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# Effects of Oxide Inclusions on Flow Stress Behavior of 1235 Aluminum Alloy During Hot Compression

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**Flow stress characteristic of 1235 aluminum alloy treated by different purification methods was studied by dynamic thermo-simulation test. The effects of oxide inclusions on steady flow stress, peak stress, and true strain corresponding to peak stress were also examined in this study. The results showed that there is a steady flow feature in 1235 aluminum alloy during hot compression deformation. 1235 aluminum alloy with lower inclusion content shows higher strength, therefore, the plasticity and toughness are better and improve the hot-working character of the alloy. Therefore, reducing inclusion content is effective for improving the hot deformation character of aluminum foil (1235 aluminum alloy).**

**Keywords** 1235 aluminum alloy, flow stress, hot compression, oxide inclusions

## 1. Introduction

Aluminum foil is a kind of flexible metal which is made by repeatedly rolling commercially pure aluminum. 1235 aluminum stock is mainly used for cigarette foil, aluminum foil containers, and cooking bags; all of them have the advantage of innocuity, health, high flexibility, moisture resistance, etc. (Ref 1). Melt purification treatment is the key to improving the metallurgical qualities and forming properties of 1235 aluminum alloy; therefore, such treatment affects the mechanical behaviors during hot deformation. Oxide inclusion is the key factor throughout the process (Ref 2, 3). The flow stress behaviors of 1235 aluminum alloy treated by different purification methods were analyzed in this study, including the effects of inclusions. Studying this phenomenon is of theoretical significance and practical value in hot processing analysis and design.

## 2. Experiments

1235 aluminum alloys (aluminum foil) were used as the experimental material. The chemical composition of the 1235 aluminum alloy is shown in Table 1. Melt treatments including no melt-purification, conventional flux treatment, conventional refining, refining-filtering treatment, and high-efficiency purification (Ref 4, 5) were used in 1235 aluminum alloy. The effects of melt treatment are listed in Table 2. Ingots were dealt with homogenizing annealing under conditions of annealing temperature of 560 °C, holding for 13 h, and air-cooled (Ref 6). Isothermal axisymmetric compression tests were performed in Geeble-1500 dynamic thermal/mechanical simulation machine under conditions of deformation temperature of 400-450 °C, strain rate of 0.01-0.1 $s^{-1}$, and deflection of 50%. In the hot deformation tests, the system carried out the real-time measurement of temperature, displacement, true stress, true strain, and other parameters.

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## 3. Results and Discussion

Effects of different melt purification methods of 1235 aluminum alloy on hot compression deformation are different. Figure 1 shows the true stress-strain curves of differently-purified 1235 aluminum alloy obtained from hot compression test data. Table 3 lists the steady-flow stress, peak stress, and true strain corresponding to peak stress of Fig. 1.

As shown in Fig. 1 and Table 3, all the true stress-strain curves of 1235 aluminum alloy have peak stresses. Flow stress ascends with the increase in strain before it arrives at the peak. Such performance is called work hardening. However, flow stress descends with the increasing strain after the peak stress and expresses the trait of dynamic softening (Ref 7, 8). With the hot compression being continued, the flow stress increased, but the strain remained unchanged and displayed steady flow characteristics. In addition, the flow stress under hot compression varies with the changing deformation temperature and strain rate. At different deformation conditions, the flow stress first increases rapidly, then decreases, and comes to a steady-state. 1235 aluminum alloy has the characteristic of steady flow stress during hot compression deformation. The steady-state flow stress shrinks with the increasing deformation temperature; however, it enlarges with the increasing strain rate. Therefore, there is a steady flow characteristic in 1235 aluminum alloy during hot compression deformation. The plasticity and toughness are better for the higher flow stress. Consequently, the hot-working character of efficiency-purified 1235 aluminum alloy is good.

