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Simulation of Thermal Deformation Behaviors of AZ80 and ZK60 Magnesium Alloys

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This paper aims to research the thermal deformation behaviors of AZ80 and ZK60 magnesium alloys. Specifically, the AZ80 and ZK60 magnesium alloys were experimented under different temperatures and in different molds, and then their thermal deformation data were compared. Results have shown that the tensile strength and elongation of the AZ80 magnesium alloy extruded parts were positively correlated with the increase of extrusion temperature, but the tensile strength and elongation showed inflection points at 380°C and 350°C, respectively. As for ZK60 magnesium alloy in the 70° cone mold, the extrusion force is minimal, so the cone mold with the die angle of 70° were used in all thermal extrusion experiments on ZK60 pipe. It is concluded that the stress and strain curves of AZ80 and ZK60 magnesium alloys obtained from the experimental model in this paper are accurate, indicating high accuracy of the model.

1. Introduction

Currently, the energy consumption of various countries in the world is large on the whole, especially the severe consumption of mineral resources and metal resources. With the change of people's ideas, more and more people gradually pay attention to the energy saving and reuse and emission reduction. As a relatively common metal material, magnesium alloy features light weight and reuse, attracting a large number of domestic and foreign scholars to carry out related research. However, the promotion and use of magnesium alloys still face major problems, mainly because some scholars believe that magnesium metal is relatively costly, inflammable and explosive, and is easy to corrode with active chemical. However, some scholars have developed molten magnesium through certain techniques. This material has good cutting properties, which can guarantee the accuracy of processing to a certain extent, reduce material processing losses, and save costs. At the same time, flammable and explosive issues were solved by adding gaskets. It can be seen that magnesium alloys have great development potential in the future under the impetus of new technologies.
In this paper, the thermal deformation data of AZ80 and ZK60 magnesium alloys were compared under different temperatures and different mold experimental conditions, and their thermal deformation behaviors were simulated. A lot of domestic and foreign references were used during the experimental preparation to ensure the accuracy and objectivity of the experimental results. This paper aims to provide reference for relevant persons through the experimental results.

2. Literature review

The quality of weaponry has largely determined its ability to respond quickly on the battlefield. Therefore, the quality indicators of weapons and equipment have a crucial role in modern high-tech warfare. It can even affect the war situation. In the Gulf War, for example, the tanks equipped by Iraq were not only inadequate in range, but they were bulky and weak in armor protection. They had little resistance in front of the new US tanks. Therefore, all countries in the world have invested a lot of human and material resources in the study of lightweight structural materials and advanced manufacturing technologies to reduce the quality of weapons and equipment, continuously improve the mobility and flexibility of weapons and equipment, increase their strength, and improve their combat capabilities. Magnesium alloys have low density, high specific strength, specific stiffness and fatigue strength. The electromagnetic shielding performance is excellent, the conductivity

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and thermal conductivity are good, and the cutting and polishing performance is excellent. Magnesium alloys have the properties of high relative strength, good shock absorption capability, good heat dissipation and recycling use as one of the lightest engineering metal material. It is very suitable for the lightweight materials of automobile wheel. It is the ideal metal material to realize the light weight of the equipment. Due to the dense hexagonal structure of magnesium alloys and poor molding ability, most varieties of magnesium alloys have better casting properties. As a result, there are currently fewer magnesium alloy shaped products. It is mainly cast. However, the mechanical properties of the casting are not ideal. It is prone to tissue defects. At the same time, the shape and size of product processing have certain limitations. The application range of magnesium alloys is very limited. Therefore, research on deformed magnesium alloys has become an important direction for the research of magnesium alloy industry in the world, and has achieved many significant results.

