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Hot deformation behavior of spray formed Al−22Si−5Fe−3Cu−1Mg alloy

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Abstract: The hot deformation behavior of a spray formed Al−22Si−5Fe−3Cu−1Mg alloy was investigated by isothermal compression tests at temperature ranging from 350 °C to 500 °C and strain rate from 0.001 s^{-1} to 0.1 s^{-1}. At the beginning of deformation, work hardening is the major factor. The flow stress quickly reaches a peak, followed by a continuous reduction, then a balance is established between the tendency to work harden and the tendency to flow soften. The stress curves appear almost in flat shape. A constitutive equation in the hyperbolic sine function for describing the deformation behavior was established and the hot deformation activation energy was determined to be 312.65 kJ/mol. It can be concluded that the temperature of extrusion should not be more than 500 °C in order to avoid primary silicon coarsen.

Key words: spray forming; Al−Si alloy; hot deformation behavior; constitutive equation

1 Introduction

Hypereutectic Al−Si alloys with low density, high specific strength, low coefficient of thermal expansion, excellent wear resistance and corrosion resistance, have been widely applied in automobile industry, electronics and aerospace [1−4]. Unfortunately, conventional cast techniques in hypereutectic Al−Si alloys lead to a coarse-grain microstructure with extensive macro-segregation caused by the low cooling rate. The second phase often consists of plates of intermetallics, which is the main reason responsible for the poor properties of hypereutectic Al−Si alloys, and greatly limits the applications of these materials [5−6].

Spray forming (SF) offers a relatively new approach to resolve such problems mentioned above. This technique has the advantages of reducing grain size and eliminating macrosegregation, due to a high cooling rate [7−8]. Spray-formed hypereutectic Al−Si alloys are already widely investigated during the past decades. These researches mainly focused on processing technology, addition of alloy elements and relationship between microstructure and mechanical properties [9−11]. However, little attention has been devoted to study the deformation behavior of spray formed hypereutectic Al−Si alloy. The hot deformation behavior of spray-formed Al−22Si−5Fe−3Cu−1Mg alloy was investigated in this work in order to examine its deformability by means of hot compression test. Furthermore, the constitutive equation of strain rate as a function of flow stress and temperature was established based on the flow curves obtained from the compression tests. The influence of compression temperature on microstructure was also investigated in order to establish the optimized condition for extrusion process.

2 Experimental

The experiments were carried out on a hypereutectic Al−Si alloy with nominal chemical compositions of 22 Si, 5 Fe, 3 Cu, 1 Mg and Al balance (mass fraction, %). The alloy was prepared by spray forming technique. Cylindrical compression specimens with 8 mm in diameter and 12 mm in height were manufactured from the deposited billet with the compression axis parallel to the deposition direction.

Hot compression tests were performed on a Gleeble−1500 thermo-simulation machine at strain rates of 0.001, 0.005, 0.01 and 0.1 s^{-1} as well as deformation temperatures were 350, 400, 450 and 500 °C, respectively. The specimens were heated to the corresponding temperature at a heating rate of 10 °C/s, followed by a holding period of 300 s to maintain temperature uniformity. A thermocouple was used to monitor the temperature at the middle of the specimen. In order to

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minimize the friction between specimen and punch, graphite powder mixed with machine oil was used as a lubricant. Specimens were deformed to 55% of the original height then water quenched immediately for microstructure observation. The microstructure of the compressed specimens was characterized by scanning electron microscopy (SEM).

3 Results and discussion

3.1 True stress—true strain curves

Figure 1 shows a series of typical true stress—strain curves of spray formed Al−22Si−5Fe−3Cu−1Mg alloy during hot compression tests. It can be seen that the flow stress abruptly increases with increasing true strain during the early stage of the deformation. After reaching the peak flow stress, the stress slightly decreases with increasing true strain. It should be pointed out that there is a slight increase at 500 °C as strain rates are 0.1 s^{-1} and 0.01 s^{-1}.

As shown in Fig. 1, the deformation behavior of Al−22Si−5Fe−3Cu−1Mg alloy at a given strain rate is very sensitive to temperature. The steady flow stress decreases with increasing temperature at a given strain rate. Work hardening and flow softening are two competing mechanisms that are concurrent in the isothermal hot compression of the spray-formed Al−22Si−5Fe−3Cu−1Mg alloy. The stress—strain curves can be divided into two apparent parts. At the beginning, the motion of the dislocations is blocked due to the existence of many defects in the alloy. Hardening rate is greater than the rate of softening [12], therefore, work hardening is the major factor. The stress increases rapidly to the maximum flow stress. In the following part, a balance is established between the tendency to work harden and the tendency to flow soften, as can be seen that the curves are almost in flat shape. The flow softening is possibly caused by dynamic recovery, recrystallization and particle damage [7].

