The Effect of Deformation Temperature on the Bauschinger Effect in Polycrystalline Aluminium

By Tadashi Hasegawa*, Takao Yakou*, Masafumi Shimizu**
and Seiichi Karashima***

In order to study the temperature dependence of the Bauschinger effect and to obtain information about the origin of the effect, compressive flow behavior of polycrystalline aluminium pre-strained by tension up to a fixed value of σ/E (σ : stress, E : the Young's modulus) was investigated at temperatures between 20 and 300°C. Several kinds of parameters to evaluate the Bauschinger effect, which are respectively in terms of stress, strain and energy, were measured at various amounts of reversed strains. These parameters, which are considered to be closely related to dislocation structures due to pre-straining and reversed straining, showed different temperature dependences. This fact indicates that the greatest care must be taken in comparing the results by different authors.

From the parameters obtained at small reversed strains it is concluded that the degree of the effect decreases with increasing temperature. Such temperature dependence of the effect is well explained from the change in dislocation structures with deformation temperature. The parameters determined at relatively large reversed strains seem to be greatly influenced by the change in dislocation structures during the reversed straining.

(Received August 9, 1975)

I. Introduction

The Bauschinger effect⁽¹⁾ has been reported not only in polycrystals but also in single crystals such as alpha-brass⁽²⁾, copper⁽³⁾, aluminium⁽⁴⁾ and zinc⁽⁵⁾; Buckley and Entwistle⁽⁴⁾ have shown that the magnitude of the Bauschinger strain in aluminium single crystal is comparable to that in polycrystalline aluminium of the same purity. Deformation behaviors during unloading and/or reloading in the reversed direction have since been investigated extensively^{(6)~(12)} on various metals and alloys pre-strained plastically, with a view to making clear the factors which control the effect. From these results it is now generally accepted that a large part of the Bauschinger effect does not originate from macroscopic residual stresses due to heterogeneous deformation of the grains in polycrystals⁽¹³⁾⁽¹⁴⁾, but from elastic interactions among disloca-

tions within the grains.

On the other hand, it is also well established that, with the increase in deformation temperature, the dislocation structures developed during plastic deformation change from cell structures to subgrain ones⁽¹⁵⁾⁽¹⁶⁾. Hence, if the Bauschinger effect is caused by the elastic interactions among dislocations, it is reasonably expected that the degree of the effect would change with deformation temperature. In most of researches reported hitherto, however, tension-compression tests or reversed torsion tests have been made at or below room temperature; few results have been obtained at high temperatures where subgrain structures are formed. In the present study compressive flow behavior of polycrystalline aluminium pre-strained by tension was examined over a wide range of temperature in order to examine the temperature dependence of the Bauschinger effect and to obtain information about the origin of the effect.

II. Experimental Procedure

Aluminium polycrystalline specimens (purity of 99.99%) with the gauge length of 20 mm and the cross section of 9×10 mm² were prepared by the same procedure as described

* Department of Mechanical Engineering, Tokyo University of Agriculture and Technology, Koganei-shi 184, Tokyo, Japan.

** Graduate School, Tokyo University of Agriculture and Technology, Koganei-shi, Tokyo.

*** Department of Materials Science, Tohoku University, Sendai 980, Japan.

Fig. 1 Sketch of tension-compression testing machine.

in a previous paper⁽¹⁷⁾. The grain size was about 0.9 mm. The contents of main impurities by wt% were as follows: Cu < 0.001, Fe < 0.008, Si < 0.002 and Mg < 0.001.

Specimens were deformed by tension-compression test with an Instron-type testing machine modified for tension-compression cyclic loading. In all cases the initial loading was in the tensile direction. A sketch of the testing machine used is shown in Fig. 1. Both ends of a specimen were firmly clamped by the grips using screws. A special jig was designed for the clamping. The axially of the push-pull rod of the machine during testing was ensured by the alignment joints and alignment cylinders. The buckling of the specimen was scarcely observed at least up to about 10% compressive strain.