In recent years, major military powers have begun to apply magnesium alloy materials to weapons and equipment and related combat platforms. The application of magnesium alloys mainly focuses on aerospace, aviation, and military industries, such as aircraft landing gear wheels, missile engine bearings, and seat supports. According to the excellent comprehensive performance of magnesium alloy materials, it can be predicted that in the near future, its usage will greatly exceed the pot alloy material and become the most widely used metal structural material in weapons and equipment (Singarapu et al., 2015). According to the website, the supporter and cooling system of the booster Saturn rocket has all adopted magnesium alloys, which reduced the weight by a total of kilograms and achieved very good results. In particular, compared with aluminum alloys, there are many researches and comparisons on the properties of magnesium alloys at present. The Ballistics Conference reported that the United States Army Research Laboratory and the Dutch Defense Security Corporation conducted in-depth studies on the ballistic performance of new magnesium alloys. Ballistic tests show that the new magnesium alloy armor is superior to the current mainstream alloy armor in its resistance to the millimeter armor piercing projectile. Therefore, in the future, magnesium alloys will become the most promising new alloy in the military industry. The mechanical properties of wrought magnesium alloys are significantly better than cast magnesium alloys (Liu et al., 2015). At present, high strength deformed magnesium alloys are widely used in industry. Magnesium alloys have good comprehensive mechanical properties and moderate price. There are more researches on the toughening and hot processing of alloys, and some progress has been made (Salich, 2017). The price of the alloy is several times that of the alloy, but it is the highest strength among the existing common magnesium alloys. Alloys have low density and low mass. Therefore, the alloy has almost the highest specific strength among all metal structural materials. It has broad application prospects. However, there are few studies and literatures on the basic theories of hot working of alloys and hot forming engineering techniques. Dusunceli and Drozdov systematically studied the thermal deformation properties of the alloy, the mechanical properties of the formed system, and the thermal shock resistance, and then evaluated its value in armor protection. It lays a theoretical foundation for its application to guide the engineering applications of magnesium alloys in the military industry (Dusunceli and Drozdov, 2017).

Magnesium alloys have poor plasticity at room temperature because of their hexagonal structure. As the temperature increases, the non-basal slip increases and the strength decreases. The shaping is improved, so the forming process should be carried out under high temperature conditions. In the hot deformation process, work hardening, dynamic recovery and dynamic recrystallization may occur simultaneously and lead to grain refinement and reduced deformation resistance (Deng and Qian, 2017). The alloy's warm deformability was studied. The results show that the thermal simulation curves are not exactly the same. The thermal simulation curve of magnesium alloy is a typical dynamic recrystallization type, and the material can be continuously deformed. When studying thermal simulation curves, most of the temperature points have dynamic recrystallization characteristics. After the stress variable reaches its peak, the stress drops sharply in the metallurgical structure. The analysis shows that, to a certain extent, twins dominate the deformation mechanism. It is a feature of plastic deformation of magnesium alloys (Deka and Datta, 2017). Magnesium alloy plastic deformation generally has the following process. The deformation begins with a twinning mechanism, and then activates the dislocation source to strengthen the material. As the energy increases, dynamic recrystallization occurs, the material softens, and the above process continues to be repeated (Sabat et al., 2017). Kondori and Mahmudi analyzed the thermal processing maps of magnesium alloys and cast magnesium alloys using a theoretical system of processing maps (Hadadzadeh et al., 2017). It is generally believed that the mechanism of high temperature plastic deformation of various magnesium alloys is similar. Many scholars have established a corresponding flow stress model based on their systematic analysis and research. In addition, a two-stage flow stress model was established for dynamic recovery and dynamic recrystallization of work hardening. A two-dimensional cell automaton model was established to simulate the dynamic recrystallization process of polycrystalline metal materials.

3. Methods

The experimental materials were AZ80 and ZK60 magnesium alloys, respectively. The AZ80 magnesium alloy was semi-continuously cast to obtain a casting bottle that was kept at a temperature of 400°C for 12 hours for homogenization; and a ZK60 magnesium alloy was a bar obtained by hot extrusion of an ingot. The compositions of the experimental materials are shown in Table 1 and Table 2.

