Constitutive behavior and novel characterization of hot deformation of Al-Zn-Mg-Cu aluminum alloy for lightweight traffic

Hao Xindi¹, Ren Dong¹, Dong Juan², Haiming Zong¹ and Lv Zhengfeng²

¹ College of Engineering, Yantai NanShan University, Yantai 265713, Shandong, People’s Republic of China
² National Engineering Research Center for Plastic Working of Aluminum Alloys, Shandong NanShan Aluminum Co Ltd, Yantai 265700, Shandong, People’s Republic of China

E-mail: zonghaiming666@163.com

Keywords: Al-Zn-Mg-Cu aluminum alloy, automotive lightweight, constitutive equation, hot processing map, safety strain rates map

Abstract

Isothermal compression tests of 7A21 aluminum alloy were carried out on a Gleeble-3500 thermal simulator, and the stress-strain curves were obtained at temperatures ranging from 350 to 500 °C and strain rates ranging from 0.01 to 10 s⁻¹. The Arrhenius-type constitutive models with/without strain compensation were established to predict hot deformation mechanical behavior of the alloy based on friction and temperature corrected stress-strain curves, respectively. The model with strain compensation shows a higher prediction accuracy by calculating the average absolute relative error and correlation coefficient. The hot processing maps at different strains were constructed based on the dynamic material model (DMM). The safety strain rates map, a new form of processing map which reflects the variation of critical safety strain rates with the deformation temperatures and true strains, was generated to simplify the acquisition of safety zones throughout the whole deformation process.

1. Introduction

With the development of the society, the requirements for safety, luxury and performance of vehicles are increasing. At the same time, the automobile industry must comply with the increasingly stringent fuel efficiency standards and emission regulations, and the overall vehicle weight must be reduced. The application of aluminum auto parts is considered to be one of the most promising ways to solve this contradiction [1]. Nowadays aluminum alloys have been widely used in automobile panels. For example, 6xxx series aluminum alloy such as A6016, A6111 and A6181A were used in automobile outer panels [2], and 5xxx series aluminum alloy such as AA5052, AA5182 and AA5754 were used in automobile inner panels [3, 4]. However, 5xxx and 6xxx aluminum alloy can not meet the strength requirements of some key automotive structures (such as A pillar and B pillar). The application of 7xxx series aluminum alloy with high strength density ratio and excellent mechanical properties in automobile industry gets more and more attentions [5–8].

In order to optimize the hot-working characters of 7xxx aluminum alloy, improve its mechanical properties and expand its application in the field of automobile, some efforts have been made to study the hot deformation behavior of the material. Lin et al [9] studied the hot deformation behavior of Al-Zn-Mg-Cu alloy under time-dependent strain rate and established a constitutive model based on the dislocation density principle and iterative method. S Y Park et al [10] explored a possibility for directly using the as cast 7075 aluminum as a billet for hot working by using hot processing maps. Sun et al [11] developed a continuous dynamic recrystallization model of extruded AA7075 aluminum alloy based on the internal-state-variable (ISV) method to predict the flow stress and microstructure evolution during the deformation process. Mirzadeh [12] contrasted the prediction accuracy of the phenomenological and physical constitutive equations of 7075 aluminum alloy, and the results showed that physical constitutive equations was more suitable for describing the hot deformation behavior of 7075 aluminum alloy. Li et al [13] established an artificial neural network (ANN) model for Al–5.4Zn–2.0Mg–0.35Cu–0.3Mn–0.25Sc–0.10Zr alloy based on back-propagation learning algorithm, and higher accuracy was achieved when compared with Arrhenius-type equation. Li et al [14] analyzed the processing maps...
of Al-6.2Zn-0.70Mg-0.3Mn-0.17Zr alloy at different strains, and the optimum processing conditions were in deformation temperature range from 703 K to 773 K and strain rate range from 0.03 s\(^{-1}\) to 0.32 s\(^{-1}\). However, there are few reports on the hot deformation behavior of 7A21 aluminum alloy for automotive lightweight.

In this paper, a single pass isothermal compression test for 7A21 aluminum alloy was carried out, and a thermodynamic constitutive equation describing the relationship between flow stress, deformation temperature, strain rate and strain was established to predict its hot deformation flow behavior. The hot processing map was built to optimize the hot process parameters. An attempt has been made to conduct a new type of hot processing map expressed by strain rates to simplify the acquisition mode of hot working safety zone at any deformation conditions.

