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Material driven workability simulation by FEM including 3D processing maps for magnesium alloy

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Abstract: The three-dimensional (3D) processing maps considering strain based on the two-dimensional (2D) processing maps proposed by PRASAD can describe the distribution of the efficiency of power dissipation and flow instability regions at various temperatures, strain rates and strains, which exhibit intrinsic workability related to material itself. Finite element (FE) simulation can obtain the distribution of strain, strain rate, temperature and die filling status, which indicates state-of-stress (SOS) workability decided by die shape and different processing conditions. On the basis of this, a new material driven analysis method for hot deformation was put forward by the combination of FE simulation with 3D processing maps, which can demonstrate material workability of the entire hot deformation process including SOS workability and intrinsic workability. The hot forging process for hard-to-work metal magnesium alloy was studied, and the 3D thermomechanical FE simulation including 3D processing maps of complex hot forging spur bevel gear was first conducted. The hot forging experiments were carried out. The results show that the new method is reasonable and suitable to determine the appropriate process parameters.

Key words: material driven workability simulation; 3D processing maps; magnesium alloy; hot forging

1 Introduction

In the conventional trial-and-error design stage, process engineers merely consider materials inputs and new process development mainly depends on the previous experience of designers and manufacturers. Moreover, the characteristics of materials themselves are always neglected. Fierce competition, however, leads to a growing demand for more efficient process design to reduce lead time, increase productivity, decrease cost and improve product quality. Finite element (FE) simulation can help designers to develop new processes and determine appropriate process parameters because the metal flow conditions and the distribution of stress, strain, strain rate and temperature can be obtained by numerical simulation. With the development of computer technologies, FE simulation has become an effective tool to design the entire process; moreover, it has been proven its efficiency and usefulness in analyzing and predicting possible product defects. During FE simulation, however, the flow stress data are only regarded as the required input parameters. As a matter of fact, the flow stress curves not only describe the influence of strain, strain rate and temperature on stress, but imply material flow characteristics of hot deformation as well. Among material analysis methods, processing maps provide a new approach to employ the flow stress curves to evaluate the workability in relation to material.

In general, processing maps describe the workability depending on material, which can be divided into three categories: the first is deformation mechanism maps put forward by FROST and ASHBY [1]; the second is Raj's maps built by RAJ [2]; the third is processing maps based on dynamic material model (DMM) proposed by PRASAD and SASIDHARA [3]. The deformation mechanism maps are based on creep mechanism and only applicable to lower strain rates. The

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Raj's maps are based on the theoretical models of fracture mechanisms by using an atomistic method, which are able to determine the safe regions and are suitable for pure metal and dilute alloys; nevertheless, for most commercial alloys many fundamental material parameters are difficult to determine in advance. The Prasad's processing maps are a superimposition of a power dissipation map and an instability map under the conditions of various temperatures and strain rates [4]. They not only describe the microstructural evolution mechanism and the flow instability regions under certain deformation condition, but provide optimum temperature and strain rate range as well. In the latest decade or so, processing maps have become a powerful tool to design and optimize hot deformation processes [5].

Magnesium alloys, recently, have attracted great attention as lightweight structural materials because of low density, high specific strength and stiffness. Due to their hexagonal crystal structure, magnesium alloys have relatively low workability at room temperature and high workability at elevated temperature. The complex forging process of magnesium alloys was considered to be very difficult due to the poor flowability and the sensitivity to strain rate and temperature. In view of processing map's merits, ZHOU et al [6], ANBUSELVAN and RAMANATHAN [7] and QUAN et al [8] analyzed the workability of magnesium alloy AZ80 and ZE41A by processing map.

The conventional two-dimensional (2D) processing maps built by PRASAD et al do not include the variation of strain, so they cannot show the effect of strain on workability. LIU et al [9] put forward and built the three-dimensional (3D) processing maps considering strain, which can demonstrate the influence of strain on workability. In Ref. [9], 3D processing maps and 2D FE simulation were further integrated and the workability (the state-of-stress (SOS) workability and the intrinsic workability) of cylindrical hot compression for magnesium alloy AZ31B was investigated. SIVAPRASAD et al [10] obtained the optimum process parameters of 2D extrusion by considering the FE simulation and processing map; however, processing map and FEM are not combined tightly yet. LIU [9] pointed out that both of them cannot be integrated without the establishment of 3D processing maps and the reason is that the distribution of strain varies greatly in the whole deformation zones, showing that 3D processing maps and 2D FE simulation can be integrated to analyze the workability of simple 2D deformation process. Complicated 3D FE simulation of hot working is in the nature of larger deformation, higher computation cost and grid remeshing and refinement, and it is difficult to integrate with 3D processing maps. For this reason, up to now, this workability analysis method of combination of FE simulation of 3D processing maps has not been used to 3D hot working to the best of our knowledge.

