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ARTICLE

Hot Deformation Behavior of 3003/4004 Two-layered Aluminum Alloy

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Abstract: The hot compression test was conducted by a Gleeble 3500 dynamic hot-simulation testing machine to study the hot deformation behavior of 3003/4004 two-layered aluminum alloy. The test was conducted at various temperatures (300, 350, 400 and 450 ℃) with various strain rates of 0.05, 0.5, 5, 25 s^{-1}. The compression curve shows a sharp increase due to effect of work-hardening, and then it becomes smooth because of dynamic softening. According to the experimental results, the peak stress decreases as the strain rate decreases or the temperature increases. Finally, a constitution equation that describes the relationship of strain rate ($\dot{\varepsilon}$), deformation temperature (T) and flow stress (σ) is achieved.

Key words: 3003/4004 two-layered alloy; hot compression; constitution equation

Composite materials that combine the physical, mechanical, and surface properties of several materials are now widely used. Two-layered alloy, for instance, possessing different properties between the core alloy and clad alloy can be used in a special situation. 3003/4004 two-layered alloy which combines the high thermal conductivity of 3003 alloy and good welding performance of 4004 alloy is now widely used in heat exchangers as a replacement of Cu alloy[1,2].

The flow behavior of 3003/4004 alloy during hot deformation is rather complex and the deformation behavior of 3003/4004 two-layered alloy were not well studied. The work-hardening and dynamic softening occur simultaneously during the deformation. The flow stress is affected by the strain rate ($\dot{\varepsilon}$), deformation temperature (T) and deformation degree. The constitution equation is often used to describe the plastic flow properties of metal and alloy because it can predict the flow stress during hot deformation.

In the present work, a hot compression test was conducted by a Gleeble3500 testing machine to study the flow stress behavior of 3003/4004 two-layered alloy for the workability. Based on the test, a constitutive equation was established to characterize the flow behavior of 3003/4004 two-layered alloy.

1 Experiment

The 3003/4004 two-layered alloy was achieved in a former study[3,4] and chemical composition is shown in Table 1. After annealing at 450 ℃ for 24 h, the samples were cut into column with 10 mm in diameter and 15 mm in height. Compression tests at strain rates of 0.05, 0.5, 5, and 25 s^{-1} were performed using a Gleblee-3500 dynamic hot-simulation testing machine at temperatures ranging from 300 to 450 ℃, with the achieved maximum true strain exceeding 0.9. The specimens were electrically heated by their own resistance to deformation temperature at a heating rate of 6 ℃/s by thermocoupled feedback-controlled alternating current and kept for 30 s to ensure the homogeneous heating. The samples for optical microscopy were polished, and then etched in a solution of 0.5% HF. The microstructures were investigated by optical

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microscope (ZEISS Imager A2m).

2 Results and Discussion

2.1 Flow behavior

True stress-true strain curves of 3003/4004 two-layered alloy obtained at different temperatures and strain rates during hot compression are depicted in Fig.1a~1d. The results show that the flow stress increases up to a peak value at the beginning and then goes into a steady-state stage. This indicates distinct work-hardening behavior occurring at first. Then, dynamic recovery happens and is nearly equal to work-hardening. Comparing the curves in Fig.1a~1d, it can be drawn that at the same strain rate, the flow stress decreases with the increase of deformation temperature, while at the same deformation temperature, the flow stress increases with the increase of strain rate. This reveals that the 3003/4004 two-layered alloy possesses positive strain rate sensitivity under current deformation condition.

2.2 Microstructures

The as-cast and the deformed microstructures of 3003/4004 two-layered alloy are shown in Fig.2. It delineates of the interface before and after deformation.

In Fig.2b~2e the microstructures are mainly composed of broken second phase and elongated grain which are typically deformed microstructure. The flow stress goes smooth after a sharp increase because dynamic softening happens during the deformation.

