Study on modified Johnson-Cook constitutive material model to predict the dynamic behavior Mg-1Al-4Y alloy

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Abstract

An accurate prediction of high speed impact behavior of metals by considering the combined effects of strain, strain rate and temperature is essential for understanding dynamic impact deformation of metals. To understand the effect of strain, strain rate and temperature on the high-speed impact behavior of Mg-1Al-4Y alloy, the dynamic impact compression experiments for Mg-1Al-4Y alloy were carried out by split Hopkinson pressure bar (SHPB). The mechanical properties of Mg-1Al-4Y alloy specimens were studied at different strain rate and temperature. The number of extension twins decreases with the strain rate increasing from the electron backscatter diffraction (EBSD) technology, because of the formation of extension twins is suppressed with the strain rate increases, and dislocations become the main mode of dominant deformation. It is also found that the increase of strain rate has a positive effect on the strength of the material. But, the temperatures have a negative impact on the strength of the material. A modified Johnson-cook model has been presented, which shows good predictions with experimental results at different strain rates and temperatures. Especially, the predictions of the Johnson-cook equation are completely consistent with experimental results in small deformation stage.

1. Introduction

Magnesium alloys have been widely used in the transportation field of vehicle and aircraft manufacturing due to their low density, and high specific stiffness and strength [1–5]. In the service environment of these fields, magnesium alloy components including car doors and aircraft shells, often face high-speed impact, and the impact strain rate can even reach more than 10^3 s^{-1} [6–8]. The plastic deformation behavior and mechanical properties of magnesium alloy under high speed impact are more complicated than those under static load [9–12]. It is no longer just a dislocation glide deformation mode. Therefore, in order to obtain various performance parameters of magnesium alloy at high strain rate, in addition to mastering the deformation mechanism of magnesium alloy under quasi-static load conditions, it is necessary to study their organization evolution and mechanism performance under the conditions of high-speed impact. The research results of high-speed impact can provide references for the parameters of magnesium alloy components in automotive, aerospace, and other fields, it will effectively reduce the serious accidents such as fracture of these components under the high-speed impact and increase the reliability and working life of high-speed vehicle which used a large amount of magnesium alloy materials [13–15].

The high-speed impact experiments of magnesium alloys have been widely studied [16–20]. It is important to ensure that the accuracy to predict the mechanism performance of materials, which is tightly related to the effectiveness of constitutive material model in representing the actual alloy components under the high strain rate loading [21–23]. There are many of constitutive material models have been reported in literatures [24–26].
Such as Johnson–Cook (JC) model, Split Johnson–Cook (SJC), Bammann–Chiesa–Johnson (BCJ) model and Mechanical Threshold Stress (MTS) model, they have been largely used for successfully modeling of different materials [27–30]. However, these models involve large number of material constants and properties than empirical models which may not be readily available. Meanwhile, these models usually derive from an empirical basis and provide a simple formula, which may not always give precise predictions of the material deformation behavior.

In this work, the mechanical behaviors of Mg-Al-4Y along the normal direction (ND) at high strain rates were investigated using a SHPB apparatus. The micro-deformation mechanism of Mg-Al-4Y alloy is further studied by EBSD technology. The number of {10–12} extension twins decreases with the strain rate increasing because the formation of extension twins is suppressed with the strain rate increases, and dislocations become the main mode of dominant deformation. The Jonson–Cock constitutive equation of Mg-Al-4Y alloy was constructed and considered the factors including temperature and strain rates. It is found that the predicted value of the JC equation has a large deviation from the experimental one. Thus, the JC constitutive equation was modified, which aims at providing much better results comparing to those achievable from the origin JC model. The similar computational framework was employed in the modified JC model and adopt the same type of experimental data available for calibration. The deformation behaviors of Mg-Al-4Y alloys under different strain rates at different temperatures were studied. It was found that the modified JC equation gives precise predictions of the material deformation behavior.