**Table 1 Chemical composition of 1235 aluminum alloy**

| Element | Si | Fe | Cu | Mn | Mg | Ni | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| Composition, wt.% | 0.095 | 0.38 | 0.002 | 0.002 | 0.0001 | 0.0001 | 0.006 | 0.015 | Remains |

**Table 2 Comparison among 1235 aluminum alloy after different melt purification treatment**

| Treatment conditions | Impurity content, % | Average size of inclusions, μm | Remarks |
|---|---|---|---|
| No melt-purification | 0.4154 | 54.6 | Impurity content was obtained by flux irrigation method (Ref 5). |
| Conventional flux treatment | 0.2443 | 40.9 | Average size of inclusions or grains was assessed by quantitative |
| Conventional refining | 0.1537 | 37.0 | metallography method (linear intercept method). |
| Refining-filtering treatment | 0.0828 | 25.3 | Average size of inclusions was obtained from the metallograph |
| High-efficiency purification | 0.0510 | 24.0 | Aanalyzing system mounted on a horizontal metallurgical microscope. |

**Table 3 Steady state flow stress ($\sigma_p$), peak stress ($\varepsilon_p$), true strain ($\sigma_s$) corresponding to peak stress of Fig. 1 (MPa)**

| Treatment conditions | (a) $\dot{\varepsilon} = 0.1$ s$^{-1}$, $t$ = 400 °C | | | (b) $\dot{\varepsilon} = 0.01$ s$^{-1}$, $t$ = 400 °C | | | (c) $\dot{\varepsilon} = 0.1$ s$^{-1}$, $t$ = 450 °C | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\sigma_p$ | $\varepsilon_p$ | $\sigma_s$ | $\sigma_p$ | $\varepsilon_p$ | $\sigma_s$ | $\sigma_p$ | $\varepsilon_p$ | $\sigma_s$ |
| No melt-purification | 30.72 | 0.062 | 27.62 | 22.54 | 0.041 | 19.10 | 27.29 | 0.024 | 18.12 |
| Conventional flux treatment | 30.61 | 0.063 | 26.45 | 25.82 | 0.035 | 18.67 | 26.79 | 0.028 | 17.96 |
| Conventional refining | 34.65 | 0.050 | 28.51 | 23.64 | 0.026 | 17.03 | 28.71 | 0.033 | 20.66 |
| Refining-filtering treatment | 31.60 | 0.059 | 25.35 | 28.34 | 0.042 | 20.55 | 27.88 | 0.034 | 19.40 |
| High-efficiency purification | 34.67 | 0.064 | 29.67 | 30.09 | 0.050 | 23.43 | 29.82 | 0.039 | 20.52 |

Under the same deformation condition, the lower the impurity content of 1235 alloy during hot compression, the higher the peak flow stress. Thus, the peak flow stress of 1235 aluminum alloy treated by high-efficiency purification is higher than those of other treatments, as shown in Fig. 1. At a strain rate of 0.1 s$^{-1}$ and deformation temperature of 400 °C, the peak flow stress of 1235 aluminum alloy treated by high-efficiency purification is 35 MPa, which is the highest. Then comes the conventional refining, and the peak flow stress of 1235 aluminum alloy without melt purification is only 31 MPa, which is the lowest.

The peak flow stress in 1235 aluminum alloy treated by high-efficiency purification appears later than those of other purification methods. Under the conditions of $\dot{\varepsilon}$ of 0.01 s$^{-1}$ and temperature of 400 °C, the appearance of peak is followed by no-melt purification, conventional flux treatment, conventional refining treatment, refining-filtering treatment, and high-efficiency purification as shown in Fig. 1(b). The true strains corresponding to peak stresses are 0.041, 0.035, 0.026, 0.042, and 0.050, respectively. It will be shown that 1235 aluminum alloy with low inclusion content has higher yield strength and tensile strength; as a result, the plasticity and toughness are better.

