Microstructural evolution during tension-compression in-plane deformation of a pure aluminum sheet

M Härtel, B Bohne and M F-X Wagner

Institute of Materials Science and Engineering, Chemnitz University of Technology, 09125 Chemnitz, Germany

Abstract. Classically, the Bauschinger effect refers to a reduction of yield strength after a load path change. In this contribution, we present results of an experimental and microstructural investigation on Bauschinger effects in an AA1050 sheet metal (with 1 mm thickness) subjected to in-plane uniaxial loading. We performed tension-compression tests with different values of maximum tensile strains in a novel tool that was specifically designed to avoid buckling under compressive loading. Our experimental results show that the sheet material exhibits distinct Bauschinger effects. At different stages of deformation, we interrupted the tests and prepared samples for transmission electron microscopy. Our microstructural observations allow rationalizing the occurrence and magnitude of the observed Bauschinger effects.

1. Introduction

The well-known Bauschinger effect typically refers to a reduction of yield strength after a load path change [1]. Different reasons for this material behavior have been discussed in a variety of materials: According to Masing, different strengths in adjacent grains and developing residual stresses during the initial deformation are the main reason for macroscopic Bauschinger effects [2] after load reversal; this model certainly holds for simple, polycrystalline materials. Sachs and Shoji [3], as well as Buckley and Entwistle [4], however, also observed Bauschinger effects in single crystals. Margolin explained this phenomenon by considering the formation of substructures, and the corresponding anisotropic mechanical properties, in individual grains [5]. Brown [6] and various other groups [7-9] identified the interaction of free dislocations with grain boundaries, precipitates, impurities and other dislocations, and the resulting back stress after load removal, as important mechanisms affecting the Bauschinger effect in metals. Clearly, a detailed analysis of microstructural evolution during the different stages of mechanical loading is required to fully rationalize Bauschinger effects in different materials. For example, Lewandowska [10], Hasegawa et al. [11], Caceres et al. [12] and Vincze et al. [13] carefully documented the formation of substructures (and their decomposition after a load path change) and related these observations to the macroscopic Bauschinger effect. Previous experimental work made use of tension and subsequent compression tests of bulk materials [11-12]. Sheet materials have been studied in shear tests (by shearing in one direction, load removal, and subsequent shearing in the opposite direction, [10, 13]); evaluation of mechanical data from testing with different shear specimen geometries, however, is not trivial [14, 15]. In the present study, the goal is to perform tension-compression tests on a sheet material. This experimental approach is quite challenging as well because sheet materials are prone to buckling under compressive loading [16]. Different groups have overcome this issue by using devices that provide additional support from the samples’ sides to prevent buckling [17-23]. Based on their reports [17-23], we designed and established a comb-shaped...
support that has been described in [16]. The present paper primarily reports the first results of the tension-compression tests on a pure aluminum alloy AA1050 that were performed using our new experimental setup. We evaluate the magnitude of the Bauschinger effect based on experimental stress-strain data [7, 16]. Moreover, we document the development of the microstructure at different stages of the deformation by transmission electron microscopy (TEM).

2. Experimental

In the experiments presented in this paper, an aluminum sheet material with a thickness of 1 mm was used. The pure aluminum alloy (AA1050) consists of 99.5 (wt.-)% Al, 0.08 % Si, 0.341 % Fe, 0.002 % Cu, 0.003 % Mn, 0.05 % Mg, 0.005 % Zn and 0.013 % Ti. Prior to testing, the material was annealed for 120 min at 500 °C to ensure a homogeneous microstructure with a low dislocation density.

For all mechanical tests, our new tension-compression setup [16] was used, see figure 1. The setup consists of four comb-shaped parts (two of them with a notch of 1 mm) that can move relative to each other, and clamps to hold the sample and to avoid buckling under compression. This setup was installed in a conventional testing machine (ZWICK/ROELL ZMART PRO UNIVERSAL 100 kN). A standardized tensile specimen (following the design specified in [24]) with a gauge length of 50 mm and a width of 12.5 mm was used. Force measurements, force data correction and strain measurements with a digital image correlation system were performed as described in [16]. All mechanical tests were performed at room temperature and at a strain rate of $10^{-3}$ s$^{-1}$.

