.

2.2 Finite element method simulation

During the TES process of Al/Mg bimetallic composite tube, extrusion temperatures have a great influence on the metallurgical bonding behavior. The DEFORM^{TM}-3D software has been used to predict the effects. DEFORM is an engineering software which enables designers to analyze metal forming. Process simulation using DEFORM has been instrumental in cost, quality, and delivery improvements at leading companies for two decades [13]. In order to obtain the best process parameters, it is necessary to carry out numerical simulation analysis many times before carrying out the TES experiment. In this paper, the billets and die are defined, respectively, and the constitutive equation of AZ31 is imported [14]. Parameters used in numerical simulation including material characteristics of the TES process, the parameters of billet temperatures, the coefficients of friction between the die and the workpiece, etc., have been listed in Table 2. In the design of die, the shearing area of the mandrel does not have the same horizontal height as the shearing area of the die, which is 2 cm higher than the shearing area of the die; the die is composed of

Table 2 Simulation parameters of TES

Name	Parameter
Inner diameter of AZ31 (mm)	20.3
Thickness of AZ31 (mm)	4.5
Outer diameter of AA6063 (mm)	39.8
Thickness of AA6063 (mm)	4.5
Inner diameter of container (mm)	40
Outer diameter of container (mm)	20
Extrusion temperature (°C)	360, 390, 420
Extrusion velocity (mm/s)	1, 2, 3
Friction factor	0.1, 0.2, 0.3
Thermal conductivity between billet and mold (N/°C. S . mm^2)	11

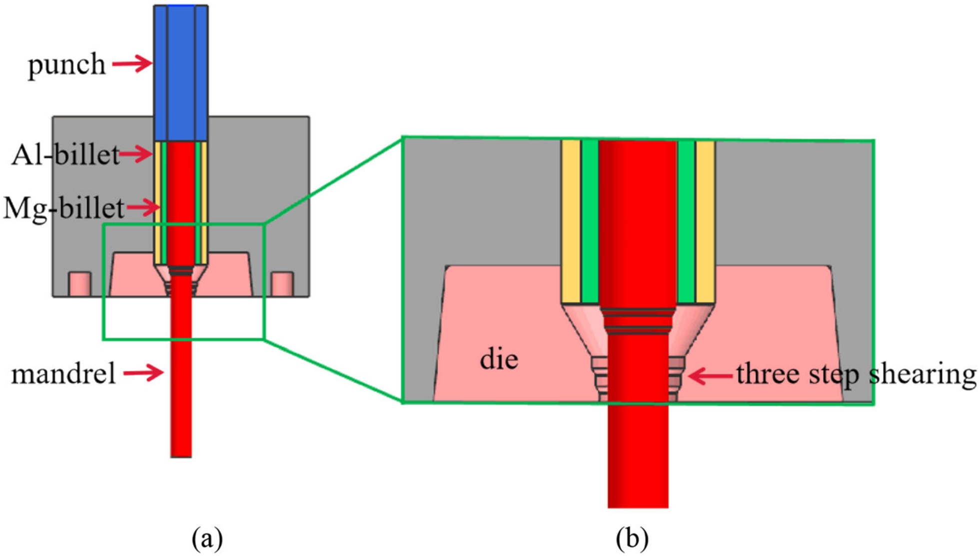


Fig. 1 Schematic diagram of the CVCES process: **a** diagram of punch, the die, workpiece, and container; **b** the detail of the forming zone for the TES process

the upsetting area, the shearing deformation area, and the sizing area as shown in Fig. 1.

The CVCES equipment and the cross section of the tube are shown in Figs 2a and 2b.

2.3 Microstructure characterization

Optical microscopy (OM; DMI5000M), scanning electron microscopy (SEM; ZEISS SIGMAHD), and microhardness tester (HVS-1000)were used to investigate the microstructure of the composite material after the extrusion. All the samples for microstructure observation have been carried out in common extrusion region, shearing region, and bonding layer region, respectively. The specimens for OM were polished and etched in picric acid (5 g picric acid +5 g glacial acetic acid+10 ml H_2O+100 ml ethyl alcohol). The specimens which are prepared for SEM observation have been ground and polished. The specimens for microhardness tester were identical with those for SEM specimens.

