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Effect of solute concentration on the serrated flow in solution-treated Al–4%Cu alloys*

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In order to compare with annealed Al–4%Cu alloys, the influence of solute concentration on the serrated flow is investigated by solution treatment. In this paper, some dynamic parameters, such as critical time and the ultimate tensile strength are obtained. Moreover, the change of the strain rate range for serrated flow in Al–4%Cu alloys prepared by annealing and quenching heat treatments is reported too. The difference between them is attributed to the increasing solute concentration in the bulk of the solution treated materials.

Keywords: Portevin–Le Chatelier effect, solution treatment, dynamic strain aging
PACC: 6220F, 8140C

1. Introduction

As is well known, the mechanical behaviour of industrial materials depends strongly on their microstructures. For example, the addition of alien solutes to a pure metal always produces an alloy that is stronger than the pure metal.[1−4] Moreover, the interactions between solute atoms and dislocations also play an important role in the process of materials plastic deformation. The Portevin–Le Chatelier (PLC) effect,[5−9] as an intriguing macroscopic representation of those microscopic interactions, manifests itself as localized deformation bands in the sample and repeated serrations in stress-strain curve, which is also referred to as 'serrated flow' or 'repetitive yielding'. Owing to its fascinating spatio-temporal characteristics, this special plastic instability has been extensively studied since the last several decades. And the most popularly accepted explanation for the PLC effect is the dynamic strain aging (DSA), i.e. the dynamic interaction of mobile dislocations with the diffusing solute atoms, which is first introduced by Cottrell[10] and later extended by others.[11−15]

Our interest in this paper is to investigate the temporal characteristics of the PLC effect in solution-treated Al–4%Cu alloys. Some dynamic parameters, such as the critical time and the ultimate tensile strength etc, are also to be obtained. And the difference from that in annealed materials is attributed to the change of solute concentrations in the bulk.

2. Experimental procedure

Before heat processing, polycrystalline flat samples with a gauge of 55mm×20mm×3mm were cut from a 3mm-thick plate along the rolling direction. The material used in our tests is A2017 aluminium alloy, which has a 4wt% copper element as its main solute component. In this alloy, the copper content far exceeds the solubility limit of Cu in Al (typically 0.2%) at room temperature. Therefore, a supersaturated solid solution with high concentration solutes (nearly 4%) can be obtained by solution treatment, i.e. annealed at 773K for 3h and then quenched in water. Since the material is prone to natural aging after quenching, all the solution-treated samples were immediately tested in tension at room temperature with a constant imposed strain rate in the range of 10^{-5} to $5\times10^{-3}s^{-1}$.

To detect the spatial aspects associated with the serrated flow, the dynamic digital speckle pattern interferometry (DSPI) technology is used in our

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tests. More details can be referred to our precious work.[16−19] The sampling rate of the CCD camera was chosen in the range of 0.5 to 30 Hz, depending on the imposed strain rate. The load and displacement data were recorded at a rate of 100 Hz. Additionally, for comparison, the experimental results for annealed A2017 alloys are also presented in this paper, and the annealing procedure can be referred to Ref.[18].

3. Experimental results

Under appropriate conditions, from the appearance of the recorded load/stress serrations or the spatial propagation features of the deformation bands, three types of PLC effect can be distinguished.[15,20,21] For type A, the deformation bands propagate continuously along the sample surface with repeated slight upper-yield stress fluctuations, as shown in Fig.1(a). However, associated with rather regular stress drops, as depicted in Fig.1(c), the type B bands propagate in a discontinuous way, giving a visual impression of a hopping propagation. When the type C PLC effect occurs, one may find strong regular stress drops and randomly nucleated static deformation bands, as presented in Fig.1(e).

