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Effect of deformation mode and grain size on Bauschinger behavior of annealed copper

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A B S T R A C T

The present investigation looks into the effect of forward deformation mode, monotonic and cyclic, but asymmetric, on the Bauschinger phenomenon of annealed polycrystalline copper in terms of different Bauschinger parameters for 2.5–18% unidirectional tensile strain. Apart from the amount of deformation, the Bauschinger phenomenon has also been looked into as a function of stress rate used for forward deformation and also the grain size. It is found that Bauschinger effect is less pronounced when the forward deformation is carried out through asymmetric cyclic loading as compared to monotonic loading. This difference in the Bauschinger effect is attributed to lower back stress developed during asymmetric cyclic loading as compared to monotonic deformation. In the present investigation very negligible influence of stress rate on Bauschinger effect has been observed. On the other hand, for both monotonic and asymmetric cyclic deformation it is observed that Bauschinger effect is more in case of fine grain size.

1. Introduction

It is known that the symmetry in the stress–strain relationship in tensile and compressive direction is only maintained as long as deformation is restricted in the elastic domain. In 1981 Bauschinger [1] showed that this symmetry in the elastic stress–strain relationship breaks down as the deformation in any direction, called forward direction, exceeds the yield stress of the material. It is well established that if a material is plastically deformed in one direction, plastic flow in the reverse loading direction occurs at a lower stress as compared to forward loading direction. In general, during monotonic or cyclic plastic deformation dislocations are piled-up against different kinds of barriers. As a result, back stress is generated, which subsequently reduces the yield stress of a material when the direction of deformation is reversed. Such reduction of yield stress in the reverse loading direction due to prior forward loading in the plastic regime is known as Bauschinger effect or Bauschinger phenomenon. Since the publication of the results by Bauschinger, numerous investigations have been done for a deep understanding of the phenomenon involved in lowering the reverse flow stress in different metals and alloys once it has been plastically deformed in the forward direction. Challenger and Vining [2] have studied the evolution of dislocation structure and the development of back stress in $2\frac{1}{4}$ Cr–1Mo steel at 755 K. In this study Challenger et al. observed the variation in Bauschinger effect between symmetric and asymmetric strain-control cyclic loading. In this study by asymmetric loading means strain-control loading with a dwell period at only one strain limit. However, the effect of dwell period on dislocation structure and the development of back stress have been studied not only at either peak tensile strain or the peak compressive strain, but also at both the tensile and compressive strain limits. It was observed that due to constant-strain holding the Bauschinger effect was reduced due to lowering of back stress which happens due to thermally activated motion of some dislocations which were piled up against barriers. It may be noted here that in this kind of asymmetric loading experiments there is no scope for strain accumulation with progressing of cyclic loading. In spite of so many investigations the Bauschinger phenomenon in case of prior unidirectional deformation that occurs during stress control asymmetric cyclic loading has not been studied separately. It is known that permanent deformation occurs in the direction of mean stress during stress controlled asymmetric cyclic loading of metals and alloys in the elastic–plastic domain, and the rate of accumulation of such permanent deformation depends upon stress rate, mean stress and

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Nomenclature

β_σ	Bauschinger stress parameter
β_h	Bauschinger hardening parameter
β_ε	Bauschinger strain parameter
β_E	Bauschinger energy parameter
σ_P	maximum pre stress
σ_{y1}	0.2% offset yield stress
σ_{y2}	yield stress in the direction of reverse strain (0.05% strain)
ε_P	pre-strain
ε_r	Bauschinger strain, the strain in the reverse direction corresponding to the point of reverse stress equal to the maximum pre stress (σ_P)
E_P	energy spent during pre-strain
E_s	energy saved during reverse straining due to the Bauschinger effect
σ_b	back stress
σ_{ef}	effective stress
σ^*	thermal part of effective stress
σ_μ	athermal part of effective stress

stress amplitude. Such unidirectional plastic deformation during asymmetric cyclic loading in the elastic–plastic domain is known as ratcheting or ratcheting deformation.