The mechanism of dynamic softening includes dynamic recovery and dynamic recrystallization. As aluminum alloys are high stacking fault energy material, dynamic recovery is more easier to happen compared with dynamic recrystallization which needs a certain extent of activation energy. There is no dynamic recrystallized grain in the deformed microstructure, which means the dynamic softening mechanism in the current test is mainly dynamic recovery.

Table 1 Chemical composition of 3003/4004 two-layered alloy (wt%)

Alloy	Mn	Fe	Si	Cu	Zn	Other	Al
3003	1.2	0.7	0.6	0.1	0.1	<0.15	Bal.
4004	0.1	0.8	10	0.25	0.2	<0.15	Bal.

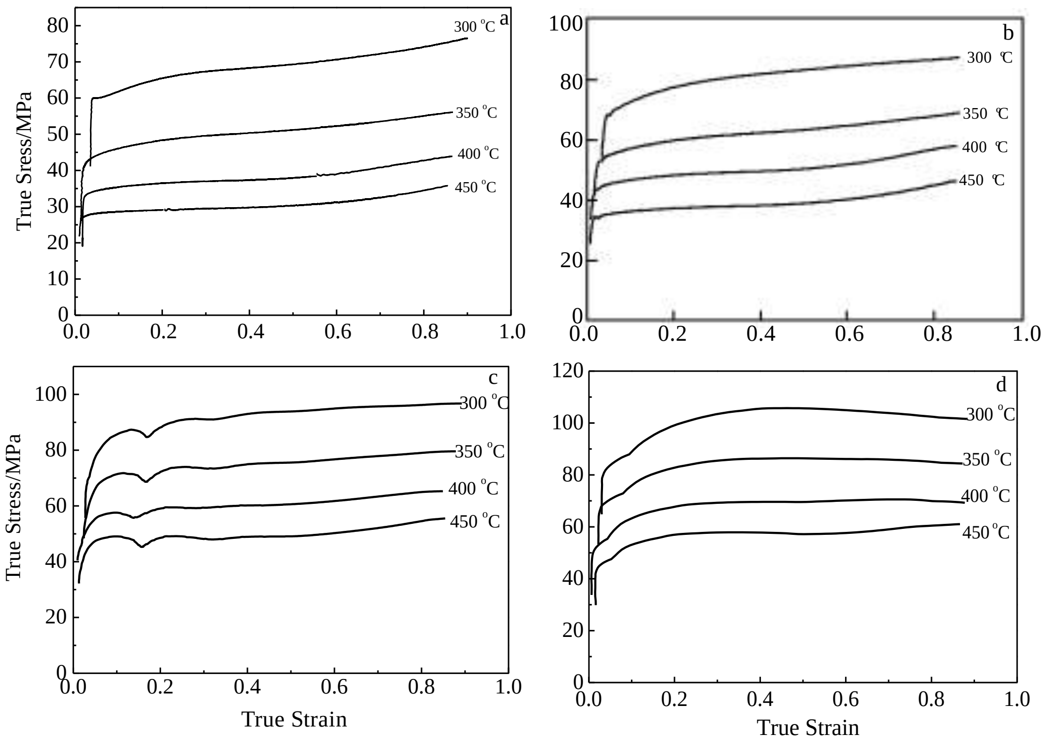

Fig.1 True stress-true strain of 3003/4004 two-layered alloy at different strain rates and temperatures: (a) $\dot{\varepsilon}$ =0.05 s^{-1}, (b) $\dot{\varepsilon}$ =0.5 s^{-1}, (c) $\dot{\varepsilon}$ =5 s^{-1}, and (d) $\dot{\varepsilon}$ =25 s^{-1}