Table 1: Chemical composition of AZ 80 magnesium alloy (% by mass, %)

Al	Zn	Mn	Si	Cu	Ni	Fe	Mg
8.6	0.45	0.15	0.03	≤0.01	≤0.001	≤0.005	Bal.

Table 2: Chemical composition of ZK60 magnesium alloy (% by mass, %)

Al	Zn	Mn	Si	Cu	Ni	Fe	Mg
5.7	0.6	0.1	0.003	0.002	0.001	0.003	Bal.

The heat-compressed sample was cut into small cylinders of 8imn*15mm by wire cutting, and the surface of the samples was polished by a grinder. In order to reduce the effect of friction, carbon powder was smeared at the end of the specimen as a lubricant. The deformation temperature was 240-440°C and the actual strain rate was 0.001-1S-1. The heating rate of the sample was 5°C/s. Before the compression, the sample was kept at the deformation temperature for 3 minutes, and the total compression deformation was 60%. Immediately after the deformation, the water is quenched to retain the thermally deformed structure.
The thermal compression experiment was performed on a Gleeble-2000 thermal/force simulator. The simulator consists of three main control systems and five equipment units, and the entire experimental machine can be completely controlled by the computer, all manually controlled, and manual-computer compositely controlled, with the characteristics of accurate control, excellent performance and easy operations. The signal positions such as temperature, stress, strain, etc. collected from the sample by Gleeble-2000 thermal simulation compressor were consistent, and the wet micro-tissue change had a very good correspondence with the mechanical behaviors. The sensor was placed on the middle surface of the sample to detect the sample strain and other information. The experimental principle is shown in Figure 1.

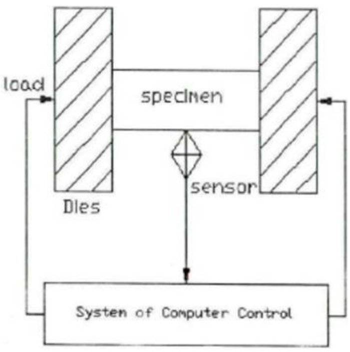

Figure 1: Experimental schematic

The experimental machine is equipped with a high temperature radial (transverse) strain εr extensometer and an axial (horizontal) strain εp sensor. The true strain expressions are:

$$\varepsilon_r = In\left(\frac{D_0^2}{D^2}\right)$$

$$\varepsilon_p = In\left(\frac{l}{l_0}\right)$$

In the formula, D0 and L0 are the original diameter and length of the sample respectively; D and l are the instantaneous diameter and length of the sample, respectively.
According to the principle of volume invariance, radial strain and axial strain should be equal. Due to the occasional deviation of the C-Strain sensor during radial strain measurement (the beam centering error

caused by the sample's lumbar bulging or uneven deformation, etc.), this article used the axial strain measurement method in the experiment, namely the stroke control to collect changes in load and displacement at any time.
Commonly used chemical etching agents for the production of magnesium alloy specimens are weak acids, such as nitric acid, picric acid, ammonia acid, and other ethanol solutions. It is mainly through oxidation that the different phases in the specimen are subjected to different degrees of oxidation and dissolution to reflect the contrast and achieve the purpose of displaying the tissue.

4. Research Results and Discussion

4.1 Thermal Backward Extrusion Process of AZ80 Magnesium Alloy Multilayer Cup-shape Specimens

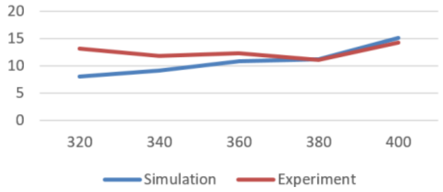

Figure 2: Comparison of grain size of AZ80 magnesium alloy at different extrusion temperatures

Figure 2 compares experimental and simulated values of grain size for AZ80 magnesium alloys at different temperatures. It can be seen from the figure that at 350°C, the experimental values of the grain size of AZ80 magnesium alloy at different temperatures are consistent with the simulated values. Only at 320°C, due to incomplete dynamic recrystallization in the actual deformation process, grains are not fully refined, resulting in a large difference between the experimental value and the simulated prediction. The average error between simulated prediction and experimental value is 18.5%, which indicates that the prediction of grain size in AZ80 magnesium alloy extrusion deformation is relatively accurate. It also illustrates the accuracy and a certain practical value of the dynamic recrystallization model and grain growth model of the AZ80 magnesium alloy established in this paper.