In Ref. [11], the two-stage hot forming process of magnesium alloy AZ31B (preforming operation without gear shape and finish forging operation) was determined and the optimum preform die shape was obtained by FE simulation, and the experiments were conducted. However, the experiments were based on empirical process parameters determination, lacking of theoretical analysis. The material driven workability simulation of 3D complex forging was conducted to analyze instability characteristic of hard-to-work metal AZ31B and build an approach to obtaining optimum process parameters.

In this work, firstly, the basis for 3D processing maps is presented, which demonstrate the variation of power dissipation efficiency and flow instability regions at different temperatures, strain rates and strains. A new method of numerical simulation integrated with 3D processing maps to analyze workability (SOS workability and intrinsic workability) is put forward. Then, in order to study the hot forging process for magnesium alloy, by FE simulation including 3D processing map, the effects of deformation velocity and temperature on workability of AZ31B spur bevel gear during finish forging operation are discussed, and the optimum deformation velocity and temperature are obtained. Finally, according to the simulated results the hot forging experiments of magnesium alloy AZ31B are conducted.

2 FE simulation including 3D processing maps

2.1 Basis for 3D processing maps

The 3D processing maps are based on the 2D processing maps proposed by PRASAD et al [3,5], which consist of two parts: a 3D power dissipation map and a 3D instability map, describing the distribution of the efficiency of power dissipation and flow instability regions under the conditions of various temperatures, strain rates and strains. The 3D processing maps employ the macroscopic flow stress as the input data.

The flow stress at constant strain and deformation temperature is assumed to conform to DMM, which is given by [3−5]

$$\sigma = K\dot{\varepsilon}^{m} \tag{1}$$

where K is a material constant and m is the strain rate sensitivity which can be written as

$$m = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}} \tag{2}$$

The workpiece undergoing plastic deformation can be regarded as a dissipator of power. The total dissipation power P may be separated into two complementary parts, G content and J co-content:

$$P=\sigma\dot{\varepsilon}=G+J=\int_0^{\dot{\varepsilon}}\sigma\mathrm{d}\dot{\varepsilon}+\int_0^{\sigma}\dot{\varepsilon}\mathrm{d}\sigma \tag{3}$$

where G content represents the power dissipation through plastic deformation, most of which is transformed into viscoplastic heat; J co-content represents the power dissipation through metallurgical changes. The dissipation power partitioning between G and J is governed by the constitutive flow behavior of the material, i.e., the strain rate sensitivity m.

$$\frac{\mathrm{d}J}{\mathrm{d}G}=\frac{\dot{\varepsilon}\mathrm{d}\sigma}{\sigma\mathrm{d}\dot{\varepsilon}}=\frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln\dot{\varepsilon}}=m \tag{4}$$

In comparison of J co-content with the maximum possible dissipation, $J_{\max}$, the efficiency of power dissipation, a dimensionless parameter η, is given by

$$\eta=J/J_{\max} \tag{5}$$

where $J_{\max}$ is referred to a linear dissipator (m=1).

So, the efficiency of power dissipation is obtained as [3−5]

$$\eta=\frac{2m}{m+1} \tag{6}$$

From the above equation, the key to acquire the efficiency of power dissipation η is to determine the value of m. The computational procedure of m is as follows. Firstly, extract the flow stress values at constant temperatures and strain rates at different strains from the material tests; secondly, carry out cubic spline interpolation to compute the flow stress values at much smaller temperature and strain rate intervals using the experimental data points as knots; thirdly, at every fixed temperature, fit the data to third-degree polynomial using least square method, and the form is as follows:

$$\lg\sigma=a+b\lg\dot{\varepsilon}+c\left(\lg\dot{\varepsilon}\right)^2+d\left(\lg\dot{\varepsilon}\right)^3 \tag{7}$$

Therefore, the strain rate sensitivity m is written as follows:

$$m=\frac{\mathrm{d}\lg\sigma}{\mathrm{d}\lg\dot{\varepsilon}}=b+2c\lg\dot{\varepsilon}+3d\left(\lg\dot{\varepsilon}\right)^2 \tag{8}$$

After the value of m is determined at different temperatures and different strain rates, the value of efficiency of power dissipation η can be obtained. By plotting color grid map of the parameter η, the 3D power dissipation map is obtained, which represents the power dissipation through microstructural evolution under the conditions of different temperatures, strain rates and strains.