1235 aluminum alloy with lower inclusion content has higher steady flow stress during hot deformation. As shown in Table 3, the steady flow stresses of 1235 aluminum alloy treated by high-efficiency purification are 29.67, 23.43, and 20.52 MPa corresponding to deformation factors of (a), (b), and (c), respectively. However, the steady flow stresses of 1235 aluminum alloy without melt purification are 27.62, 19.01, and 18.12 MPa, which are lower than other purification conditions in sequence.

As seen clearly, the amount of impurity in 1235 aluminum alloy affects the flow stress immediately in hot deformation. Figure 2 shows the relationships between inclusion content and peak flow stress, and steady-state stress, respectively, for the conditions of $\dot{\varepsilon}$ of 0.1 s$^{-1}$ and temperature of 400 °C. Figure 3 shows the relationship between inclusion content and true strain corresponding to peak stress. Figures 2 and 3 show that peak flow stress, steady-state stress, and true strain corresponding to peak stress decrease with the increasing inclusion content; however, they show a slow decline when the amount of inclusions exceeds a certain value.

In short, there is a steady-state flow feature in 1235 aluminum alloy during hot compression deformation. 1235 aluminum alloy with lower inclusion content shows that higher strength; the plasticity, and toughness are also better, resulting in improved hot-working character of the alloy. Therefore, reducing the inclusion content is effective to improve the hot-working character of aluminum foil (1235 aluminum alloy).

## 4. Discussion

Aluminum alloys have a strong dynamic recovery effect for their high stacking fault energies; aluminum is easier to deform by cross slip and consumes less activation energy. Therefore, it is generally believed that aluminum alloys easily experience dynamic recovery, but not dynamic recrystallization (Ref 9, 10). However, it is found that it has obvious dynamic recrystallization in deformation by studying the true stress-strain curves. Dynamic recrystallization would increase to some degree in high-efficiency purified 1235 aluminum alloy under different deformation conditions.

