The Bauschinger Effect in an Age Hardenable Cu-30Ni-1Si Alloy

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Polycrystalline specimens of Cu-30Ni-1Si alloy containing G. P. zones, semicoherent γ' and the equilibrium γ phases have been subjected to a 2% plastic deformation in tension at ambient temperature. This was followed by a unidirectional compression. The observed Bauschinger effect has been analysed in terms of the current theories of precipitation hardening. The relative importance of the various contributions to precipitation hardening and the Bauschinger effect can be predicted on the basis of the present observation.

It is concluded that most of the Bauschinger effect in specimens containing G. P. zones can be accounted for by normal work-hardening in the matrix. The effect is found to increase with the coarsening of G. P. zones and reaches a maximum in the presence of semicoherent γ' precipitate phase. This is due to an excessive pile-up of back stresses which assist in the reverse deformation. The Bauschinger effect decreases during the formation and coarsening of the equilibrium precipitate phase, γ , but the effect is still larger than those observed during the formation of G. P. zones in the very early stages of the precipitation process. The present observation matches very well with the data reported for an Al-4 wt%Cu alloy having a similar precipitation sequence. A mathematical equation has been developed to describe the variation of the total strain with the permanent softening.

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I. Introduction

Bauschinger⁽¹⁾ first reported that after plastic deformation of a metallic material, the elastic limit was higher for subsequent loading in the same direction than for loading in the reverse direction. The Bauschinger effect is most clearly defined in terms of the "Bauschinger Stress", σ_B , which is the difference between the flow stress, σ_F , in the forward direction after some strain and the yield stress, σ_R , in the reverse direction. The strain in the forward direction is conveniently defined as "pre-strain".

An understanding of the Bauschinger effect has importance in structural materials subjected to alternating stresses or those that are pre-deformed. To understand the Bauschinger effect in an age hardenable alloy, it is necessary to have a knowledge of the structure, shape and distribution of precipitate phases. This information is known for a cupronickel alloy containing silicon from an earlier investigation⁽²⁾.

On aging solution treated cupronickel alloy

containing Si, densely populated coherent precipitate particles (G. P. zones) are formed in the alloy which coarsen with time at the aging temperature, Photo. 1(a). Upon prolonged aging, a semicoherent precipitate phase (γ') with a cube shaped morphology is formed, Photo. 1(b). The transformation of the solid solution to the γ' phase also results in an abundance of dislocation dipole clusters, Photo. 1(c). Finally, the equilibrium precipitate phase (γ) takes over forming continuously in the matrix and further aging results only in the coarsening of these particles. Earlier⁽³⁾⁽⁴⁾ mechanical property (hardness) results indicated that the hardness of the alloy increased with aging time, reached a maximum and then decreased continuously. The peak hardness has been found to correspond to the structure of the alloy consisting of the semicoherent γ' phase. Except for a change in shape and the absence of the θ'' phase, a similar age hardening sequence is observed for Al-4 wt%Cu alloy⁽⁵⁾⁽⁶⁾. It is the purpose of this investigation to determine the Bauschinger effect in a Cu-30Ni-1Si alloy and to correlate it with the observed structure on the basis of the current theories on precipitation hardening. Because of the similarity in the transformation behavior, a comparison will be made between the present data and those reported for Al-4 wt%Cu alloy.

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Photo. 1(a) Electron micrograph showing dense G. P. zones in a Cu-30Ni-1Si alloy.

(b) Electron micrograph showing cube shapes γ' precipitate.

(c) Electron micrograph showing dislocation dipole clusters in specimens containing semicoherent γ' precipitate.

II. Experimental Procedure

Alloys for this investigation were prepared by melting together appropriate amounts of copper, nickel and silicon in an induction furnace under a continuous flow of argon. High purity metals were used in preparing alloys. The alloys were

cast by pouring the melt into a copper mold preheated to approximately 400°C. The casting, 3 inches long and $\frac{1}{2}$ an inch in diameter, was cold swaged to a diameter of 0.4". The cold swaged rods were homogenized at 1000°C for a period of one day under dynamic vacuum in a quartz tube. In order to obtain rods suitable for small tensile specimens, the homogenized alloys were further cold swaged to a diameter of 0.234". Double shoulder specimens suitable for tension and compression tests were machined from the cold swaged rods.

All specimens were solution treated for 1 hr at 1000°C and quenched into a mixture of water and ice maintained at 1°C. In order to obtain various microstructures, the solution treated specimens were aged at preselected temperatures. The solution treatment and aging of all specimens was carried out under dynamic vacuum in a quartz tube.