It is known that dynamic recrystallization in aluminum alloys does not occur easily during hot compression due to their high stacking-fault energy, and dynamic recovery is the mainly softening mechanism [13]. However, ceramic reinforcements in aluminum alloys can promote dynamic recrystallization due to its high dislocation density around the edges of the hard particles during hot deformation. In the spray formed Al−22Si−5Fe−3Cu−1Mg alloy, the primary silicon phases act as reinforcement in the α(Al) matrix [14]. Therefore, it is supposed that dynamic recrystallization has occurred in the hot compression process. From Fig. 1, it can be seen that the flow stress value decreases with the increase of temperature at the same strain rate. This is considered to be related to the enhancement of atomic

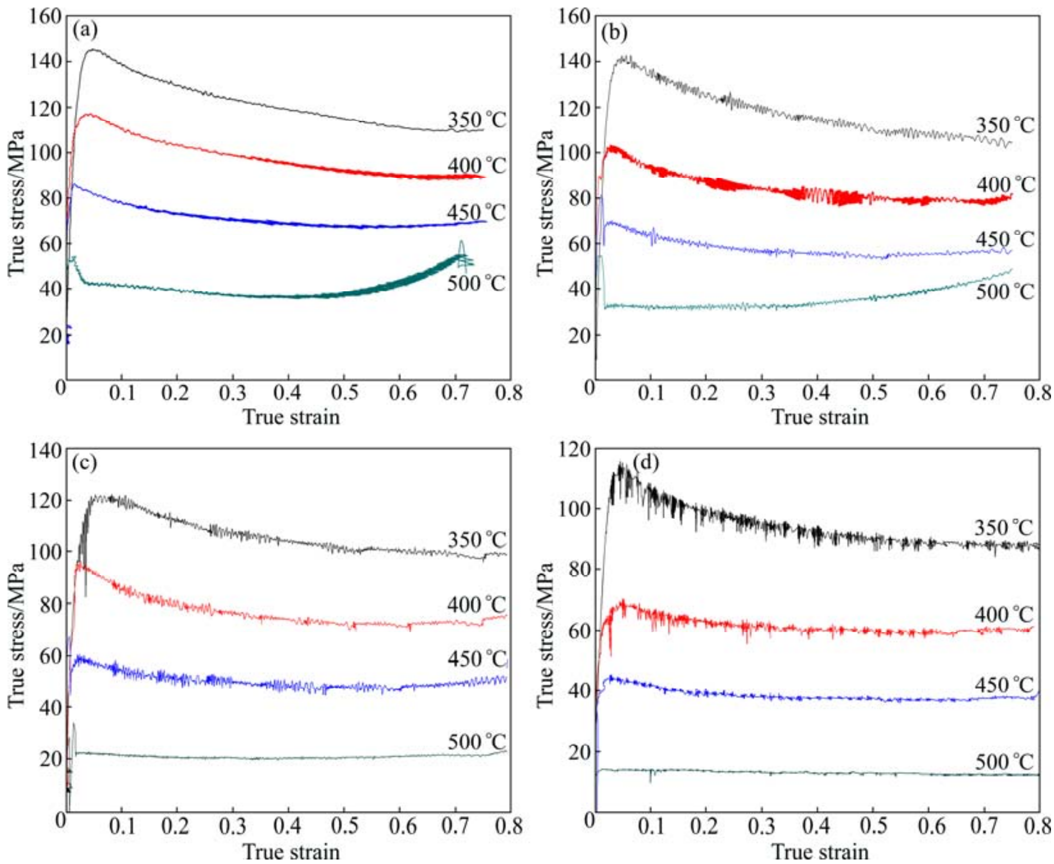

Fig. 1 True stress—strain curves of Al−22Si−5Fe−3Cu−1Mg alloy: (a) 0.1 s^{-1}; (b) 0.01 s^{-1}; (c) 0.005 s^{-1}; (d) 0.001 s^{-1}

thermal activation and dynamic recrystallization as well as decrease in interatomic critical shear stress.