2. Materials and methods

An as cast 7A21 aluminum alloy prepared in laboratory was used in this investigation, and its chemical composition (wt.%) was given in table 1. The experimental material was processed into cylindrical specimens with a diameter of 10 mm and a height of 15 mm for experiments. In order to simulate the mechanical behavior and microstructure evolution during the rolling process, the as cast cylindrical specimens were homogenized at 550\(^{\circ}\)C for 24 h, as shown in figure 1(a). The microstructure of the alloy after homogenization was shown in figure 2.

The isothermal compression tests for these homogenized cylindrical specimens were carried out on a Gleeble-3500 thermal simulator. In order to reduce friction effect and make the specimen deformed uniformly during the thermal deformation process, the tantalum and graphite sheets were added to both polished ends of the specimens separately with high temperature lubricants before the experiments. Four deformation temperatures (350, 400, 450 and 500\(^{\circ}\)C) and four strain rates (0.01, 0.1, 1 and 10 s\(^{-1}\)) were chosen in the experiments. The specimen was heated to the deformation temperature at a heating rate of 10\(^{\circ}\)C.s\(^{-1}\), and held for 3 min to make the temperature uniform. The height reduction of the specimen was 55\%, and the corresponding true strain was 0.8. The specimen was quenched to room temperature immediately after the deformation process, as shown in figure 1(b). Vernier caliper was used to measure the size of the sample after deformation.

3. Correction of the flow stress curves

3.1. The principle of friction correction for the flow stress curves

The friction at the die–workpiece interface makes the deformation of the specimen uneven with a phenomenon of the ‘waist drum’ and affects the accuracy of the measured flow stress. Tantalum sheets and graphite sheets are generally added between the indenter and the specimen to reduce friction, but its adverse effects can not be

---

### Table 1. Chemical composition of 7A21 aluminum alloy (wt.%).

| Element | Mg | Zn | Cu | Zr | Al |
|---------|----|----|----|----|----|
| Content  | 1.5 | 5.5 | 0.2 | 0.12 | Bal |

---

![Figure 1. Schematic diagram of (a) homogenization process; (b) thermal compression process.](image)
completely eliminated. The specimen after hot compression at strain of 0.8 is shown in Figure 3. It can be seen that the phenomenon of 'waist drum' is still very prominent under high strain. Therefore, following equation is used to modify the stress-strain curves obtained by compression test [15]:

$$\sigma = \frac{C^2 P}{2[\exp(C) - C - 1]}$$

in which

$$C = \frac{2\mu R_0}{H_0}$$

Where $P$ is the flow stress after friction correction, $\sigma$ is the flow stress obtained by experiment, $R_0$ and $H_0$ are initial radius and height of the specimen respectively, $\mu$ is friction coefficient which can be determined by following equation [16]:

$$\mu = \left[ \frac{\Delta H}{\sqrt[3]{R_M - \sqrt[3]{\frac{3H_0R_0^2}{H} - 2R_0^3}}} - \frac{2H}{3\sqrt[3]{H}} \right]^{-1}$$

where $H$, $R$, $R_M$ and $\Delta H$ are theoretical deformation height, theoretical deformation radius, maximum deformation radius and height reduction respectively, as shown in Figure 4.

Figure 2. Microstructure of 7A21 aluminum alloy after homogenization.

Figure 3. Morphology of samples after compression at true strain of 0.8.
3.2. The principle of temperature correction for the flow stress curves

A large amount of deformation heat will be generated inside the specimens during plastic deformation. At low strain rate, these deformation heat spreads to the surrounding environment by heat conduction. At high strain rate, the heat diffusion efficiency is far lower than the formation efficiency which leads to the increase of the temperature of the specimen. Figure 5 shows the actual temperature changes with strain rates at the setting temperature of 350 °C. It can be seen that the temperature fluctuation increases with the increase of strain rate. When the strain rate rises to 10 s\(^{-1}\), the actual maximum temperature exceeds the setting temperature of 16.37 °C. Therefore, the temperature rise of the specimens due to deformation heating must be corrected to obtain the accurate flow stress of a specific temperature at high strain rates. The relationship between flow stress before and after temperature correction at a certain strain rate can be expressed as follows [17]:

\[
\sigma_1 = \begin{cases} 
\exp \left( \frac{\partial (\ln \sigma)}{\partial \left( \frac{1}{T_s} \right)} \cdot \frac{1}{T_i} \right) & \text{for low stress levels} \\
\frac{\partial \sigma}{\partial \left( \frac{1}{T_s} \right)} \cdot \frac{1}{T_i} & \text{for high stress levels}
\end{cases}
\]

(4)

Where \(\sigma_1\) and \(\sigma\) are flow stress before and after temperature correction respectively, \(T_i\) is setting temperature, \(T\) is actual temperature which can be calculated by [18]:
3.3. Flow stress behavior

The flow stress curves at different deformation temperatures and different strain rates after the friction and temperature correction are shown in figure 6. It can be seen that the deformation temperature and the strain rate have great influence on hot deformation behavior of 7A21 aluminum alloy, and the flow stress increases significantly with the decrease of deformation temperature and the increase of strain rate. At the early stage of deformation, the flow stress increases rapidly due to dislocation formation and accumulation [7, 9, 14]. Then, the flow stress reaches a peak value with a declining rate of growth, indicating that the dynamic recovery (DRV) and the dynamic recrystallization (DRX) counteracted part of the work hardening [19]. After that, flow stress tends to maintain or decrease to a steady state, which proves the dynamic equilibrium between work hardening and dynamic softening [20].