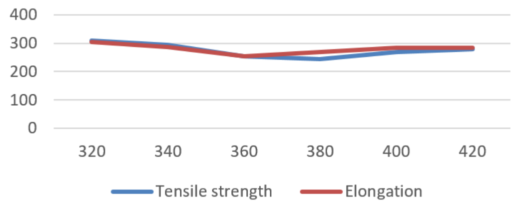

Figure 3: Mechanical properties of AZ80 alloy gland parts

As shown in Figure 3, the tensile strength and elongation of the extruded parts decreased first and then increased with increasing extrusion temperature. Specifically, at the extrusion temperature of 320°C, the tensile strength and elongation was higher, and the tensile strength and elongation showed an inflection point at 380°C and 350°C respectively. The influence of the extrusion temperature on the mechanical properties of the magnesium alloy is mainly related to the grain size, stress state, and deformation structure. The mechanical properties are the result of the combined action of work hardening and dynamic recrystallization of the AZ80 magnesium alloy during deformation. The differences are mainly related to the recrystallized equiaxed grains in the sample and the number and morphology of the plastically deformed structure. At 410°C, the extruded specimen was composed of uniformly distributed equiaxed crystals. Therefore, the specimen exhibited the best comprehensive mechanical properties and higher elongation.
The mold temperature has a certain influence on the surface quality of formed parts. As the mold temperature rises, the formability of the parts becomes better. It is because during the backward extrusion process of the parts, when the billet contacts with the punch and die at the same time, the billet will transfer heat to the mold and the actual extrusion temperature will be reduced if the mold temperature is much lower than the billet temperature. In addition, the metal is forced to flow upward at the same time as the billet is under stress in the mold. When the die friction force is greater than the tensile strength of the metal surface, cracks will occur. When the high-temperature billet forms, cracks can hardly occur due to lower strength, higher plasticity, better metal fluidity, relatively small extrusion force used in forming, and small additional frictional tensile stress.

However, the low-temperature billet, due to higher strength, poorer plasticity, relatively poor fluidity of the metal during forming, large extrusion force used in the forming, and relatively large additional frictional stress, is prone to have cracks.

4.2 Thermal Forward Extrusion Process of ZK60 Magnesium Alloy Pipe

In order to minimize the extruding force on the ZK60 tube for forming, the hyperbolic dies and cone dies with half-angles of 60°, 65°, and 70° were tested according to the experimental scheme of pipe extrusion. The billet temperature was 300°C., the mold temperature was 270°C., and the extrusion speed was 1 mm/s. The experimental results are shown in Figure 4.

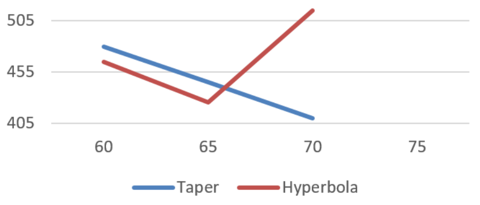

Figure 4: Relationship between die and extrusion force

From the experimental results, it can be seen that the 70° cone extrusion suffered the smallest force, confirming the accuracy of the physical simulation of the lead pipe extrusion test. Therefore, the ZK60 pipe thermal extrusion test adopted a cone die with the die angle of 70°.

In the extrusion process, the extruded billet first produced elastic deformation, and the extrusion force rose rapidly. As the extrusion force continued to increase, the alloy plastically deformed and entered the plastic flow stage, and the extrusion force decreased. As the extrusion continued, the metal entered the die opening, with the flow resistance and the extrusion force increasing. When the metal flowed into the calibration bench, the extrusion force reached its maximum value. As the metal flowed out of the calibration bench, the extrusion force decreased. Afterwards, it gradually became stable. According to the numerical simulation and experimental measurement results, the extrusion force comparisons of pipes with different extrusion ratios are shown in Figure 5.

