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Research Progress of the Simulation on the Hot Extrusion of the Magnesium Alloys

Mengjun Zhao\textsuperscript{1,a}, Hongming Cai\textsuperscript{1,b}, Zhiлин Wu\textsuperscript{2,c,*} and Renshu Yuan\textsuperscript{1,d,*}

\textsuperscript{1}The School of Mechanical Engineering, Nanjing University of Science & Technology, Nanjing 210094, China
\textsuperscript{2}Office of Science and Technology Research, Nanjing University of Science & Technology, Nanjing 210094, China
Email: \textsuperscript{a}511720141@qq.com, \textsuperscript{b}652491109@qq.com, \textsuperscript{c}wuruinan-1994@njust.edu.cn, \textsuperscript{d}101ab211@vip.sina.com

Abstract. Simulation technology is one of the important means in the extrusion process of metal. This paper reviewed the recent the simulation studies on the hot extrusion of magnesium alloys: at first, the constitutive equations of several commonly used in Mg alloy were presented; afterwards, simulation on forming processes of Mg alloy were analyzed, and then product defects were summarized and discussed in detail. The reviewed results showed that the simulation technology has widely been applied in forming research of magnesium alloy.

1. Introduction
As the lightest structural materials, magnesium alloys have been widely used in the fields of automobile, aerospace, high-speed train, and information industries, due to their low density, heat conduction, high damping, superior specific stiffness and strength. At present, casting and plastic deformation is the primary forming methods for the application of magnesium alloys, while the mechanical properties of the latter are obviously better than that of the former because of the absence of casting defects and remarkable grain refinement for wrought magnesium alloys. However, due to its hexagonal close packed properties, magnesium alloys are generally hot worked at temperatures above 225\degree C [1].

The extrusion technology of magnesium alloys has attract much attention in recent years because of its ability to achieve the superior precision, improved quality, and homogeneous properties throughout the component of the profile. However, the most traditional design of extrusion dies is based on the trial-and-error method, and the performance of dies is mainly dependent on the experience of die designers and waste lots of resource.

With the progress of computer technology and the FEM (Finite Element Method), extensive studies on the numerical simulation of extrusion process have been carried out to improve the product quality and production efficiency, especially, in hot extrusion technology; the simulation technology method is an important analysis tool.

The simulation of metal forming began in 1960’, whose core is the Finite Element Method, whose calculation thought and general process [2] are shown in Figure 1:
According to different used constitutive equations [3] in algorithm. The FEM can be divided into three types: the elastic-plastic, the rigid-plastic and the viscid-plastic, as shown in Table 1.

| Classification                  | Materials model  | Application                        | commonly used software          |
|---------------------------------|------------------|------------------------------------|---------------------------------|
| The elastic-plastic FEM         | elastic-plastic  | suitable small plastic             | DEFORM-3D, MARC, ANSYS,ABAQUS    |
| The rigid-plastic FEM           | rigid-plastic    | severe plastic deformation[^4]     | MSC.SuperForge, MSC.SuperForm,   |
| The viscid-plastic FEM          | viscid-plastic   | suitable for hot deformation of metal or soft metal without hardening | HyperXtrude, FAROF-3D            |

In this paper, the objective is to let interested scholars know the current situation of simulation on hot extrusion of magnesium alloys and enhance them to further study the simulation technology in magnesium alloys. The constitutive equations of different magnesium alloys are stated and extensive performance of simulation on magnesium are shown and analyzed.

2. Constitutive equations
The accuracy of numerical simulation depends strictly on the input data regarding the physical properties of materials, of which the basic data model in simulation is the constitutive equation, that is, stress-strain curves at different temperatures and strain rates.

2.1. AZ31 magnesium alloy
Based on the Arrehniius equation, Kun Yu, R.C. Wang, W.X. Li, et al [5], established a constitutive equation to describe the hot compression of AZ31 magnesium alloy, as follows:

\[
\sigma = \frac{1}{0.017297} \ln \left( \frac{Z}{4.85 \times 10^{15}} \right)^{1/5.8567} + \left[ \frac{Z}{4.85 \times 10^{15}} \right]^{2/5.8567} + 1 \right]^{1/2}
\]  

(1)

Where, \[Z = \dot{\varepsilon} \exp \left( \frac{163.51 \times 10^3}{RT} \right)\]

The above equation was built on the experiments of the hot compression of AZ31, which were carried out on the Gleeble-1500 thermal simulator at a strain rate of \(1 \times 10^{-3} - 10 \text{ s}^{-1}\) and temperature range of 150—500°C. In the above equation, the parameter \(\sigma\) is determined by peak stress (MPa) for a given strain, and \(T\) denotes absolute temperature. The \(R\) and \(T\) denote molar gas constant (8.31 J mol\(^{-1}\) K\(^{-1}\)) and absolute temperature respectively.

