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Study of Bauschinger Effect by Reverse Shearing of 70:30 Brass

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Abstract. Reverse shear experiments were conducted on a low stacking fault energy (SFE) material, namely 70:30 brass, and for comparison a high SFE material, namely commercial pure aluminum 1100, was chosen. Interesting results on the Bauschinger effect were observed. Appreciable Bauschinger effect was seen for 70:30 brass and this was explained through a new possible de-twinning theory, investigated here, which causes the fraction of twin to decrease during the reverse cycle leading to a decrease in the flow stress level. The other possible reason considered is the appreciable back stress developed due to the presence of obstacles (deformation twins) causing dislocation pile-ups, a theory previously investigated. The de-twining hypothesis was verified using deformation path change tests (changing deformation mode from simple shear to simple compression). It was also seen that the Bauschinger effect was negligible for aluminum (a high SFE material). Microscopic study was conducted on the sheared samples to study the microstructure evolution during forward and reverse shear deformation.

Keywords: Bauschinger effect, Simple shear, Brass, Aluminum, Deformation twinning.

Introduction

When certain metals are loaded uniaxially into the plastic regime, unloaded, and then reloaded in the reverse direction, they may yield during the reloading, at a stress lower than if the reloading were carried in the original direction. This direction dependent yield behavior is known as the Bauschinger effect, after Bauschinger, who first reported this phenomenon in 1881. Qualitative and quantitative information of hardening and softening mechanisms can be obtained from Bauschinger experiments. The drop in flow stress upon stress reversal has been attributed largely to the back stress developed in a dislocation pile-up. One of the earliest concepts to explain strain hardening was the idea that dislocation pile-up on slip planes at barriers such as grain boundaries second phases or sessile dislocations [1]. Dislocations piled up against a barrier produce a back stress that acts to oppose the motion of additional dislocations along the slip plane in the slip direction. The back stress developed as a result of dislocation piling up at barriers during the first loading cycle aid dislocation movement when the direction of slip is reversed. Furthermore, when the slip direction is reversed, dislocations of opposite sign could be created at the same sources that produced the dislocation responsible for strain in the first slip direction. Since the dislocation of opposite signs attract and annihilate each other, the net effect would be a further softening of the lattice (dynamic recovery). This can explain why the flow curve in the reverse cycle lies below the curve for continued flow in the original direction for some metals. Figure 1 depicts the main characteristics of reverse yield behavior commonly observed for a group of metals. If the load is removed, the material will unload elastically, if loading is then recommenced in the reverse direction, curve B-D is produced (curve BD is re-plotted as absolute stress versus accumulated strain). The plot shows the transient softening at small reverse strains as well as the permanent softening at large reverse strains. Compare curve BD with curve AC which is produced if the re-loading was recommenced in the original direction.

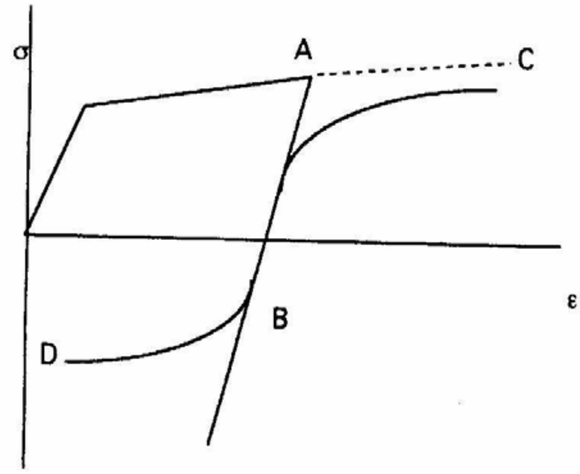

Fig. 1. Schematic presentation of reverse loading behavior for metals displaying the Bauschinger effect.