3.2 Constitutive modeling

In hot deformation of metallic materials, constitutive equations are commonly used to determine the material constants. The relationships between peak stress or steady state stress, strain rate and temperature are usually described by the following equations [12, 15−18]:

$$Z=\dot{\varepsilon}\cdot\exp(\frac{Q}{RT}) \quad (1)$$

$$\dot{\varepsilon}=A_1\sigma^m\exp(-\frac{Q}{RT}) \quad (2)$$

$$\dot{\varepsilon}=A_2\exp(\beta\sigma)\exp(-\frac{Q}{RT}) \quad (3)$$

$$\dot{\varepsilon}=A[\sinh(\alpha\sigma)]^n\exp(-\frac{Q}{RT}) \quad (4)$$

where n, m, α, β, A_1, A_2, and A are constants independent of the temperature, $\alpha=\beta/m$, σ is the flow stress; $\dot{\varepsilon}$ is the strain rate; Q is the activation energy of deformation, R is the universal gas constant, T is the thermodynamic temperature and Z refers to the Zener–Hollomon parameter. The power law, Eq. (2), and the exponential law, Eq. (3), break at a high stress and at a low stress, respectively. The hyperbolic sine law, Eq. (4), is a more general form suitable for stresses over a wide range.

So, we can choose steady state stress value when the true strain is 0.2. By taking the logarithms of both sides, Eqs. (2) and (3) are transformed into:

$$\ln\dot{\varepsilon}=\ln A_1+m\ln\sigma \quad (5)$$

$$\ln\dot{\varepsilon}=\ln A_2+\beta\sigma \quad (6)$$

The linear relationships of $\ln\dot{\varepsilon}$—$\ln\sigma$ and $\ln\dot{\varepsilon}$—σ are shown in Fig. 2. The values of m and β are calculated as 8.766 4 and 0.134 775 MPa^{-1} from the slopes of Fig. 2, and $\alpha=\beta/m$=0.015 374 MPa^{-1}.

Taken partial differential equation of Eq. (4), we can obtain Eq. (7):

$$Q=R\frac{\mathrm{d}\ln\dot{\varepsilon}}{\mathrm{d}\ln[\sinh(\alpha\sigma)]}\bigg|_T\cdot\frac{\mathrm{d}\ln[\sinh(\alpha\sigma)]}{\mathrm{d}(1/T)}\bigg|_{\dot{\varepsilon}}=R\cdot n\cdot s \quad (7)$$

Figure 3 depicts the relationships of $\ln\dot{\varepsilon}$—$\ln[\sinh(\alpha\sigma)]$ and $\ln[\sinh(\alpha\sigma)]$—T^{-1}. The values of n and s are determined by calculating the average slopes of the two groups of lines. The activation energy Q is obtained as about 312.65 kJ/mol.

By substituting the values of Q and different hot deformation conditions into Eq. (1), Z values are calculated. Combining Eq. (1) with Eq. (4), then, taking

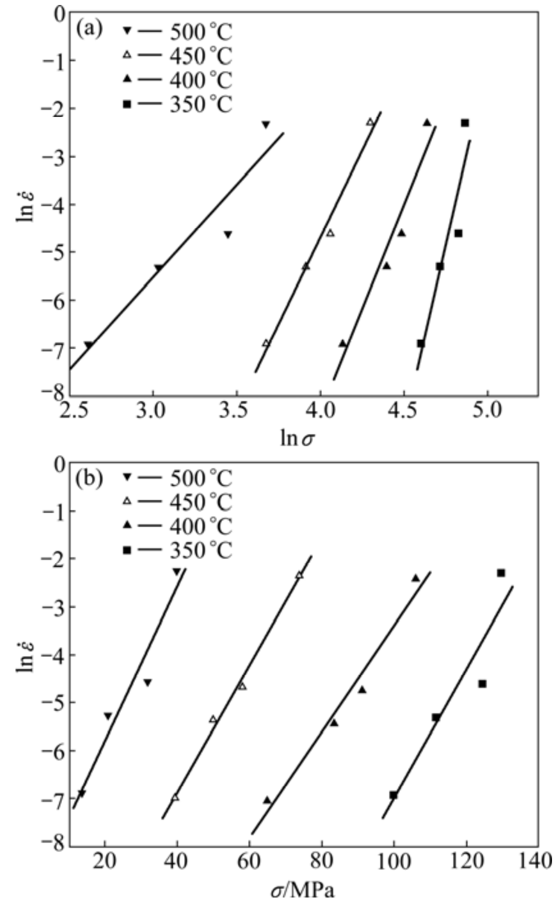

Fig. 2 Relationship between peak stress and strain rate: (a) $\ln\dot{\varepsilon}$ vs $\ln\sigma$; (b) $\ln\dot{\varepsilon}$ vs σ

