Investigation on critical strain of dynamic recrystallization for SiCp/Al-Cu composite

Yali Sun, Jingpei Xie14, Shiming Hao3, Aiqin Wang12, Pei Liu1 and Min Li1

1School of Materials Science and Engineering, Henan University of Science and Technology, Luoyang 471023, China
2Collaborative Innovation Center of Non-Ferrous Materials of Henan Province, Luoyang 471023, China
3School of Physics and Engineering, Henan University of Science and Technology, Luoyang 471023, China
E-mail: Xiejp@haust.edu.cn

Abstract. Using Gleeble-1500D simulator, the critical strain of dynamic recrystallization of SiCp/Al-Cu composite were investigated at 623-773 K with strain rate of 0.01-10 s\(^{-1}\). The results show that the main softening mechanism is the dynamic recrystallization through the stress-strain curves of SiCp/Al-Cu composite, the activation energy is 272.831 KJ/mol. \(\ln \theta - \varepsilon\) and \((-\partial (\ln \theta)/\partial \varepsilon) - \varepsilon\) curves were plotted based on the experimental data to further obtain the critical strain and steady strain of DRX. Then the critical strain model and the steady-state strain model of DRX were set up. Furthermore, the dynamic recrystallization volume fraction of SiCp/Al-Cu composite was investigated.

1. Introduction
Aluminum matrix composites (AMCs) reinforced with SiCp have received great attention because of their high specific stiffness, improved wear resistance and high specific strength. The composites which have a higher content of SiC have more enhanced characteristics. Material deformation and microstructure change with technological parameters, material deformation region is divided into stability region and instability region, Stability region was the region where the material can be machine normally. But instability region often appear failure mode such as particle cracking, separation and wedge cracking. Dynamic recrystallization (DRX) was an important mechanism belong to stability region for the microstructure control during hot deformation, DRX not only can fine grains, but also can controlling mechanical properties during processing [1-3]. But using microstructure or stress-strain curves to determine the time when DRX begun was difficulty. So, it is necessary to study the critical strain of dynamic recrystallization. The purpose of this article is to study the critical strain of dynamic recrystallization and recrystallization fraction of SiCp/Al-Cu composite.

2. Experimental
As the experimental material, the preparation method of SiCp/Al-Cu composite was powder
metallurgy. 30% SiCp particles with the average size of 3.5 microns which the shape is irregular sharp polygonal blocks, and 70% 2024Al powders that belonged to Al-Cu alloy which with main chemical compositions 3.8wt.% Cu, 1.5wt.% Mg and Al balance, and the average diameter is 10 μm, were mixed using a QQM/B roller mixer for 24 h, and subsequently sintered at 580°C by vacuum hot-pressing. Figure 1 shows the optical micrograph of the sintered composite. Organization is relatively dense, no obvious gap, the gray phase is the Al matrix, the particles appear gray black is SiC particles, and the white phase is Al-Cu alloy phase that scattered in the matrix.

Figure 1. Microstructures of SiCp/Al-Cu composite.

The size of Cylindrical specimens that used for compressive is φ8×12 mm. Machine oil mixed with graphite powder were used for lubrication during hot deformation so that the friction between the specimen and die surface could be minimized. The isothermal constant strain rate deformation was achieved by Utilizing Gleeble-1500D simulator in the temperature range of 623-773 K with the strain rate of 0.01-10 s⁻¹. After straining, specimens were quenched within two seconds to preserve the hot worked microstructures.

Figure 2. Typical stress-strain curves of SiCp/Al-Cu composite under
3. Results and analysis

3.1. Stress-strain curves

Figure 2 shows the true stress-strain curves of SiCp/Al-Cu composite in different deformation conditions. The stress-strain curves exhibit a typical dynamic recrystallization behavior. The flow stress revealed a trend of increase quickly to the maximum and then decrease slowly during the whole deformation process. This is an emergent property resulting from interactions among the work hardening, dynamic recovery and recrystallization softening. The strain hardening plays a leading role in the initial stages of deformation, and the flow stress increase rapidly. Peak stress appearance in the stress-strain curves when the work hardening and softening balance, recrystallization softening become the main mechanism subsequently, stress decreases gradually and reached a stable value finally.