Most Bauschinger experiments were performed at quasistatic loading rates (10^{-5} /s to 10^{-2} /s) and at room temperature [2-4]. However, it is well established that the dislocation substructure resulting from deformation is strongly influenced by the strain rate and the temperature of deformation. Thakur *et al.* [1] studied the Bauschinger effect in Haynes 230 alloy, and showed that at high strain rate (10^{3} /s) a drop in flow stress of about 240 MPa was observed upon stress reversal, at room temperature. Reducing the temperature to 77 k, with high strain rates, increased the Bauschinger effect significantly, to about 440 MPa drop in stress level. The Bauschinger effect depends largely on the definition of the reverse yield point. Certain materials exhibit a yield point or a yield stress plateau in the reverse direction. On the other hand, the stress–strain curve for reverse deformation for Al-Cu [2] alloys was very rounded at small reverse strains and did not exhibit a yield stress plateau. For these alloys, the reverse yield stress was defined as a fixed deviation from the proportional behavior. Thakur *et al.* [1] used the stress corresponding to reverse offset strain of .002 as a measure of the reverse yield stress closely related to the offset yield strength defined in the ASTM standards . Gracio *et al.* [4] conducted strain reversal experiments on 6022 aluminum alloy under different aging conditions in simple shear in order to characterize the Bauschinger effect for the different heat treatment conditions. It was shown that the T4 and under-aged conditions, where high strain hardening rates were observed, lead to permanent softening of the flow stress.

In 1953, Woolley [5] performed rigorous Bauschinger experiments on fcc and bcc metals. Woolley observed that the Bauschinger effect is more pronounced in fcc metals compared to the bcc metals investigated. In addition, the Bauschinger effect in polycrystalline fcc metals that deform only by slip was independent of grain size and temperature. However, Thakur *et al.* [1] reported that the Bauschinger effect increases slightly with the reduction of grain size for materials that deform by twinning .

Wilson [6] observed that two-phase alloys showed a large drop and a permanent lowering in the flow stress upon stress reversal with respect to the forward loading cycle compared to single-phase alloys. He observed that this permanent softening (i.e. permanent drop in the flow stress for a given strain) increased with a decrease in the stacking fault energy (SFE) of the material. For a relatively constant volume fraction of precipitates, the permanent softening increased with the decrease in the mean spacing of precipitates. Thus, the Bauschinger effect was attributed to the effectiveness of precipitates and other kinds of dislocation barriers, as well in impeding the motion of dislocation and accumulate internal stress during the forward deformation. The influence of the γ'-precipitates on the Bauschinger effect, in the Inconel X-750 Nickel-base superalloy, has been investigated [7] for: solution heat treated, underaged, and overaged samples. It is found that the internal stresses increase with the aging time, providing evidence on the appearance of unshearable particles in the microstructure.

Moan and Embury [2] defined the Bauschinger stress parameter B_σ to evaluate the Bauschiner effect, as $(\sigma_f - \sigma_r) / 2\,\sigma_f$, where σ_f is the maximum flow stress in the forward direction, and σ_r is the yield stress upon reloading in the opposite direction. $(\sigma_f - \sigma_r)$ represents the back stress developed in piled up dislocations, which aids yielding in load reversals. Reverse yielding asymmetry is common in most classes of metals. While often overlooked, this is a regime of interesting and technologically important inelastic behavior. For example, it is the unloading and reloading response during sequences of metal forming that dictates residual stress fields in a work piece. For instance, a study of OFHC copper revealed a directionally-dependent strain softening behavior after reyielding in reverse yield experiments which is linked to rapid dissolution and reformation of dislocation cells [8]. This phenomenon has been observed in other cell forming materials [9-11]. Modeling sheet metal forming operations requires understanding of the plastic behavior of sheet alloys along non-proportional strain paths. Measurement of hardening under reversed uniaxial loading is of particular interest because of its simplicity of interpretation and its application to material processing [12]. Rolett *et al.* [13] reported the texture of reverse torsion experiments in aluminum, in which the equi-axed grain shape is restored and a weak shear texture is retained.

The objective of this study is to: (1) document and compare the Baushinger effect, in simple shear deformation, in a high and low SFE material; in other words, a material that deform by slip only versus a material that deform by twinning beside slipping respectively. (2) A new hypothesis for Bauschinger effect in metals that deform by twinning, through de-twinning during the reverse loading cycle, is tested. (3) The study will document, as well, the microstructure evolution during forward and reverse shear deformation.