The 3D instability maps are developed on the basis of an instability criterion, which is derived from the extremum principle of irreversible thermodynamics and applied to continuum mechanics of large plastic flow. The instability criterion was proposed by ZIEGLER [12]. Instable flow will occur if the differential quotient satisfies the inequality [12]:

$$\frac{\mathrm{d}D}{\mathrm{d}\dot{\varepsilon}}<\frac{D}{\dot{\varepsilon}} \tag{9}$$

where D is the dissipative function which represents the constitutive behavior of the material. Since J determines the dissipation through metallurgical processes, the dissipative function D can be substituted by J,

$$\frac{\mathrm{d}J}{\mathrm{d}\dot{\varepsilon}}<\frac{J}{\dot{\varepsilon}} \tag{10}$$

Thus, a dimensionless parameter for microstructural instability is given by:

$$\xi\left(\dot{\varepsilon}\right)=\frac{\partial\ln[m/(m+1)]}{\partial\ln\dot{\varepsilon}}+m<0 \tag{11}$$

From the preceding computational results of m value, the instability criterion is rewritten as follows [3−5]:

$$\frac{2c+6d\lg\dot{\varepsilon}}{m\left(m+1\right)\ln 10}+m<0 \tag{12}$$

The 3D instability map can be obtained by plotting grey-white grid map at different temperatures, different strain rates and different strains, where the grey regions represent instable regions. PRASAD et al [3,5] pointed out that the flow instability is mainly in the form of adiabatic shear bands or flow localizations in the microstructure.

According to the processing maps, the safe regions and flow instable regions can be determined. The microstructure mechanisms of the safe regions correspond to dynamic recrystallization (DRX), dynamic recovery (DRV) and superplasticity. The temperature, strain rate and strain ranges corresponding to the peak efficiency in safe regions are chosen as the optimum parameters for hot working.

The 3D processing maps demonstrate the workability related to material under the conditions of various temperatures, strain rates and strains. Unlike the traditional processing maps, the 3D processing maps consider the influence of strain, which is essential for the material with strain softening and for process design and optimization. From the viewpoint of material, the flow stress of metal characterized by strain softening increases with increasing strain and attains a maximum value, after which the stress decreases and eventually attains a steady state value. During the whole deformation process, the flow stress greatly varies with strain, so the strain is a significant and non-negligible influential factor. From the viewpoint of process design and optimization, the distribution of strain for complicated shape parts is very non-uniform due to the influence of die shape, friction and various temperatures. Like temperature and strain rate, strain is also the vital factor affecting metal flow and workability. The conventional 2D processing maps ignore the effect of strain, so they have difficulty in analyzing the workability of complicated shape parts during hot deformation process. In summary, the 3D processing maps consist of 3D power dissipation maps and 3D flow instability maps considering the influence of strain, which describe the influence of temperature, strain and strain rate on material workability during hot working, and can be regarded as a tool to entirely describe material workability.

2.2 Material driven workability simulation by FEM including 3D processing maps

Workability is referred to be the plastic deformation ability that metals and alloys can be deformed easily without fracture during bulk deformation process such as forging, extrusion and rolling. The workability consists of two independent parts: SOS workability and intrinsic workability [3].

The SOS workability is governed by the geometry of deformation region, temperature, strain, strain rate and the externally imposed stress state. With the development of computer technology, the reliability and accuracy of finite element method (FEM) are greatly improved. The metal flow behavior and distribution of strain, temperature and strain rate during hot deformation process can be obtained by means of FE simulation. So, FEM can be considered a tool of analyzing SOS workability.

The intrinsic workability is decided by the microstructural evolution under certain deformation condition (temperature, strain rate, and strain), which is implicitly governed by the flow stress curves of material. The intrinsic workability is sensitive to the initial microstructure. In order to optimize the deformation process and control the microstructural evolution during hot working, the constitutive behavior related to material must be deeply investigated. DMM considers dynamic response of material flow behavior to process parameters, thus, the 3D processing maps based on DMM can exhibit that the characteristics of material itself vary with process parameters (deformation temperature, strain rate and strain), and demonstrate the intrinsic workability.