the logarithms, we can obtain:

$$\ln Z=\ln A+n\ln[\sinh(\alpha\sigma)] \quad (8)$$

The value of A and more exact value of n can be obtained as 1.344×10^{21} s^{-1} and 5.67 as shown in Fig. 4. The flow stress can be expressed as a function of Zener–Hollomon parameter. The constitutive equations for hot deformation behavior of Al−22Si−5Fe−3Cu−1Mg alloy are determined as:

$$\sigma=\frac{1}{0.015\,374}\ln\left\{\left(\frac{Z}{1.344\times10^{21}}\right)^{1/5.67}+\left[\left(\frac{Z}{1.344\times10^{21}}\right)^{2/5.67}+1\right]^{1/2}\right\} \quad (9)$$

$$Z=1.344\times10^{21}[\sinh(0.015\,374\sigma)]^{5.67} \quad (10)$$

3.3 Microstructure

Figure 5 shows the microstructures of the spray-formed Al−22Si−5Fe−3Cu−1Mg alloy got under different conditions. At low compression temperature,

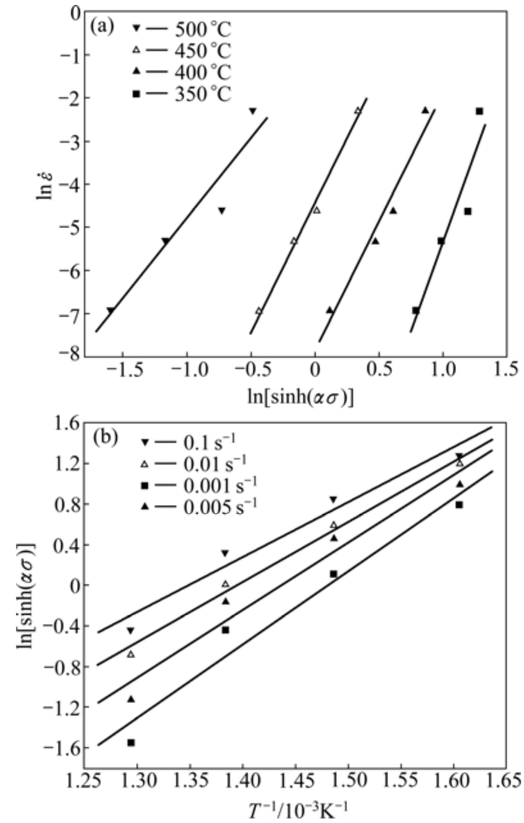

Fig. 3 Relationship among ln[sinh($\alpha\sigma$)], strain rate and temperature: (a) ln $\dot{\varepsilon}$ vs ln[sinh($\alpha\sigma$)]; (b) ln[sinh($\alpha\sigma$)] vs T^{-1}

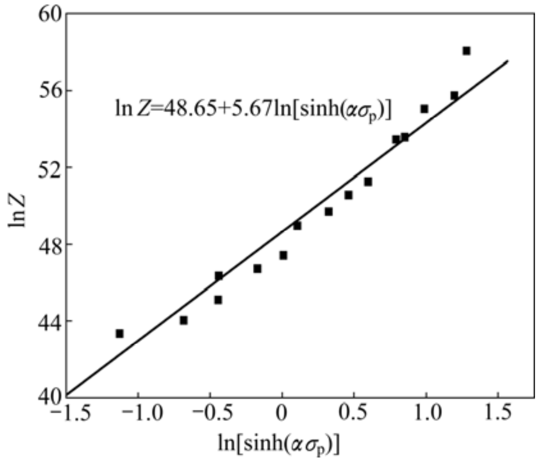

Fig. 4 Relationship between ln Z and ln[sinh($\alpha\sigma$)]

much porosity is observed in the compressed samples, as shown in Figs. 5(a) and (b). However, the amount of porosity decreases significantly with the increase of compressed temperature (Fig. 5(c)) at the same strain rate. Figure 5(d) indicates that the sample is fully densified at 500 °C after deformation.

The increase in density is considered to be related to flow ability. The alloy has better flow ability at high temperature compared with low temperature, because the ability of dislocations to cross-slip and climb is strengthened [16].