Experimental Procedure

The geometry of the sample and the experimental setup for simple shear is shown in Fig. 2. The sample is made of three-bulk pieces comprising two-gauge sections in between. The side bulk pieces are constrained from motion, where as the middle bulk piece is linked to a crosshead that moves vertically up and down (cross head moves down for forward cycle, and up during reverse cycle), thus exerting a simple shear deformation to the two-gauge sections. The test was conducted at a strain rate of about 0.0015 s^{-1} . The rate sensitivity parameter was measured to be about 0.01 in strain-rate jump test. In deformation path change tests (changing deformation mode from simple shear to simple compression), a compression sample is machined, by wire cutting, out of the gauge section as shown in Fig. 2, and compressed in direction (3).

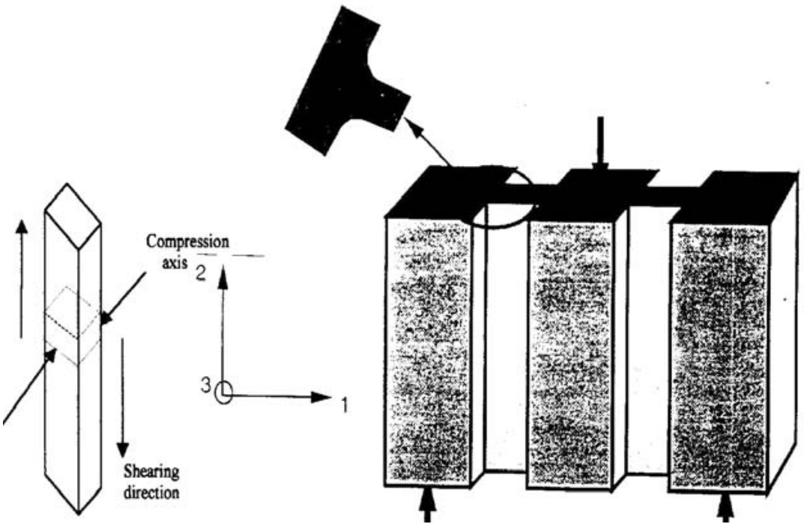

Fig. 2. Schematic of sample used in simple shear testing and the compression sample (used in deformation path change test) machined out of the gauge section showing the compression axis.

Results

Figure 3 represents the shear stress versus accumulated shear strain response for forward and reverse cycles for 70:30 brass as a representative of a low SFE material. Figure 4 represents the shear stress versus accumulated shear strain response for aluminum as a representative of a high stacking fault energy material. The Bauschinger stress parameter B_σ calculated for aluminum is 0.068 and for 70:30 brass is 0.385 (calculated form Figs. 3 & 4). The reverse yield stress value for 70:30 brass was chosen to correspond to offset reverse strain of 0.002, since there was no clear yield plateau. Samples of annealed 70:30 brass were first deformed in simple shear to a shear strain of 0.75 (Von Mises equivalent strain of 0.45) and 1.5 (Von Mises equivalent strain of 0.95), respectively. Then thin tiny rectangular parallelepiped samples were machined from their gauge sections and tested in simple compression (loaded along the 3-axis; Fig. 2). Figure 5 show the results of these tests.

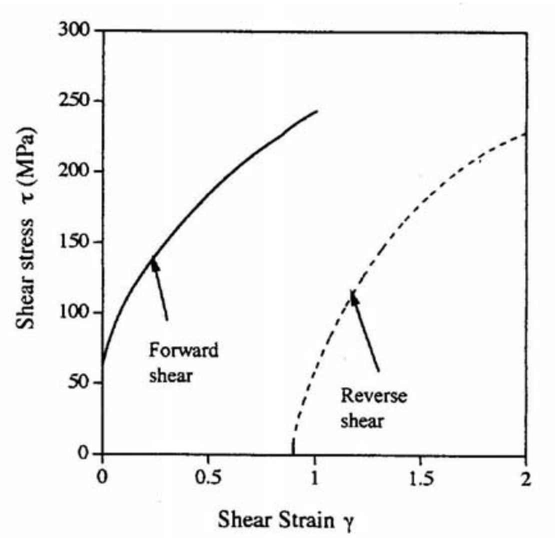

Fig. 3. Shear stress-shear strain response for forward and reverse shear of 70-30.

