Effect of Deformation Heating on the Flow Behavior and Processing Maps of Al–Zn–Mg–Cu Alloy

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The effects of deformation heating on hot deformation and processing maps of AA7050 aluminum alloy were investigated by hot compression tests at temperatures ranging from 300°C to 450°C with strain rates ranging from 0.001 s⁻¹ to 10 s⁻¹. The results show that deformation heating results in a decrease in flow stress and an increase in deformation resistance. The processing maps and microstructures exhibit that deformation heating may be responsible for flow instability. Compared to the processing maps of AA7050 aluminum alloy with deformation heating, the optimum hot-working area without deformation heating is smaller, which is determined to be at temperatures of 420–450°C and strain rates of 0.001–0.03 s⁻¹. The main deformation mechanisms are dynamic recrystallization (DRX) and dynamic recovery (DRV).

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1. Introduction

AA7050 aluminum alloy is a highly alloyed alloy with complex chemical composition, resulting in high strength and high fracture toughness.¹ Hot deformation is an essential step to meet the wrought need of the advanced aerospace equipment. Many studies showed that hot deformation of Al–Zn–Mg–Cu alloy was carried out extensively in the temperatures ranging from 300 to 450°C, strain rate between 0.01 and 10 s⁻¹.²⁻⁴ The processing maps showed that flow stability was related to the adiabatic shear bands or crack.⁵⁻⁷ Flow stress is not the actual value due to the increase of deformed temperature at high strain rates (≥10 s⁻¹). Recently, new revised methods considering deformation heating have been developed, which provides different flow stress models.⁸ However, the reliability and security of the revised methods have not yet been assessed by experimental analysis.

It is well known that hot deformation behavior and deformation mechanism of Al–Zn–Mg–Cu alloy were directly affected by deformation parameters. In order to avoid the impact of deformation heating, hot deformation of Al–Zn–Mg–Cu alloy was carried out in the strain rate range of 0.001–1 s⁻¹.⁹⁻¹¹ For AA7085 aluminum alloy, the flow stress exhibits a continuous strain hardening behavior as the result of continuous dynamic recrystallization (DRX) during isothermal compression at 450°C with strain rate of 10⁻³ s⁻¹, whereas the steady flow stress is obtained owing to discontinuous dynamic recrystallization (DDRX) at a strain rate of 0.1 s⁻¹.¹² Zhao et al.¹³ found that different dynamic recrystallization mechanisms resulted in two different constitutive equations within strain rates from 10⁻⁵ s⁻¹ to 10⁻³ s⁻¹ and from 10⁻² s⁻¹ to 10⁻¹ s⁻¹. However, comparison study of Al–Zn–Mg–Cu alloys between low strain rate and high strain rate is not widely reported. Therefore, the investigation of deformation behavior and processing map evolution of Al–Zn–Mg–Cu alloy at the different strain rates range is necessary, which is contributed to understanding the deformation process for controlling the optimum hot deformation parameter.

In this study, the effects of deformation heating on flow stress behavior and processing maps of AA7050 aluminum alloy during hot compression are investigated with the help of microstructure characterization combined with flow curves and constitutive analysis. The aim is to obtain the optimum hot-working parameters, which are relevant to the industrial hot rolling processes.

2. Experimental

The alloy used in this study is a homogenized commercial AA7050 aluminum alloy, the chemical composition and homogenization processing could be referred to literature 14. Cylindrical compressive samples were prepared with 10 mm in diameter and 8 mm in height. The slices of tantalum were employed between the sample’s ends and the anvils to reduce friction during hot compression. The compression tests were carried out on a Gleeble 3500 mechanical testing machine at temperatures from 300°C to 450°C and strain rates varying from 0.001 s⁻¹ to 10 s⁻¹ with a total strain of 0.9. The samples were heated to the deformation temperature at a heating rate of 300°C/min and held for 3 min to eliminate thermal gradients prior to deformation. As soon as the hot compression ended, the samples were quenched in cold water to preserve the deformation microstructure.