2. Experimental procedures

The samples used in this work were as-cast Mg-1Al-4Y alloys which were solution-treated at 773 K for 24 h. The specimen geometry was utilized for the quasi-static and dynamic compressive stress-strain measurements: cylindrical specimen (diameter = 8 mm, length/diameter = 0.625), which was machined from the as-cast Mg-1Al-4Y alloy along the ND, where the axial direction of the cylindrical sample was parallel to the plate ND, since the most typical engineering application of the Mg alloy components involves subjecting them to external loading along the plate ND. The configurations of the samples used for the SHPB tests, along with the impact direction relative to ND. The dynamic impact tests were performed using a compressive SHPB equipment at high strain rates (dε/dt = 900–2500 s⁻¹) and temperatures of 293 K, 423 K, 523 K, 623 K. Figure 1 presents a schematic illustration of the SHPB apparatus and the measuring procedures. The SHPB system basically comprises an incident bar, a transmitted bar and a strike bar, which are coaxial. During the SHPB testing, the specimen was positioned between the incident bar and the transmitted bar. When carried out at elevated temperature, specimen was heated by a furnace independently and remained stable for 5 min. 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. Hence, we obtained the true stress-strain curves at high strain rates and with varied temperatures. Finally, the microstructures of cast samples were observed by ZEISS-6035 field-emission scanning electron microscope (SEM), and electron back-scattered diffraction (EBSD) technology was used to analyze the microstructure of samples after deformation.

3. Results and discussion

3.1. Microstructure and phase structure

The morphology of Mg-1Al-4Y alloy was observed by SEM (figure 2(a)). Figure 2(b) shows the x-ray diffraction (XRD) analysis results of the as-cast Mg-1Al-4Y alloy. The black contrast area should be Mg matrix, the EDX spectra result show that the grey contrast marked yellow circle in figure 2(a) should be precipitate phase Al₂Y (from figure 2(c)). As can be seen from SEM image, there is an amount of Al₂Y phase embedded in the alpha-Mg matrix.

Figure 2. (a) SEM image of Mg-1Al-4Y; (b) XRD analysis results of Mg-1Al-4Y alloy; (c) EDX spectra of precipitation acquired from the area marked by a yellow circle in (a).
3.2. Johnson-cook model

The JC model fully considers the strain, strain rate and temperature influence on the plastic deformation mechanism of the alloy. Therefore, the JC model is chosen to study the high-speed impact deformation behavior of Mg-1Al-4Y. When the JC model is constructed, the parameters of the model at reference temperature need to be modified, and the correction coefficient \( D \) is added. The specific form of the JC model is

\[
\sigma = \left( A + Be_p^n \right) \left( 1 + C \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) + D \left( 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right)
\]

(1)

where, \( \sigma \) is flow stress, \( A \) is quasi-static yield stress, \( B \) is strain hardening parameter, \( C \) is strain rate hardening parameters, \( m \) is material thermal softening index, \( n \) is strain hardening index, \( T_m \) is reference melting temperature, \( T_r \) is the reference temperature. Therefore, those six parameters in the constitutive equation should be specifically determined: \( A, B, C, m, n \) and the modified coefficient \( D \). 293 K is taken as reference temperature \((T_r)\) to evaluate the material constants of the JC model. Firstly, the \( A \) of Mg-1Al-4Y alloy is determined. The elastic deformation part of the curve is fitted with a straight line to determine the elastic modulus of the sample. As shown in figure 3, the true stress-strain curve is fitting well with the elastic fitting curve in elastic deformation stage of sample. It is found that the Mg-1Al-4Y alloy has no obvious yield point, therefore, 0.2% of the inelastic deformation of the material is taken as the yield point. So, the quasi-static yield stress \( A = \sigma_{0.2} = 112.97 \text{ MPa} \).

3.2.1. Determination of parameters \( B \) and \( n \)

At the reference temperature and reference strain rate, the influences of strain rate strengthening and thermal softening are ignored:

\[
\sigma = A + Be_p^n
\]

(2)

Therefore, equation (2) can be transformed into:

\[
\ln(\sigma - A) = n \ln \dot{\epsilon}_p + \ln B
\]

(3)

The curve \( \ln \dot{\epsilon}_p - \ln(\sigma - A) \) is a linear relationship, the fitting line was plotted and the slope is \( n = 1.34 \) and the intercept is \( \ln B = 8.07, B = 3197.10 \), as shown in figure 4(a).