There are two kinds of mechanisms behind the Bauschinger effect [3,4]. In one mechanism, during plastic deformation dislocations accumulate at barriers and produce both long range and short range interactions and dislocation pile-ups are formed [3]. As a result back stress is developed in the material, which assists the movement of dislocation in the reverse loading direction. In the second mechanism [4], when the loading direction is reversed, dislocations of opposite sign are produced from the same source, attract each other and annihilation of dislocations occur. Since strain hardening is related to dislocation density, reducing the number of dislocations reduces the strength. The net result is that the yield strength in reverse loading direction becomes lower than what is observed in case of forward loading direction.

According to the back stress theory [3], Bauschinger effect should be pronounced with the increase of dislocation density. It is known that with increase in the amount of forward strain piling up of dislocations becomes more resulting in the development of more back stress which, in turn, influences the Bauschinger parameters [5–9]. But once a dislocation becomes immobile by interaction, it does no longer contribute to back stress in a dislocation pile-up [10–12]. With increase in the amount of forward strain the mobile dislocation density may be reduced due to more and more dislocation interaction and possible formation of more stable dislocation structure [13]. Therefore, increasing the amount of prestrain the back stress increases up to a certain level of prestrain and then decreases or saturates depending upon the number of mobile dislocations present in the material [6,7,14]. In dealing with the Bauschinger phenomenon, besides the amount of forward deformation another factor, e.g. stress rate, also needs to be considered as it is known that flow stress of a material increases with increase of stress rate due to higher mobile dislocation density and dislocation velocity. The increase of flow stress occurs due to the formation of more barriers against dislocation movement because of more dislocation–dislocation interaction apart from the interactions between dislocations with different barriers. Accordingly, it is expected that increasing the stress rate in the forward direction would lead to the development of higher back stress and consequently the Bauschinger parameters would be influenced when the change in stress rate is sufficient to significantly alter the work hardening behavior of that material [5,15–20].

It is well known that grain size of a material profoundly influence the mechanical properties of materials. The dislocation model of the well known Hall–Petch relationship, which describes the yield strength variation in terms of the grain size [21–24] is based on piling-up and retardation of dislocation movement at grain boundaries, and number of dislocations present within a grain. The decrease of flow stress with increase of grain size is due to easy movement of dislocations in coarse grain sized material, and as a result piling-up of dislocations becomes less [25–27]. According to Kocks–Mecking–Estrin model [28,29] dislocations stored in the vicinity of grain boundary or within a grain contribute both to forest hardening and to building up of back stresses. Even at small strain, grain boundaries act as perfectly opaque barriers to dislocations. Piling-up of dislocations against grain boundaries leads to the development of back stress and hence impede the movement of similar dislocations. Due to annihilation of dislocations during cyclic deformation the stored dislocation density becomes less as compared to monotonic deformation [30–32]. Therefore, a comparative study about the effect of grain size on the development of back stress vis-à-vis Bauschinger effect under both modes of forward deformation, monotonic and cyclic, is considered to be an important task.

The objective of the present investigation is to make a comparative study on the effect of forward deformation mode (monotonic and cyclic, but asymmetric) and stress rate on the Bauschinger behavior of annealed polycrystalline copper of varying grain size. While to study the effect of deformation mode different amounts of unidirectional (+ve, i.e., tensile) strain has been considered, the effect of stress rate has been investigated for a fixed amount of forward strain.

2. Experimental procedure

2.1. Material and optical metallography

The present investigation has been done on annealed polycrystalline copper with a purity level of 99.97%. The material was received in the form of 12 mm diameter rod. Cylindrical specimen blanks of 120 mm length were annealed at 520 °C and 770 °C for an hour and then quenched in water. Specimens for optical metallography were obtained by transverse sawing of annealed specimen blanks and then mounted in bakelite using Struers hot mounting press, CitoPress-1. The bakelite mounted specimens were metallographically polished using abrasive papers in successively finer order and final polishing was done with the help of Struers make auto-polisher TegraPol-21. After metallographic polishing the specimens were etched with $FeCl_3$ solution. The polished and etched specimens were observed under an inverted optical microscope, Leica DMILM. Microstructures were grabbed by using a digital camera, Leica DC300 coupled with a personal computer. The average grain size of annealed copper samples was measured by using linear intercept method. The mean linear intercept grain size (L) was converted to grain size/diameter (d) by using ASTM standard E112.