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 TES (Tube Extrusion Shearing) process, which combines direct extrusion with two step shearing, is developed to Al/Mg bimetallic tube. To explore the deformation mechanism for Al/Mg bimetallic tube during TES process, both experiments and numerical simulations have been carried out. The stroke loads during TES process of Al/Mg bimetallic tubes have been simulated by establishing three-dimensional finite element model. Experiments show that by use of TES process the microstructures can be refined to 50% of the original grain size and with more uniform grain distribution. TES process could improve hardness obviously by comparing which fabricated by direct extrusion. Numerical results indicate TES increases the cumulative strains effectively by direct extrusion and additional shearing. The micro-structures and mechanical properties of the bonded layer were analyzed, The results showed that under the extrusion temperature of 420℃, the bonding layer of the sample obtained by extrusion shearing had no hole defects, and the thickness was about 22um, among which the stable layer was about 11um.The average hardness of the bonding layer is 221HV.

1. Introduction

Magnesium alloys have characteristic of low density, high specific strength and excellent machinability etc., which is known as a green material for sustainable development of resource and environment in the 21st 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 system and poor plastic deformation ability, which hinders its wide application in various fields at room temperature. Mg alloys have a poor corrosion resistance, because second phases or impurity elements could cause galvanic corrosion and oxidation films on surface of Mg alloys, which are porous structure and cannot protect Mg alloys from corrosion effectively comparing to other alloys[6-8].In contrast to Mg alloys, the aluminum is light metal alloy also, aluminum alloy is the most widely used material besides steel. Aluminum alloy will form a dense 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 depends on its crystal structure. The double-layer composite tube is a kind of composite material composed of two kinds of metals with different properties, which are difficult to be achieved 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 light weight and non-corrosion resistant, while aluminum alloy is the opposite. Both metals have their own advantages, combine the advantages of the two metals. The aluminum alloy and magnesium alloy were extruded to produce a bimetallic composite with magnesium as the inner layer and aluminum as the outer layer.

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 metals compound 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, serious environmental pollution etc. Some methods also have some shortcomings as follows: process is complex, and the position and thickness of the bonding interface is 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 shorten as “TES” (Tube Extrusion Shearing) in this paper. The technology is a composite process which uses the local or overall plastic deformation of the pipe to realize the close combination between the inner pipe and the outer pipe Both laboratory and numerical FE modelling are carried out. To illustrate the potential industrial application of the TES process, a complex extrusion die is designed. In this experiment, bimetallic alloy tubes were prepared by extrusion compounding, and the bonding layer was observed and analyzed under different temperature gradients. Microstructural analysis and hardness tests have been performed on the deformed tube. The present study employs DEFORM^{TM}-3D finite element software to simulate the extrusion force, effective stress and strain evolution during TES process.

2. Experimental Procedure

2.1 materials

The key factor of bimetallic composite forming lies in the physical and chemical properties of the two matrix metals selected. For example, the melting point of two metals, composition content, thermal conductivity, etc. All kinds of comprehensive properties need to be considered when two kinds of materials are selected for composite forming, so that the bimetallic composite material that meets our requirements[12].The experimental material is commercial AZ31 magnesium and AA6063 aluminum, The chemical composition of AZ31 magnesium alloy and AA6063 aluminum alloy used in this study is shown in the table 1.The magnesium material was cut into specimens with 80mm length, inner diameterφ20.2mm,outer diameterφ24.8mm,respectively.The aluminum was cut into specimens with 80mm length, inner diameterφ24.9mm, outer diameterφ39.7mm,respectively. The samples are then polished and polished. Then ultrasonic cleaning is carried out to remove the surface impurities. Magnesium alloy tube was put into aluminum alloy tube. The mold and billets were heated to 360°C, 390°C, 420°C, respectively. Then the extrusion experiment is performed.

2.2 Finite element method simulation

During TES process of Al/Mg bimetallic tube, temperature has a great influence on the deformation behavior of materials. Plastic deformation and temperature field affect each other, and then affect the mechanical properties of materials. Therefore, it is necessary to analyze the coupling of plastic deformation and heat transfer.