It was observed that, with a change in deformation path from simple shear to simple compression, the equivalent flow stress of the first sample jumped from 370 MPa to about 580 MPa, and from 440 MPa to about 650 MPa in the second sample. Note that the flow stress values after the change in the deformation path are in reasonable agreement with the corresponding values for monotonic simple compression deformation path. Similar results were seen for a low SFE super alloy MP35N (Co-Ni-Cr-Mo) [14]. Microstructure evolution study on MP35N and 70:30 brass revealed that the amount of deformation twins were similar in the two deformation modes, namely simple compression and simple shear, at comparable equivalent strain levels and that it was a merely a geometrical effect behind the lower strain hardening rates observed in simple shear compared to simple compression (twins developed in simple shear being parallel to the primary slip systems, thus they do not pose as effective dislocation barriers). Figure 6 shows the microstructure of 70:30 brass gauge section subjected to a shear strain of 1.6. The study revealed a morphology of elongated grains making 45 degrees with the shear direction and twin markings predominantly parallel to the plane of the imposed shear deformation.

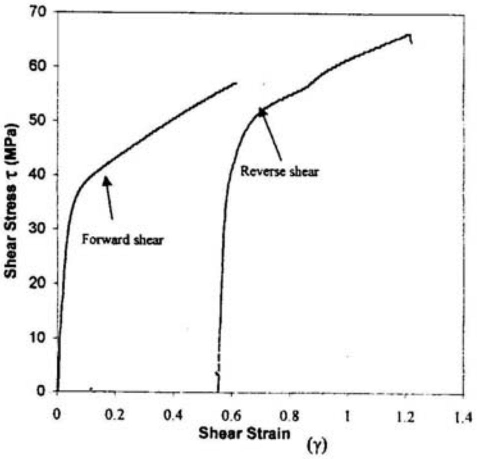

Fig. 4. Shear stress-shear strain for forward and reverse shear for aluminum.

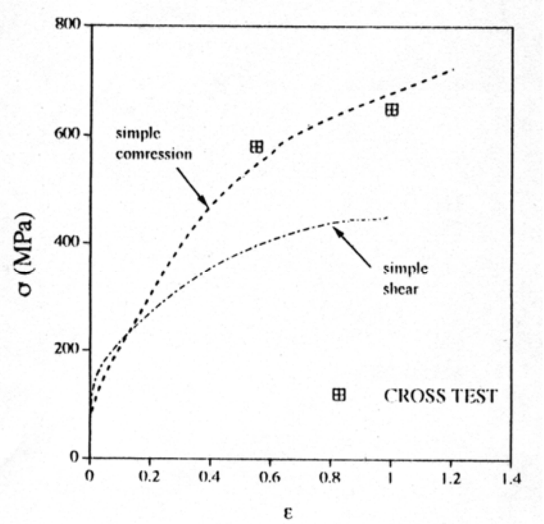

Fig. 5. Equivalent stress strain response of 70:30 brass in simple shear and simple compression. The square symbols show the yield strength values after the deformation path change from simple shear to simple compression.

Fig. 6. Microstructure of 70:30 brass gauge sectin subjected to a shear strain of 1.6.

Discussion

The detailed microscopic study revealed that the twinning activity is predominantly coplanar to the shear direction, which causes the twins to be ineffective barriers to dislocation motion on the most active slip planes. The co-planarity of the deformation twins (Fig. 6) is the reason for the low strain hardening rates in simple shear compared to simple compression (Fig. 5). The instant jump in the flow stress values when the deformation path was changed from simple shear to simple compression indicates that the volume fraction of twins nucleated in simple shear during deformation is quantitatively comparable for the same equivalent strain to simple compression, as deformation twins plays a major role in determining the flow stress level in low SFE materials such as 70:30 brass. Changing the stress state caused the twins to be effective barriers, once more, as the co-planarity is lost in simple compression. Similar study on MP35N revealed same observations [14].

