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ARTICLE

Effect of Hydrostatic Pressure on Fiber Orientation and Deformation of C_{sf}/AZ91D Composite in Thixo-extrusion

Su Lizheng[1, 2], Qi Lehua[3], Wang Xinya[1], Wang Kejun[1]

[1] Xi'an Institute of Electronic Engineering, Xi'an 710100, China; [2] Tsinghua University, Beijing 100084, China; [3] Northwestern Polytechnical University, Xi'an 710072, China

Abstract: In the thixo-extrusion process, the fiber orientation can be effectively controlled by applying the hydrostatic pressure (i.e., backpressure), and consequently improves the mechanical properties of short fiber reinforced composites. The variation regularities of the deformation field and fiber orientation of C_{sf}/AZ91D composites during the thixo-extrusion process with and without backpressure were investigated experimentally. The equivalent strain rates along the flow line were obtained based on the flow function method. By employing the image processing techniques, the angle of fiber orientation after extrusion was statistically analyzed. The results show that there is an obvious equivalent strain rate gradient from the outer wall to the core of the composite without applying backpressure (WBP). At the same position, the fiber orientation angle is almost proportional to the equivalent strain rate. Furthermore, the applied backpressure (BP) enhances the ability of the composite to fill the outer corners of the mold, resulting in a smaller equivalent strain rate gradient across the cross-section. Compared with the thixo-extrusion without backpressure, the equivalent strain rate distribution is more uniform and the fiber orientation angle is more consistent by the application of backpressure. The research results have important guiding significance for regulating the plastic deformation of C_{sf}/AZ91D composites.

Key words: C_{sf}/AZ91D composite; fiber orientation; thixo-extrusion; backpressure

Owing to their low density and high specific strength, short fiber reinforced magnesium composites have broad prospects as advanced materials for technical applications, particularly in automotive and aircraft components, as well as in electronic devices[1-3]. However, the fibers within the matrix can be aligned in a specific direction when the samples are fabricated by extrusion technique with high compression and high shear[4]. The fiber alignment will lead to direction dependency of the tensile properties of fiber-reinforced magnesium-based composites[5,6]. Consequently, in order to design an efficient manufacturing process during thixo-extrusion, it is important to clarify the effect of plastic flow on fiber orientation. For the composites which are difficult to deform, by applying a backpressure in extrusion, the mode of deformation can be changed to simple shear, which can effectively improve uniformity of plastic strain and prevent cracking in the material[7,8]. In previous work, the orientation of short fiber composites has been extensively analyzed experimentally using scanning electron microscope (SEM)[9,10], and mathematical models were implemented to predict the orientation distribution based on the orientation distribution function (ODF)[11,12]. However, the reported experimental results are in good agreement with the theoretical predictions only under the simple shear flow. In case of thermal stress and high strain rates, the rotations of fibers in the deformed zones have more complicated motion patterns.

The evolution of the fiber orientation during deformation of composites has been found to be strongly dependent on the stress acting on these fibers [13,14]. The different fiber distribution features are closely related to the plastic flow pattern and a link can be established between the mi-

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Corresponding author: Su Lizheng, Ph. D., Senior Engineer, Xi'an Institute of Electronic Engineering, Xi'an 710100, P. R. China, Tel: 0086-29-85616855-610, E-mail: suliz1007@163.com

cro-structural characteristics and the macroscopic plastic behaviors [15]. In order to quantitatively evaluate the fiber orientation of short fiber reinforced composites during extrusion, it is important to understand the macro-scale deformation mode of extrusion. Recently, some experiments have demonstrated that it is more reasonable and easier to analyze the deformation behavior during plastic deformation from the view of metal flow line than by the general simple shear theory[16,17]. The equivalent strain rates of deformation field along the flow line can be calculated based on the viscoplastic model, in which the strain rates are integrated along a streamline to estimate the accumulated strains of the materials.

In this study, 10 vol% Csf/AZ91D composites were fabricated by thixo-extrusion process with and without backpressure. The deformation mechanism was investigated based on analytic flow function. Furthermore, the orientation distribution of the final part was obtained by SEM and image processing. Finally, the effects of the different plastic flows on the fiber orientation were analyzed.

