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Crystal plasticity-based impact dynamic constitutive model of magnesium alloy

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ABSTRACT

The impact dynamic mechanical behavior of a magnesium alloy (extruded AZ31B) is first investigated by using the split-Hopkinson pressure bar (SHPB) apparatus. The dynamic tensile and compressive tests are performed at various strain rates ranging from 1250–2150 s^{-1} and from 1600–3500 s^{-1}, respectively. The loading direction is set perpendicular to the extrusion direction of the AZ31B alloy. Experimental observation shows that the strain-rate sensitivity of the AZ31B alloy present under dynamic tension is higher than that under compression. Based on crystal plasticity and the approach of strain-rate sensitivity control used in the Preston–Tonks–Wallace model, a new impact dynamic constitutive model is established to describe the dynamic stress-strain responses of the AZ31B alloy. Finally, comparing simulations with corresponding experiments, the simulations are found to agree well with the experiments, thus verifying the developed model.

1. Introduction

Light structural materials are used with increasing frequency to decrease the weight of products. Among metal structural materials, magnesium alloys are the lightest. They possess many excellent mechanical properties and are used in many advanced industries, such as the aeronautics, astronautics, and automotive industries. Because magnesium alloys have many advantages like low density and high specific strength, they are used to substitute traditional structural materials, such as steels, aluminum alloys, and plastics in cars and high-speed trains [10,16,18,19].

In structural applications, magnesium alloys may experience deformation at high strain rates, by mechanisms including impact loading, explosive forming, and high-speed machining [1]. The material mechanical properties change significantly when the material is loaded under impact, versus static or quasi-static conditions. Therefore, studying the dynamic stress–strain behavior of magnesium alloys is very important now. However, the research on the mechanical response of magnesium alloys to impact loading (e.g., strain rates exceeding 10^3 s^{-1}) is currently insufficient [33].

Gao et al. [12] investigated the dynamic compressive stress–strain responses and the related microstructural evolution of a cast magnesium alloy by a split-Hopkinson pressure bar (SHPB) apparatus. The results showed that magnesium alloy deformation showed properties of both face-centered cubic (FCC) and body-centered cubic (BCC) metal deformation. Asgari et al. [1] tested cast AZ magnesium alloys at strain rates from 1000 to 1400 s^{-1} and showed that the magnesium alloy structure was strengthened after compressive impact loading because of twinning. Yokoyama [28] studied the anisotropy of magnesium alloys in dynamic loading at strain rates of 1000–2000 s^{-1}, and demonstrated that the magnesium alloy presented a much more obvious strain-rate effect in dynamic tensile testing than it did in dynamic compressive ones. Galiyev et al. [7] tested the dynamic deformation of a magnesium alloy by SHPB at room temperature, demonstrating that higher impact speeds could cause the formation of finer twins and grains, thereby improving the deformation capacity of the alloy. Mukai et al. [20] studied the relationship between the yield strength and grain size of a magnesium alloy under impact loading at room temperature, and demonstrated the validity of the Hall–Petch formula under the impact loading condition. These experimental studies have been useful, but the total data from dynamic experiments on magnesium alloys is not enough.

To describe the dynamic mechanical responses of materials, Johnson and Cook [13] first developed a dynamic constitutive model directly from the existing macroscopic experimental data, known today as the Johnson-Cook model (or J-C model). However, the original J-C model and its modified versions were mainly employed to simulate the dynamic mechanical responses of metals with BCC and FCC crystal structures. Zerilli and Armstrong [31], proposed a constitutive model by employing thermal activation analysis to predict the dynamic

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deformation of metals with hexagonal close-packed (HCP) crystal structures, based on the argument that HCP metals had partial structural characteristics of both BCC and FCC metals. Subsequently, Gao [12] proposed a dynamic constitutive model to describe the dynamic stress-strain responses of magnesium alloys by extending the work of Zerilli and Armstrong [32]. However, these models did not consider the different microscopic deformation mechanisms (i.e., dislocation slipping and twinning) of magnesium alloys in different loading modes.

To capture the deformation micro-mechanisms of the materials, phase field theories [8,9] and crystal plasticity are good candidates. Compared with phase field theory, crystal plasticity is more intuitive in the description of the deformation. Therefore, based on the crystal plasticity and the approach of strain-rate sensitivity control used in the Preston–Tonks–Wallace (PTW) model [21], a dynamic constitutive model for magnesium alloys is established in this work. From the crystal plasticity and observed plastic deformation mechanisms of magnesium alloys, the total plastic strain of magnesium alloys is divided into two parts: that caused by twinning and that determined by dislocation slipping. For describing the overall deformation of polycrystalline magnesium alloys, the β-rule [3] is a famous explicit scale-transition, which is used in this study to extend the model from a single crystal to a polycrystalline material. The model is verified by comparing simulations with corresponding dynamic stress–strain responses of the extruded AZ31B magnesium alloy.

2. Experimental

2.1. Experimental process

The material used in the test was extruded AZ31B magnesium alloy, whose composition is listed in Table 1. The loading direction was perpendicular to the extrusion direction of the AZ31B bars, and the ambient temperature was room temperature.

The dynamic tensile tests of the AZ31B magnesium alloy were first performed by using the split Hopkinson tension bar (SHTB) apparatus. The shape and size of the dynamic tensile specimens are shown in Fig. 1.

In the dynamic tensile tests, the applied strain rates were prescribed as 1250, 1650, and 2150 s^{-1}. The obtained dynamic tensile stress–strain curves of the AZ31B alloy are shown in Fig. 2.