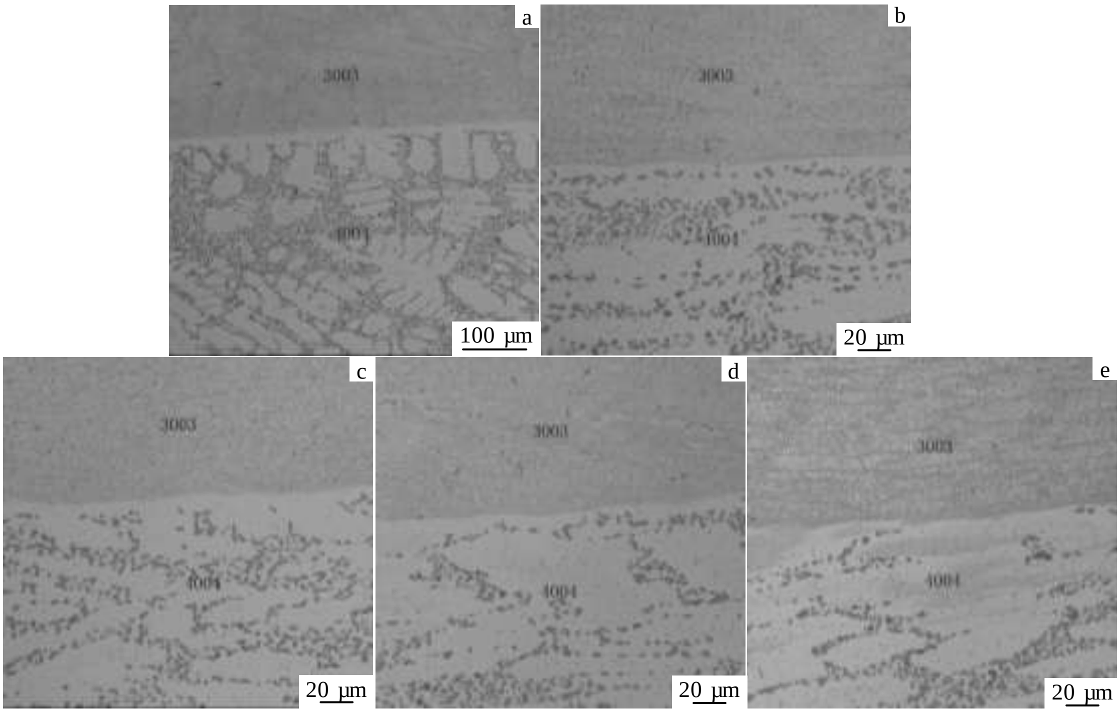

Fig.2 As cast microstructure and deformed microstructure at 400 ℃ with different strain rates: (a) as cast, (b) $\dot{\varepsilon}$ =0.05 s^{-1}, (c) $\dot{\varepsilon}$ =0.5 s^{-1}, (d) $\dot{\varepsilon}$ =5 s^{-1}, and (e) $\dot{\varepsilon}$ =25 s^{-1}

2.3 Establishment of the constitution equation

During hot deformation, the relationship between the maximum stress, strain rate and temperature can be described by the Arrhenius equation[5-8].

$$\dot{\varepsilon}=A[\sinh(\alpha\sigma)]^n \exp(-Q/RT) \tag{1}$$

where A, α, and n are constants depending on material; α is the stress level parameter; R is the gas constant; n is the stress exponent; T is thermodynamic temperature; σ is peak stress. Q is the activation energy of hot deformation, kJ·mol^{-1}. This equation is appropriate for all stress levels. For low stress level ($\alpha\sigma$<0.8) and high stress level ($\alpha\sigma$>1.2) this equation can be written in the form of Eq.(2) and Eq.(3), respectively.

$$\dot{\varepsilon}=A_1\sigma^{n1} \tag{2}$$

$$\dot{\varepsilon}=A_2 \exp(\beta\sigma) \tag{3}$$

where $\alpha=\beta/n_1$, β is the temperature-independent material constant, MPa^{-1}; and n is the stress exponent. A_1 and A_2 are constants independent on temperature. Moreover, the relationship between true stress and true strain can be expressed by Z parameter：

$$Z=\dot{\varepsilon}\exp(Q/RT)=A[\sinh(\alpha\sigma)]^n \tag{4}$$

From Eq.(2) and Eq.(4) another two equations i.e. Eq.(5) and Eq.(6) can be obtained.

$$\ln\dot{\varepsilon}=\ln A_1 +n_1\ln\sigma \tag{5}$$

$$\ln\dot{\varepsilon}=\ln A_2 +\beta\sigma \tag{6}$$

When the curves of $\ln\dot{\varepsilon}$ - $\ln\sigma$ and $\ln\dot{\varepsilon}$ -σ were drawn, n_1 and β were determined. Then the value of α can be obtained for $\alpha=\beta/n_1$.