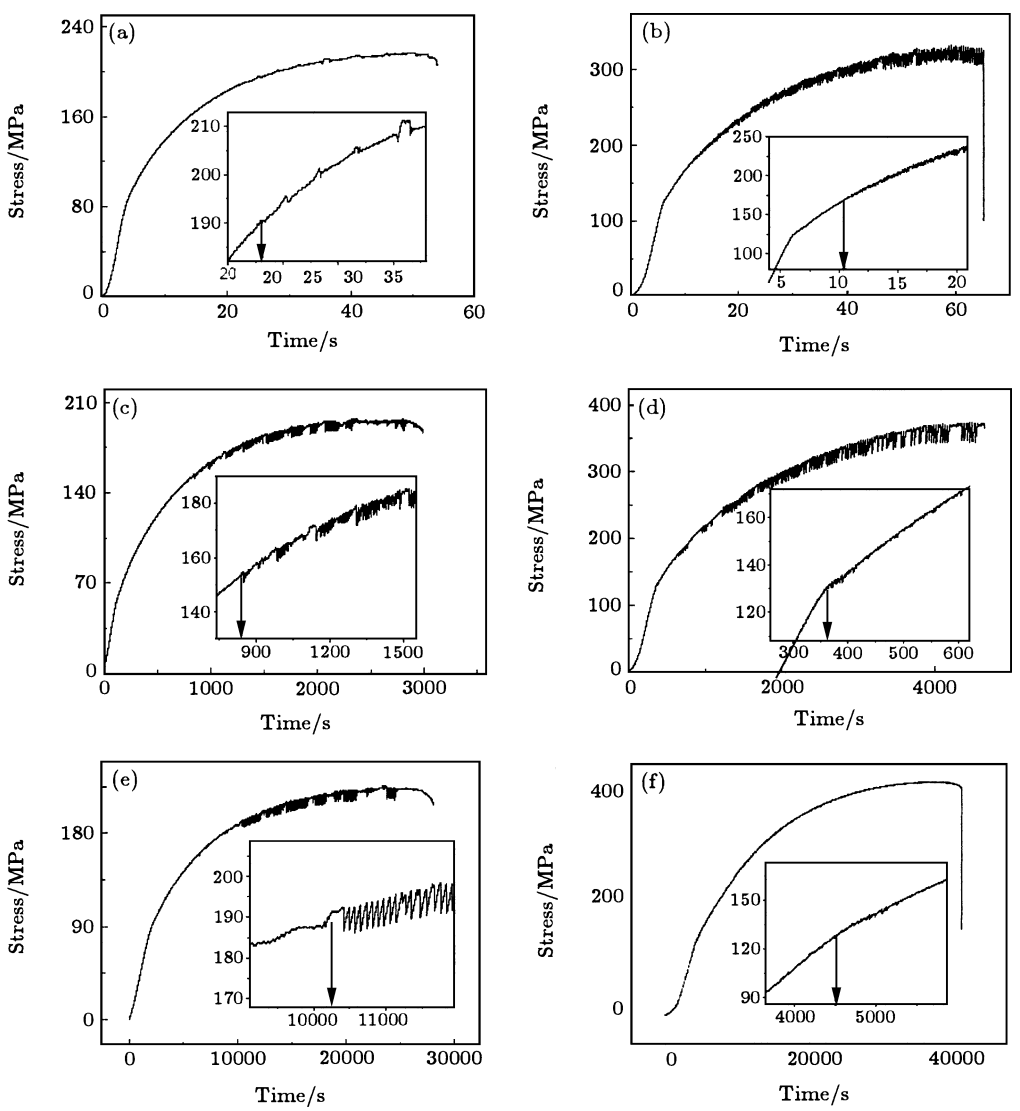


Fig.1. Serrated flow in Al–4%Cu alloys with different heat treatments and imposed strain rates, (a) annealed and the applied strain rate equal to $5\times10^{-3}s^{-1}$; (b) solution treated, $5\times10^{-3}s^{-1}$; (c) annealed, $10^{-4}s^{-1}$; (d) solution treated, $10^{-4}s^{-1}$; (e) annealed, $10^{-5}s^{-1}$; (f) solution treated, $10^{-5}s^{-1}$. Arrows in these figures indicate the critical time for the onset of the PLC effect.

Generally, the PLC effect in annealed materials will transit from type A to B to C by decreasing the imposed strain rate or increasing deformation temperature. From these figures, the representative type A PLC effect is expected in solution-treated materials at the same imposed strain rate of $5\times10^{-3}s^{-1}$. However, once the deformation entering into the plastic stage, the PLC effect emerges immediately with heavily serrated stress drops, depicting a traditional type C serrated flow, as shown in Fig.1(b). Similar phenomenon is obtained in Fig.1(d), even when the applied strain rate is lowered to $10^{-4}s^{-1}$. When the applied strain rate is lowered to $10^{-5}s^{-1}$, the stress–time curve of the solution-treated Al–4%Cu alloys possesses a smooth profile, compared with the distinct serrations in the annealed one, as shown in Fig.1(f). However, with the aid of the DSPI technology, some PLC deformation bands were detected to nucleate at the right initial stage of plastic deformation, and to disappear with further deformation. Correspondingly, an amplified portion of the whole stress–time curve, the illustration in Fig.1(f), presents the serrated stress fluctuations, depicting the temporal behaviour of the PLC effect. With development of deformation, the PLC effect will die out (no PLC deformation bands can be seen), leaving some tiny serrations in the stress–time curves. Moreover, it should be noted that, from Fig.1(b), 1(d) and 1(f), the ultimate tensile strength is increased from 331 to 371 to 418MPa with decreasing imposed strain rate in solution-treated Al–4%Cu alloy.