3 Results and discussion

3.1 Load evolution with strokes at different temperatures

Figure 3 shows load evolution with strokes at different temperatures 360°C, 390°C, and 420°C, respectively. It can be

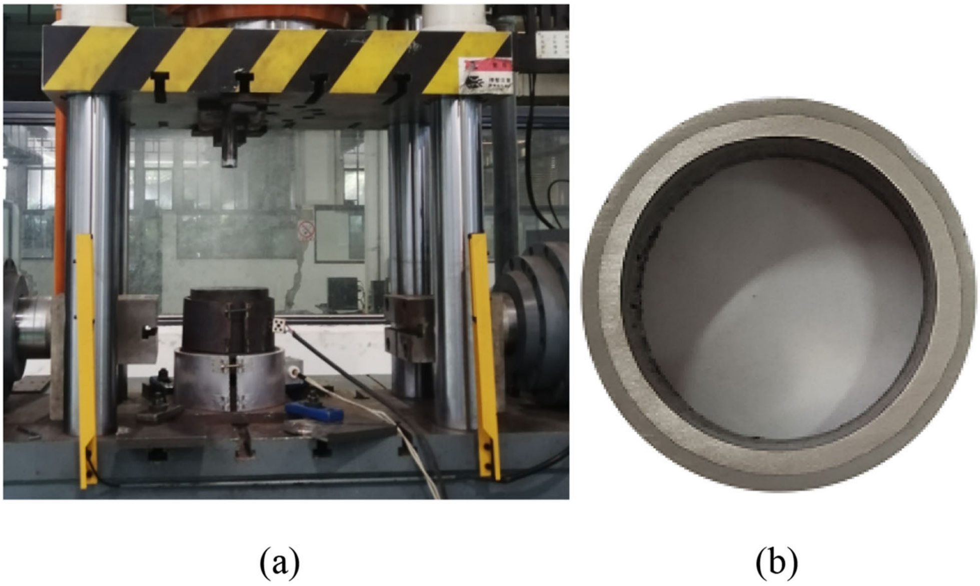
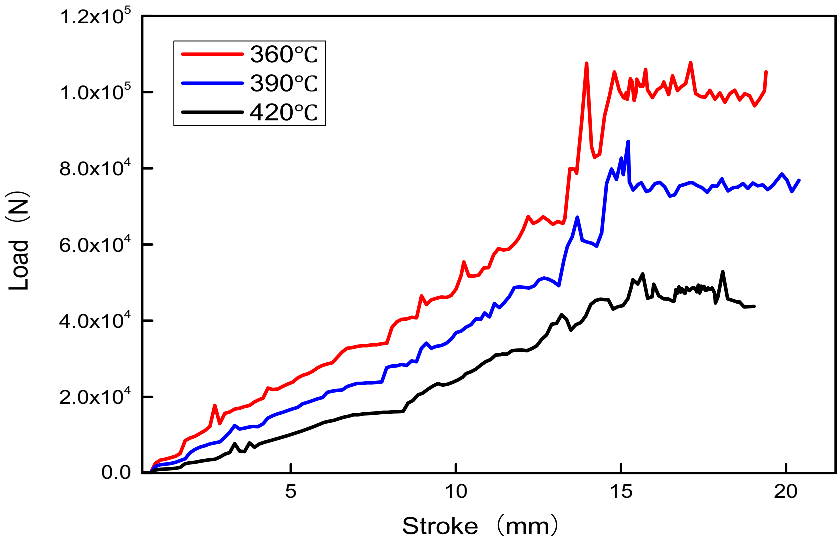


Fig. 2 TES equipment (**a**) and Al/Mg bimetallic tube (**b**)

Fig. 3 Load-stroke curves for different extrusion temperatures



seen that the extrusion temperatures have obvious influences on the curves of load stroke, and the stroke load is in inverse proportion to the extrusion temperature. When the temperature is higher, the load is lower. The load-stroke trend is basically the same at different extrusion temperatures. The required maximum extrusion load is 1.0×10^5N approximately when extrusion temperature is 360°C. The required maximum extrusion load is approximately equal to 8.0×10^4N when the extrusion temperature is 390°C. And the maximum extrusion load required is approximately equal to 4.0×10^4N when the extrusion temperature is 420°C. Deformation resistance of bimetal alloy decreases with temperature rise, and the required load decreases. If the bimetals are fully combined with the mandrel, the maximum extrusion load would be achieved when stroke is about 16 mm.

3.2 Interface analysis of composite materials

Figure 4a is a schematic diagram of the extrude-shearing bimetallic composite tube at 420 °C. The composite tube consists of upsetting section and bimetallic tubes. The surface quality of the composite tube is satisfied, there is no crack and gap and other bad conditions occurred, and the combination effect of the Mg and Al is well. Figure 4b is the intercepted bimetallic composite tube. Figure 4c is the lateral profile diagram of the composite tube. It can be clearly seen from the figure that there are two different metallic lusters with obvious binding characteristics, which proves that the bimetallic bonding is successful. The interface of bimetallic bonding layer was analyzed at different temperatures.