When the temperature is constant, Eq.(1) can be changed into：

$$\ln\dot{\varepsilon}=A'+n\ \ln[\sinh(\alpha\sigma)] \tag{7}$$

where A'=ln$A$－Q/(RT).

On the other hand, when the strain rate keeps constant Eq.(4) can be written as:

$$\ln[\sinh(\alpha\sigma)]=B/T+C \tag{8}$$

where B and C are constants. Also Eq.(1) could be written as Eq.(9) through partial derivative transform.[9]

$$Q=R\left[\frac{\partial\ln\dot{\varepsilon}}{\partial\ln[\sinh(\alpha\sigma)]}\right]_T\left[\frac{\partial\ln[\sinh(\alpha\sigma)]}{\partial\ln(T^{-1})}\right]_{\dot{\varepsilon}} =Rn\left[\frac{\partial\ln[\sinh(\alpha\sigma)]}{\partial(T^{-1})}\right]_{\dot{\varepsilon}} \tag{9}$$

Then the activation energy Q can be obtained by figures of $\ln\dot{\varepsilon}$ -ln[sinh($\alpha\sigma$)] and ln[sinh($\alpha\sigma$)]-T^{-1}.

Fig.3 shows the curves of $\ln\dot{\varepsilon}$ -lnσ and $\ln\dot{\varepsilon}$ -σ. Fig.4 and Fig.5 show the relationship between $\ln\dot{\varepsilon}$ -ln[sinh($\alpha\sigma$)] and ln[sinh($\alpha\sigma$)]-T^{-1}. According to the figures and Eqs, the constants A, Q, n and α can be obtained. Finally, the flow stress can be estimated:

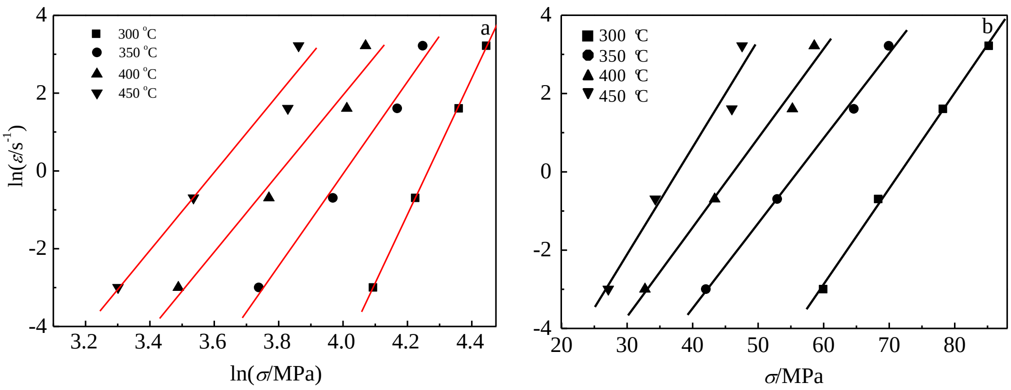

Fig.3 Relationship between peak stress and strain rate: (a) ln $\dot{\varepsilon}$ -lnσ and (b) ln $\dot{\varepsilon}$ -σ

