Flow Stress Behavior and Microstructural Evolution of DC Cast 7065 Aluminum Alloy During Hot Compression Deformation

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Abstract. The deformation behavior and microstructure evolution of DC cast 7065 aluminum alloy was investigated in the temperature range of 340-460 °C and strain rate range of 0.1-8 s⁻¹. The flow stresses of the 7065 alloy are forceful function of deformation strain rate and temperature. The peak stress raises with reducing compression temperature, and at a designated deformation temperature, the peak stress increases with the increasing of strain rate. The hot deformation equation of the alloy is generated, and the deformation activation energy of the alloy is 117.869 kJ/mol. When the samples were deformed above 380°C, the α-aluminum dendrite in the initial microstructure was replaced by recrystallized grains, dynamic recrystallisation occurred during compression.

1. Introduction

The 7000 series alloys, typically, 7075, 7050, 7055 and 7085 alloys, are based on the Al-Zn-Mg-Cu system, have a combination of excellent strength and fracture toughness, as well as stress corrosion resistance by proper heat-treatment. These alloys are very useful in the aircraft and aerospace industry applications [1-3]. Recently, a novel 7065 alloy was developed based on these alloys, which exhibits higher comprehensive properties such as strength, toughness, corrosion resistance, quench sensitive, etc. Hot workability is the degree of deformation that a material can endure without breaking and get proper deformation microstructures at a supposed strain rate and temperature. Ameliorating hot workability means improving the processing capacity and raising properties of the materials, these possibly can be
obtained by optimized deformation parameters. However, the investigation on the hot deformation behavior of the 7065 alloy has seldom been reported. In our previous work, billets of 7065 alloy 150 mm in diameter were achieved via direct chill (DC) casting. The purpose of this present work is to investigate the flow stress behavior and microstructure evolution of a DC cast 7065 alloy.

2. Experimental procedure
The 7065 aluminum alloy (chemical composition see Table 1) was prepared by 99.94wt% pure Al, 99.99wt% pure Zn, 99.92wt% pure Mg, Al-50wt%Cu, Al-5wt%Zr and Al-5wt%Ti master alloys. The alloy melt was prepared in an induction furnace and DC cast to manufacture billets with diameter of 150 mm, and the pouring temperature was 780°C, while casting velocity was 3 mm/s. After degassing, Al-5wt%Be master alloy was added to the alloy melt with an adding temperature of about 800°C, and kept for about 20 min before DC casting. The billets were homogenized at 470°C for 12 h and follow by air cooling.

| Zn | Cu | Mg | Ti | Zr | Others | Al |
|----|----|----|----|----|--------|----|
| 7.6| 2.1| 1.7| 0.02| 0.1| 0.05   | 0.15| Balance |

Table 1. Chemical composition of the 7065 alloys (wt.%)

Isothermal and constant-strain rate compression tests were carried out on a Gleeble 1500 testing system over a range of temperatures (300, 340, 380, 420 and 460°C) and strain rates (0.1, 0.3, 1, 4 and 8 s⁻¹), as to investigate the flow stress behavior and microstructural evolution of the 7065 alloy. Specimens for compression test were 10 mm in diameter and 15 mm in height. Compression test specimens were cut from the middle part of the billets parallel to the casting direction. The specimens were homogenized for 1 h at the testing temperature in a salt bath before compression. The compression specimens were daubed with lubricant and deformed to 60% the original height, and quenched in water quickly after compression. The compressed specimens were cut along the compression direction for microstructure inspection. The metallographic samples were ground, polished and etched using normative methods. The microstructure was inspected with an optical microscope (ZEISS Axio vert. A1) and a scanning electron microscope (ZEISS EVO 18).

3. Results and discussion

3.1 Flow stress-strain behavior
Fig. 3 shows the true stress-true strain curves achieved by the compression tests, where Fig. 3(a), Fig. 3(b), Fig. 3(c), Fig. 3(d) and Fig. 3(e) correspond to deformation temperature of 340, 340, 380, 420 and 460 °C, respectively. It can be seen that the curves are characterized by an instant increasing in flow stress and followed by slow decrease, and the flow stress eventually approached a stable condition at strain about 0.2. As can be seen, the flow stresses of the 7065 alloy are forceful function of deformation strain rate and temperature. The peak stress raises with reducing compression temperature, and at a designated deformation temperature, the peak stress increases with the increasing of strain rate. From the figure we can see that the work hardening is increased with the increase of strain rate and decrease of temperature. The figure also shows that the curve at the strain rate of 8 s⁻¹ show a little difference compare with that of the other strain rates. At the strain rate of 8 s⁻¹ and deformation temperature of 300°C, the flow stress approached a stable condition at a strain of 0.2. While the deformation temperature increases to 340, 380, 420 and 460 °C, the flow stress decreases when the strain is increasing. The flow stresses all reach a small valley at the strain of about 0.25, then gradually increase with the increasing of strain. The higher the deformation temperature is, the more obvious the
flow stress decrease. Dynamic softening is a common characteristic for many alloys deformed at elevated temperature and high deformation strain rate [4].

3.2 Constitutive equations
There are many constitutive equations shown below have been used [5-10] for illumination the working process during hot deformation.

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

where \( \sigma \) is the flow stress, \( T \) is the deformation temperature, \( R \) is the gas constant, \( Q \) is the activation energy for deformation, \( Z \) is the Zener–Hollomon parameter, \( A_1, A_2, A, n, \beta, \alpha \) and \( n \) are constants.