The DEFORMTM-3D software package has been used. 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 for many times before extrusion. In this paper plasticity material has been used for the billet and a rigid material model for the dies. The flow stress-strain data of the AZ31 alloy were input the module of material library [14]. Parameters used in numerical simulation including material characteristics of the TES process, the parameters of billet temperature, the coefficient of friction between the die and the workpiece , etc. has been list in Table 2. The establishments of the finite element model including the workpiece , the punch and the die model have been established respectively by using 3D modeling software and have been saved as STL file format seen in Fig.1a. Fig.1b presents the schematic diagram of the ES experiments [15].

2.3 Microstructure characterization

Optical microscopy (OM:DMI5000M),scanning electron microscopy (SEM: ZEISS SIGMAHD), microhardness tester (HVS-1000) were used to investigate the microstructure of the composite material after the extrusion. All the samples for microstructure observation were carried out in common extrusion region, shearing region, bonding layer region, respectively. The specimens for OM were polished and etched in picric acid (5g picric acid +5g glacial acetic acid+10ml H_2O+100ml ethyl alcohol). The specimen preparation for SEM was Polished and grinding just. The specimens for microhardness tester was identical with that for SEM specimens.

3. Results And Discussion

3.1 Stroke load distribution at different temperatures

Fig.4 shows the stroke load distribution respectively at 360°C, 390°C, 420°C.It can be seen that the extrusion temperature of bimetal billet has an obvious influence on the stroke load, and the stroke load is inversely proportional to the extrusion temperature. The higher the temperature is, the lower the stroke load is required. The stroke load trend is basically the same at different extrusion temperatures, reaching the maximum at about 16mm.At 360°C, the required maximum extrusion load is approximately 1.0×10^5N; At 390°C, the required maximum extrusion load is approximately 8.0×10^4N.At 420°C, the maximum extrusion load required is approximately 4.0×10^4N.With the increase of temperature, the deformation resistance of bimetal alloy decreases, and the required load decreases. At about 16mm, the

bimetal and extrusion rod are fully combined with the extrusion barrel and mandrel to achieve the maximum extrusion load.

3.2 Interface analysis

Samples of the bimetallic tubes obtained by TES process at 420℃ as shown in the fig.4a.The surface of the obtained samples was full of metallic luster without obvious defects. It can be seen from Fig.4c that there are obvious differences in metallic luster between the inside and outside of the extruded pipe, which proves that the bimetallic bonding is successful. The bimetallic interfacial bonding area was further analyzed by selecting the samples under extrusion and shear at different temperatures.

The bonded layer of the prepared bimetallic pipe was analyzed, and its morphology was shown as follows:

At a certain temperature, the magnesium aluminum bimetal tube can be diffused between the two metals under the action of die extrusion. It can be seen from Fig.6a that at 360 ℃, the bimetallic contact area of magnesium alloy and aluminum alloy is subject to large plastic deformation under extrusion. At this temperature, most of the bonding areas are still holes and cracks, with no obvious bonding diffusion and no effective bonding between magnesium and aluminum. It can be seen from Fig.5b that there are still holes and gaps between the two alloys at 390℃, which is closer than that at 360℃, but the interface bonding is not obvious. It can be seen from Fig.5c that there is a good bonding layer between magnesium alloy and aluminum alloy after extrusion and shearing at 420℃. There is no obvious holes gap at the bonding layer, and the bonding layer is obviously different from the alloys on the left and right sides. Enlarge it as shown below:

It can be seen from Fig.6that there is a diffusion layer between magnesium alloy and aluminum alloy. The formation of the bonding layer is the macroscopic migration of two matrix atoms at high temperature, and a new phase is generated at the interface after the atomic number migrates to a certain extent. The elements diffuse with each other and combine in layers to form new compounds. The bonding zone can be divided into magnesium side diffusion layer, diffusion stable layer and aluminum side diffusion layer.

3.3Element distribution of binding layer

Point scanning was carried out on the bonding layer, and the results were as follows:

At 420℃, the content of magnesium and aluminum changes in a gradient, and the element concentration decreases gradually from the diffusion layer to stability and reaches a relatively stable state in the binding stability area.$Mg_{17}Al_{12}$ (γ) was formed on the magnesium side, Mg_2Al_3 (β)on the aluminum side, and MgAl (ε) was formed on the stable layer[16]. MgAl phase belongs to the mesophase formed by solid state reaction. Its hardness is higher than that of $Mg_{17}Al_{12}$ and Mg_2Al_3,and the hardness of the combined stable layer is higher. Due to the different lattice types of magnesium alloy and aluminum alloy, the

solubility decreases with the decrease of temperature in the limited solid solution formed by Al/Mg. Three eutectic intermetallic compounds, Mg_2Al_3, MgAl and $Mg_{17}Al_{12}$ can be formed in the interface transition zone of Mg/Al diffusion welding. During the diffusion process, element concentration is different due to the influences of element diffusion coefficients and the growth rates of each phase layers, so the formation of compounds in the interface transition zone has a certain order, namely $Mg_{l7}Al_{12}$-MgAl-Mg_2Al_3. The properties of these compounds are brittle, and which have great influences on the properties of the joint surfaces.