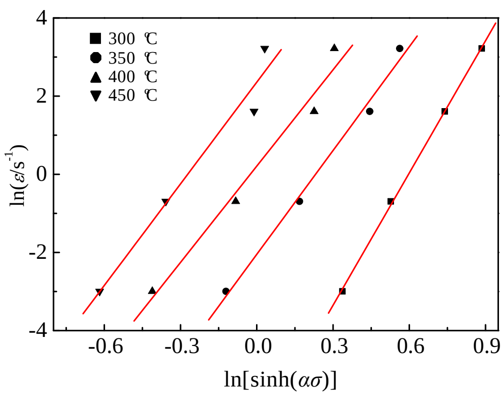

Fig.4 Relationships between true strain and flow stress

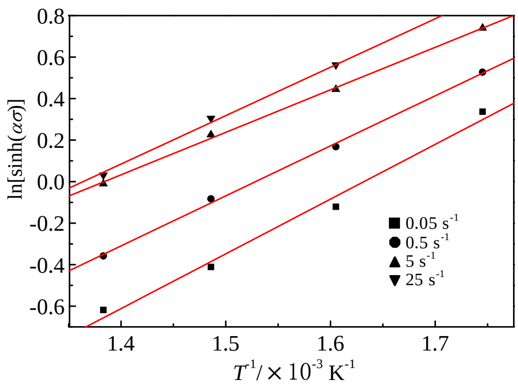

Fig.5 Relationships between flow stress and temperature

$$\dot{\varepsilon}=1.3\times10^{14}[\sinh(0.019\sigma)]^{9.2543}\exp(-1.814\times10^{5}/RT) \quad (10)$$

3 Conclusions

1) The flow stress of 3003/4004 two-layered alloy under current deformation condition decreases with the increasing temperature and increases with the increasing strain rate.

2) The dynamic softening mechanism in current deformation condition is mainly dynamic recovery.

3) The constitution equation describing the relationship of $\dot{\varepsilon}$, T and σ is:

$$\dot{\varepsilon}=3\times10^{14}[\sinh(0.019\sigma)]^{9.2543}\exp(-1.814\times10^{5}/RT).$$

References

1 Amir R Baserinia, Etienne J F R, Mary A Wells *et al*. *Metallurgical and Materials Transactions B*[J], 2013, 44B: 1017

2 Yoon J S，Lee S H, Kim M S. *Journal of Materials Science Letters*[J], 2011, 20: 229

3 Zheng Ren, Zhu Xiurong, Sun Jianbo *et al*. *Advanced Material Research*[J], 2012, 479-481: 114

4 Ren Zheng, Zhang Xiao, Zhu Xiurong *et al*. *Rare Metal Materials and Engineering*[J], 2014, 43(4): 986 (in Chinese)

5 Zhan M Y, Chen Z H, Zhang H *et al*. *Mechanics Research Communications*[J], 2006, 33: 508

6 Rao K P, Doravivelu S M, Roshan H Md *et al*. *Transactions of the Indian Institute of Metals*[J], 1983, 37(5): 471

7 Yang Sheng, Yi Danqing, Hong Zhang *et al*. *Journal of Wuhan University of Technology-Materials Science*[J], 2008, 23(5): 694

8 Wei Xiuyu, Zheng Ziqiao, Xin Fu *et al*. *Trans Nonferrous Met Soc China*[J], 2007, 17: 280

9 Yan Liangming, Shen Jian, Li Junpeng *et al*. *International Journal of Minerals, Metallurgy and Materials*[J], 2010, 17(1): 46

3003/4004 层合板铝合金热变形行为研究

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摘　要：利用Gleeble 3500热模拟机对3003/4004层合板铝合金进行了热压缩模拟实验，研究了在变形温度分别为300，350，400和450 ℃以及应变速率分别为0.05, 0.5, 5, 25 s^{-1}的变形条件下3003/4004层合板铝合金的热变形行为。合金的热压缩曲线显示在开始阶段由于加工硬化效应，应力应变曲线迅速上升；随后由于合金的软化，应力应变曲线进入平稳状态。实验结果表明，合金的峰值应力随着应变速率的升高而升高，随着温度的升高而降低。同时，通过计算分析获得了描述应变速率、变形温度以及流变应力三者之间关系的本构方程。

关键词：3003/4004层合板铝合金；热压缩；本构方程

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