The dynamic compressive tests of AZ31B alloy were performed by using a SHPB apparatus. The specimens were cylinders of ϕ10×8 mm. The strain rates were prescribed as 1648, 2092, 2950, and 3544 s^{-1}. The dynamic compressive test results are shown in Fig. 3.

2.2. Summary of experimental results

From the results shown in Figs. 2 and 3, it is concluded that, as shown in Fig. 3, an apparent rate-dependent stress–strain response occurs in the dynamic tensile loading of AZ31B magnesium alloy. The maximum stress and yield stress of the alloy increase obviously with the increasing strain rate. In the dynamic compressive tests, the stress–strain response of the alloy is not sensitive to the variation of strain rate. A comparison of the results in Figs. 2 and 3 shows that the AZ31B presents different dynamic mechanical responses under the dynamic tensile and compressive loading conditions. Remarkable strain hardening is observed in the dynamic compressive tests, and the responding stress linearly increases with the dynamic compressive strain. However, in the dynamic tensile cases, after a certain tensile strain, the responding stress stops increasing with further increases of the tensile strain. The dynamic ultimate strain of the AZ31B alloy increases with the increasing strain rate, which shows that the toughness of the AZ31B alloy increases with the increase of the strain rate.

The different dynamic mechanical responses of the extruded AZ31B demonstrated in the dynamic tensile and compressive tests are determined by the different mechanisms of plastic deformation. As demonstrated by Proust et al. [22,23], for the extruded magnesium alloy, in the tensile tests, dislocation slipping is the main mechanism of plastic deformation; in the corresponding compressive cases, twinning is the dominant microstructural source of plastic strain. Since twinning is generally considered an instantaneous shear deformation that is independent of the strain rate, but dislocation slipping is a thermal activation process that depends on the variation of the strain rate, different strain rate effects are observed in the tensile and compressive tests of the magnesium alloy.

3. Constitutive model

From the previous experimental discussion, a crystal plasticity-based dynamic constitutive model is developed in this section to describe the dynamic tensile and compressive mechanical responses of the extruded magnesium alloy. Notably, the constitutive model is first constructed on the scale of a single crystal. Clayton's model [4,6] considers the elastic part as being non-linearly elastic. Based on the experimental results here, however, the elastic deformation of the magnesium alloys is considered to follow linear elasticity. The total plastic strain tensor $\boldsymbol{\varepsilon}^p$ is decomposed into two parts: the plastic strain caused by twinning $\boldsymbol{\varepsilon}^p_{twin}$ and that caused by dislocation slipping $\boldsymbol{\varepsilon}^p_{ship}$ [30].

The plastic strain rate caused by twinning can be calculated by the following formula:

$$\dot{\boldsymbol{\varepsilon}}^P_{twin} = \sum_{\alpha=1}^{ntwin} \dot{\gamma}^\alpha_{twin} \mathbf{P}^\alpha_{twin} \tag{1}$$

where $ntwin$ is the number of twin systems. The plastic strain rate is expressed in terms of the twinning shear rate $\dot{\gamma}^\alpha_{twin}$ and the Schmidt tensor $\mathbf{P}^\alpha_{twin} = (\mathbf{s}^\alpha_{twin}\mathbf{n}^\alpha_{twin} + \mathbf{n}^\alpha_{twin}\mathbf{s}^\alpha_{twin})/2$ for the α-th twinning system. $\mathbf{s}^\alpha_{twin}$ and $\mathbf{n}^\alpha_{twin}$ are the vector normal to the twinning plane and the shear direction of the α-th twinning system, respectively.

$$\dot{\gamma}^\alpha_{twin} = g_{twin} \dot{f}^\alpha \tag{2}$$

where g_{twin} is the characteristic shear and $\dot{f}^\alpha$ is the rate of twinning volume fraction for the α-th twinning system.

The twinning shear rate $\dot{\gamma}^\alpha_{twin}$ is commonly assumed as

$$\dot{\gamma}^\alpha_{twin} = \begin{cases} \dot{\gamma}_0 \left|\tau^\alpha_{twin}/\tau^\alpha_{ctwin}\right|^m & \tau^\alpha > 0 \\ 0 & \tau^\alpha \le 0 \end{cases} \tag{3}$$

where $\dot{\gamma}_0$ is the referential twinning shear rate, τ^α_{ctwin} is the critical resolved shear stress (CRSS) of twinning, and τ^α_{twin} is the driving force of twinning. Regardless of dislocation slipping or twinning, the driving force of the shear rate $\dot{\gamma}^\alpha$ is the resolved shear stress $\tau^\alpha = \boldsymbol{\sigma}: \mathbf{P}^\alpha$, where $\boldsymbol{\sigma}$ is the Cauchy stress tensor. m represents the strain-rate sensitivity.

Because the value of m indirectly controls the strain-rate effect, when the variation of the strain rate is relatively large, the rate-dependence of the deformation of the material becomes very difficult to be described by using m. In addition, because the twin deformation is very fast [29] for strain rates below 10^5 s^{-1}, the speed of the twin deformation is far greater than that of the material deformation. Therefore, in this condition, twinning is generally considered an instantaneous deformation, it can be set as independent of the strain rate. Therefore, Eq. (3) can be written as

Table 1
Composition of AZ31B magnesium alloy.

Element	Weight%	Atom%
Mg	95.94	96.82
Al	3.06	2.81
Zn	1.00	0.38