However, by increasing the imposed strain rate to $2\times10^{-2}s^{-1}$, the representative type A serrated flow can be obtained all the same, as shown in Fig.2. It should be noted here that this applied strain rate has exceeded the upper limit of the strain rate range for serrated flow existing in annealed Al–4%Cu alloy at room temperature, which is not more than $10^{-2}s^{-1}$. Additionally, notwithstanding a short segment of serrated flow is detected in Fig.1(f), the applied strain rate, i.e. $10^{-5}s^{-1}$, should be considered as the lower limit for solution-treated Al–4%Cu alloy, which is obviously larger than that for annealed ones. Therefore, it is readily concluded that the strain rate range for serrated flow in solution-treated Al–4%Cu alloy has been shifted to a larger value than that for annealed ones.

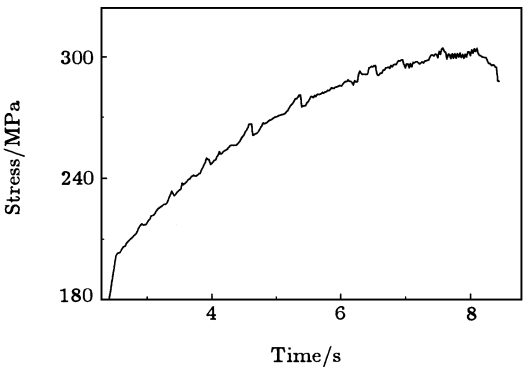


Fig.2. Type A serrated flow in solution-treated Al–4%Cu alloy with an imposed strain rate of $4\times10^{-2}s^{-1}$. Elastic portion of deformation is cut for a better view.

4. Discussion

In the theoretic frame of DSA, the dislocation glide is intermittent, which has been proved both by acoustic emission measurements and numerical simulations.[22] After a mobile dislocation being impeded by obstacles (such as forest dislocations, precipitates and grain boundaries etc.), solute cloud may form around it in response to solute segregations by preferred pipe diffusion, and the mobile dislocation is effectively pinned. With the aid of applied stress, obstacles can be overcome by thermally activated dislocation motion, and this unpinning process of dislocation may cause a stress drop on macroscopic stress curve. Thereby, the serrated flow is in response to the dynamic repeated pinning and unpinning process between mobile dislocation and solute atoms.

The occurrence of the PLC effect is governed by the strain rate sensitivity of the material and the latter decreases with increasing solute concentration in the bulk.[23] Additionally, some other ingredients should be considered too, such as initial dislocation densities and precipitation during deformation etc. In solution-treated materials, it is difficult to distinguish the influences of all types of defects. However, it is reasonable to attribute the immediate occurrence of the PLC effect at the beginning of plastic deformation, as shown in Fig.1(b) and 1(d), to the remarkable increase of solute concentration, i.e. from 0.2% in annealed materials to nearly 4% in the as-prepared solution-treated ones. Moreover, the experimental result in Fig.1(f), namely the PLC effect emerges at the initial stage of plastic deformation and vanishes with further strain, confirms the simulation deduction in the dislocation model of Kubin.[24]

By solution treatment, supersaturated solid solution can be obtained. Compared with annealed materials, the effect of DSA is enhanced in solution-treated materials as a result of more solutes diffusing to dislocations temporarily impeded by obstacles. Resulting from this, strong regular stress drops representing type C temporal behaviour may occur even when the imposed strain rate is rather high, as shown in Fig.1(b). In as-quenched Al–4%Cu alloys, copper atoms will aggregate in the (110) plane of supersaturated solid solution to form the Guinier–Preston (GP) zones during natural aging. When the applied strain rate is decreased, more GP zones will be formed with increasing aging duration. Therefore, the phenomenon that the ultimate tensile strength of the material increases with decreasing imposed strain rate is in response to the enhanced additional interactions of dislocations with more GP zones. Furthermore, it should be noted that the ultimate tensile strength of solution treated materials is larger than that in annealed ones, as shown in Fig.1. However, this enhancement should be attributed to the residual stress and large quantities of defects kept in solution-treated materials.

Generally, the serrated flow occurs when the dislocation mobility and solute diffusion ability are of the same order of magnitude.[10,25] In solution-treated materials, the solute diffusion ability is enhanced as a result of increasing solute concentration in the bulk. Correspondingly, to keep up with solute diffusion, the applied strain rate should be increased, since it is proportional to the dislocation mobility. Thus, the strain rate range for serrated flow in solution-treated Al–4%Cu alloy is larger than that in annealed one.

5. Conclusion

In this paper, serrated flow in solution-treated Al–4%Cu alloy has been investigated and compared with that in annealed one. At the same imposed strain rate, the critical time for the serrated flow occurrence is remarkably decreased in solution-treated materials. With decreasing imposed strain rate, the ultimate tensile strength is increased for solution-treated Al–4%Cu alloy. Moreover, the strain rate range for serrated flow in solution-treated Al–4%Cu alloy has been shifted to a larger value than that in annealed one. All the changes mentioned above should be attributed to the enhanced solute concentration in the bulk by solution treatment.

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