Eq. (1) and Eq. (2) are suitable for low stress and high stress, respectively. Eq. (3) is a hyperbolic sine law, which is more common and satisfactory for broad scope.

By carrying out natural logarithms of both sides of Eq. (3) and Eq. (4) we have

\[ \ln(\dot{\varepsilon}) = \ln A - \frac{Q}{RT} + n \ln[\sinh(\alpha \sigma)] = B_1 + n \ln[\sinh(\alpha \sigma)] \]  
\[ (B_1 = \ln A - \frac{Q}{RT}) \]  
\[ \ln[\sinh(\alpha \sigma)] = \frac{1}{n}(\ln \dot{\varepsilon} - \ln A) + \frac{Q}{nR T} = B + AT^{-1} \]  
\[ (B_1 = \ln \dot{\varepsilon} - \ln A, A = \frac{Q}{nR}) \]  
\[ \ln Z = \ln A + n \ln[\sinh(\alpha \sigma)] \]  

In this study, Fig. 2. shows the curves of relationship between peak stress and deformation temperature, strain rate and \( Z \) value. The peak stress and deformation temperature, strain rate and \( Z \)
value show a linear relationship, which can tally with Eqs. (5)–(7). Table 2 shows the constants and $Q$ value of 7065 alloy, which were achieved from Eqs. (1)–(4) and Fig. 2.

![Graph showing the relationship between σ and ε, σ and T, σ and ln Z](image)

*Fig. 2. The relationship of: (a) σ and ε; (b) σ and T; (c) σ and ln Z*

We could obtain the hot deformation equation of 7065 alloy by substitution of the above parameters into Eq. (3), shown as Eq. (8), and finally we can get a deformation activation energy of 117.869 kJ/mol.

| $A$ (s$^{-1}$) | $\alpha$ (MPa$^{-1}$) | $n$ | $Q$ (kJ/mol) |
|--------------|----------------|-----|--------------|
| 5.529×10$^8$ | 0.008875       | 5.901 | 117.869      |

$\dot{\varepsilon} = 6.72 \times 10^7 [\sinh(0.008875\sigma)]^{5.901} \exp\left(\frac{-117869}{RT}\right)$  (8)

The flow stress can be characterized by the Zener–Hollomon parameter as follow

$$\sigma = 112.671\ln\left\{\frac{Z}{5.529 \times 10^8}\right\}^{0.5901} + \left[\frac{Z}{5.529 \times 10^8}\right]^{0.5901} + 1\right\}^{0.5901}$$  (9)

3.3 Microstructural evolution

Fig.3 (a) and Fig.3 (b) show the microstructures of the as-cast and homogenized alloys, respectively. They consist of α-aluminum dendrite with coarse intermetallic compounds and Al-Cu-Mg-Zn eutectics segregated into the interdendritic regions. After homogenization, the α-aluminum dendrite transforms to equiaxed crystals, and the coarse intermetallic compounds dissolve into the α-aluminum.

The microstructures of the samples compressed at different conditions are shown in Fig.4. It can be seen from the figures that when the sample was deformed at 300°C and strain rate of 0.1 s$^{-1}$, there are extensive intermetallic compound particles in the matrix (Fig. 4(a)). When increase the deformation temperature to 460°C, the intermetallic compound particles decrease obviously, there is little intermetallic compound particle in the matrix, leaving discontinuous particles on the grain boundaries (Fig. 4(b)). Optical microstructural analysis revealed that when the samples were deformed above 380°C, the α-aluminum dendrite in the initial microstructure was replaced by recrystallized grains, which confirms that the process of dynamic recrystallisation occurred during compression. It can be seen from Fig.1(e) that the flow stress of the specimen compressed at temperature of 460 °C and strain rate of 8 s$^{-1}$ decreases obviously after reaching the peak, which is a typical curve of dynamic softening.
Fig.3. Microstructure of the 7065 alloy: (a) as-cast and (b) homogenized

Fig.4. Microstructure of the compressed samples deformed at:
(a) \( T=300{\degree}C, \varepsilon=0.1\ \text{s}^{-1} \); (b) \( T=460{\degree}C, \varepsilon=0.1\ \text{s}^{-1} \); (c) \( T=380{\degree}C, \varepsilon=8\ \text{s}^{-1} \); (d) \( T=460{\degree}C, \varepsilon=8\ \text{s}^{-1} \)

4. Conclusions
Hot deformation tests were carried out on 7065 aluminum alloy. The flow stress was achieved in the strain rate range of 0.1-8 s\(^{-1}\) and temperature range of 300-460 ℃. The conclusions can be given below:

1. The flow stresses of the 7065 alloy are forceful function of deformation strain rate and temperature. The peak stress raises with reducing compression temperature, and at a designated deformation temperature, the peak stress increases with the increasing of strain rate.

2. The deformation activation energy of the alloy is 117.869 kJ/mol, the hot deformation equation of the alloy can be describe as
\[
\dot{\varepsilon} = 6.72 \times 10^4 \left[ \sinh(0.0088754\sigma) \right]^{0.5901} \exp\left(-\frac{117869}{RT}\right).
\]
3. When the samples were deformed above 380℃, the α-aluminum dendrite in the initial microstructure was replaced by recrystallized grains, dynamic recrystallisation occurred during compression.

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