3.2. Determination of constitutive equations

Determine the peak stress in the material deformation can help choose appropriate processing equipment and then improve the machining efficiency. Phenomenological power-Arrhenius was widely used to describe the constitutive equations, and the formula can be written as [4]:

\[ \varepsilon = A_1 \sigma^n \exp\left(\frac{-Q}{RT}\right) \]  
(1)

\[ \dot{\varepsilon} = A_2 \exp(\beta \sigma) \exp\left(\frac{-Q}{RT}\right) \]  
(2)

\[ \dot{\varepsilon} = A \left[ \sinh(\alpha \sigma) \right]^n \exp\left(\frac{-Q}{RT}\right) \]  
(3)

Where \( \sigma \) is the flow stress, \( \dot{\varepsilon} \) is the strain rate, \( T \) is the deformation temperature, \( Q \) is the activation energy for deformation, \( R \) is the ideal gas constant, \( A_1, A_2, A, n \) and \( \alpha (= \beta / n') \) are material constants.

Zener-Hollomon parameter (\( Z \)) is widely used to state the hot deformation behavior, which correlates with the strain rate, deformation temperature, and activation energy by the expression [5]:

\[ Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = A [\sinh(\alpha \sigma)]^n \]  
(4)

From figures 3(a) and 3(b), the values of \( n' \) and \( \beta \) were evaluated, which \( n' \) and \( \beta \) are taken as the average values of the slopes of the \( \ln \dot{\varepsilon} - \ln \sigma \) and \( \ln \dot{\varepsilon} - \sigma \) plots [6], and the value of \( \alpha \) was 0.01166 for the SiCp/Al-Cu composite.

The activation energy \( Q \) could be calculated and shown by the following equation through differentiating equation (3).
Figure 4. (a) $\ln \sigma$ versus $\ln \dot{\varepsilon}$ plots; (b) $\sigma$ versus $\ln \dot{\varepsilon}$ plots a.

\begin{equation}
Q = R \frac{\partial \ln[\sinh(\alpha \sigma)]}{\partial (1/T)} \left|_{T_f} \right. \frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha \sigma)]}
\end{equation}

Where $n$ is the mean slope of $\ln \dot{\varepsilon} - \ln[\sinh(\alpha \sigma)]$ plots (figure 4(a)), and $S$ is the mean slope of the $\ln[\sinh(\alpha \sigma)] - 1/T$ plots (figure 4(b)). The value of activation energy of SiCp/Al-Cu composite is calculated to be $Q = RnS = 272.831 \text{ kJ/mol}$.

Figure 5 shows the relationship between $\ln[\sinh(\alpha \sigma)]$ and $\ln Z$, the intercept of the straight line is $\ln A = 44.5$. Then the hot deformation equation of SiCp/Al-Cu composite can be written as

\begin{equation}
\dot{\varepsilon} = e^{44.5}[\sinh(0.01166\alpha \sigma)]^{2917} \exp\left(-\frac{272.831}{RT}\right)
\end{equation}

Figure 5. Relationships between peak stress and $Z$ parameter of SiCp/Al-Cu composite.

Figure 6. The comparison of calculated and measured values of peak stress for SiCp/Al-Cu composite at (a) 0.1s$^{-1}$; (b) 1s$^{-1}$.

Using thermal simulation test data to verify the exactness of constitutive equation. Figure 6 is the comparison of calculated and measured valued of peak stress at 0.1s$^{-1}$, 1s$^{-1}$ respectively. The relative
error are 1.42% and 1.73%. The relative error is small, and the difference of the values in different strain rate is very small. It expressed that the results between calculated and measured had good agreement, indicating that the establishment of constitutive equation can provide theoretical basis for practical production.

3.3. Hot deformation characteristics
The true stress-strain curve is the outward manifestation of microstructure during hot deformation, and the appearance of peak stress indicates the onset of dynamic recrystallization. But it is difficult to reflect directly when and where the dynamic recrystallization is initiated for the true stress-strain. So this experiment adopts the proposed by Poliak and Jonas [7, 8] to determine the SiCp/Al-Cu composites dynamic recrystallization critical strain:

\[
\frac{\partial}{\partial \sigma} \left( \frac{\partial \theta}{\partial \sigma} \right) = 0 \quad \left( \frac{\partial \theta}{\partial \sigma} \right)_\varepsilon = \left( \frac{\partial \ln \theta}{\partial \varepsilon} \right)_\varepsilon
\]  

(7)

According to the above equation, the characteristic of dynamic recrystallization is that not only the \(\theta-\sigma\) curve but also the \(\ln \theta - \varepsilon\) curve presents an inflection point. The \(\ln \theta - \varepsilon\) and the \((-\partial (\ln \theta) / \partial \varepsilon) - \varepsilon\) curve can be drawn based on figure 2. Using the relationship of \(-\partial^2 (\ln \theta) / \partial \varepsilon^2 = 0\), the critical strain of dynamic recrystallization can be obtained directly.