All specimens were tested first in tension to a plastic strain of 2% and then tested immediately in compression in an Instron testing machine at a strain rate of 10^{-4} sec^{-1} . Yield stress (0.1% proof stress) in compression and tension was read directly from the chart. Flow stress in the forward direction was measured at 2% plastic strain. In order to determine the magnitude of the strain required to eliminate permanent softening of the material, the cumulative strain tests were also carried out. The experiment consisted of a large deformation in tension. The flow stress in the forward direction, σ_F , after a successively higher strain was compared to the stress obtained at the same cumulative strain, which represents the total strain of the forward and reverse directions.

III. Results and Discussion

The yield strength in tension is shown in Fig. 1 as a function of the time of aging at two temperatures (577 and 547°C). The plot follows the general trend of an age hardenable alloy where the stress to initiate plastic flow increases gradually in the early stages of aging followed by a rapid rise, a peak and then a gradual decrease. In terms of the distinction made by Orowan⁽⁷⁾, we can classify two types of dislocation barriers. In the first group corresponding to the G. P. zones, the dislocation barriers are expected to be

Fig. 1 The effect of aging time on the initial yield strength at 0.1 % proof stress.

relatively permeable. The slip dislocations can easily shear the particles and do not have to bow between them for continuous plastic flow. This is consistent with the nature of the slip which is coarser and less wavy in crystals containing G. P. zones⁽⁸⁾⁽⁹⁾. In the second group, corresponding to the semicoherent γ' and the equilibrium γ phases, the dislocation barriers are relatively strong. The plastic deformation is achieved by the dislocations bowing between the particles and forming loops, which create back stresses to approaching dislocations. The precipitate size and the relative interparticle spacing has significance in this respect.

The relative magnitude of the Bauschinger effect, represented by the difference between the flow stress in the forward direction (at 2 % strain) and the yield stress (at 0.1 % proof stress) in the reverse direction, for various stages of the precipitation process is shown in Fig. 2. In the presence of the G. P. zones the Bauschinger effect is relatively small. A maximum Bauschinger effect for specimens containing a semicoherent precipitate phase is apparent. This maximum in the Bauschinger effect is reached after the same time that gives a maximum stress to initiate yielding in the alloy. At the onset of γ , the magnitude of the above effect decreases.

Following treatments of Abel and Ham⁽¹⁰⁾, the flow stress in the forward direction, σ_F , after some pre-strain, may be regarded as having two components, a frictional stress σ_f and a back stress σ_b . At the flow stress in the forward direction $\sigma_F = \sigma_f + \sigma_b$, giving positive signs to σ_f and σ_b both of which give resistance to deformation. On stress reversal, yielding starts at

Fig. 2 The effect of aging time on the Bauschinger stress, defined as the difference between the flow stress (at 2 % strain) in the forward direction and the yield stress (at 0.1 % proof stress) in the reverse direction.

σ_R given by $\sigma_R = \sigma_f - \sigma_b$. The back stresses created during plastic deformation in the forward direction aid in the initiation of yielding on reverse straining. This produces Bauschinger effect as indicated by earlier investigators. From a knowledge of the flow stress in the forward direction and yield stress in the reverse direction, values of σ_f and σ_b can be evaluated.

In specimens containing G. P. zones and the θ'' phase of Al-4.25wt%Cu alloy, it has been reported⁽¹⁰⁾ that the Bauschinger effect is quite small. Moreover, less than 10 % of the flow stress is back stress, so that over 90 % is friction stress due to dislocation interaction, solution hardening and particle shearing. Cupronickel alloys of this investigation show about the same pattern where back stresses are approximately 4.23 and 5.23 kg/mm² respectively for flow stress levels of 45 and 59.17 kg/mm² in specimens containing G. P. zones. In specimens containing semicoherent γ' and equilibrium γ phases, proportion of the back stress is relatively high.

As pointed out by earlier investigators^{(11)~(13)} the resistance of the particles to cutting by matrix dislocation generated during deformation can be attributed to the following possible contributions:

- Disordering within the particles and/or at the particle matrix interface during cutting.
- The interaction of the matrix dislocations with coherency strains near the particle.
- The interaction of the matrix dislocations with the stress field of the transformation induced dislocations.

- (d) The formation of particle-matrix interfacial dislocations during cutting.
- (e) Repulsion of the matrix dislocations from the particle due to the elastic modulus of the particles being greater than that of the matrix.
- (f) Repulsion of matrix dislocations from the particles, due to gradients of solute near the particles.

In consideration of the Bauschinger effect in crystals containing G. P. zones, mechanism (a) will operate for particles that are sheared backward along the same planes on which they were sheared initially; mechanism (d) will do the same even if the reverse shear does not occur on the forward plane⁽¹⁰⁾. Since there is a small Bauschinger effect for crystals containing G. P. zones, it appears that shearing of the G. P. zones does not occur precisely on the same plane on which it occurred in the forward direction. This results in a higher σ_R and thus a low Bauschinger Stress. Small back stresses built up in the forward direction also play an important role in giving a small Bauschinger effect. This occurs because of the relative ease with which the G. P. zones can be sheared in the forward direction. Our observations are quite consistent with those of Abel and Ham⁽¹⁰⁾ and Wilson⁽¹⁴⁾, both of whom have reported small Bauschinger effect for crystals of Al-4 wt %Cu alloy containing G. P. zones.