3.2.2. Determination of parameters \( C, D \):

The parameter \( C, D \) is determined by fitting the data with a strain rate of \( 914 \text{ s}^{-1} \) at reference temperature. And the JC constitutive equation is simplified to:

\[
\sigma = (A + Be_p^n) \left( 1 + C \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) + D
\]

(4)

When the strain rate is determined, \( f(\dot{\epsilon}) = 1 + C \ln \dot{\epsilon}^* \) is a constant, where \( \dot{\epsilon}^* = \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \), the reference strain rate \( \dot{\epsilon}_0 = 1.0 \times 10^{-3} \), so the equation can be transformed into:

![Figure 3. True stress-strain curve of Mg-1Al-4Y.](image-url)
The fitting line of $\varepsilon_n$ versus $\sigma$ is plotted (as in figure 4(b)), the slope of the line is 5441.74, the slope is 165.70, and A, B is taken into the formula (5). So, $C = 51.20 \times 10^{-3}, D = -26.58$. The expression of the JC constitutive equation at reference temperature is:

$$\sigma = B \left(1 + C \cdot \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) \times \varepsilon^n + A \times \left(1 + C \cdot \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) + D$$  \hspace{1cm} (5)

The fitting line of $\varepsilon^n$ versus $\sigma$ is plotted (as in figure 4(b)), the slope of the line is 5441.74, the slope is 165.70, and A, B is taken into the formula (5). So, $C = 51.20 \times 10^{-3}, D = -26.58$. The expression of the JC constitutive equation at reference temperature is:

$$\bar{\sigma} = (112.97 + 3197.1 \times \dot{\varepsilon}_p^{1.34} \left(1 + 0.0512 \times \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) - 26.58$$  \hspace{1cm} (6)

The comparisons between experimental flow stress values and predicted values by the JC model are shown in figure 5. According to the fitting equations and the true stress-strain curves of different strain rates at reference temperature, there’s a similar pattern: Firstly, the predictions are higher than the results of experiment in the small deformation stage ($\text{strain} < 0.03$); Then, the JC fit results are good agreement with the experimental one ($0.03 < \text{strain} < 0.1$); Finally, the deviations between the predictions of the JC equation and experimental results are increased with the strain increases. The JC model shows good prediction only in a small deformation range ($0.03 < \text{strain} < 0.1$). Meanwhile, the tendencies of prediction of JC equation are not consistent with the experimental one. In order to obtain a better prediction, a modified JC model needed to be constructed.

### 3.3. Modified johnson-cook model

Apparently, the JC model only just simply supposes that the three influencing factors of strain, strain rate and temperature are mutually independent, which does not reflect the accumulation effect of any influencing factor. Taking consideration into the interaction influences of the three factors on flow stress, the modified JC model was constructed. Similarly, 293 K is taken as reference temperature ($T_p$) and 0.001 s$^{-1}$ as the reference strain rate ($\dot{\varepsilon}_0$) to evaluate the magnesium alloy constants of the modified JC model.
where $A, B_1, B_2, C_1, C_2, D$ and $m$ are material coefficients and the meanings of the other parameters are the same as that in the Johnson-Cook model.

### 3.3.1. Determination of constant $A, B_1, B_2, C_1, C_2, D$

At the reference temperature and reference strain rate, equation (7) could be expressed as follow:

$$
\sigma = \left\{ (A + B_1\varepsilon_p) \left( 1 + C_1 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) + B_2 \left( 1 + C_2 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \varepsilon_p^2 + (D + \ln \varepsilon_p) \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right\} \times \left( 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right)
$$

(8)

Substituting the data of stress and strain under the deformation conditions in equation (8), draw $\sigma-\varepsilon$ curve, and conduct two-order polynomial fitting. According to the coefficient of the fitted polynomial, the value of $A, B_1, B_2$ are determined (in figure 6). With the results of SHPB tests, the values of $C_1, C_2, D$ were calculated at reference temperature with strain rate of $1322 \text{ s}^{-1}$. So, the modified JC constitutive equation can be express as follow:

$$
\sigma = A + B_1\varepsilon_p + B_2\varepsilon_p^2
$$

(9)

The comparisons between experimental flow stress values and predicted values by the modified JC model are shown in figure 7. The modified JC model shows good predictions with experimental results at different strain rates. Meanwhile, the tendencies of prediction of the JC equation are consistent with the experimental one. It is found that the accuracy of the modified Johnson-Cook model advances significantly. Especially, the predictions of the JC equation are completely consistent with experimental results in small deformation stage.