A hypothesis, provided and tested here, for the high Bauschinger effect seen for 70:30 brass is the possibility of the reduction in the volume fraction of twin content during the reverse cycle through de-twinning. When the shear responsible for producing the twins in the forward cycle is reversed, this causes the disappearance of existing twins, as well as the production of new fresh twins. Thus, there are two competing mechanisms among which it is believed the net result is a decrease in the twin content. For a brass sample deformed monotonically in simple shear in a complete forward cycle to an equivalent strain of 1.0, the corresponding flow stress level was about 440 MPa. Upon changing the deformation path to simple compression, the flow stress jumped instantly to 660 MPa which is close to the yield strength value obtained in monotonic simple compression tests at the same strain. This indicates that the twin content is similar in the two deformation modes, but the difference in hardening rates was merely due to a geometrical effect as discussed above. Figure 7 shows the equivalent stress versus equivalent strain, for simple compression, and simple shear (forward and reverse cycle, plotted as strain is accumulated) for a total equivalent plastic strain of 1.1. A sample was cut from the gauge section at the end of the reverse cycle and deformed in simple compression. If the twin content at the end of the reverse cycle (total accumulated equivalent plastic strain of 1.1) is similar to the twin content at the end of a complete forward shear cycle to the same equivalent strain, the results of the deformation path change test should yield similar result as the one shown in Fig. 5 (the flow stress would jump to about 650 MPa, or at least the instant increase in stress level, $\Delta\sigma$, would be about 210 MPa) .

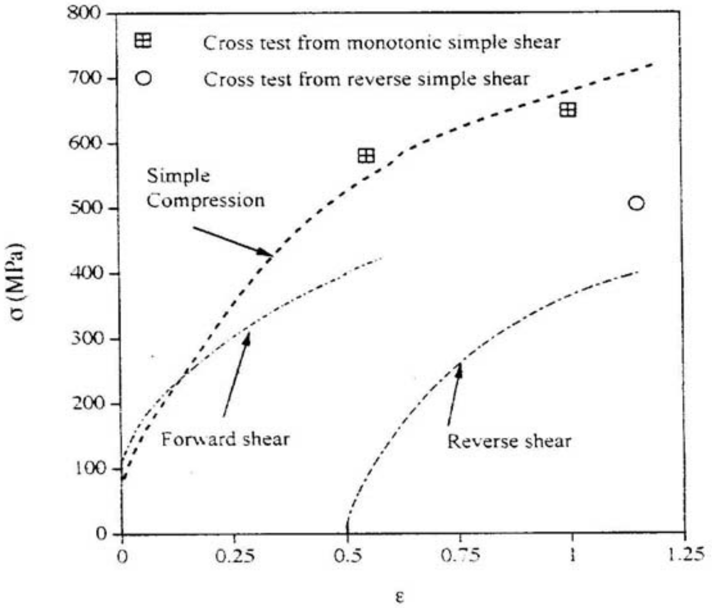

Fig. 7. Equivalent stress strain response for 70:30 brass in simple compression and forward and reverse shear against the accumulated plastic strain. The square symbols are the same as in Fig. 6. The round symbol is theyield strength value after the deformation path change is conducted on the reversed sheared sample.

Figure 7 shows the result of the deformation path change test after the stress reversal cycle. The jump was from 400 MPa (yield strength at the end of the reverse shear cycle) to about 500 MPa (yield strength after compressing the reverse sheared sample). An increase of only 100 MPa compared to the increase of 210 MPa (yield strength increase obtained from compressing the forward sheared sample) for the same total plastic strain. This provides strong evidence that the twin content after the reverse cycle has decreased Significantly, since the amount of deformation twins after the reverse cycle could not take the stress level to the expected value upon changing the deformation path. The permanent lowering of the flow stress values during the reverse cycle compared to the forward monotonic shear cycle also points towards the less volume fraction of twins. The twin boundaries in 70:30 brass are hard obstacles to the dislocation motion. The result is arrays of dislocation pile-ups containing large number of dislocations. When the direction of stressing is reversed, these barriers are removed and hardening approximately reverts to its initial rate in the undeformed material, which results in the permanent softening observed in these materials. The new hypothesis of de-twining beside the back stress theory discussed previously [1-3] can give an explanation to the high Bauschinger effect for materials that deform by twinning observed here as well as previously [2-6].