1 Model of Flow Line

Early work on description of deformation field during extrusion test has been reviewed [18]. However, those calculations are completely dependent on experimental data and cannot describe the deformation field in a continuous way. In the present work, the viscoplasticity model is used to overcome this disadvantage. The details of the model can be found in Ref. [19], and a brief review of the model is given below.

The entire flow field is described by flow-function elements in the form of third-order polynomials.

$$R(z)=R_0[1-f(z)]+R_1f(z) \tag{1}$$

$$f(z)=3(z/l)^2-2(z/l)^3 \tag{2}$$

where R_0 is the initial (upstream) radius and R_1 is the outer (downstream) radius of a given flow line (see Fig.2 for the coordinate system). The length of plastic deformation zone is l. Based on the theory of kinematically admissible velocity fields and the velocity boundary conditions, an incompressible velocity field can be defined from Eq. (1) as follows:

$$\begin{cases} v_r = -\lambda r f'(z) v_0 \dfrac{1}{[1-\lambda f(z)]^2} \\ v_z = v_0 \dfrac{1}{1-\lambda f(z)} \end{cases} \tag{3}$$

$$\lambda = \frac{R_0 - R_1}{R_0} \tag{4}$$

where v_0 is the ram speed. The strain-rate components can be determined at each point (r, z) by further numerical differentiation and the following:

$$\begin{cases} \dot{\varepsilon}_r=-\dot{\varepsilon}_z=-\dfrac{\partial v_z}{\partial z} \\ \dot{\varepsilon}_{rz}=\dot{\varepsilon}_{zr}=\dfrac{1}{2}(\dfrac{\partial v_z}{\partial r}+\dfrac{\partial v_r}{\partial z}) \end{cases} \tag{5}$$

The effective strain rate $\dot{\bar{\varepsilon}}$ can be defined as:

$$\dot{\bar{\varepsilon}} = \frac{\sqrt{2}}{3}\sqrt{(\dot{\varepsilon}_\theta-\dot{\varepsilon}_r)^2+(\dot{\varepsilon}_r-\dot{\varepsilon}_z)^2+(\dot{\varepsilon}_z-\dot{\varepsilon}_\theta)^2+6\varepsilon^2_{rz}} \tag{6}$$

2 Experiment

The 10 vol% short carbon fiber-reinforced AZ91D composite was fabricated by gas pressure infiltration process. The chemical composition of Mg-9.1Al-0.84Zn is listed in Table 1; density (ρ), solidus temperature (T_S), liquidus temperature (T_L) of the matrix are listed in Table 2. The dimensions of the carbon fiber are 5~6 μm in diameter and 200 μm in initial length.

The extrusion experiments were carried out at 709 K in argon gas with an extrusion ratio of 4:1 using an Y32-315 type hydraulic machine. The initial dimensions of the specimens were Φ45 mm×30 mm. A grid of spacing of 3 mm×3 mm and a line depth of 1.5 mm representing the flow lines were engraved on the internal surface using a wire cutting machine. The extrusion velocity with a forward punch is 2.5 mm/s. During the thixo-extrusion, the backpressure was set as 0 and 478 MPa for the first and second samples, respectively. Before each extrusion, the die was lubricated using graphite. Load-ram displacement data were real-time recorded. After extracting the samples from the die, the grid was photographed. Fig.1a shows the deformed sample without applying a backpressure (WBP). For comparison, the Csf/AZ91D composite was also deformed with applying backpressure (BP) of 478 MPa, while Fig.1b displays the flow lines. The fiber distribution and cavities of the composites formed in the deformation process were observed with LEO1530 field emission SEM.

3 Results and Discussion

3.1 Effect of backpressure on plastic deformation zone of Csf/AZ91D composite

As shown in Fig.1, the shape of the flow lines severely changes when backpressure is applied. The flow lines were fitted with the flow function presented in Eq. (1). For each line, the parameters are different. R_0, R_1 and l are parameters as a function of the entry position which can be determined.

Table 1 Chemical composition of Mg-9Al-0.84Zn(wt%)

Al	Zn	Mn	Si	Mg
9.1	0.84	0.30	0.04	Bal.