The interface between the inner and outer tube layers is the most important factor which affect the performance of double-layer composite pipe. The bonding between them can be divided into two stages: (1) the pressure welding stage under the action of pressure and friction force; (2) the diffusion welding stage of mutual diffusion.

In the first stage, under the action of pressure, the two materials contact each other, and the mutual diffusion and dynamic crystallization will occur between the two materials, so the metallurgical bonding interface can be obtained. When the initial bonding region between the inner and outer layers of metal is achieved, the second stage will be entered, and materials for inner and outer layer continue to diffuse, and the thickness of diffusion bonding layer continues to increase, so the strength of metallurgical bonding could be improved further .

The diffusion process plays an important role in recrystallization and the formation of intermetallic compounds of the interface between the inner and outer tube layers. In diffusion welding of dissimilar metals, the diffusion of atoms near the interface is an important factor which affect the phase transformation, interfacial reaction and bonding quality of the joint.

3.4 bonding layer interface analysis

The mechanical properties of bimetallic pipe bonding layer are the key to the bonding quality. The microhardness distribution diagram at the interface joint measured at 420°C is as follows:

As can be seen from Fig.8, there are significant differences in the hardness of magnesium alloy matrix, binding layer and aluminum alloy matrix. On both sides of the region, the hardness value is relatively balanced. The average hardness value of magnesium matrix is 62HV, the average hardness value of aluminum matrix is 90.2HV, and the hardness of intermetallic compound at the bonding layer is 221HV.Unfortunately, the high hardness of the bonding layer is unfavorable to the bonding of bimetals, and the bonding layer is easy to break in this area due to insufficient quality toughness.

The extrusion of double-layer Al/Mg bimetallic tube can realize short process and near net forming production and the metallurgical bonding can be achieved between forming interfaces, and the obtained tubes have uniform length and radial dimensions, and the freedom degree of blank combination is relatively large. The results show that the dimensions along longitudinal direction and radial dimension of the tube are uniform.

4. Conclusions

In this paper, Deform-3D technology is used to simulate Al/Mg bimetal extrusion and shear composite forming process and experimental research is carried out. The results showed as following:

1. In the process of extrusion shearing, the stroke load decreases with the increase of extrusion temperature. When the temperature increases by 60℃, the stroke load decreases by about $6.0x10^4$ The temperature has significant effect on the stroke load.
2. The bonding layer of the bimetal was closely related to the extrusion temperature. The higher the extrusion temperature was, the better the bimetal bonding would be. The bonding step can be divided into two stages: the pressure welding stage under the action of pressure and friction force; the diffusion welding stage of mutual diffusion. At t=420℃, Al/Mg bimetal bonding layer with a thickness of about 22um was formed, among which the stable layer was about 11um.The diffusion layer on the magnesium side was $Mg_{17}Al_{12}$ (γ), and the diffusion layer on the aluminum side generated Mg_2Al_3 (β), and the stable layer formed MgAl (ε).The average hardness of magnesium matrix is 62HV, that of aluminum matrix is 90HV, and that of bonding layer is 221HV.

Declarations

Ethical Approval

No animals have been used in any experiments.

Consent to Participate

There are no human who have been used in any experiments.

Consent to Publish

The Author confirms:

- that the work described has not been published before (except in the form of an abstract or as part of a published lecture, review, or thesis);
- that it is not under consideration for publication elsewhere;
- that its publication has been approved by all co-authors, if any;
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Authors Contributions

- Hongjun Hu is corresponding author of this paper done the examples
- Ye Tian who wrote the paper and done the experoments .
- Dingfei Zhang researahed the microstructures analysises in this paper

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Competing Interests

The authors declare no competing non-financial/financial interests.

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.

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