The bonded layers of the prepared bimetallic tube with different extrusion temperatures have been analyzed. Magnesium-aluminum bimetallic tube can be diffused between the two kinds of metals prepared by the TES process with certain temperatures. It can be seen from Figs. 5a and 5b that the bonding region of magnesium alloy and aluminum alloy is subject to large plastic deformation under the TES process with extrusion temperatures of 360 °C and 390°C, and there are some holes and cracks in the bonding region, and bonding diffusion is not obvious. There is no effective bonding between magnesium and aluminum alloys.

Figure 5c is a schematic diagram of aluminum-magnesium bimetallic bonding under extrusion shearing process at 420 °C. As can be seen from the figure, a uniform long strip bonding layer is formed between aluminum and magnesium, and the bonding layer has good quality and no defects on the

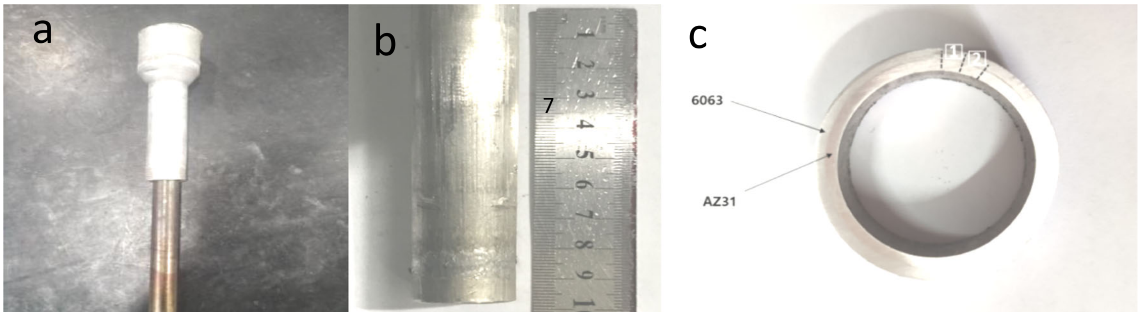


Fig. 4 **a** Forming billet and **b** extruded tube, **c** cross section of extruded tube

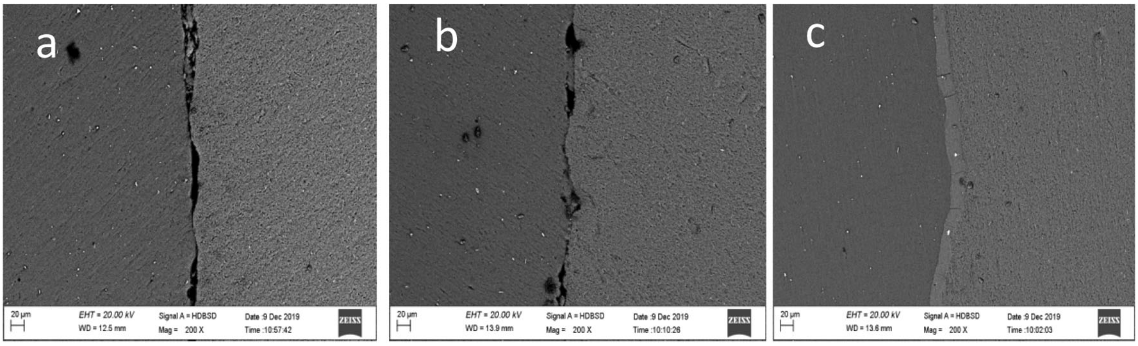


Fig. 5 Morphologies of bonding layers with different extrusion temperatures. **a** 360°C, **b** 390°C, **c** 420°C

surface. There is a certain height difference between the new bonding layer and Al matrix and Mg matrix, which is a typical metallurgical bonding mode. The thickness of the bonding layer is about 20 μm. Different binding effects were obtained at the three temperatures, and the following rules are obtained: the higher the temperature, the better the binding effect.