4. Constitutive equation of 7A21 aluminum alloy

4.1. Constitutive equation considering peak stress

The hot deformation behavior of material is mainly determined by the deformation parameters such as strain rate and deformation temperature. The relationship between flow stress, temperature and strain rate can be expressed as following equation [21]:

\[ \dot{\varepsilon} = f(\sigma) \exp\left(-\frac{Q}{RT}\right) \]  

(7)
in which

\[
A \ln A_1 \sigma_n \text{ for low stress levels}
\]
\[
A_2 \exp(\beta \sigma) \text{ for high stress levels}
\]
\[
A \{\sinh(\alpha \sigma)\}^p \text{ for all stress levels}
\]

Where \(A, A_1, A_2, n, n_1, \beta\) and \(\alpha\) are temperature independent material constants, \(Q\) is activation energy of hot deformation (\(J\ mol^{-1}\)), \(T\) is deformation temperature, \(R\) is gas constant (8.314 \(J\ mol^{-1} K^{-1}\)), \(\sigma\) is a characteristic stress on the flow stress curve. In this paper, the peak stress is used as the characteristic stress to study the hot deformation behavior of 7A21 aluminum alloy.

By substituting equation (8) into equation (7) respectively and taking natural logarithms on both sides, equation (7) are changed into:

\[
\ln \dot{\varepsilon} = \begin{cases} 
\ln A_1 + n_1 \ln \sigma - Q/RT & \text{for low stress levels} \\
\ln A_2 + \beta \sigma - Q/RT & \text{for high stress levels} \\
\ln A + n \ln \sinh(\alpha \sigma) - Q/RT & \text{for all stress levels}
\end{cases}
\]
Then \( n, \beta, \alpha, \) and \( Q \) can be expressed as:

\[
\begin{align*}
\dot{\varepsilon}_s &= \frac{\partial}{\partial \ln \sigma} \left( \ln 10 \right) T \\
\dot{\varepsilon}_a &= \frac{\partial}{\partial \ln \sigma} \left( \ln 11 \right) T \\
\dot{\varepsilon}_a &= \frac{\partial}{\partial \ln \sigma} \left( \ln \sinh 12 \right) T \\
\dot{\varepsilon}_a &= \frac{\partial}{\partial (1/T)} \left( \ln A \right) T
\end{align*}
\]

According to equations (10) and (11), \( n_1 \) and \( \beta \) are the mean slope of \( \ln \dot{\varepsilon} - \ln \sigma \) and \( \ln \dot{\varepsilon} - \sigma \) plots at different deformation temperatures respectively, as shown in figures 7(a) and (b). The value of \( n_1 \) and \( \beta \) were calculated as 5.16998 and 0.11518 MPa\(^{-1}\), and the value of \( \alpha = \beta/n_1 = 0.02228 \). Then substitute \( \alpha \) into equation (10), the value of \( n \) and \( Q \) can be easily determined by calculating the average slope of \( \ln \dot{\varepsilon} - \ln \sinh (\alpha \sigma) \) and \( \ln [\sinh (\alpha \sigma)] - 1/T \) plots, as shown in figures 7(c), (d). The values of \( n \) and \( Q \) are 4.49226 and 231.87313 KJ/mol, respectively. Thermal activation energy \( Q \) of pure aluminum under dynamic mechanism of cross-slip of dislocation is 117 kJ mol\(^{-1}\). The reason for the high thermal activation energy of the experimental 7A21 aluminum alloy is that the addition of Zn, Mg and other alloying elements significantly reduces the stacking fault energy and restrains the cross slip of dislocation, which increases the energy required for dislocation aggregation before cross slip [22–24].