2.2. AZ80 magnesium alloy
Based on the Arrehniius equation, H.T. Zhou, Q.B. Li, Z.K. Zhao, et al [6], established a constitutive equation to describe the hot compression of AZ80 magnesium alloy, as follows:
\[ \varepsilon = 2.9 \times 10^6 \left[ \sinh(0.01744\sigma) \right]^{0.905} \exp\left[ \frac{-154.6 \times 10^3}{8.314T} \right] \]  

(2)

The above equation was built on the experiments of the hot compression of AZ80, which were carried out on Gleeble-1500 thermal simulator at a strain rate of $1 \times 10^{-3}$—20 s$^{-1}$ and temperature range of 200—500°C.

### 2.3. AZ61 magnesium alloy

Based on the Arrhenius equation, Xu Yan, Lian-Xi Hu, Yu Sun [7], established a constitutive equation to describe the hot compression of AZ61 magnesium alloy, as follows:

\[ \varepsilon = 3.77^{13} \left[ \sinh(0.011\sigma) \right]^{7.56} \exp\left[ \frac{-173.66 \times 10^3}{RT} \right] \]  

(3)

The above equation was built on the experiments of the hot compression of AZ61, which were carried out on Gleeble-1500 thermal simulator at a strain rate of $1 \times 10^{-3}$—1 s$^{-1}$ and temperature range of 220—380°C.

### 2.4. ZX115 magnesium alloy

The hyperbolic-sine Arrhenius equation was presented by SELLARS [8]. Based on that equation, Han-Lin Ding, Cheng-Zhi Xu, et al [9], established a constitutive equation to describe the hot compression of ZX115 magnesium alloy, as follows:

\[ \varepsilon = 2.716 \times 10^5 \left[ \sinh(0.016\sigma) \right]^{1.30} \exp\left[ \frac{-172.7 \times 10^3}{RT} \right] \]  

(4)

The above equation was built on the experiments of the hot compression of ZX115, which were carried out on Gleeble-3500 thermal simulator at a strain rate of $1 \times 10^{-3}$—1 s$^{-1}$ and temperature range of 300—450°C.

### 2.5. AE21 magnesium alloy

Based on the Arrhenius equation, L. X. Wang, G. Fang, M.A. Leeflang, et al [10], established a constitutive equation to describe the hot compression of AE21 magnesium alloy, as follows:

\[ \varepsilon = 1.3 \times 10^4 \left[ \sinh(0.0128\sigma) \right]^{0.88} \exp\left[ \frac{-167 \times 10^3}{8.314T} \right] \]  

(5)

The above equation was built on the experiments of the hot compression of AE21, which were carried out on Gleeble-1500D thermal simulator at a strain rate of $1 \times 10^{-3}$—10 s$^{-1}$ and temperature range of 350—480°C.

### 3. Simulation on hot extrusion

Based on the constitutive equation for magnesium alloys, the properties of hot extrusion, such as extrusion loads, stress, strain, strain rate, temperature distribution and micro structure were simulated by thermo-mechanical coupled simulation. Meanwhile, defect of the extruded products was also studied by many researchers.

#### 3.1. Simulation on forming process

In simulation on forming process, technological parameters, such as initial temperature of materials, extrusion rate, and friction factor, the geometrical parameters of die, and different forming process and so forth were considered as critical controlled variable to study the extrusion loads, stress, strain, strain rate, temperature distribution and micro-structure. Currently, main researches are as follows:

Extensive simulations on forming process [11-13] show the stress-strain at different strain rate possess the obvious characteristics: stress increase rapidly with the strain in the initial stage and reach a peak value, then decrease slowly, at last tended to stable, as shown in Figure 2. Besides, the
The corresponding load-displacement are consistent with the stress-strain, as shown in Figure 3, meanwhile, under the different preheated temperature of billet, there are the same simulated result [13], as shown in Figure 4. The above simulated results accord with the experimental results [14, 15] basically. However, some other researches [16] showed there is no obvious pressure peak value in load-displace process. Additionally, the maximal load increases slightly with the bearing length [17]. The above existing difference of load-displacement has yet been not further studied at present.

Figure 2. Stress-strain curves at 300°C at different strain rates [11].

Figure 3. The simulated load-displacement curves under different friction conditions [12].