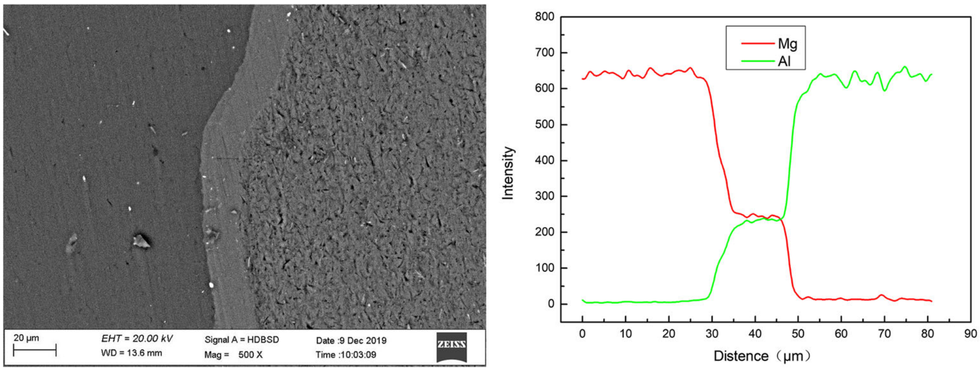
It can be seen from Fig. 6a that there is a diffusion layer between magnesium alloy and aluminum alloy. There are two steps to form the diffusion layer: firstly, the macroscopic migration of atoms in the two kinds of matrix at high temperatures; secondly, a new phase is formed if the atoms on the interface reach a certain concentration. Due to the mutual diffusion of elements for the two kinds of matrix, the original metal interface is replaced by a new compound layer. The bonding region can be divided into magnesium side diffusion layer, stable layer, and aluminum side diffusion layer for atomic diffusion.

In order to study the distribution of elements in the bonding layer of bi-metal tube prepared by the TES process, the samples with good forming quality have been analyzed by EDS. The scanning direction is perpendicular to the interface of the two kinds of matrix. Figure 6b shows the element distribution in the bonding layer of a bi-metal tube with extrusion temperature 420°C. The elements contents of Mg and Al show a gradient change, and are distributed in the whole bonding region. The element concentration decreases gradually from the base metal to diffusion layer. In Fig. 6b, there is a concentration zone with a linear distribution for elements of Mg and Al, and their concentrations are almost equal. According to the analysis of point scanning results, Mg17Al12 (γ) is formed in the diffusion layer on the magnesium alloy side, and Mg2Al3(β)on the aluminum side, and MgAl (ε) was formed on the stable layer [15]. MgAl phase is the intermediate phase formed by solid-state reaction, and the hardness is lower than that of Mg17Al12 and Mg2Al3. The structures of the bonding region are beneficial to improve the bonding quality of bimetallic tube.

Due to the different lattice types of magnesium alloy and aluminum alloy, the solubility decreases with the dropping of temperature in the limited solid solution. Three eutectic intermetallic compounds, Mg_2Al_3, MgAl, and $Mg_{17}Al_{12}$, can be formed in the interface transition zone. During the diffusion process, element concentration is different due to the influences of element diffusion coefficients and the growth rates of each phase layer, so the formation of compounds in the interface transition zone has a certain order, namely $Mg_{17}Al_{12}$-MgAl-Mg_2Al_3. The properties of these compounds are brittle, but have great influence on the properties of the joint surfaces.

The mechanical properties of bonding layer for the bimetallic tube are the key to the bonding quality. The microhardness distribution diagram at the interface joint, measured when extrusion temperature is 420°C, can be seen from Fig. 7; there are significant differences in the

Fig. 6 **a** Schematic diagram of bimetallic bonding layer. **b** Chemical analysis shows the distribution of constituent elements



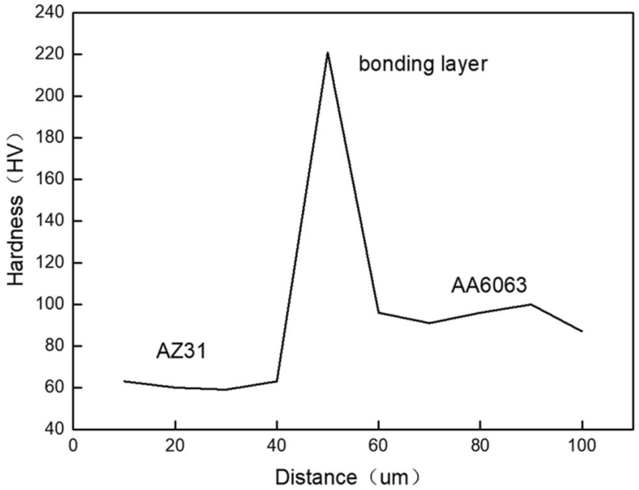


Fig. 7 Schematic diagram of microhardness

hardness of magnesium alloy matrix, binding layer, and aluminum alloy matrix. The average hardness value of magnesium matrix is 62HV, and the average hardness value of aluminum matrix is 90.2HV, and the average hardness of the bonding layer is 221HV. Unfortunately, the higher hardness of the bonding layer is unfavorable to the bonding layer for the bimetallic tube, and the bonding layer is easy to fracture in this area for the quality and toughness of the bonding layer are not enough.