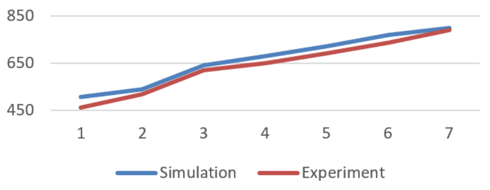

Figure 5: Extrusion force with different extrusion ratios

It can be clearly seen from Figure 4 that as the extrusion ratio increases, the pressing force also gradually and sharply increases. As the extrusion ratio increases by 4 or so, the extrusion force increases by nearly 20%. Although the extrusion ratio increase raises the temperature inside the billet and boosts the softening effect of the material, the work hardening effect caused by the increase in deformation is much greater than the softening effect, and the deformation resistance is still large. Therefore, the extrusion force increases as the extrusion ratio increases.

Comparing the extrusion force under different extrusion ratios, the change trend of the extrusion force under the numerical simulation prediction is close to that of the experimental result. The basic trend is consistent and slightly larger than the measured value, indicating that the numerical simulation prediction result is more accurate and the extrusion force under the numerical simulation prediction can guarantee the smooth progress of production.

With the increase of the extrusion ratio, the grain size after the metal deformation is significantly smaller. This is mainly because each type of alloy has a critical degree of recrystallization. And when this level is reached, the grains begin to recrystallize. As the degree of deformation increases, the storage energy increases, with increased internal humidity of the material during deformation and enhanced driving force for recrystallization, dynamic recrystallization occurs easily. The larger the deformation, the easier the original crystal grains break into fine grains. The newly generated crystals are dominated by small grains. From this, it can be concluded that as the extrusion ratio increases, the grains are clearly refined. In the extrusion deformation, by changing the extrusion ratio, it is easier to obtain more fine grains, which can effectively eliminate the coarse grains and deflection in the alloy.

The magnesium alloy extrusion pipe underwent the tensile experiment under room temperature, with the tensile speed of 1.5mm/min, to obtain the magnesium alloy tensile strength, yield strength, elongation, and the curve of the relationship between the extrusion-stress ratio and mechanical properties of the magnesium alloy pipe under different extrusion ratios. From the curves, it can be seen that the tensile strength of the magnesium alloy material increases by 11.2% to 23.1% from 260 MPa to 289-320 MPa, and the elongation rate increases by 15.4% to 47.9% from 8.45% to 9.75%-12.5%. Also, the yield strength increases by 5%-20% from 200Mpa to 210-240MPa. It can be concluded that as the extrusion ratio increases, the mechanical properties of the pipe increase compared with original billets.

5. Conclusion

In order to study the thermal deformation behaviors of AZ80 and ZK60 magnesium alloys, the AZ80 and ZK60 magnesium alloys were experimented under different temperatures and in different molds, and then their thermal deformation data were compared. Results have shown that the tensile strength and elongation of the AZ80 magnesium alloy extruded parts were positively correlated with the increase of extrusion temperature, but the tensile strength and elongation showed inflection points at 380°C and 350°C, respectively. As for ZK60 magnesium alloy in the 70° cone mold, the extrusion force is minimal, so the cone mold with the die angle of 70° were used in all thermal extrusion experiments on ZK60 pipe. It is concluded that the stress and strain curves of AZ80 and ZK60 magnesium alloys obtained from the experimental model in this paper are accurate, indicating high accuracy of the model.

Deformed magnesium alloy has been widely used in China’s automobile manufacturing, aerospace, defense and other fields due to its significant advantages, indicating huge development potential of deformed magnesium alloys. However, magnesium alloys are not perfect. Under normal temperature conditions, their plasticity is poor. Therefore, it should be a focus in the magnesium alloy research to further research deformed magnesium alloys in the future.

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