Since the processing maps were proposed by PRASAD et al [5] the processing maps and FEM have been regarded as the two separated branches and directions. The former emphasizes the property of material and the latter emphasizes the analysis of forming processes. On one hand, the distribution of the efficiency of power dissipation and flow instability regions can be obtained at different strains, strain rates and temperatures according to the 3D processing maps. On the other hand, the distribution of the strain, strain rate and temperature can be obtained according to FEM. Thus, the distribution of the efficiency of power dissipation and flow instability regions can be obtained at different moments of deformation process and in different locations of workpiece. As a result, the workability (SOS workability and intrinsic workability) of hot deformation can be determined using FE simulation including 3D processing maps.

3 Workability simulation of AZ31B spur bevel gear hot forging process

AZ31B magnesium alloy is a typical alloy characterized by DRX and its flow stress varies greatly with strain as shown in Fig. 1.

For hard-to-work metal magnesium alloy, the 3D processing maps considering strain can represent the variation of the power dissipation efficiency and flow instability regions with strain, as shown in Fig. 2 [9]. It can be seen that the efficiency of power dissipation increases with increasing strain at higher temperatures and lower strain rates or at lower temperatures and higher strain rates, but decreases at lower temperatures and higher strain rates or at higher temperatures and lower strain rates; the flow instability regions increase with increasing strain, which can demonstrate the influence of strain on intrinsic workability decided by material.

The spur bevel gear hot forging process of AZ31B magnesium alloy was taken an example, and the entire forging process consists of preforming operation and finish forging operation. Preform shape plays an important role in the quality of finish forgings and reasonable preform shape can be determined through FE simulation. In Ref. [11], the optimized perform dimensions were obtained by FEM. The preform drawing and forging drawing are shown in Fig. 3. Because the simulation of preforming operation can be simplified as 2D axisymmetric model, this paper merely focuses on the workability analysis by 3D thermomechanical FE simulation including 3D processing maps during the finish forging operation.

The flow stress model proposed in Ref. [13] was embedded in Marc by the secondary development using Fortran language. The density elastic modulus and Poisson ratio of AZ31B magnesium alloy are 1780 kg/m^3, 46 GPa and 0.30, respectively. The heat-transfer coefficient between preforms and environment is 20 W/(m^2·°C), and that between workpiece and dies is 11000 W/(m^2·°C). Due to the larger deformations and severer mesh distortion, tetrahedral automatic remeshing is applied to the 3D FE simulations combined with local refinement technique in order to effectively control mesh distortion and improve computational accuracy. The effects of velocity and temperature on workability are discussed in the following sections.

