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A modified Johnson–Cook constitutive model for Mg–Gd–Y alloy extended to a wide range of temperatures

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ABSTRACT

In this paper, a new phenomenological and empirically based constitutive model was proposed to change the temperature term in the original Johnson–Cook constitutive model. The new model can be used to describe or predict the stress–strain relation of the metals deformed over a wide range of temperatures even though the current temperatures were lower than the reference temperature. Based on the impact compression data obtained by split Hopkins pressure bar technique, the material constants in the new model can be experimentally determined using isothermal and adiabatic stress–strain curves at different strain rates and temperatures. Good agreement is obtained between the predicted and the experimental stress–strain curves for a hot-extruded Mg–10Gd–2Y–0.5Zr alloy at both quasi-static and dynamic loadings under a wide range of temperatures ever though the current temperatures were lower than the reference temperature.

1. Introduction

It has been reported that the recently developed lightweight magnesium alloys, especially to the Mg–Gd–Y alloys, present higher specific strength and better creep resistance [1–5]. Therefore, the Mg–Gd–Y alloys offered a high potential for weight reduction to improve fuel economy and emissions in aerospace, outer space, weapons and high performance automobiles [6,7]. However, comparing to steel and aluminum alloys, the mechanical behavior of the Mg–Gd–Y alloys under impact loading has been much less studied. Obviously, the knowledge of dynamic plastic response of the Mg–Gd–Y alloys, especially to their dynamic plastic response at the temperatures lower than the ambient temperature, is necessary to develop product resistance to shock loading, for crashworthiness, safety, and reliability.

It is well recognized that mechanical behavior of most metals is dependent on strain rate and temperature. An understanding of the deformation behavior of the metals over a wide range of temperatures and strain rates is important in designing the structures [8,9]. Comparing with plastic deformation under quasi-static loading conditions which can be treated as an isothermal process, deformation at high strain rate is essentially adiabatic, where some of the heat produced by the plastic deformation cannot conduct and radiate. Thus, the adiabatic temperature rise is produced within the specimen. This temperature rise has a significant effect on the plastic deformation behavior of metals at high strain rates of loading, causing thermal softening. Obviously, the influences of strain rate, temperature, strain, and adiabatic temperature rise on the plastic deformation of the metals are coupled during the high rate deformation. Therefore, it is necessary to study the coupling effect on the metals to describe or predict their plastic deformation behavior. Fortunately, constitutive model which is the mathematical representation of the flow behavior of metals can be used as input to the finite element codes to describe or predict the plastic response of the metal under specified loading conditions [10–12]. Therefore, the accuracy of the numerical simulation largely depends on how accurately the deformation behavior of the material is being represented by the constitutive model [13]. Recently, several empirical, semi-empirical, phenomenological and physically based constitutive models have been proposed to describe or predict the plastic response of the structure under such coupling [8,9,14–17]. Physically based models can provide more accurate representation for the deformation behavior of the metals over a wide range of temperatures and strain rates. However, these models are not always preferred by the users, as physically based models often need more data from precisely controlled experiments. More importantly, these models involve large number of material constants and properties than empirical models which may not be readily available [18] in open literatures. Ideally, a model should involve a reasonable number of material constants that can be evaluated using limited experimental data, and should be able to represent the flow behavior of the material with accuracy and reliability over a wide processing domain. Because of its simple multiplication form, the empirical based Johnson–Cook (J–C) model

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has been successfully incorporated in finite element analysis packages to describe the mechanical behavior of metals at high strain rates and various temperatures [8,9,15,19].

Nevertheless, it can be found from the literatures about using the J–C models [8,9,15,19] that the current temperature was commonly higher than the reference temperature because the minimum experimental temperature was commonly used as the reference temperature. However, it is inappropriate to use the minimum experimental temperature as the reference temperature in these models when the minimum experimental temperature is lower than the ambient temperature because it is not easy to conduct the quasi-static experiment at such temperature. Besides, from a mathematical view, the temperature coefficient which is obtained by least squares fitting method in the original J–C model [15] cannot be solved in the real ranges when the current temperatures are lower than the reference temperature. That is to say, from a mathematical view, it is almost impossible to get such temperature coefficient which can be expressed as a fraction with even numerator. So, it is necessary to modify the original J–C model from reasonable mathematical view to make it can describe or predict the plastic response of the metals whatever the current temperatures are higher or lower than the reference temperature.

It seems that some modified J–C models proposed to study the plastic response of the body-centered cubic (b.c.c.) [8] and face-centered cubic (f.c.c.) [9] metals can be used to study the plastic response of the metals over a wide range of temperatures even though the current temperatures were lower than the reference temperature. However, it is not suitable to use those models to study the plastic response of the magnesium alloys because of their hexagonal closed-packed (h.c.p.) structure. Fortunately, the original J–C model [15] could not only be used to study the plastic response of the b.c.c. and f.c.c. metals, but be used to study the plastic response of the h.c.p. metal.