The hot deformation behavior of materials at different deformation temperatures and strain rates can also be expressed by Zener-Hollomon parameters [13]:

\[
Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right) = A [\sinh (\alpha \sigma)]^\beta
\]

\[
\sigma = \frac{1}{\alpha} \ln \left\{ \left( \frac{Z}{A} \right)^\frac{1}{\beta} + \left( \frac{Z}{A} \right)^\frac{2}{\beta} + 1 \right\}^{\frac{1}{2}}
\]
Taking natural logarithms on both sides of equation (14), following equation can be obtained:

\[ \ln Z = \ln A + n \ln [\sinh (\alpha \sigma)] \]  \hspace{1cm} (16)

By substituting the value of Q into equation (14), the value of Z at different deformation conditions can be obtained. According to equation (20), \( \ln A \) is the average intercept of \( \ln Z - \ln [\sinh (\alpha \sigma_p)] \) plots, as shown in figure 7(e), and the value of A was calculated as \( 1.15695 \times 10^{16} \).

When substituting the value of \( \alpha, n, Q, A \) into equation (7), the constitutive equation of 7A21 aluminum alloy can be expressed as:

\[ \dot{\varepsilon} = 1.15695 \times 10^{16} \sinh (0.02228 \cdot \sigma_p) \times 1.6998 \exp (-231873/RT) \] \hspace{1cm} (17)

According to equation (15), the peak stress of hot deformation can also be expressed as a function of Z:

\[ \sigma_p = \frac{1}{0.02228} \ln \left\{ \left( \frac{Z}{1.15695 \times 10^{16}} \right)^{1.6998} + \left( \frac{Z}{1.15695 \times 10^{16}} \right)^{2.6998} + 1 \right\}^{1/2} \] \hspace{1cm} (18)

Table 2. Coefficients of polynomial functions for \( \alpha, n, Q \) and \( \ln A \) in equation (19).

| \( B_0 \) | \( C_0 \) | \( D_0 \) | \( E_0 \) | \( A_0 \) |
|---------|---------|---------|---------|---------|
| 0.03150 | 5.41790 | 292.5298 | 45.39391 |
| -0.18046 | -28.6709 | -1110.7843 | -160.14900 |
| 1.47356 | 365.61513 | 6293.2024 | 937.62040 |
| -7.64796 | -2372.05311 | -19836.57179 | -3052.63147 |
| 24.96637 | 8739.67177 | 32162.66612 | 5190.96077 |
| -50.51042 | -18979.81590 | -1837.29956 | -3578.17861 |
| 61.12467 | 24008.71125 | -16454.23524 | -1489.79981 |
| -40.44042 | -16335.95262 | 29184.17611 | 3729.34011 |
| 11.23734 | 4616.16984 | -11952.49172 | -1613.91571 |

Figure 9. Comparison between the predicted value and experimental value of true stress at strain rates of: (a) 0.01 s\(^{-1}\); (b) 0.1 s\(^{-1}\); (c) 1 s\(^{-1}\); (d) 10 s\(^{-1}\).
4.2. Constitutive equation considering compensation of strain

The constitutive equation established above only consider the effect of deformation temperature and strain rate on the mechanical behavior of materials during hot deformation, and the effect of strain was neglected. However, the study shows that the strain has great influence on the hot deformation activation energy (Q) and other material constants (i.e. α, n, A) [8, 21, 25]. Therefore, constitutive equations considering compensation of strain should be established in order to predict the flow stress more accurately.

Similar to the solution method mentioned above, the value of materials constants α, n, Q and lnA were calculated in the strain range from 0.025 to 0.2 with the interval of 0.025 and strain range from 0.25 to 0.8 with the interval of 0.05. By analyzing the correlation and generalization, an eighth order polynomial was used to represent the influence of strain on materials constants, as shown in equation (19) and figure 8. The coefficients of polynomial functions for those material constants are given in table 2.

\[\begin{align*}
\alpha(c) &= B_0 + B_1 \varepsilon + B_2 \varepsilon^2 + B_3 \varepsilon^3 + B_4 \varepsilon^4 + B_5 \varepsilon^5 + B_6 \varepsilon^6 + B_7 \varepsilon^7 + B_8 \varepsilon^8 \\
n(c) &= C_0 + C_1 \varepsilon + C_2 \varepsilon^2 + C_3 \varepsilon^3 + C_4 \varepsilon^4 + C_5 \varepsilon^5 + C_6 \varepsilon^6 + C_7 \varepsilon^7 + C_8 \varepsilon^8 \\
Q(c) &= D_0 + D_1 \varepsilon + D_2 \varepsilon^2 + D_3 \varepsilon^3 + D_4 \varepsilon^4 + D_5 \varepsilon^5 + D_6 \varepsilon^6 + D_7 \varepsilon^7 + D_8 \varepsilon^8 \\
\ln(A(c)) &= E_0 + E_1 \varepsilon + E_2 \varepsilon^2 + E_3 \varepsilon^3 + E_4 \varepsilon^4 + E_5 \varepsilon^5 + E_6 \varepsilon^6 + E_7 \varepsilon^7 + E_8 \varepsilon^8
\end{align*}\]