Figure 7 shows the relationship between strain hardening rate and strain in different deformation conditions. The derivative of the strain hardening rate as a function of the strain in different conditions was calculated according to figure 7. Figure 8 are the \((-\partial (\ln \theta) / \partial \varepsilon) - \varepsilon\) curves. The critical strain \(\varepsilon_c\) is the point at which the strain value is minimum in the plot.

The Sellars is widely used to build the prediction model of critical strain of SiCp/Al-Cu composite [9]:

\[
\varepsilon_c = kZ^n
\]  

(8)

Figure 7. The \(\ln \theta - \varepsilon\) curves of SiCp/Al-Cu composite under different deformation conditions(a) \(\dot{\varepsilon} = 0.01\) s\(^{-1}\); (b) \(\dot{\varepsilon} = 0.1\) s\(^{-1}\); (c) \(\dot{\varepsilon} = 1\) s\(^{-1}\); (d) \(\dot{\varepsilon} = 10\) s\(^{-1}\).
Figure 8. The $-\frac{\partial(ln\theta)}{\partial \varepsilon}$ curves of SiCp/Al-Cu composite under different deformation conditions (a) $\dot{\varepsilon}=0.01$ s$^{-1}$; (b) $\dot{\varepsilon}=0.1$ s$^{-1}$; (c) $\dot{\varepsilon}=1$ s$^{-1}$; (d) $\dot{\varepsilon}=10$ s$^{-1}$.

Where $k$ and $m$ are constants. Figure 9 illustrates the relationship between natural logarithm of the calculated strain and natural logarithm of the Zener-Hollomon parameter. It is clear that the value of $ln\varepsilon_c$ increases with the increase of Zener-Hollomon parameter [10]. and $ln\varepsilon_c$ shows higher linear relationship with $lnZ$, Therefore, the equation is determined as follows: $ln\varepsilon_c=0.079lnZ-6.62$. The equation for critical strain is given by: $\varepsilon_c=1.32\times10^{-3}Z^{0.079}$.

Figure 9. $ln\varepsilon_c$ versus $lnZ$ plot.

The steady-state strain can be obtained from figure 10 which shows the relationship between the strain hardening rate ($\dot{\theta}$) and strain ($\varepsilon$), these plots reduce quickly and then rise slowly, and the minimum points are below zero and represent the position where the dynamic dynamic softening is maximized. After this minimum point the work hardening rate increases and in the steady-state strain, the strain hardening rate reaches zero [11].
Figure 10. Strain hardening rate vs. strain for SiCp/Al-Cu composite (\(\dot{\varepsilon} = 0.01 \text{ s}^{-1}\)).

3.4. DRX kinetics

The critical strain is the point that dynamic recrystallization starts to happen, but it is difficult to understand the change of recrystallized fraction from the above calculation. \(X_{\text{DRX}}\) represent the recrystallized fraction. The Avrami equation can directly conduct the relationship between \(X_{\text{DRX}}\) and \(\varepsilon\) [12-15]:

\[
X_{\text{DRX}} = 1 - \exp \left[-B\left(\frac{\varepsilon - \varepsilon_c}{\epsilon_{0.5}}\right)^n\right]
\]  \(8\)

Where, \(B\) is the Avrami constant, \(n\) is the Avrami exponent, \(\varepsilon_c\) is the critical strain and \(\epsilon_{0.5}\) is the strain that the value of \(X_{\text{DRX}}\) is 50%. In order to avoid the interference of human factors in traditional observation of metallographic specimen, equation (9) is employed in the paper to determine the \(X_{\text{DRX}}\) [9]:

\[
X_{\text{DRX}} = \frac{\left(\sigma_{\text{drvss}}\right)^2 - \left(\sigma_{\text{drxss}}\right)^2}{\left(\sigma_{\text{drvss}}\right)^2 - \left(\sigma_{\text{drxss}}\right)^2}
\]  \(9\)

Where, \(\sigma_{\text{drvss}}\) and \(\sigma_{\text{drxss}}\) are the saturation and steady stresses, respectively. \(\sigma_{\text{drvss}}\) is the flow stress when DRV plays the important role in the softening mechanism. \(\sigma_{\text{drxss}}\) is the flow stress when DRX plays the important role in the softening mechanism.