The deformed samples were sectioned parallel to the compression axis. Microstructure characterization was performed on the central deformation zone of the samples. The deformation samples were mechanically polished and then subjected to a electro-polishing in a mixed solution of 10% HClO₄ and 90% C₂H₅OH at −20°C with the current densities of 0.2–1.6 × 10⁻³ A/mm², after which they are etched in solution of 1.5% HBF for 6 min. Grain characterization was performed by metallurgical microscopy analysis. TEM investigations were performed on the twin-jet polished samples to grain structure, dislocation configuration and the

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particle morphology in a FEI G2 60-300 microscope operated at 200 kV. The samples were cut from the central section parallel to the compression axis at a true strain of 0.9, ground to 100 µm thickness, and then were twin-jet polished in a 30% HNO₃ and 70% CH₃O solution at −30°C and 25 V.

3. Results and Discussion

3.1 Flow stress behavior

The true stress-strain curves of AA7050 aluminum alloy deformed under different conditions are shown in Fig. 1. The flow stress increases with increasing strain rate and decreases with increasing temperature. At low strain rate and low temperature (Fig. 1(a)–(c)), the flow stress increases firstly and then decreases, indicating a dynamic flow softening phenomenon due to dynamic recovery, dynamic precipitation and coarsening. This is because that extensive recovery leads to dislocation density decrement after the peak strain. The newly formed fine particles coarsen and become less and less effective in pinning dislocations with strain increasing. As a consequence, continuous decrease in the flow stress is observed at 300–350°C. As the deformation temperature increases, dynamic softening can offset the work hardening, resulting in a plateau flow curve. At a strain rate of 1 s⁻¹ (Fig. 1(d)), the flow stress increases monotonically with increasing strain, indicating that dynamic softening can’t counteract work hardening during hot compression. Similar conclusions have been reported in ultra-high strength Al–Zn–Mg–Cu–Zr alloy. As the strain rate increases (Fig. 1(e)), the flow curves display a rapid decrease after the peak strain, which is attributed to DRV, DRX as well as deformation heating. The deformation temperature analysis confirms the occurrence of deformation heating at a strain rate of 10 s⁻¹, as shown in Fig. 2. The increment of temperature nearly 18–35°C compared to the pre-set temperature at a strain rate of 10 s⁻¹, while they are −2–4°C at strain rates of 0.001–1 s⁻¹. The temperature rise is negligible at low strain rates during hot deformation, while it leads to the occurrence of thermal softening at strain rate above 1 s⁻¹. Although several methods were proposed to consider the compensation of the deformation heating, yet they still have some deficiencies. Under this case, the samples deformed within the strain rates of 0.001–1 s⁻¹ indicate isothermal compression, while the samples compressed at a strain rate of 10 s⁻¹ exhibit obvious deformation heating. The further illustration for constitutive equation and processing maps would be identified by the linear regression method needed at least 3–4 strain rates. In order to investigate the effects of deformation heating on constitutive equation and processing maps, the ranges of strain rate are determined to be 0.001–1 s⁻¹ and 0.001–10 s⁻¹ with/without deformation heating, respectively. Therefore, study on the hot deformation behavior of AA7050

![Fig. 1](image_url) True stress-true strain curves of AA7050 aluminum alloy during hot deformation: (a) 0.001 s⁻¹, (b) 0.01 s⁻¹, (c) 0.1 s⁻¹, (d) 1 s⁻¹ and (e) 10 s⁻¹.
aluminum alloy with deformation heating and without deformation heating is necessary.

3.2 Analysis of constitutive equation

The Arrhenius-type equation has been successfully applied to predict the flow stress of materials, which can be described by the following law:17,18)

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

(1)

where

\[ \dot{\varepsilon} = \begin{cases} 
A_1\alpha^n \exp\left(-\frac{Q}{RT}\right) & \alpha \sigma < 0.8 \\
A_2\exp(\beta\sigma) \exp\left(-\frac{Q}{RT}\right) & \alpha \sigma > 1.2 \\
A[\sinh(\alpha\dot{\varepsilon})]^n \exp\left(-\frac{Q}{RT}\right) & \text{for all } \sigma 
\end{cases} \]

(2)

(3)