Microscopic study was conducted on the gauge section subjected to simple shear after the reverse cycle (accumulated shear strain of 1.6, or a total equivalent strain of 1.0). Figure 8 shows such microstructure. The equiaxed grain shape was restored, and quantitatively through measuring the area fraction of twin content. It was observed that the deformation twin markings has decreased compared with the microstructure achieved at a total shear strain of 1.6 obtained in a single forward shear cycle. Again, it was noticed that the amount of deformation twins after the reverse cycle (a total accumulated plastic equivalent strain of 1.0 achieved in the forward followed by the reverse cycle) was comparable to the amount of twins obtained at a strain of only 0.5 in simple compression, which again provides evidence for de-twinning.

Fig. 8. Microstructure of 70:30 brass after the reverse shear cycle, at a total accumulated plastic shear strain of 1.6.

Conclusion

1. High Bauschinger effect is seen for 70:30 brass (deforming by twinning beside slip) in simple shear deformation consistent with previous observations. The hypothesis offered here explains the observation through a combination of de-twinning and back stress developed due to dislocation piling up against deformation twins.

2. Deformation twins that developed during the forward shear cycle for 70:30 brass were mainly coplanar to the primary slip systems and thus less effective in obstructing the dislocation motion and consequently in increasing the strength. The amount of twins were similar in simple shear and simple compression at comparable equivalent strain levels. This was proved through changing the deformation path from simple shear to compression which resulted in an instant increase in strength (from the flow shear stress–strain response to the simple compression response). This was also shown through microstructure study.

3. Reverse shearing the samples restored the equiaxed grain structure morphology. It is believed that during reverse shearing, the grains rotate and the twins are no longer coplanar to the slip direction so they would be expected to play a role in the strain hardening during the reverse cycle. On the contrary, the thing that is seen is the permanent softening through out the whole reverse cycle. This again proves that the reverse cycle has led to a decrease in the amount of twinning, the thing that could mainly be the reason for the permanent softening as well as partly for the transient softening seen in the case of low SFE 70:30 brass.

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دراسة تأثير باوشنجر بإستخدام القص المعاكس لمادة النحاس الأصفر (٣٠/٧٠)

إيهاب عادل الدنف

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(قدِّم للنشر في ١٩/١٢/٢٠٠٥م؛ وقبل للنشر في ٢٤/٠٩/٢٠٠٦م)

ملخص البحث. تم في هذه الدراسة تطبيق إجهاد القص والقص المعاكس على مادة النحاس الأصفر ٣٠/٧٠ كممثل للمواد ذات طاقة الرص الخاطئ المنخفضة، ومادة الألومنيوم كممثل للمواد ذات طاقة الرص الخاطئ المرتفعة. أظهرت الدراسة تأثيرا كبيرا لباوشنجر في المواد ذات طاقة الرص الخاطئ المنخفضة مقارنة بالتأثير الموجود في المواد ذات طاقة الرص الخاطئ المرتفعة. تم تصميم تجربة حيث تم تغيير الانفعال من قص إلى ضغط على نفس المادة، ومن خلال نتائج هذه التجربة وبمساعدة دراسة البنية المجهرية وجد أن التأثير الكبير لباوشنجر يمكن أن يكون نتيجة لعملية انعكاس عملية التوأمية (عكس اتجاه القص أدى إلى اختفاء بعض التوأمية التي ظهرت في عملية القص المباشر). فسر التأثير الكبير لباوشنجر أيضا عن طريق نظرية الإجهاد المعاكس الذي يتولد نتيجة تكدس الإنخلاعات أمام الحواجز التي تتمثل في حدود الحبيبات ونطاقات التوأمية التي تتكون أثناء التشكل اللدن للمواد.