Turning now to specimens containing γ' and γ phases, the very large Bauschinger effect is very consistent with the theory of the build up of back stresses during the forward deformation. This theory after Orowan suggests that during forward deformation there is a continuous build up of back stresses at the particle matrix interface. These stresses, at least in part, are utilized in reverse flow to initiate yielding thus giving rise to a large Bauschinger effect. The dispersion hardening theory of Ansell and Lenel⁽¹⁵⁾⁽¹⁶⁾ on the other hand can not explain such a large Bauschinger effect for crystals containing γ' and γ phases. According to this theory, shearing of the particle occurs at a very early stage which is followed by a build up of back stresses. Measurements by Wilson⁽¹⁴⁾ have indicated that back stresses contribute between a quarter and a

Fig. 3 The effect of aging time on the rate of work hardening $(d\sigma/de)$. $(d\sigma/de)_T$ and $(d\sigma/de)_C$ represent work hardening at 2% strain in tension and after an additional 2% reverse strain respectively.

half of the total flow strength during reverse straining of crystals containing the semicoherent θ' phase of the Al-Cu system.

The work hardening rate in tension at 2% strain as a function of the time of aging is shown in Fig. 3. There is a continuous increase in the work hardening rate from coherent G. P. zones to the incoherent γ phase. The work hardening measured at the same strain level after an additional reverse straining indicates that there is a continuous increase, followed by a maximum and then a gradual decrease. If back stresses are developed in prestraining they will at first assist dislocation movement on reverse straining. However, continued reverse straining will progressively annul back stresses created during forward deformation and eventually a new pattern of such stresses will be developed. The sign of these stresses will be opposite to the original ones. In crystals containing G. P. zones, the shear is retracable to a large measure giving rise to a lower work hardening rate in reverse straining. However, in crystals containing γ' precipitate, reversal of the internal stress system will develop inhomogeneously and in a much more complex manner giving rise to a rather large work hardening rate. Dislocation interaction plays an important role in this respect.

In order to study the total strain required to remove the permanent softening of the material, difference in the flow stress and the stress after the same cumulative strain was measured. The data is plotted in Fig. 4 for various precipitation stages in this alloy system. In all cases, the data

Fig. 4 The difference between the flow strength in continued forward deformation and the reverse deformation at the same cumulative strain, ϵ_c . A cumulative strain is the sum of the forward and the reverse strains applied to the same specimen.

appears to fall on a straight line represented by a relationship of the following type:

$$\sigma_R = m \log \epsilon + k,$$

where m and k are constants. The three straight lines appear to have the same slope. The only difference lies in the constant k of the above equation. The value of " k " increases with the time of aging. A relatively small value of " k " indicates a small degree of permanent softening, which is consistent with the work of Wilson⁽¹⁴⁾ on specimens of Al-Cu alloys containing G. P. zones. Wilson⁽¹⁴⁾ presented similar data as a ratio of the stress in the reverse direction to the flow stress in the forward direction at the same total strain.

The permanent softening of a material can also be measured by finding the difference between the flow stress in the forward direction after a small strain and the stress after an additional reverse straining to the same magnitude. Measurements made on Cu-30Ni-1Si alloys have indicated negligibly small permanent softening for crystals containing G. P. zones, Fig. 5. Similar analysis made in the stability range of γ' and γ phases has given a rather large degree of permanent softening. The flow stress in the forward direction (tension in this case) at 2% strain is also plotted in this figure for comparison. A slight shift in the time to attain maximum softening is apparent. This results from a decreased work hardening rate in reverse straining at the onset of γ phase precipitation as can be seen from Fig. 3.

Fig. 5 The effect of aging time on the initial tensile flow stress (σ_F) at 2% strain and the degree of permanent softening measured after the same reverse strain.

IV. Conclusions

(1) The Bauschinger effect in specimens of Cu-30Ni-1Si alloy containing coherent precipitates (G. P. zones) is similar to that in pure fcc metals. It can be explained by work-hardening in the matrix. It is also similar to the G. P. zones of Al-4 wt % Cu alloy.

(2) A maximum Bauschinger effect is observed in the alloy consisting of semicoherent γ' precipitate and can be explained by an ease in the reverse flow due to continued build up of back stresses at the particles during forward deformation.

(3) A linear relationship between $(\sigma_F - \sigma_c)$ and $\log \epsilon$ is obtained for experiments carried out on cumulative straining. The slope of the curves, m , remains almost the same. The constant k in the equation $(\sigma_F - \sigma_c) = m \log \epsilon + k$ gives the strain required to remove the permanent softening of the material during reverse straining.

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