(4)

where \( A, \alpha, n, \beta \) are materials constants, \( R \) is the universal gas constant, \( Q \) is the activation energy of hot deformation (J/mol), \( Z \) is the Zener-Hollomon parameter, \( T \) is the absolute temperature, \( \sigma \) is the stress, \( \dot{\varepsilon} \) is the strain rate (s\(^{-1}\)). The eqs. (2) and (3) are applied to low stress level and high stress level, respectively. The eq. (4) is suitable for a wide range of temperatures and strain rates.19) The evaluation procedure of material constants is shown in Fig. 3 at a true strain of 0.5 as an example. The values of \( \beta \) and \( n' \) can be calculated from the mean slopes of the lines in \( \sigma-\ln \dot{\varepsilon} \) and \( \ln \sigma-\ln \dot{\varepsilon} \) plots, respectively (Fig. 3(a) and (b)). The value of \( \alpha \) can be defined by \( \alpha = \beta/n' \). Taking the natural logarithm at both sides of the eq. (1):

\[ \ln \dot{\varepsilon} = \ln A - \frac{Q}{RT} + n \ln[\sinh(\alpha\dot{\varepsilon})] \]

(5)

The \( Q \) can be expressed by the following relationship:

\[ Q = R \left| \frac{d \ln \dot{\varepsilon}}{d \ln[\sinh(\alpha\dot{\varepsilon})]} \right|_T \left| \frac{d[\ln[\sinh(\alpha\dot{\varepsilon})]]}{d(1/T)} \right|_{\dot{\varepsilon}} \]

(6)

The relationships of \( \ln \dot{\varepsilon}-\ln[\sinh(\alpha\dot{\varepsilon})] \) and \( \ln[\sinh(\alpha\dot{\varepsilon})] - 1/T \) are shown in Fig. 3(c) and (d), respectively. According to the eqs. (4)–(6), the values of \( \alpha, n, \ln A \) and \( Q \) are obtained with/without deformation heating, respectively. The values of \( n \) and \( Q \) can reflect the workability of materials. The lower the values of \( n \) and \( Q \), the better hot workability of materials. The material constants and \( Q \) exhibit an obvious difference in the different strain rate ranges, indicating different constitutive equations. In the case of the compensation of strain, the variations of the material constants and \( Q \) can be well described by the 5th order polynomial fitting for considering/without considering deformation heating, as shown in eqs. (7) and (8), respectively.

\[
\begin{align*}
\alpha_1 &= -0.0153e^5 + 0.0464e^4 - 0.0559e^3 \\
&+ 0.0307e^2 - 0.0042e + 0.0128 \\
n_1 &= -9.1577 + 34.8088e^4 - 49.9726e^3 \\
&+ 34.6954e^2 - 11.8632e + 7.0517 \\
Q_1 &= -453.8462e^5 + 1667.4825e^4 - 2364.5338e^3 \\
&+ 1625.6084 - 567.5976e + 270.0717 \\
\ln A_1 &= -61.1343e^5 + 251.7220e^4 - 385.8515e^3 \\
&+ 281.4042e^2 - 103.6325e + 47.4422 \\
\alpha_2 &= 0.0344e^5 - 0.0724e^4 + 0.0536e^3 - 0.0203e^2 \\
&+ 0.0066e + 0.0131 \\
n_2 &= 20.2266e^5 - 45.1881e^4 + 31.1938e^3 \\
&- 2.8005e^2 - 4.6767e + 6.0347 \\
Q_2 &= 598.0769e^5 - 1317.7448e^4 + 847.4097e^3 \\
&+ 36.7847e^2 - 250.5065e + 247.6667 \\
\ln A_2 &= 243.3978e^5 - 584.9683e^4 + 474.1825e^3 \\
&- 119.8055e^2 - 27.1070e + 41.5911
\end{align*}
\]

(7)

(8)

Based on the relationships between the strain and material parameters within the different strain rate ranges, it can be seen that the \( \alpha \) value increases with increasing strain and then
reaches a stable state, whereas the values of $n$, $Q$ and $\ln A$ gradually decrease, indicating that the deformation resistance gradually reduces as the deformation proceeds (Fig. 4). Compared to the samples with deformation heating, the values of $\dot{\varepsilon}$ in the samples without deformation heating are higher, while the values of $n$, $\ln A$ and $Q$ are lower. The activation energy is usually used as an indicator of the degree of difficulty of plastic deformation during the hot deformation process. The values of $Q$ decrease from 227.17 kJ/mol to 178.12 kJ/mol with deformation heating, whereas they decrease from 223.67 kJ/mol to 158.12 kJ/mol without deformation heating (Fig. 4(b)). This suggests that the samples without deformation heating have better the hot workability than that of the samples with deformation heating, which is agree with the report in AA7085 aluminum alloy by Yang et al. This is because at high strain rate, the heat generated by deformation heating can not release in time and promotes the occurrence of the flow instability and flow localization, which is not beneficial for the workability. With decreasing strain rate, the stable flow curves show that the samples undergo uniform and isothermal deformation. The occurrence of dynamic recrystallization is beneficial for making the microstructure reconstituted, indicating a low degree of deformation difficulty.