Mechanical testings (strain rate: 4.2×10^{-4} sec⁻¹) were carried out at temperatures between 20 and 300°C (0.31–0.61 T_m ; T_m : the melting temperature in °K) using a silicone oil bath (below 200°C) and a 50%NaNO₃–50%KNO₃ salt bath (above 250°C). The temperature was controlled within $\pm 1^\circ\text{C}$ throughout the test. Stress was determined by the load cell and strain was measured from

cross-head displacement. In the present experiment, the loading direction was reversed from the points where tensile pre-stress, σ , normalized by the Young's modulus, E , at the deformation temperature⁽¹⁸⁾ attained to a fixed value ($\sigma/E = 1.44 \times 10^{-4}$).

III. Experimental Results

1. Stress-strain curves

Some examples of stress-strain curves at various temperatures are shown in Fig. 2. After a small tensile pre-strain at a relatively low deformation temperature work-hardening rate at an early stage of the compression test was smaller than just before the stress reversal (see, for example, the curve at 200°C). This tendency in work-hardening behavior became more remarkable with increasing temperature and increasing pre-strain. At higher temperatures the plastic deformation proceeded at an approximately constant stress in a strain region bounded by two arrows (see curves at 250 and 300°C). This region was called "Region of Constant Flow Stress"⁽¹⁹⁾. Details of the effects of temperature and of pre-strain on the work-hardening behavior at the stress reversal have been reported in a previous paper⁽¹⁹⁾.

2. Parameters to evaluate the Bauschinger effect

A number of parameters have been used for evaluating the degree of the Bauschinger effect.

Fig. 2 Some examples of stress-strain curves in tension-compression test.

For example, this effect has been estimated by the drop in the yield stress⁽²⁰⁾ or by the proof stress⁽¹⁰⁾⁽²¹⁾ at the stress reversal. Woolley⁽²²⁾, and Buckley and Entwistle⁽⁴⁾, on the other hand, referred to the effect in terms of the strain in the reversed direction (the Bauschinger strain). Abel and Muir⁽¹¹⁾ have recently proposed a parameter related to the energy in describing the effect. It seems impossible, however, to describe the effect completely by the use of a single parameter⁽¹¹⁾.

In the present work, the following parameters which are respectively related to the stress, strain and energy as schematically shown in Fig. 3 were measured at various amounts of the reversed strains.

(i) Parameters Related to Stress: σ_R/E and $\sigma_{0.1\%}/E$. The former is the normalized yield stress at which the stress-strain curve deviates from the linear elastic line and the latter the normalized 0.1% proof stress in the reversed deformation.

(ii) Parameters Related to Strain: β_0 , $\beta_{0.5}$ and β_1 . These are the so-called Bauschinger strains⁽⁴⁾ at $\sigma=0$, $-0.5\sigma_p$ and $-\sigma_p$, respectively, where σ_p is the tensile stress at the end of pre-straining in tension.

(iii) Parameters Related to Energy: $(E_s)_0$, $(E_s)_{0.5}$ and $(E_s)_1$. These energies corresponding to the areas of ΔABC , ΔADE and ΔAFG respectively have been called the Bauschinger energies⁽¹¹⁾ in the sense that they may help

Fig. 3 Schematic stress-strain curve showing the parameters to evaluate the Bauschinger effect.

Fig. 4 Change in parameters related to stress with deformation temperature. (a) σ_R/E and σ_R and (b) $\sigma_{0.1\%}/E$ and $\sigma_{0.1\%}$.

the deformation at the time of reversed loading.

(1) Parameters related to stress

The changes in σ_R/E and $\sigma_{0.1\%}/E$ with deformation temperature are shown in Figs. 4(a) and (b), respectively. As can be seen from the figures σ_R/E decreases and $\sigma_{0.1\%}/E$ increases monotonously with increasing temperature. In the figures also given are the absolute values of σ_R and $\sigma_{0.1\%}$ which respectively show the same temperature dependence as that of σ_R/E and $\sigma_{0.1\%}/E$.