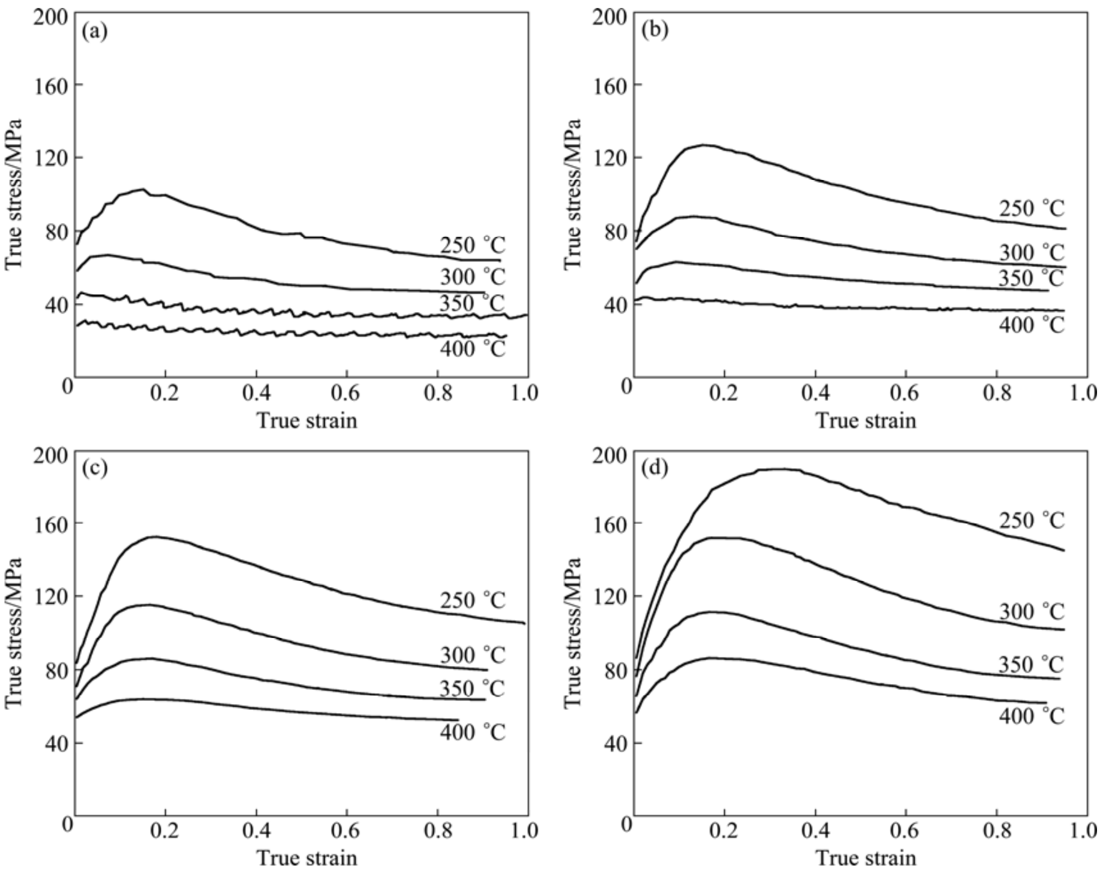

Fig. 1 Stress—strain curves of AZ31B magnesium alloy: (a) $\dot{\varepsilon}$=0.001 s^{-1}; (b) $\dot{\varepsilon}$=0.01 s^{-1}; (c) $\dot{\varepsilon}$=0.1 s^{-1}; (d) $\dot{\varepsilon}$=1 s^{-1}

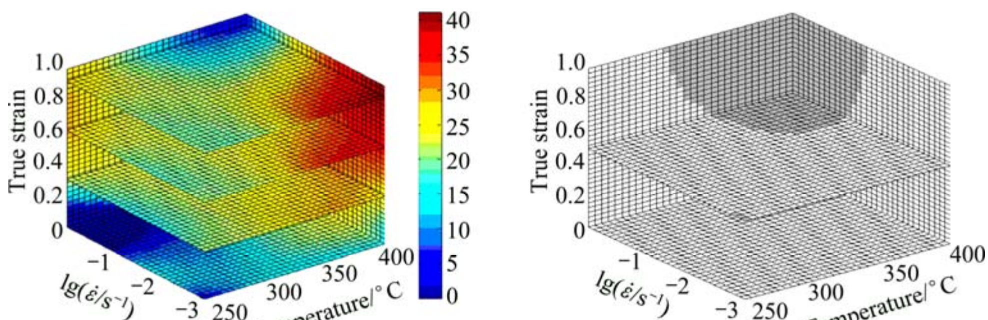

Fig. 2 3D processing maps: (a) 3D power dissipation maps at strains 0.3, 0.6 and 0.9; (b) 3D flow instability maps at strain 0.5

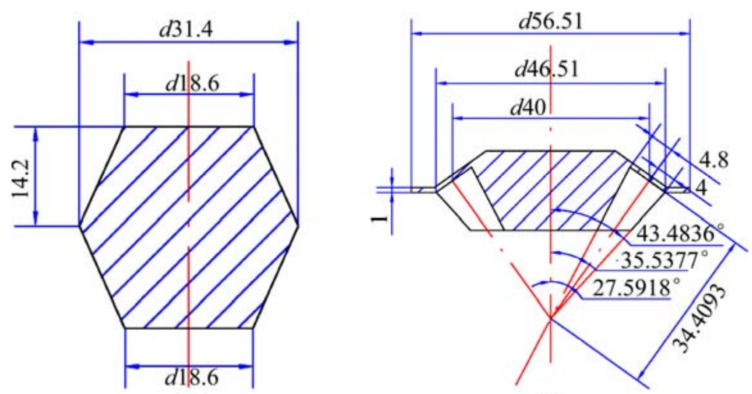

Fig. 3 Schematics of preform drawing (a) and forging drawing (b) (unit: mm)

3.1 Influence of velocity on workability during gear hot forging

First of all, the influence of deformation velocity on workability was investigated using the commercial FE analysis software Marc. The simulation parameters are as follows: the deformation temperature 350 °C and the compression speeds 0.1, 0.5 and 1.0 mm/s. The processing maps are integrated with FEM by an in-house code using Fortran program language. The results are shown in Fig. 4, where the blue regions are the regions of flow instability and the yellow regions are the regions of flow stability. It can be seen that the size of flow instability regions increases as the deformation velocity increases at the temperature of 350 °C. When the velocity of upper die equals 0.1 mm/s, the flow instability occurs at the areas of addendum and back cone; as the velocity increases to 0.5 mm/s, the flow instability occurs at the whole gear shape areas; when the velocity reaches 1.0 mm/s, the flow instability takes place at most of areas except the upper and lower center areas with smaller strain.