The double-layer Al/Mg bimetallic tube prepared by the TES process can realize short process and near net forming production, and the metallurgical bonding can be achieved between Mg matrix and Al matrix, and the results show that the dimensions along longitudinal direction and radial dimension of the tube are uniform.

4 Conclusions

The bonding layers of bimetallic tubes have been researched by metallographic microscopy, scanning electron microscopy, EDS, microhardness testing, etc.

Deform-3D has been used to simulate Al/Mg bimetal tube prepared by the TES process and experimental researches have been carried out. The research results showed as follows: Higher extrusion temperature would decrease the extrusion loads.

No obvious defects such as cracks and cavities have been found in the bonding layer when extrusion temperature of the TES process is 420°C. The extrusion temperature is higher, and defects appear less, and the bonding layer of the bimetal tube has better quality. Three eutectic intermetallic compounds, Mg_2Al_3, MgAl, and $Mg_{17}Al_{12}$, can be formed in the interface transition zone.

Author contribution Hongjun Hu is corresponding author of this paper who wrote the paper. Ye Tian did the experiments in this paper. Dingfei Zhang analyzed the microstructure in this paper.

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Availability of data and materials The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Declarations

Ethical approval No animals have been used in any experiments.

Consent to participate There are no humans who have been used in any experiments.

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References

1. Kai M, Horita Z, Langdon TG (2007) Developing grain refinement and superplasticity in a magnesium alloy processed by high-pressure torsion[J]. Mater Sci Eng A 488(1):117–124
2. Li MJ, Tamura T, Omura N, Miwa K (2010) Microstructure formation and grain refinement of Mg-based alloys by electromagnetic

vibration technique. Transactions of Nonferrous Metals Society of China 20(07):1192–1198
3. Han D, Zhang J, Huang JF, Yong L, He GY (2020) A review on ignition mechanisms and characteristics of magnesium alloys. J Magnes Alloys 2:329–344
4. GUO LL, FU F (2018) Effect of deformation mode, dynamic recrystallization and twinning on rolling texture evolution of AZ31 magnesium alloy. Trans Nonferrous Metals Soc China 28:1094–1102
5. Mehra D, Mahapatra MM, Harsha SP Magnes J (2018) Processing of insitu RZ5-10wt%TiC magnesium matrix composite J Magnes and Alloy 6:100–105
6. Sullivan J, Cooze N, Gallagher C et al (2015) In situ monitoring of corrosion mechanisms and phosphate inhibitor surface deposition during corrosion of zinc–magnesium–aluminium (ZMA) alloys using novel time-lapse microscopy. Faraday Discuss 180:361–379
7. Jang Y, Collins B, Sankar J, Yun Y (2013) Effect of biologically relevant ions on the corrosion products formed on alloy AZ31B: An improved understanding of magnesium corrosion. Acta Biomater 9: 8761–8770
8. Haghshenas M (2017) Mechanical characteristics of biodegradable magnesium matrix composites: A review. J Magnes Alloy 5:189–201
9. Huang H, Liu H, Wang C, Sun J, Bai J, Xue F, Jiang J, Ma A (2019) Potential of multi-pass ECAP on improving the mechanical properties of a high-calcium-content Mg-Al-Ca-Mn alloy. J Magnes Alloys 7:617–627
10. Yu JM, Xiao YZ, Wang QJ et al (2000) New development of technology of clad metal. J Mater Res 14:12–16
11. Yang YJ (2013) Present situation of processing technology and equipment development for metals composite sheet[J]. Nonferrous Metal Processing 42(02):4–6
12. Qiao HS et al (2015) Microstructure and mechanical properties of interfaces of extruded cladding Mg-Al rods. Chinese Journal of Rare Metals 39(06):481–486
13. Xu K, Huang YL (2014) Research on forging process and numerical simulation technology of thin-walled parts. Forging & Stamping Technology 39(02):128–132
14. Wang ZT, Zhang SH, Qi GX, Wang F, Li YJ (2008) Constitutive equation of thermal deformation for AZ31 magnesium alloy. The Chinese Journal of Nonferrous Metals 18(11):1977–1982
15. Yang X et al (2021) Precipitation behavior of intermetallic compounds and their effect on mechanical properties of thick plate friction stir welded Al/Mg joint. J Manuf Process 64:1059–1069