Therefore, the main objective of the present paper is to study the dynamic plastic response of the hot-extruded Mg–10Gd–2Y–0.5Zr alloy compressed at $\sim 8 \times 10^2$–$4 \times 10^3\ s^{-1}$ and a wide range of temperatures. Based on the impact data for the alloy, a modified J–C model was proposed to describe or predict the dynamic plastic response of the hot-extruded Mg–10Gd–2Y–0.5Zr alloy whatever the current temperatures are higher or lower than the reference temperature.

2. Experimental materials and procedures

One commercial Mg–10Gd–2Y–0.5Zr alloy used in the current study was in the form of hot-extruded bar with a 20 mm diameter. The as-received bar was machined into $\Phi 10$ mm × 4 mm, $\Phi 10$ mm × 5 mm, and $\Phi 10$ mm × 10 mm using a wire electrodischarge machine. The flank surfaces of each specimen were finished in a centerless-grinding operation to ensure a low dimension tolerance of approximately ±25 μm. The two flat ends of each specimen were then surface-ground using a #120 grit size grinding wheel until a parallel divergence of less than 0.8 μm/mm was obtained between the two ends. To minimize friction effects and fix the tested specimens during impact testing, the end faces of the specimens were lubricated using grease.

The quasi-static compression test was performed on a specimen with size of $\Phi 10$ mm × 5 mm at ambient temperature (18 °C in the present work) and strain rate of $4 \times 10^{-3}\ s^{-1}$ using a hydraulic universal testing machine. Meanwhile, the dynamic impact tests were performed using a compressive split Hopkinson pressure bar (SHPB) apparatus at strain rates of $\sim 8 \times 10^2$–$4 \times 10^3\ s^{-1}$ and temperatures of −100 to 460 °C. Fig. 1 presents a schematic illustration of the SHPB apparatus and the measuring procedures. It can be found that SHPB system basically comprises an incident bar, a transmitted bar and a strike bar. During compression testing, the specimen was positioned between the incident bar and the transmitted bar. The free end of the incident bar was then subjected to an axial impact by the strike bar. This impact generated a compressive loading pulse wave, which propagated along the incident bar until it reached the interface with the specimen. At the interface, part of the wave was reflected back along the incident bar, while the remainder was transmitted through the specimen and into the transmitted bar. The amplitudes of the reflected wave (ε_r) and the transmitted wave (ε_t) were recorded using strain gauges mounted on the incident bar and the transmitted bar, respectively. Based on one-dimensional elastic wave propagation theory, strain (ε), strain rate ($\dot{\varepsilon}$) and flow stress (σ) in the specimen were obtained from the measured values of the reflected wave amplitude (ε_r) and the transmitted wave amplitude (ε_t) via the following formulae:

$$\varepsilon = \frac{-2C_0}{L} \int \varepsilon_r \, dt \tag{1}$$

$$\dot{\varepsilon} = \frac{-2C_0}{L} \varepsilon_r \tag{2}$$

$$\sigma = \frac{EA_0}{A_S} \varepsilon_t \tag{3}$$

where C_0 and E are the elastic wave velocity and the Young's modulus in the bars, respectively, L is the initial length of the specimen, and A_0/A_S is the ratio of the bar cross-sectional area to that of the specimen.

Before the tests performed at temperature of −20 °C or lower, the specimens were cooled to the setting temperature and then hold for 2 min using a cooling tank into which the liquid nitrogen was poured before the testing. Before the impact tests performed at temperature of 200 °C or higher, the specimens were heated to the setting temperature then hold for 2 min using a high-temperature electric resistance furnace.

3. Results and analysis

3.1. Experimental results

Fig. 2a shows the results of the quasi-static and some typical impact compression stress–strain curves for the hot-extruded Mg–10Gd–2Y–0.5Zr specimens with $\Phi 10$ mm × 5 mm. It can be seen that the typical strain hardening curve can be obtained. Besides, it is obvious that the strain rate and temperature have significant effect on the flow stress of the specimens. The flow stress increases with increasing strain rate at the same initial temperature. On the contrary, the flow stress decreases with increasing initial temperature at a similar strain rate. The flow stress for the samples compressed at above 340 °C and strain rate of $\sim 3.2 \times 10^3\ s^{-1}$ is even lower than that for the sample compressed at quasi-static. The similar stress–strain characteristics can be obtained from the impact compression curves for the hot-extruded Mg–10Gd–2Y–0.5Zr specimens with $\Phi 10$ mm × 4 mm and $\Phi 10$ mm × 10 mm, as shown in Fig. 2b and c. It can be found that the influences of strain, strain rate, and temperature on the plastic deformation of the hot-extruded Mg–10Gd–2Y–0.5Zr alloy are coupled during the high rate deformation. Therefore, it is necessary to build constitutive model to express such coupling effects in the alloy to describe or predict its dynamic plastic response.

3.2. Constitutive model and parameters solving

3.2.1. Constitutive model

Johnson and Cook [15] proposed an empirically based constitutive model for metals subjected to large strains, high strain rates,