Comparing the different curves of the stress and strain at different strain rates and varied temperature (figure 8). It can be found that the yield strength and tensile strength of the material are obviously improved with the strain rate increase, which indicates that the increase of strain rate has a positive effect on the strength of the material. The plasticity of the material exhibited significant improvements at the high strain rate. The larger the
strain rate is, the larger the elongation at fracture will be. When the strain rate is increased to 2025 s\(^{-1}\) at reference temperature, the elongation at fracture of the material reaches 17.2%, the strength of the sample reaches the maximum value of all sets of experiments at reference temperature (figure 8(a)). While the strain rate is 914 s\(^{-1}\) at reference temperature, the strain is only 7.3%. The stress versus strain in SPHB tests at different strain rates show a similar change rule under other temperature conditions. There is a complex deformation behavior for the material. Studies have shown that the formation of twins is promoted during the initial stage of deformation at high strain rate [31–36]. Excessive strain rate usually leads to the formation of a large number of \{10–12\} twins inside the materials. On the one hand, the twin lamellae subdivide grains lead to grain refinements, and on the other hand, the twin crystal texture is formed, which cause obvious work hardening. These characteristics are in good agreement with the trend of the true stress-strain curves shown in figure 8. Temperature also plays an important role in the plastic behavior of magnesium alloy at high speed impact.
Magnesium alloys have limited slip systems at room temperature. The critical resolved shear stress (CRSS) value of some slip surfaces is too high to start slip at low temperatures. Thus, the twins is the dominant deformation mode. With the temperature elevated, the yield strength and tensile strength of the material is decreased. Under the similar strain rate, the yield strength $\sigma_s$ and tensile strength $\sigma_b$ of the sample show a decreasing trend with the temperature elevated. Meanwhile, as the experimental temperature elevated, the elongation at break continuously increases, which indicates that the elevated temperature promotes the plasticity of the sample.

3.3.2. Determination of parameter $m$

There are three sets of experimental data with the same strain are selected to calculate the parameter $m$, which is obtained at reference temperature 293 K, 423 K and 523 K, respectively. Under the same strain, the ratio of formula (7) and formula (9) is:

$$f_1 = 1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m$$

(10)

It can be seen from the Mg-Al-Y ternary phase diagram that the Mg-1Al-4Y alloy melting point is $T_m = 893$ K. But, it is impossible to ensure that the strain and the strain rate of the selected data are strictly the same, only the closest of any selected for equation (10) calculation. At the same time, the ratio method of calculating $m$ has a great randomness. Therefore, on the premise of ensuring that the calculation result of $m$ is as accurate as possible, the 20 calculated values of $m$ are averaged, and take as the parameter $m$ of the modified JC constitutive equation. The data selected are shown in the table 1. The average of $m$ is 0.734. Therefore, the relation among stress $\sigma$, strain $\varepsilon$, deformation rate $\dot{\varepsilon}$ and deformation temperature $T$ was established according to the modified JC model. A complete description of the modified JC constitutive equations at different temperatures and strain rates is:

$$\dot{\varepsilon} = \left(29.11 + 3066.82\varepsilon_p\right) \left(1 + 0.037 \ln \frac{b}{\dot{\varepsilon}_0}\right) - 7493.86 \left(1 + 0.078 \ln \frac{b}{\dot{\varepsilon}_0}\right)$$

$$\times \varepsilon^m_p + (4.69 + \ln \varepsilon) \ln \frac{b}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^{0.734}\right)$$

(11)