Table 2 Density (ρ), solidus temperature (T_S) and liquidus temperature (T_L) of AZ91D alloy matrix

ρ/g·cm^{-3}	T_S/°C	T_L/°C
1.81	470	595

Based on the calculation of effective strain rate by Eq.(4), the extent of the plastic zone during extrusion process can be identified, as shown in Fig.2. An important finding from Fig.2 is that for the WBP case, the plastic deformation zone is relatively small and most of the regions close to the punch are rigid zone. Furthermore, the difficult deformation region or "dead zone" exists in cavity die radius. On the contrary, the deformation close to the die wall increases when the backpressure is applied. The plastic deformation zone increases significantly and it is extended nearly to the whole cavity die radius region. The dead zone almost disappears in the BP case, which means that the use of backpressure will help to improve the plastic deformation in the process.

Fig.3 shows the Von Mises equivalent strain rate along the flow line. As shown in Fig.3, the strain rate measured from the symmetry plane (Fig.1) is plotted as a function of radial position. It can be seen that the strain rate varies significantly along the flow line. This effect is particularly obvious along the flow line 7 situated close to the inner axis for WBP case, which has the maximum strain rate values. Farther away from the flow lines, the strain rate variation from one line to the other is less pronounced. For BP cases, the maximum strain rate appears in flow line 4. From the overall distribution of strain rate, the contour area of plastic zone is larger. It shows that the internal deformation is more uniform. By comparing Fig.3a and Fig.3b, it can be found that the strain rate is much reduced for the BP case. More specifically, it is only about half with respect to the WBP case. From the quality of the sample surface in both cases, we can also find that there is a small amount of lateral crack on the surface for the WBP case, while the surfaces smooth when applying backpressure. To analyze this phenomenon comprehensively, it is a significant increase in the deformation uniformity for BP case. Without backpressure, metal in core axis flows faster than in die edges, resulting in an additional tensile stress on the surface and an additional stress in the core. Furthermore, the additional tensile stress reaches the maximum value at the outlet of die. This leads to the development of the crack on the surface of sample when the additional tensile stress is beyond the actual breaking strength of the material. During the extrusion process with backpressure, the metal flow adjacent to core axis is reduced under the back-pressure punch. The deformation and flow tend to become uniform in the plastic zone, so the crack occurring on the surface becomes difficult.

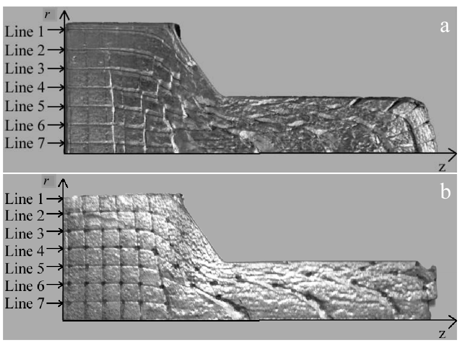

Fig.1 Photographs of the C_{sf}/AZ91D composite samples deformed by thixo-extrusion showing the flow lines: (a) WBP and (b) BP

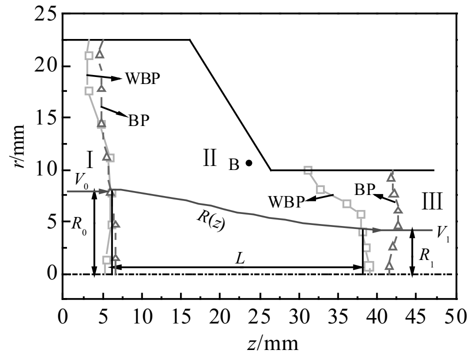

Fig.2 Plastic zones calculated based on the flow lines for the case of BP and WBP