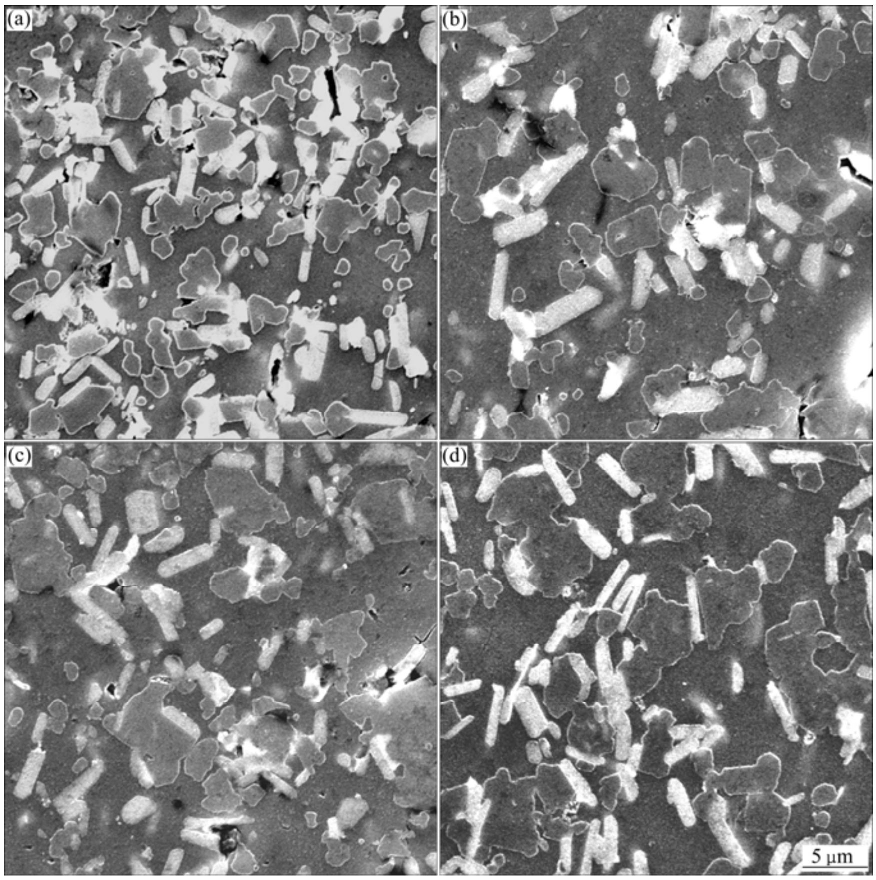

Fig. 5 SEM images of Al−22Si−5Fe−3Cu−1Mg alloy under different conditions: (a) 350 °C, 0.01 s^{-1}; (b) 400 °C, 0.01 s^{-1}; (c) 450 °C, 0.01 s^{-1}; (d) 500 °C, 0.01 s^{-1}

The average particle size of primary silicon remained when the compression temperature is elevated from 350 °C to 450 °C. However, a size increase in primary silicon was observed when compressed at 500 °C. This observation indicates that the extrusion temperature should not be more than 500 °C.

4 Conclusions

1) The true stress—strain curves of the spray formed Al−22Si−5Fe−3Cu−1Mg alloy during hot compression tests exhibit a peak stress at a critical strain. The steady state stress increases with decreasing deformation temperature and increasing strain rate, which can be described by constitutive equation in the hyperbolic sine function with hot deformation activation energy of 312.65 kJ/mol and a Zener-Hollomon parameter.

2) In the hot compression process, it has two competing mechanisms: work hardening and flow softening.

3) The temperature of extrusion should not be more than 500 °C to avoid primary silicon coarsen.

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喷射成形 Al−22Si−5Fe−3Cu−1Mg 合金的热变形行为

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摘　要：通过等温压缩试验，对喷射成形 Al−22Si−5Fe−3Cu−1Mg 合金在试验温度为 350～500 °C 和应变速率为 0.001～0.1 s^{-1} 条件下的热变形行为进行研究。在开始变形阶段，加工硬化是主要的影响因素，流变应力迅速达到最大值，随后持续降低，这时加工硬化的趋势和流变软化的趋势相平衡，应力曲线几乎趋于稳定。采用双曲正弦函数建立的本构方程来描述合金的变形行为，热变形激活能为 312.65 kJ/mol。为了防止初晶硅相的长大，热挤压的温度不超过 500 °C。

关键词：喷射成形；Al−Si 合金；热变形行为；本构方程

(Edited by YANG You-ping)