In order to verify the accuracy of the modified JC equation, the high speed impact experiments under different strain rates were carried out at 423 K, 523 K and 623 K, respectively. It is found that the modified JC
The model shows good predictions with experimental results at different strain rates and varied temperatures. The true stress-strain behaviors of the alloy sample at elevated temperature are similar to that of initial deformation stage at reference temperature (figures 9(a)–(i)). While the strain rate is less than 1500 s\(^{-1}\), the predicted values of the JC equation have a large deviation from the experimental value. Those deviations mainly come from the influence of the parameter \(m\) of the modified JC equation. Since the coupling effect of strain rate and temperature on the alloy's deformation behavior is evident, Table 1 lists the data selected for calculation of \(m\).

| Temperature | Strain Rate | True Stress (MPa) | True Strain |
|-------------|-------------|-------------------|-------------|
| 293 K       | 1300 s\(^{-1}\) | 0.02334, 185.762  | 0.02898, 137.550 |
| 423 K       | 1213 s\(^{-1}\) | 0.02371, 186.934  | 0.02930, 137.963 |
| 523 K       | 1229 s\(^{-1}\) | 0.02446, 189.261  | 0.03025, 138.378 |

**Figure 9.** The true stress-strain curves and modified JC constitutive equations at different temperatures and strain rates. 423 K, (a)–(c): 1213 s\(^{-1}\), 1712 s\(^{-1}\), 2296 s\(^{-1}\); 523 K; (d)–(f): 1229 s\(^{-1}\), 1781 s\(^{-1}\), 2275 s\(^{-1}\); 523 K; (g)–(i): 1432 s\(^{-1}\), 1791 s\(^{-1}\), 2003 s\(^{-1}\).
temperature is not considered in the modified JC equation. Meanwhile, there is a big error because of the ratio method used in solving \( m \). With the strain rate increasing, the deviation from the prediction of the modified JC equation and the true stress-strain curve gradually decreasing.

The micro-deformation mechanism of Mg-1Al-4Y alloy is further studied by EBSD technology. The area surrounded by the red line were \{10–12\} extension twinning (figure 10). The formation and development of \{10–12\} extension twinning is substantial due to the compression along the ND. Due to the low symmetry of the hexagonal structure, magnesium and its alloys have limited slip systems, so twinning plays a critical role in deformation of Mg-1Al-4Y alloys, especially \{10–12\} extension twinning, which can be easily activated. \{10–12\} extension twinning is the dominant deformation mode and results in a decreased amount of untwinned matrix. It is found from figures 10(a)–(d) that the number of \{10–12\} extension twins decreases with the increase of strain rate, that is because the formation of tensile twins is suppressed with the strain rate increases, and dislocations become the main mode of dominant deformation. Since the twin critical shear stress is not sensitive to temperature, its role in plastic deformation gradually decreases with increasing temperature.

4. Conclusion

The mechanical behaviors of as-cast Mg-1Al-4Y along ND at high strain rates were investigated using a SHPB. Comparing the different curves of the stress and strain at different strain rates and varied temperature, it is found that the yield strength and tensile strength of the material are obviously improved with the strain rate increase, which indicates that the increase of strain rate has a positive effect on the strength of the material. But, the yield strength and tensile strength of the material is decreased with the temperature elevated, which indicates that the temperatures have a negative impact on the strength of the material. A modified strength model JC model has been presented which was chosen to study the high-speed impact deformation behavior of as-cast Mg-1Al-4Y. The modified JC model shows good predictions with experimental results at different strain rates and varied temperatures. Especially, the predictions of the JC equation are completely consistent with experimental results in small deformation stage. Since the coupling effect of strain rate and temperature is not considered in the modified JC equation, and the ratio method was used in solving \( m \), which lead to a deviation in prediction. With the strain rate increasing, the deviation from the prediction of the modified JC equation and the true stress-strain curve gradually decreasing. Finally, the micro-deformation mechanism of Mg-1Al-4Y alloy is further studied by EBSD technology. The formation and development of \{10–12\} extension twinning is substantial due to the compression along the ND. The number of \{10–12\} extension twins decreases with the increase of strain.
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