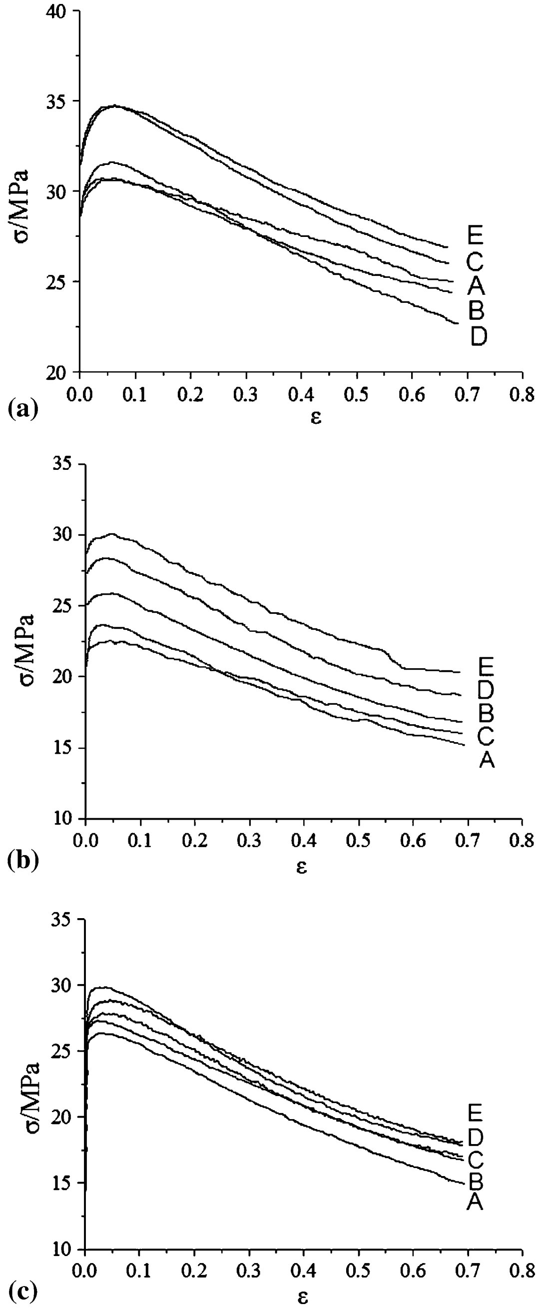


**Fig. 1** Relationship between melt purification and hot flow stress curves of 1235 aluminum alloy. The curves represent, A no melt-purification, B conventional flux treatment, C conventional refining, D refining-filtering treatment, and E high-efficiency purification. (a) $\dot{\varepsilon} = 0.1\ s^{-1}$, $t = 400$ °C, (b) $\dot{\varepsilon} = 0.01\ s^{-1}$, $t = 400$ °C, and (c) $\dot{\varepsilon} = 0.1\ s^{-1}$, $t = 450$ °C

The inclusion content and size differ in 1235 aluminum alloy of different purification methods, thus significantly affecting the hot deformation hardening. The inclusions affect the number of vacancies inside the alloy during hot deformation, causing the differences in climbing and cross slip of dislocation. Simultaneously, the stages of hardening and softening are different under the same hot deformation, as well as the peak flow stress and steady flow stress (Ref 11). Finally, the inclusion content affects the hot-working character of 1235 aluminum alloy significantly.

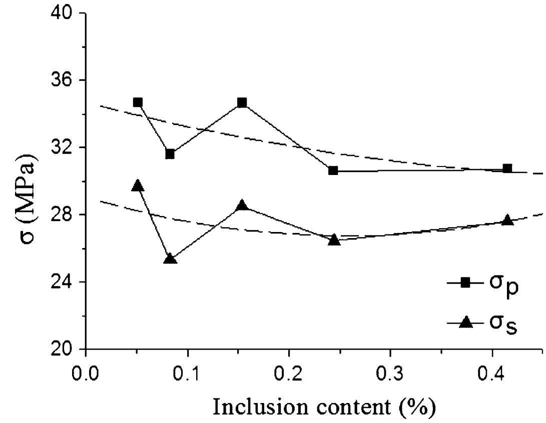


**Fig. 2** Relationship between inclusion content and stress ($\sigma_p$ vs. $\sigma_s$) ($\dot{\varepsilon} = 0.1\ s^{-1}$, $t = 400$ °C)

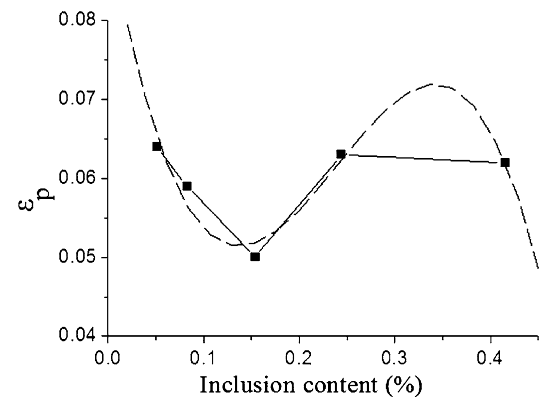


**Fig. 3** Relationship between inclusion content and true strain ($\varepsilon_p$) corresponding to peak stress ($\dot{\varepsilon} = 0.1\ s^{-1}$, $t = 400$ °C)

## 5. Conclusions

Flow stress characteristics of 1235 aluminum alloy with different inclusion contents were studied by hot compression testing. The following conclusions may be drawn from this study:

(1) 1235 aluminum alloy has the characteristic of steady-state flow stress during hot compression deformation. The steady-state flow stress shrinks with the increasing deformation temperature; however, it enlarges with increase in strain rate.
(2) Under the same deformation condition, the lower the impurity content of 1235 alloy during hot compression, the higher the peak flow stress. 1235 aluminum alloy with lower inclusion content has higher steady flow stress during hot deformation.
(3) 1235 aluminum alloy with lower inclusion content shows higher strength; the plasticity and toughness are better, thereby improving the hot-working character of the alloy. Therefore, reducing the inclusion content is effective to improve the hot deformation character of aluminum foil (1235 aluminum alloy).

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