The material constants as functions of strain are taken into the flow stress equation. According to the eqs. (1) and (4), the flow stress based on the Zener-Holloman parameter can be predicted using the following formula:

$$
\sigma = \alpha \dot{\varepsilon}^n \exp\left(\frac{Q}{RT}\right)
$$

Fig. 3 Relationships between (a) $\ln \dot{\varepsilon}$ and $\sigma$, (b) $\ln \dot{\varepsilon}$ and $\ln \sigma$, (c) $\ln \dot{\varepsilon}$ and $\ln [\sinh(\dot{\varepsilon})]$, (d) $\ln [\sinh(\dot{\varepsilon})]$ and $1/T$ at a strain of $\varepsilon = 0.5$.

Fig. 4 Effects of deformation heating on (a) $\alpha$, (b) $Q$, (c) $n$ and (d) $\ln A$. 
\[
\sigma = \frac{1}{\alpha} \ln \left\{ \left( \frac{Z}{A} \right)^{1/\alpha} + \left[ \left( \frac{Z}{A} \right)^{1/\alpha} + 1 \right]^{1/2} \right\}
\]

(9)

### 3.3 Processing maps and microstructure

The processing maps based on the dynamic materials model (DMM) considered the work-piece as a dissipater of power are a combination of the power dissipation map and the instability map. The total dissipated power \( P \) can be expressed as:

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

(10)

where \( G \) represents the power dissipated by plastic work, \( J \) represents the power dissipated by changing the internal microstructure. The partition of \( P \) between \( G \) and \( J \) is related to the strain rate sensitivity parameter \( m \), which is calculated as follows:

\[
\left( \frac{\partial J}{\partial G} \right)_{\varepsilon, T} = \frac{\partial \sigma \dot{\varepsilon}}{\partial G} = \frac{\dot{\varepsilon}}{\varepsilon} = \frac{\partial (\ln \sigma)}{\partial (\ln \dot{\varepsilon})} = m
\]

(11)

For ideally plastic flow, \( m = 1 \). The maximum value of \( J \) is obtained, \( J_{\text{max}} = p/2 \). The non-dimensional parameter \( \eta \) (the power dissipation) could be expressed as:

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

(12)

The instability map based on the extremum principle of irreversible thermodynamic can be expressed using the following equation:

\[
\xi = \frac{\partial \ln [m/(m + 1)]}{\partial \ln \dot{\varepsilon}} + m < 0
\]

(13)

The variations of the \( \eta \) and \( \xi \) are described by a contour map, respectively, as shown in Fig. 5. The colorful grids indicate the percentage of power dissipation efficiency in the power dissipation map (Fig. 5(a) and (c)). In general, the material has better workability in case of the higher efficiency of power dissipation. The instability maps indicate the variation of the instability parameter, which is represented by the green zone where \( \xi < 0 \) (Fig. 5(b) and (d)). Figure 5(a) and (c) show that the values of \( \eta \) have an obvious difference under different deformation conditions. In the case of deformation heating, the \( \eta \) of the 10 s\(^{-1}\) samples is lower than that of the other ones, as shown in Fig. 5(a). The position of the domain with the peak power dissipation changes from 450°C/0.001 s\(^{-1}\) to 450°C/0.01 s\(^{-1}\) with increasing strain. The values of \( \eta \) change from 0.48 to 0.43 with increasing strain from 0.1 to 0.9. Furthermore, the instability maps exhibit two instability regions at a strain of 0.1, which occurs in the temperature range of 300–360°C and 380–450°C, strain rates range of 0.013–10 s\(^{-1}\) and 0.32–10 s\(^{-1}\), respectively. With increasing strain, the instability zone expands gradually from low temperature/medium strain rate to low temperature/high strain rate and reaches a relatively steady state at a strain of 0.6 (Fig. 5(b)), which occurs at strain rates of 0.1–10 s\(^{-1}\) and the entire deformation temperatures. Combining with the efficiency value of DRX, the optimum hot deformation conditions are the areas of 400–450°C and 0.001–0.013 s\(^{-1}\).