From Fig. 4, the flow instability regions are mainly located in the areas with larger strain, greater strain rate and higher temperature, where the metal flow is easily instable. In conclusion, lower deformation velocity is more appropriate for complex hot forging of AZ31B magnesium alloy.

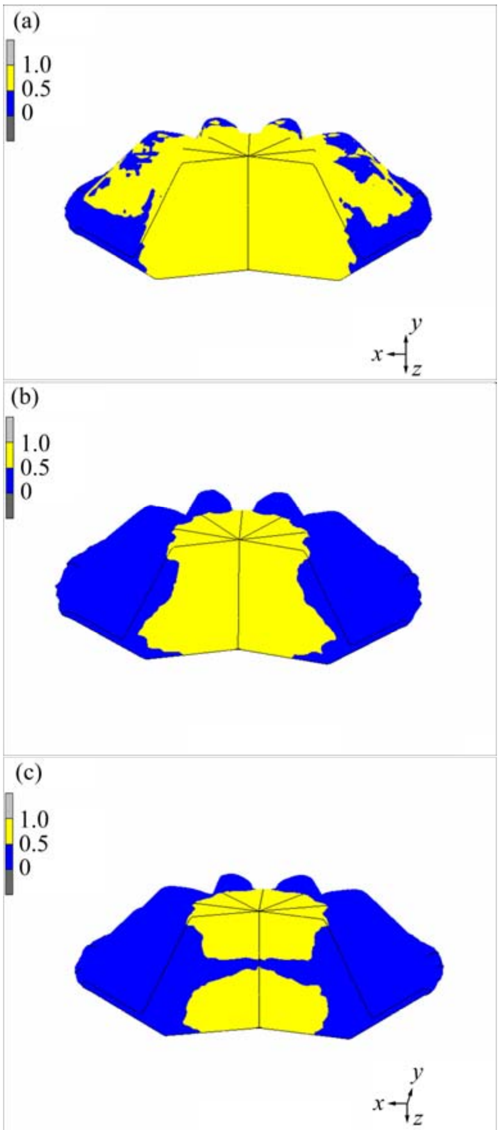

Fig. 4 Distribution of flow instability regions at end of finish forging at different upper die speeds: (a) 0.1 mm/s; (b) 0.5 mm/s; (c) 1.0 mm/s

3.2 Influence of temperature on workability during gear hot forging

Then, the influence of temperature on the workability was investigated. The simulation parameters are as follows: the deformation speed 0.5 mm/s and the deformation temperatures 300, 350 and 400 °C. The distribution of flow instability regions is shown in Fig. 5.

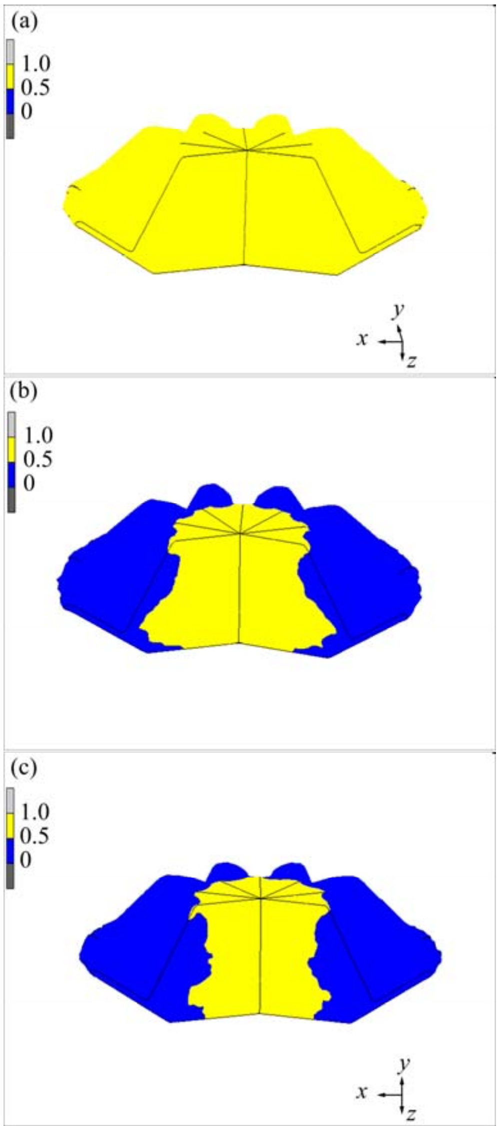

Fig. 5 Distribution of flow instability regions at end of finish forging at different temperatures: (a) 300 °C; (b) 350 °C; (c) 400 °C

It can be seen that the size of flow instability regions increases as the deformation temperature increases at the velocity of 0.5 mm/s. No flow instability region occurs at the temperature of 300 °C. The flow instability region at the temperature of 400 °C is larger than that at the temperature of 350 °C. In conclusion, the optimum deformation temperature is about 300 °C for complex hot forging of AZ31B magnesium alloy.