\(X_{\text{DRX}}\) versus \(\varepsilon\) with various strain rates at different temperatures of SiCp/Al-Cu composite is shown in figure 11. From figure 11, the \(X_{\text{DRX}}\) increases with the increasing of true strain, and when the value of \(X_{\text{DRX}}\) reaches 1 indicate correspond strain by this point is steady-state strain. Furthermore, curves show a “S” shaped growth trend. The tendency of the curves is increased slowly-increased rapidly-increased slowly. In addition, when the strain is a constant, the recrystallized fraction decreases with the increase of strain rate [16].
Figure 11. $X_{DRX}$ versus $\epsilon$ curves (a)$T=623$ K; (b)$T=673$ K; (c)$T=723$ K; (d) $T=773$ K.

Using the relationship between strain hardening rate and strain that shows in figure 10, the position of the onset of steady-state strain can be determined, and this point is usually appear on the end of the curves where the strain hardening rate reaches zero. In figure 12, the strain hardening rate and recrystallized fraction are both plotted against strain at a strain rate of 0.01 s$^{-1}$ and a temperature of 623 K. Figure 12 confirms the accuracy of the model used to predict the dynamically recrystallized volume fraction. And the point at which the strain is steady-state strain coincides with the volume fraction of dynamic recrystallization is unity. So the model of DRX kinetic can be illuminated by the Avramy-type expression.

Figure 12. $\theta-\epsilon$ curves and $X_{DRX-\epsilon}$ curves.

4. Conclusions
Hot compression tests on SiCp/Al-Cu composite were performed at various strain rates and deformation temperatures and got the following conclusions:

- The main softening mechanism of SiCp/Al-Cu composite during the thermal deformation is dynamic recrystallization mechanism. The activation energy is 272.831 KJ/mol.
The critical strain can be identified from the inflection point on the $\ln \theta - \varepsilon$ and $-\partial (\ln \theta)/\partial \varepsilon - \varepsilon$ curves. There is a linear relationship between critical strain and peak strain, i.e., $\varepsilon_c/\varepsilon_p = 0.652$. The initial critical strain of dynamic recrystallization can be calculated by Sellars model setting, and there is a relationship between $\varepsilon_c$ and $Z$, $\varepsilon_c = 1.32 \times 10^{-3} Z^{0.079}$. The steady-state strain can be determined using $\theta - \varepsilon$ curve. The dynamic recrystallization volume fraction of SiCp/Al-Cu composite is investigated. The model of DRX kinetic can be illuminated by the Avramy-type expression.

References

[1] Frommert M and Gottstein G 2009 Mater. Sci. Eng. A 506 101-10
[2] Ebrahimi G R, Keshmiri H, Maldar A R and Momeni A 2012 J. Mater. Sci. Technol. 28 467-73
[3] Mirzadeh H, Cabrera J M, Prado J M and Najafizadeh A 2011 Mater. Sci. Eng. A 528 3876-82
[4] Meysami M and Mousavi S A A A 2011 Mater. Sci. Eng. A 528 3049-55
[5] Lin Y C and Chen Xiao-min 2011 Mater. Des. 32 1733-59
[6] Xiao X, Liu G Q, Hu B F, Zheng X, Wang L N, Chen S J and Ullah A 2012 Comp. Mater. Sci. 62 227-37
[7] Poliak E I and Jonas J J 2003 ISIJ Int. 43 684-91
[8] Jonas J J and Poliak E I 2003 Mater. Sci. Forum 426 57-66
[9] Xu Yao-wen, Tang Di, Song Yong and Pan Xiang-gang 2012 Mater. Des. 36 275-8
[10] Wei Hai-lian, Liu Guo-quan, Xiao Xiang and Zhang Ming-he 2013 Mater. Sci. Eng. A 573 215-21
[11] Mirzadeh H, Cabrera J M, Najafizadeh A and Calvillo P R 2011 Mater. Sci. Eng. A 528 3876-82
[12] Wang Meng-han, Li Yu-feng, Wang Wen-hao, Zhou Jie and Chiba Akihiko 2013 Mater. Des. 45 384-92
[13] Wang Jian, Xiao Hong, Xie Hong-bao, Xu Xiue-mei and Gao Ya-nan 2012 Mater. Sci. Eng. A 539 294-300
[14] Zeng Zhou-yu, Chen Li-qing, Zhu Fu-xian and Liu Xiang-hua 2011 J. Mater. Sci. Tec. 27 913-9
[15] Xu Dong, Zhu Xiao-yong, Tang Zheng-you and Sun Chao 2013 J. Wuhan Uni. Tec.-Mater. Sci. Ed 28 819-24
[16] Shanban M and Eghbali B 2010 Mater. Sci. Eng. A 527 4320-5