(19)

According to equations (14) and (15), the constitutive equation of 7A21 aluminum alloy considering strain compensation can be written as:

\[
\sigma(c) = \frac{1}{\alpha(c)} \ln \left( \left( \frac{Z(c)}{A(c)} \right)^{1/n(c)} + \left( \frac{Z(c)}{A(c)} \right)^{1/n(c)} + 1 \right)^{1/2}
\]

\[Z(c) = \varepsilon \cdot \exp \left( \frac{Q(c)}{RT} \right)\]

(20)

Where \(\alpha(c), n(c), Q(c),\) and \(A(c)\) can be calculated by equation (19).

A comparison between the predicted flow stress and the experimental flow stress was carried out as shown in figure 9. It could be observed that the predicted value of flow stress has good agreement with the experimental data, indicating a high prediction accuracy of the constitutive equation with compensation of strain.

4.3. Verification of the constitutive equation

The average absolute relative error (AARE) and correlation coefficient (R) are used to further verify the accuracy of the constitutive equations developed above, which can be expressed as [26]:

\[
\text{AARE} = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{E_i - P_i}{E_i} \right| \times 100
\]

(21)

\[
R = \frac{\sum_{i=1}^{N}(E_i - \bar{E})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{N}(E_i - \bar{E})^2 \sum_{i=1}^{N}(P_i - \bar{P})^2}}
\]

(22)

Where \(E_i\) and \(P_i\) are predicted values and calculated values respectively, \(\bar{E}\) and \(\bar{P}\) are the average values of \(E_i\) and \(P_i\) respectively, N is the total number of data in the investigation.

Figure 10(a) shows the comparisons between calculated peak stresses by equation (22) and experimental peak stresses, and the correlation coefficient R and average absolute relative error AARE are 0.9934 and 8.40% respectively. Figure 10(b) shows the comparisons between calculated stresses by equation (24) and experimental stress at different strain, and the correlation coefficient R and average absolute relative error AARE are 0.9963 and 3.75% respectively. It can be seen that the accuracy of the constitutive equation with strain compensation is higher than that of the constitutive equation without strain compensation. Therefore, the constitutive equation with strain compensation is more suitable for predicting the mechanical behavior of 7A21 aluminum alloy during hot deformation.

5. Processing maps of 7A21 aluminum alloy

5.1. Computation of power dissipation coefficient \(\eta\) and instability coefficient \(\xi(\varepsilon)\)

The establishment and analysis of hot processing maps based on dynamic materials model (DMM) is a reliable method to understand the hot deformation behavior of different metal materials and optimize the thermal deformation process [19, 27–30]. According to the DMM, the hot deformation process of materials can be regarded as an energy dissipation process. The total power (P) absorbed by the workpiece will be consumed in two ways: the first part (G co-content) is the energy dissipated by plastic deformation; the second part (J co-content)
is the energy related to microstructure evolution in the process of deformation, such as dynamic recovery, dynamic recrystallization, phase transition, superplastic rheology and internal defects. The instantaneous total power consumption $P$ can be expressed by flow stress $\sigma$ and strain rate $\dot{\varepsilon}$:

$$ P = \sigma \cdot \dot{\varepsilon} = G + J = \int_0^\varepsilon \sigma d\varepsilon + \int_0^\varepsilon \dot{\varepsilon} d\sigma $$

(23)

At a certain strain and deformation temperature, the flow stress can be expressed as:

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

(24)

Where $K$ is materials constant, $m$ is the strain rate sensitivity which can be expressed as:

$$ m = \frac{\partial (\ln \sigma)}{\partial (\ln \dot{\varepsilon})} $$

(25)

The relationship between $m$ and $J$ co-content can be defined as following equation:

$$ J = \int_0^\varepsilon \dot{\varepsilon} d\sigma = \int_0^\varepsilon K \dot{\varepsilon}^m d\dot{\varepsilon} = \frac{m}{m+1} \sigma \dot{\varepsilon} $$

(26)

For ideal linear consumption, $m = 1$ and $J$ reaches the maximum value. For nonlinear consumption, the power dissipation of the material can be expressed by a non-dimensional parameter named the power dissipation coefficient ($\eta$)[32]:

$$ \eta = \frac{J}{J_{\text{max}}} = \frac{2m}{m+1} $$

(27)

Generally, a larger value of $\eta$ indicates that the proportion of the energy consumed in microstructure evolution is higher, which shows a better workability[19]. However, structure defects such as local rheology, local shear bands and wedge cracking may also occur at the same time. Based on the extremum principle of the irreversible thermodynamics applied to the large plastic flow body, Ziegler[8, 9] proposed the condition of thermal processing instability:

$$ \frac{\partial D}{\partial \dot{\varepsilon}} < \frac{D}{\dot{\varepsilon}} $$

(28)

Where $D$ is the dynamic metallurgical deformation function, which is equivalent to the $J$ co-content.