The workability simulation results show that the optimum deformation velocity is about 0.5 mm/s and the optimum deformation temperature is about 300 °C. Consequently, by 3D FE simulation including 3D processing maps, not only the distribution of stress, strain, strain rate and flow instability regions can be obtained, but also the appropriate process parameters can be determined. This method entirely represents the workability of the whole hot deformation process and can be applied to the industrial production.

4 Hot forging experiments of magnesium alloy spur bevel gear

In order to verify the accuracy of the FE simulation results, the finish forging experiments were carried out. The deformation temperatures of preforms are 300, 350 and 400 °C, respectively. The velocities of upper die are 0.5, 1.0 and 5.0 mm/s. The photos of die structure and finisher impression are shown in Figs. 6 and 7, respectively.

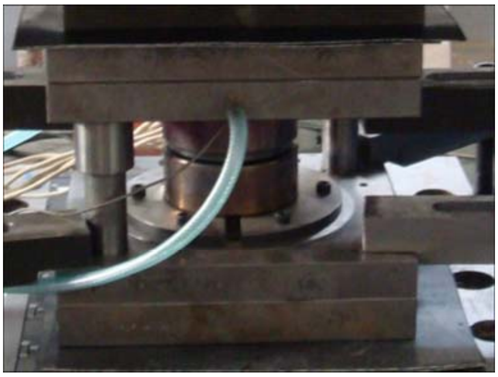

Fig. 6 Photo of experiment die

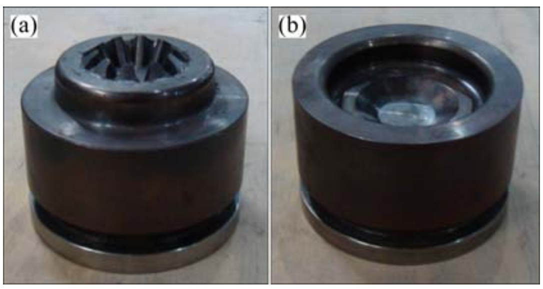

Fig. 7 Photos of finisher impression: (a) Gear-form lower die; (a) Back cone upper die

The hot forging experiments were successfully conducted and the photos of preform and finish forging part during hot forging of AZ31B magnesium alloy are shown in Fig. 8. The sampling positions of metallographic tests are shown in Fig. 9. The metallographs of AZ31B magnesium alloy located in different positions under different deformation conditions are shown in Figs. 10 and 11.

Fig. 8 Photos of preform part (a) and finish forging part (b)

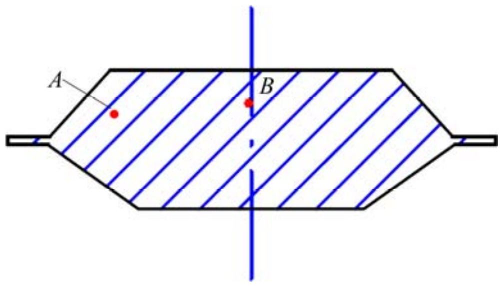

Fig. 9 Sampling positions of metallographic tests

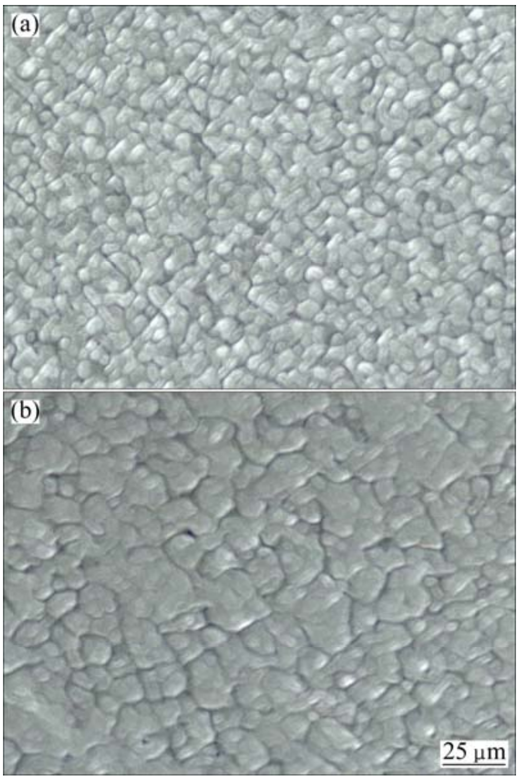

Fig. 10 Metallographs in magnesium alloy bevel gear forged at 300 °C, 0.5 mm/s: (a) Position *A*; (b) Position *B*