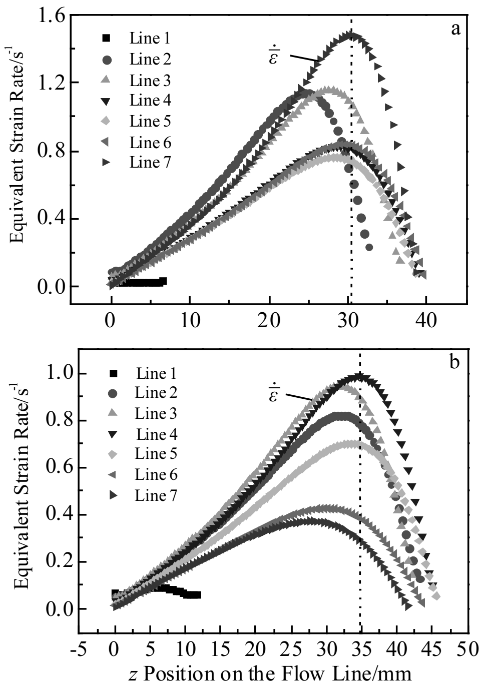

Fig.3 Von Mises equivalent strain rate along the flow line as a function of radial position at various axial stations: (a) WBP and (b) BP

3.2 Fiber orientation of short carbon fiber during thixo-extrusion process

Typical SEM micrographs of fiber orientation for the two cases in plastic zone are given in Fig.4. Fig. 4a and 4b correspond to the WBP case and the BP case, respectively. It can be seen that both methods indicate a high degree of alignment of the fibers. To analyze the characterization of fiber orientation accurately, the image processing techniques were often employed to quantify the fiber orientation in short fiber composites [20-22]. These techniques utilize SEM photographs of samples to measure the fiber orientation with reference to the orientation axis. Fiber orientation function "*f*" can be evaluated from the fiber orientation data using mathematical equations presented in previous work[23], and the fiber orientation angle "θ" is introduced from the ratio between minor and major axes of the fiber. The measured histograms of short carbon fiber orientation in C_{sf}/AZ91D composite are shown in Fig.4c and 4d. These results suggest that the short fibers are not unidirectional alignment. In WBP case, particularly, a significant asymmetry is observed. As can be seen from Fig.4c and 4d, besides the alignment of short carbon fiber along the tensile axis, it can also be found that the short fibers are randomly rotated around their own long axis.

Average orientation angle at selected points on the different flow lines in both cases is illustrated in Fig.5. It can be seen that in the extruded composite, the distribution of the short fibers after extrusion with backpressure is much more uniform than without backpressure case. Corresponding to the distribution of strain rate gradient in Fig.3, it is evident that the greater the strain rate gradient, the greater the fiber orientation angle from the outer wall to the core without backpressure case. Fibers orientation reaches 49° at the equivalent strain rate of 1.24 in the vicinity of flow line 7, and the fibers are at an angle of 24.5° at the strain rate of 1.14. This is consistent with the viewpoint that the alignment of discontinuous fibers is due to matrix flow in composites subjected to extrusion process[24]. However, fiber orientation deviates from such laws when the backpressure is applied. The variations of equivalent strain rate on the flow lines are contrary to the tendency of fiber-oriented direction. This is because that backpressure enhances the time of the shear rate acting on melt in core zone. It provids a better opportunity to attain optimum level of fiber orientation in the flow direction, and results in highly aligned fibers in BP case.