Substituting $J$ into equation (28), the criterion for the occurrence of flow instability of the material can be expressed as:

$$ \xi (\dot{\varepsilon}) = \frac{\partial \ln \left( \frac{m}{m+1} \right)}{\partial \ln \dot{\varepsilon}} + m \leq 0 $$

(29)

5.2. Safety strain rates map for thermal processing
The critical strain value of instibility zone at different strain and deformation temperature can be calculated by equation (29). In order to enrich the data points, the critical value of the safety strain rates under different deformation conditions is directly obtained through the unstable region of the processing maps with a
temperature interval of 2 °C. A three-dimensional diagram is conducted to represent the variation of the safety strain rates with the temperature and strain. The safety zone for hot working is shown in figure 11(a). It can be seen that only a single upper limit and the lower limit are presented in the safety zone. The contour map of the upper and lower limit of the safety strain rates are represented as figures 11(b) and (c) respectively. The safety strain rate map can be constituted by combining figures 11(b) and (c), and then the safety zone for hot working at any deformation condition can be obtained.

Figure 11. The establishment of safety strain rates map (a) 3D safety zone; (b) upper map; (c) lower map.

Figure 12. Critical strain rates obtained from the safety strain rates map at strain 0.4.
In order to ensure the reliability of data acquisition, corresponding acquisition principle is determined. The strain rate value of point A between contour line U₁ and U₂ and the strain value of point B just on contour line U₂ in upper limit map are both equal to the strain rate value corresponding to contour U₁. The strain rate value of point C between the contour line L₁ and L₂ and the strain value of point D just on contour line L₂ in upper limit map are both equal to the strain rate value corresponding to contour L₂. The obtained safety strain rate interval of A, B, C, D are shown in figure 11(c).

Figure 12 shows the value of critical strain rates obtained at strain 0.4 based on acquisition principle mentioned above, and the shaded region represents instability zone. It can be seen that the obtained value of critical strain rates are all in safety zone. The maximum error of critical strain rates obtained from the safety strain rates map and processing maps is 0.345 which is the gradient interval value of the contour line, indicating that the safety strain rates map and the corresponding acquisition principle is correct and reliable.

Compared with the hot processing maps, one of the advantage of the safety strain rates map is to improve the efficiency of determining the safety zone of the hot working at different strain. For example, in order to get the hot processing safety zone at deformation temperature 450°C and strains ranging from 0.1 to 0.8 with a intercept of 0.1, eight processing maps need to be analyzed. However, only one map is needed to determine the safety zone of hot processing under all the strains by using safety strain rates map, as shown in figure 13. A comparisons are made between strain rates obtained from the safety strain rates map and processing maps, as shown in figure 14. It can be seen that the obtained safety zone is equal to or slightly smaller than the actual safety zone. This is mainly determined by the gradient of the contour line of the safety strain rates map, and the deviation increases with the increase of the gradient interval.

Another advantage of the new map is that it is easy to obtain the safety zone of hot working under any strain rate range. Figures 15(b) and (c) are the hot working safety zones of the experimental materials under the strain rate ranging from 0.01 to 10 s⁻¹ and 0.05 to 1 s⁻¹ respectively, and the boundaries of which are the
corresponding contour lines in the safety strain rates map, as shown in figure 15(a). It can be seen that with the narrowing of the safety strain interval, the area of the safety zone is gradually increasing.

What’s more, two strain sensitive regions (region 1 and region 3) and two temperature sensitive regions (region 2 and region 4) can be obtained from figure 15(a). The deformation condition ranges of these regions are as follows: Region 1 and region 2 are strain rate range of $1 \sim 10 \text{ s}^{-1}$ with strain range of $0.13 \sim 0.35$, temperature range of $350 \sim 425 \degree C$ and strain range of $0.3 \sim 0.8$, temperature range of $425 \sim 465 \degree C$ respectively. Region 3 and region 4 are strain range of $0.27 \sim 0.35$, temperature range of $350 \sim 367 \degree C$ and strain range of $0.3 \sim 0.8$, temperature range of $367 \sim 387 \degree C$ respectively with strain rate interval of $0.01 \sim 0.05 \text{ s}^{-1}$. The contour line in region 1 and region 3 is dense along the direction of strain change, indicating that the occurrence of flow instability in which are sensitive to strain. While in region 2 and region 4, the deformation temperature shows decisive influence. The deformation conditions in regions listed above should be avoided in optimizing the hot deformation process especially in industrial production of 7A21 aluminum alloy.