(2) Parameters related to strain

The temperature dependences of β_0 , $\beta_{0.5}$ and β_1 are shown in Fig. 5. As in the case of σ_R/E , β_0 decreases monotonously with increasing temperature. The temperature dependences of $\beta_{0.5}$ and β_1 are somewhat different from that of β_0 ; they decrease at low temperatures ($< \text{about } 200^\circ\text{C}$), increasing at higher temperatures.

(3) Parameters related to energy

The changes in $(E_s)_0$, $(E_s)_{0.5}$ and $(E_s)_1$ with deformation temperature are shown in Fig. 6. As seen in the figure the value of $(E_s)_0$ decreases monotonously with increasing temperature as in the cases of σ_R/E and β_0 . However, $(E_s)_{0.5}$ and $(E_s)_1$ behave in the same way as $\beta_{0.5}$ and β_1 , showing the smallest values at about 200°C .

Fig. 5 Change in parameters related to strain, β_0 , $\beta_{0.5}$ and β_1 , with deformation temperature.

Fig. 6 Change in parameters related to energy, $(E_s)_0$, $(E_s)_{0.5}$ and $(E_s)_1$, with deformation temperature.

IV. Discussion

1. On the temperature dependence of the Bauschinger effect

As is described in Section III, σ_R/E , β_0 and $(E_s)_0$ decrease monotonously with increasing temperature over the temperature range examined. On the other hand, other parameters

show different temperature dependences: $\sigma_{0.1\%}/E$ increases monotonously with increasing temperature, though $\beta_{0.5}$, β_1 , $(E_s)_{0.5}$ and $(E_s)_1$ decrease below about 200°C but increase at higher temperatures, showing the smallest values at about 200°C. It may be said from these facts that different conclusions are drawn on the temperature dependence of the Bauschinger effect if the parameters shown above are respectively used. Therefore, one should be very careful in comparing the results by different authors.

It is generally accepted, as is described in Section I, that the Bauschinger effect originates from elastic interactions among dislocations, which may be in turn influenced by dislocation structures due to pre-straining and reversed straining. From this point of view the Bauschinger effect should be evaluated separately in earlier and later stages of the reversed deformation. The parameters, σ_R/E , β_0 and $(E_s)_0$, which are obtained at small strains in the reversed direction, are considered to be most suitable for the estimation of the direct influence of dislocation structures due to pre-straining on the Bauschinger effect. On this basis the Bauschinger effect may be concluded to decrease with increasing deformation temperature.

To the contrary, the parameters determined at relatively large reversed strains are considered to greatly be influenced by the change in dislocation structures during the reversed straining⁽¹⁷⁾. The abnormal increases in β_1 and $(E_s)_1$ at higher temperatures are due to the appearance of the "region of constant flow stress" where the dissolution and reformation of subgrain structures formed by pre-straining occur⁽¹⁷⁾.

2. On the origin of the Bauschinger effect

Dislocation theories which have been proposed to explain the Bauschinger effect can be divided into the following two groups: The first of these, which has originally been advocated by Seeger in his theory of work-hardening⁽²³⁾, is based on the idea of long-range back stresses built up during pre-straining. The second one arises from the consideration on the anisotropy of the resistance to dislocation motion⁽²⁴⁾ caused by the interaction of

moving dislocations with forest dislocations which are inhomogeneously distributed across the glide plane.

In a previous paper⁽¹⁷⁾ it was reported that cell structures developed during pre-straining are unstable against the stress reversal and the dissolution of cell walls occurs during the reversed straining. Ono et al.⁽²⁵⁾ have recently observed by transmission electron microscopy of Cu-Al solid solutions that the residual internal stress field, which is developed during pre-straining and is characterized by the contrast change, is removed by the reversed straining. These facts suggest that the theory which is based on the effects of long-range back stresses is more reasonable in explaining the Bauschinger effect.

Furthermore, as is shown in the Introduction, it is now well established that the dislocation structures developed by plastic deformation change from cell structures to subgrain ones with increasing deformation temperature⁽¹⁵⁾⁽¹⁶⁾. It may be also considered that the internal back stresses are larger near cell walls consisting of dislocation tangles than near sub-boundaries, because sub-boundaries with regular dislocation arrangements seem to be relatively strain-free. The above-mentioned conclusion that the Bauschinger effect decreases with increasing deformation temperature may reasonably be explained from the change in dislocation structures with deformation temperature.