From the processing efficiency maps without deformation heating, it can be found that the peak area of \( \eta \) could spread from 0.001 to 1 s\(^{-1}\) with increasing strain, as shown in Fig. 5(c). The peak area with the maximum \( \eta \) occurs at 450°C and 0.01 s\(^{-1}\). The values of \( \eta \) are about 0.45, 0.44, 0.43 and 0.40 with strains of 0.1, 0.3, 0.6 and 0.9.

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Fig. 5 Effect of deformation heating on the 3D diagram of power dissipation efficiency and instability diagram of AA7050 aluminum alloy: (a), (c) with deformation heating, (b), (d) without deformation heating.
respectively. From a three-dimensional distribution diagram of the instability parameter, it can be found that flow instability occurs at temperatures of 300–450°C and the strain rate range of 0.03–1 s⁻¹ at low strains (≤0.3). As the deformation proceeds, the instability zones gradually reduce and disappear at a strain of 0.9 (Fig. 5(d)). Combing with the power dissipation map evolution, the suitable deformation conditions (η ≥ 0.35) are the areas of 420–450°C and 0.001–0.03 s⁻¹. Compared to the processing maps with deformation heating, the suitable deformation area of the samples without deformation heating is smaller. The discrepancies of the hot-working parameters at two different ranges of strain rate could be attributed to the following factors: (1) The errors in the experimental measurement of flow stress at a strain rate of 10 s⁻¹. (2) The errors from the polynomial fitting of Cubic splines and m as functions of strain rate. (3) The cumulative errors from the successive steps to determine the η and ξ.

The hot deformation microstructures under different deformation conditions are shown in Fig. 6 and Fig. 7. Loading direction of the stress is indicated with green arrows in Fig. 6. It can be seen from Fig. 5(b) and Fig. 6(a) that adiabatic shear bands occur in the unsafe domain, which is associated with deformation heating. This suggests that a high strain rate will not allow the heat generated by the plastic deformation sufficient time to release, therefore producing a highly localized flow along the maximum shear stress plane. The corresponding TEM micrographs exhibit the majority of second phase particles within sub-grains. Additionally, dense dislocation walls (DDWs) and dislocations are anchored at large MgZn₂ particles with the other end attached to a nearby grain boundary (Fig. 7(a)). Upon medium temperature as well as strain rate, the samples exhibit a mostly recovered microstructure with an elongated grain structure and small, slightly dislocation cell structure (Fig. 6(b) and Fig. 7(b)). With decreasing strain rate and temperature, the alloy was deformed in the safe region. The microstructure is dominated by elongated grains (Fig. 6(c)). The tangled dislocations accompanied by second phase particles suggest that DRV is still at an early stage (Fig. 7(c)), where the η is only 0.21. At 450°C and 0.01 s⁻¹ with a peak efficiency of 43%, recovery is extensively developed by the movement/annihilation of dislocations. Partially low-angle grain boundaries evolve to form high-angle grain boundaries through the transformation from low angle boundaries to high angle boundaries (Fig. 6(d) and Fig. 7(d)). The deformation mechanisms are DRV and DRX.

4. Conclusions

(1) The presence of deformation heating results in a continuous flow softening behavior and flow instability of AA7050 aluminum alloy at a strain rate of 10 s⁻¹. The discrepancies between the actual temperature and the set temperature reach 18–35°C.

(2) Material constants and constitutive equations are significantly affected by the deformation heating, which leads to an increase in the deformation resistance as the result of the high activation energy during hot deformation.

(3) The processing maps of AA7050 aluminum alloy has been established without deformation heating. The optimized hot working parameter is determined at 420–450°C and 0.001–0.03 s⁻¹, with a peak efficiency of power dissipation 0.43.

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Fig. 7 Representative TEM micrographs of the samples under different deformation conditions: (a) 350°C, 10 s⁻¹, (b) 400°C, 1 s⁻¹, (c) 300°C, 0.1 s⁻¹ and (d) 450°C, 0.01 s⁻¹.