By adding the strain rate dot corresponding to the peak value of the power dissipation coefficient under different deformation conditions to safety strain rates map, a new type of processing map can also be obtained to optimize the hot deformation process, as shown in figure 15(a). The color of the dot represents the strain rate range of the peak region of the power dissipation coefficient, and the number on the dot is the peak power dissipation coefficient. It can be clearly seen from figure 15(a) that the power dissipation stay high at temperature $500 \degree C$ and strain rate ranging from $0.01 \sim 0.1 \text{ s}^{-1}$ during hot deformation, indicating it is the optimum deformation parameters. The results agree well with the analysis results of the hot processing maps.

In summary, the safety strain rates map shows good convenience, accuracy and reliability and can be used to guide industrial production.

Figure 15. The obtained safety zones of 7A21 aluminum alloy using safety strain rates map (a) under the strain rate ranging from (b)$0.01 \sim 10 \text{ s}^{-1}$; (c)$0.05 \sim 1 \text{ s}^{-1}$.
6. Summary

Based on friction and temperature modified stress-strain curves, both of the Arrhenius-type constitutive equation with and without strain compensation were obtained to describe the hot flow behaviors. The constitutive equation with strain compensation shows a higher accuracy with the correlation coefficient R and average absolute relative error AARE values of 0.9963 and 3.75% respectively.

Based on instability criterion, a novel type safety strain rates map was developed to analyze the hot deformation behavior of 7A21 aluminum alloy. The safety zone of hot processing at different deformation conditions and the optimum processing windows were obtained. The map shows good convenience, accuracy and reliability and it is of certain significance to guide the industrial production.

Acknowledgments

The work was financially supported by Key Research and Development Program of Yantai, China (Grant No.2017ZH081), A Project of Shandong Province Higher Educational Science and Technology Program, China (Grant No. 2019KJA019).

Conflicts of Interest

The authors declare no conflicts of interest.