Figure 4. The simulated load-displacement curves under different preheated temperature (A: 10mm/s; B: 50mm/s; C: 100mm/s) [13].
Figure 5. Comparison of forming-load vs stroke curve for the simulation and experiment in the extrusion process [14].

Figure 6. Simulated strain distribution (diameter 10 mm, alloy Mg ZM21) [19].

In a certain temperature range, the higher the temperature is, the higher the strain is, for example, the elongation of Mg AZ80 at 400 and 450°C was over 100% and the maximum of 161.15 was achieved at 400°C and 10^2 S^{-1}[18]. And, the strain distribution is inhomogeneous in the workpiece and generally there are bigger strain volume at exit of die than at other section, as shown in figure 6 [19]. Meanwhile, the strain distribution is severely affected by geometries (including die and workpiece), such as extrusion angle and die corner radius [20]. On the other hand, strain is subject to forming process, such as, some researches showed that direct extrusion and torsional deformation can significantly enhance the accumulation strain of deformed magnesium alloys, and the cumulative strain increases with the increase of torsional angle, the maximum equivalent strain can get up to 3.75 [21].

The temperature distribution is the most interesting output of the simulation for the process optimization, since the hot shortness sometimes observed in the industrial process; even laboratory is directly related to the temperature. By simulation, we can know, the temperature distribution in the deformation zone and the extruded bar is higher than other section, for instance, in hydrostatic extrusion of magnesium alloy ZM21, the temperature in die entrance was higher than in exit die, in other deformation zone [19]. Generally speaking, in extrusion simulation of magnesium alloys, temperature is taken as a controllable variable, so few studies are reported on reasons for temperature changing.

The studies of the deformation behavior and isothermal extrusion process simulation of AZ80 magnesium alloy showed that the grain size of magnesium alloys increased, as the temperature increased and the strain rate decreased [22], as shown in Figure 7. Subsequently, the results in the forming process of wrought magnesium alloy AZ31, further pointed that at 250, 300, 350, 400°C, the grain increased with the temperature, besides, at the same temperature, the grain decreased with strain rate at the beginning, then the grain was stable when the strain reached to a certain value [23]. As to other magnesium alloys, such as, AM30 and pure magnesium, the researchers showed the average
grain size for AM alloy was lower compared with pure magnesium, but no difference has been found in the grain sizes in the extruded rods and tubes of the same material [24].

Figure 7. Optical micrograph of AZ80 Mg alloy compressed at different temperature, different strain and strainε=1[22].

3.2. Simulation on product defects
In compare with other technology (such as, rolling, forging), microstructural characteristic of the extruded products are the non-uniformity in section and longitude. The non-uniformity is caused by the non-uniform flow of magnesium alloys material during extrusion. Because of the non-uniform flow, surface crack often happened. Therefore, it has been a research focus how to improve the uniformity of the alloys material flow. Some studies showed that the cone die can result in continuous cracks on surface of extruded bars and the streamline die can reduce approximately 15 tons of extrusion pressure than cone angle die [25], referring to Figure 8, 9. Besides the geometrical factor, the forming technology also makes an influence on the flow of magnesium alloy. For example, some scholars analyzed the generating of reason of crack of magnesium alloy extruded cylinder at bottom, and pointed the crack was mainly caused by very different orientation between anti-extrusion metal flow lines and existing metal flow lines, which made neighboring grains not coordinate anti-extrusion deformation, lead to the dislocation accumulation at the die’s corner [26].

Figure 8. Model of 3D dies (a. the tapered die of dig angle 30°C; b. streamlined die).

Figure 9. Mean square deviations of axial stress of the 21 points for two dies.
In addition, surface quality can be predicted through simulation of strain rate and real temperature. The studies showed the temperature changing of extrusion exit played an important role on surface quality of Mg-Al-Ca-Sr alloy [27]. The further studies pointed that the defects increased as strain rate decreased at constant temperature, and increased with the increase of the temperature under certain strain rate, especially is more sensitive to the temperature than the strain rate [28], as shown in Figure 10.

Although some above studies have been done in product defects, there are many work to go, such as, the simulation of bubble and crinkle, surface voids, graze in longitude, dots graze, spiral texture, circular texture, surface embedded by graphite, size deviation of product and so on, all those problem have lack of simulation research of literature.

4. Summary
Simulation technology has been wildly used in hot extrusion process. The foundation researches have also made significant progress, for example, many constitutive equations have been constructed, and simulation has been successfully applied to analyze forming process and predict product defect. However, the simulation is only as a qualitative research tool extrusion process, therefore, the simulation technology still has to be further studied in extrusion process.

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