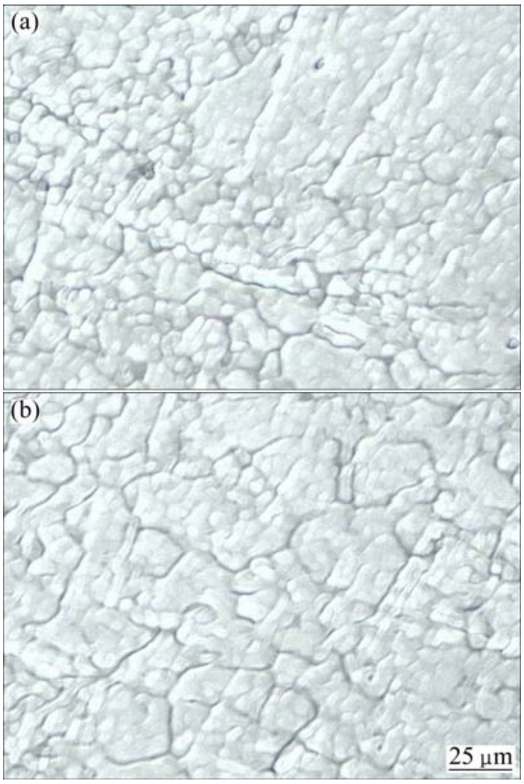

Fig. 11 Metallographs in magnesium alloy bevel gear forged at 350 °C, 1.0 mm/s: (a) Position *A*; (b) Position *B*

PRASAD pointed out that the flow instability is mainly in the form of adiabatic shear bands or flow localizations in the microstructure. An adiabatic shear band is a narrow region of very large shearing in metals and alloys. Flow localization occurs when the rate of area change at an inhomogeneous region exceeds that in the bulk or, for strain-rate sensitive materials, when the strain rate in an inhomogeneous region exceeds that in the bulk [14]. It can be seen that the grains shown in Fig. 10 are uniform and fine at the temperature of 300 °C and the velocity of 0.5 mm/s. The grains located at the gear shape areas, however, as shown in Fig. 11(a), are non-uniform, due to strain and strain-rate localization. In comparison with Fig. 4(c) and Fig. 5(a), the experimental results are generally in agreement with the simulated results.

5 Conclusions

1) The 3D processing maps of AZ31B magnesium alloy were built based on the conventional 2D processing maps put forward by PRASAD et al, considering the influence of strain on workability.

2) SOS workability and intrinsic workability can be analyzed by the combination of 3D processing maps with FE simulation, and the distribution of strain, strain rate, temperature, temperature and instability regions can be obtained.

3) Material driven workability simulations of hot finish forging operation for AZ31B magnesium alloy spur bevel gear were conducted and the optimum process parameters are the temperature of about 300 °C and the deformation velocity of 0.5 mm/s.

4) On the basis of the simulated results, hot forging experiments of AZ31B magnesium alloy spur bevel gear were successfully carried out, which verifies the accuracy of simulation and analysis.

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镁合金有限元与三维加工图相结合的材料驱动的可加工性模拟

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摘 要：基于 PRASAD 提出的传统的二维加工图理论，建立考虑应变的三维加工图，描述功率耗散系数和流变失稳区域随应变速率、温度和应变的变化。三维加工图说明了材料的内禀可加工性，而有限元分析方法可得到材料在特定工艺条件下应力、应变、应变速率及金属流动情况，说明了由模具形状和工艺条件决定的应力状态可加工性。基于此，提出一个新的由材料驱动的热变形可加工分析方法，联合考虑有限元和三维加工图，可以说明整个热加工过程的材料可加工性(包括应力状态可加工性和内禀的可加工性)。通过此方法，研究难变形金属镁合金的热锻过程，包括复杂热锻直齿锥齿轮的三维热力耦合有限元和三维加工图的集成模式。基于得到的研究结果，成功进行了热锻试验。试验表明新的方法用于确定最佳工艺参数是合理的。

关键词：材料驱动的可加工性模拟；三维加工图；镁合金；热锻成形

(Edited by Hua YANG)