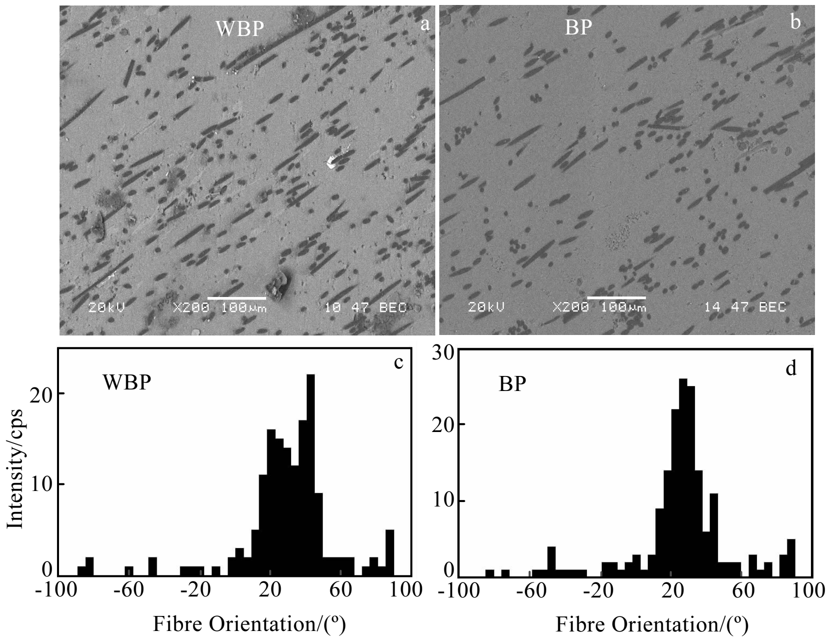

Fig.4 SEM images and corresponding histograms of short carbon fiber orientation in C_{sf}/AZ91D measured at a section cut at an angle of 30° to the nominal extrusion direction (see point B in Fig.2): (a, c) WBP and (b, d) BP

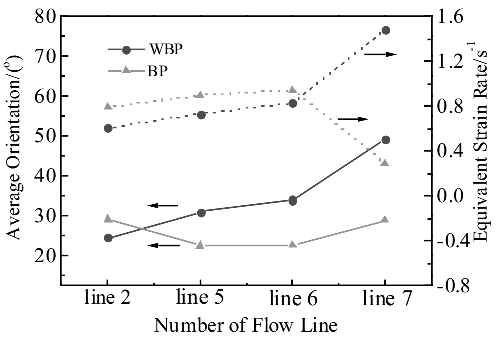

Fig.5 Average orientation of fiber and equivalent strain rate of flow lines corresponding to the vertical dot lines in Fig.3, which are the peak value line at position of z=30.6 mm for WBP and z=34.6 mm for BP

4 Conclusions

1) Using flow function, the equivalent strain rate as a function of radial position is calculated along the flow line.

The proposed model of flow line gives a varying deformation field along the flow line in C_{sf}/AZ91D composite with and without applying the backpressure.

2) The average orientation angle is determined through the computer-aided image analysis. Based on the changes of fiber orientation on flow line, the evolution mechanisms of fiber orientation induced by deformation are investigated quantitatively.

3) When applying the backpressure, the total strain is slightly reduced, while the size of the plastic zone is strongly increased. The composites achieve the highest level of fiber orientation in a preferred direction under the action of flow stress. However, the fiber alignment is not proportional to the value of equivalent plastic strain. The result is contrary to the case where back-pressure is not applied.

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静水压力对触变挤压 C_{sf}/AZ91D 复合材料变形及纤维取向的影响

苏力争[1,2]，齐乐华[3]，王新亚[1]，王克军[1]

(1. 西安电子工程研究所，陕西 西安 710100)

(2. 清华大学，北京 100084)

(3. 西北工业大学，陕西 西安 710072)

摘　要：在触变挤压过程中，通过施加静水压力（即背压）可以有效地控制纤维取向，从而改善短纤维增强复合材料的机械性能。实验研究了有、无背压情况下 C_{sf}/AZ91D 复合材料触变挤压过程中变形场及纤维取向变化规律。基于流函数法获得了 C_{sf}/AZ91D 复合材料触变挤压过程中的等效应变速率。结合图像处理技术，对挤压后纤维取向角度度进行了统计分析，探讨了背压对塑性变形区尺寸，塑性变形区内应变速率的分布以及纤维取向角度的影响。结果表明，不施加背压 (WBP) 情况下，从坯料外壁到心部存在明显的等效应变速率梯度，在相同位置，纤维取向角度与等效应变速率几乎成正比关系，而施加背压(BP)提高了坯料充填模具外侧拐角的能力，使得坯料横截面上等效应变速率梯度变小，分布更加均匀，纤维取向角度也更加一致。研究结果对于调控 C_{sf}/AZ91D 复合材料的塑性变形具有重要的指导意义。

关键词：镁基复合材料；纤维取向；触变挤压；背压

作者简介：苏力争，男，1980 年生，博士，高级工程师，西安电子工程研究所，陕西 西安 710100，电话：029-85616855-610，E-mail: suliz1007@163.com