V. Summary

The compressive flow behavior of polycrystalline aluminium pre-strained by tension was examined over a wide range of temperature in order to find appropriate parameters for representing the degree of the Bauschinger effect, to study the temperature dependence of the effect, and also to obtain information about the origin of the effect. The results are summarized as follows.

(1) Different conclusions are drawn on the temperature dependence of the Bauschinger effect if the different parameters are used. Therefore, one should be very careful in comparing the results by different authors.

(2) From the parameters, σ_R/E , β_0 and $(E_s)_0$, which may be most suitable for the estimation of the direct influence of dislocation structures

due to pre-straining on the Bauschinger effect, the effect is concluded to decrease with increasing deformation temperature.

(3) Such temperature dependence of the Bauschinger effect is well explained from the change in dislocation structures with deformation temperature.

(4) The parameters determined at relatively large reversed strains seem to greatly be influenced by the change in dislocation structures during the reversed straining.

Acknowledgments

The authors are grateful to Dr. Ryoji Watanabe and Mr. Toshio Kainuma, National Research Institute for Metals, Tokyo, for their help in the preparation of specimens, and to Mr. Masahiro Tokura for his assistance throughout the experiments.

REFERENCES

- (1) J. Bauschinger: Mitt. Mech.-Tech. München, **13** (1881), 1.
- (2) G. Sacks and H. Shoji: Z. Physik, **45** (1927), 776.
- (3) M. S. Paterson: Acta Met., **3** (1955), 491.
- (4) S. N. Buckley and K. M. Entwistle: Acta Met., **4** (1956), 325.
- (5) E. N. Edward, J. Washburn and E. R. Parker: Trans. AIME, **197** (1958), 1525.
- (6) T. Broom and R. K. Ham: Proc. Roy. Soc. A, **242** (1957), 160.
- (7) D. V. Wilson: Acta Met., **13** (1965), 807.
- (8) A. Abel and R. K. Ham: Acta Met., **14** (1966), 1489.
- (9) R. Horiuchi, S. Saito and T. Kishi: Bull. of the Inst. of Space and Aeronautical Science (Univ. of Tokyo), **6** (1970), 748.
- (10) T. Kishi and I. Gokyu: Proc. of ICSTIS, Suppl. to Trans. Iron Steel Inst. Japan, **11** (1971), 1044.
- (11) A. Abel and H. Muir: Phil. Mag., **26** (1972), 489.
- (12) A. Abel and H. Muir: Phil. Mag., **27** (1973), 585.
- (13) E. Heyn: J. Inst. Metals, **12** (1914), 3.
- (14) P. Rahlfs and G. Masing: Z. Metallk., **41** (1950), 454.
- (15) A. S. Keh and S. Weissmann: Electron Microscopy and Strength of Crystals, Interscience, (1963), p. 231.
- (16) M. R. Staker and D. L. Holt: Acta Met., **20** (1972), 569.
- (17) T. Hasegawa, T. Yakou and S. Karashima: Materials Sci. and Engg., **20** (1975), 267.
- (18) W. Köster: Z. Metallk., **39** (1948), 1.
- (19) T. Hasegawa and T. Yakou: Scripta Met., **8** (1974), 951.
- (20) A. H. Cottrell: Dislocations and Plastic Flow in Crystals, Oxford Univ. Press, (1953), p. 111.
- (21) T. Kishi and T. Tanabe: J. Mech. Phys. Solids, **21** (1973), 303.
- (22) R. L. Woolley: Phil. Mag., **44** (1953), 597.
- (23) A. Seeger, S. Mader and H. Kronmüller: Electron Microscopy and Strength of Crystals, Interscience, (1963), p. 665.
- (24) E. Orowan: Internal Stress and Fatigue in Metals, Elsevier, (1959), p. 59.
- (25) N. Ono, D. J. H. Corderoy and H. Muir: Proc. of 8th Intl. Congress on Electron Microscopy, Canberra, 1974, vol. 1, p. 586.