ORCID iDs

Haiming Zong © https://orcid.org/0000-0002-4913-0661

References

[1] Shin J, Kim T, Kim D E, Kim D and Kim K 2017 Castability and mechanical properties of new 7xxx aluminum alloys for automotive chassis/body applications J. Alloys Compd. 698 577–90
[2] Hirsch J 2014 Recent development in aluminum for automotive applications Trans. Nonferrous Met. Soc. China 24 1995–2002
[3] Rowe J 2012 Advanced Materials in Automotive Engineering 1st ed. (Cambridge, England: Woodhead Publishing) 85–108
[4] Zheng K, Politis D J, Wang L and Lin J 2018 A review on forming techniques for manufacturing lightweight complex—shaped aluminum panel components International Journal of Lightweight Materials and Manufacture 1 1–26
[5] Deng Y, Yin Z and Huang J 2011 Hot deformation behavior and microstructural evolution of homogenized 7050 aluminum alloy during compression at elevated temperature Mater. Sci. Eng. A 528 1780–86
[6] Oesterreicher J A, Kirov G, Gersd S S A, Mukeli E, Grabner F and Kumar M 2018 Stabilization of 7xxx aluminum alloys J. Alloys Compd. 740 167–73
[7] Taleghani M A J, Navas E M R, Salehi M and Torralba J M 2012 Hot deformation behaviour and flow stress prediction of 7075 aluminum alloy powder compacts during compression at elevated temperatures Mater. Sci. Eng. A 534 624–31
[8] He J, Zhang D, Zhang W, Qiu C and Zhang W 2017 Constitutive equation and hot compression deformation behavior of homogenized Al–7.5Zn–1.5Mg–0.2Cu–0.2Zr Alloy Materials 10 1193
[9] Lin Y, Dong W, Zhou M, Wen D and Chen D 2018 A unified constitutive model based on dislocation density for an Al–Zn–Mg–Cu alloy at time-variant hot deformation conditions Mater. Sci. Eng. A 718 165–72
[10] Park S Y and Kim W J 2016 Difference in the hot compressive behavior and processing maps between the as-cast and homogenized Al–Zn–Mg–Cu (7075) Alloys J. Mater. Sci. Technol. 32 660–70
[11] Sun Z, Wu H, Cao J and Yin Z 2018 Modeling of continuous dynamic recrystallization of Al–Zn–Cu–Mg alloy during hot deformation based on the internal-state-variable (ISV) method Int. J. Plast. 106 73–87
[12] MirzadchEH 2013 Constitutive description of 7075 aluminum alloy during hot deformation by apparent and physically-based approaches J. Mater. Eng. Perform. 24 1095–9
[13] Li B, Pan Q and Yin Z 2014 Microstructural evolution and constitutive relationship of Al–Zn–Mg alloy containing small amount of Sc and Zr during hot deformation based on Arrhenius-type and artificial neural network models J. Alloys Compd. 584 406–16
[14] Yan J, Pan Q, Li B, Huang Z, Liu Z and Yin Z 2015 Research on the hot deformation behavior of Al–6.2Zn–0.70Mg–0.3Mn–0.17Zr alloy using processing map J. Alloys Compd. 632 549–57
[15] Zhang C, Zhang L, Shen W, Liu C, Xia Y and Li R 2016 Study on constitutive modeling and processing maps for hot deformation of medium carbon Cr–Ni–Mo alloyed steel Mater. Des. 90 804–14
[16] Ebrahimi R and Najafzadeh A 2004 A new method for evaluation of friction in bulk metal forming J. Mater. Process. Technol. 152 136–43
[17] Li L, Zhou J and Duszczyk J 2006 Determination of a constitutive relationship for AZ31B magnesium alloy and validation through comparison between simulated and real extrusion J. Mater. Process. Technol. 172 372–80
[18] Meng Q, Bai C and Xu D 2018 Flow behavior and processing map for hot deformation of ATI425 titanium alloy J. Mater. Sci. Technol. 34 679–88
[19] Dong Y, Zhang C, Zhao G, Guan Y, Gao A and Sun W 2016 Constitutive equation and processing maps of an Al–Mg–Si aluminum alloy: determination and application in simulating extrusion process of complex profiles Mater. Des. 92 983–97
[20] Guo Y, Deng L, Wang X, Jin J and Zhou W 2013 Hot deformation behavior and processing maps of 7050 aluminum alloy Adv. Mater. Res. 815 37–42
[21] Wu H, Wen S, Huang H, Wu X, Gao K, Wang W and Nie Z 2016 Hot deformation behavior and constitutive equation of a new type Al–Zn–Mg–Er–Zr alloy during isothermal compression Mater. Sci. Eng. A 651 415–24
[22] Yang Q, Deng Z, Zhang Z, Liu Q, Jia Z and Huang G 2016 Effects of strain rate on flow stress behavior and dynamic recrystallization mechanism of Al–Zn–Mg–Cu aluminum alloy during hot deformation Mater. Sci. Eng. A 662 204–13
[23] Mirzadeh H 2015 Simple physically-based constitutive equations for hot deformation of 2024 and 7075 aluminum alloys. Transactions of Nonferrous Metals Society of China 25 1614–8
[24] Mirzadeh H 2015 Quantification of the strengthening effect of reinforcements during hot deformation of aluminum-based composites Mater. Des. 65 80–2
[25] Rokni M R, Zarei-Hanzaki A, Widener C A and Changizian P 2014 The strain-compensated constitutive equation for high temperature flow behavior of an Al–Zn–Mg–Cu Alloy J. Mater. Eng. Perform. 23 4002–9
[26] Huang C, Deng J, Wang S and Liu L 2017 An investigation on the softening mechanism of 5754 aluminum alloy during multistage hot deformation Metals 7 107
[27] Lin Y, Li L, Xia Y and Jiang Y 2013 Hot deformation and processing map of a typical Al–Zn–Mg–Cu alloy J. Alloys Compd. 550 438–45
[28] Samal S, Rahul M R, Kottada R S and Phanikumar G 2016 Hot deformation behaviour and processing map of Co–Cu–Fe–Ni–Ti eutectic high entropy alloy Mater. Sci. Eng. A 664 227–35
[29] Huang Z, Lu Z, Jiang S and Zhang K 2016 The hot deformation behavior and processing map of powder metallurgy NiAl-based alloy J. Mater. Res. 31 2964–76
[30] Zhou Z, Fan Q, Xia Z, Hao A, Yang W, Ji W and Cao H 2017 Constitutive Relationship and Hot Processing Maps of Mg–Gd–Y–Nb–Zr Alloy J. Mater. Sci. Technol. 33 637–44
[31] Fan G, Wang G, Choo H, Liaw P, Park Y S, Han B and Lavernia E 2005 Deformation behavior of an ultrafine-grained Al–Mg alloy at different strain rates Scr. Mater. 52 929–33
[32] Guo B, Ji H, Liu X, Lu G, Dong R, Jin M and Zhang Q 2012 Research on flow stress during hot deformation process and processing map for 316LN austenitic stainless steel J. Mater. Eng. Perform. 21 1455–61