For TEM analysis, samples were prepared at different stages of the deformation during the tension-compression tests, i.e., (i) at the stage of maximum tensile strain; (ii) immediately after yielding after load reversal, and (iii) at 4 % compression. All samples were ground, mechanically thinned and finally electro-polished to produce the TEM samples. TEM analysis was performed using a TEM Hitachi H8100 with an accelerating voltage of 200 kV (see [25] for further details).

![Figure 1](image.png)

**Figure 1.** Tension-compression setup, [16]: comb-shaped fingers (a) installed between a die set in a conventional testing machine. The standardized tensile specimen is placed between the two front and the two back parts of the tool (b). For sufficient illumination between the combs’ fingers, a ring of lights is placed around the DIC camera (c); the illuminated surface of the specimen is covered with speckle patterns for DIC measurement (d).

3. Results and Discussion

3.1 Mechanical behavior during tension-compression testing

Figure 2 shows the results of the tension-compression tests with different maximum tensile strains (0.5, 1, 1.5 and 2 %). The tensile stress-strain curves do not fall exactly on top of each other, similar to
our observations with the same set up for steel sheet DC06 presented in [16]. Furthermore, we observe a deviation of about 15 MPa in the initial yield strength compared with conventional tensile test data of the AA1050 sheet material. It is therefore difficult to quantify the decrease in the yield strength after load reversal. The Bauschinger effect factor $\alpha$ [7, 16], with values about 0.3, is uncharacteristically low (for such small maximum tensile strains, values of $\alpha = 0.8-0.9$ are commonly observed [7, 16]), which may be a consequence of the scatter in the experimental data. This error in our measurements is probably related to internal friction in the experimental setup during the deformation: For very soft materials such as AA1050 (initial yield strength: 25 MPa), even small amounts of internal friction affect the measurement, whereas for steel sheets (even for soft steels), this influence is negligible [16]. Despite this drawback in terms of stress data, the surface strain measurements with DIC are accurate, and this ensures that different stages of deformation can be quantified and related to the results of our TEM analysis discussed below.

![Figure 2](image.png)

**Figure 2.** Stress-strain curves of tension-compression experiments with different maximum tensile strains of 0.5, 1, 1.5 and 2 %, respectively. The initial yield strength under tensile load deviates by about 15 MPa from data determined by conventional tensile testing, which likely results from friction in the experimental setup. After load reversal, all specimens exhibit a reduced yield strength under compression, but an accurate quantification of the Bauschinger effect is unreliable.

3.2 Microstructural analysis
In figure 3, microstructures at different stages of the tension-compression tests with a low maximum tensile strain are shown. Figure 3a shows a representative microstructure after 0.5 % maximum tensile strain, figure 3b shows the microstructure immediately after yielding under compression, and figure 3c shows the microstructure after a strain of 4 % in compression. Figure 3d shows a stress-strain curve which indicates where the samples corresponding to figures 3a, b and c were taken out for TEM analysis. The microstructure shown in the bright field image in figure 3a is characterized by a very low
dislocation density. Slip seems to primarily occur on a family of favorably oriented, parallel slip systems. In the vicinity of impurities or precipitates, we observe slightly increased dislocation densities, while other parts of the microstructure are mostly free of dislocations. After load reversal and subsequent yielding under compression, the dislocation density decreases, figure 3b. Even in the vicinity of impurities or precipitates, the dislocation density seems to be smaller than in figure 3a, which indicates the occurrence of recovery processes; this interpretation is in line with previous reports [10, 11, 13]. Further deformation under compression leads to the onset of the early formation of substructures, figure 3c.

**Figure 3.** TEM bright field images of the AA1050 sheet material at different stages of the tension-compression test (maximum tensile strain: 0.5 %). After loading to the maximum tensile strain, we observe a low dislocation density (a). A decrease in the dislocation density due to annihilation is observed after the load reversal (b). After reaching a strain of 4 % in compression, we observe the beginning of the formation of substructures (c). The stress-strain-curve in (d) highlights the stages of deformation where the corresponding samples for TEM analysis were taken out.
Such observations have also been reported by other groups [10, 11, 13, 26], and the annihilation and/or interaction of the dislocations with precipitates and impurities are typically discussed as the main microstructural processes that lead to the Bauschinger effect. More specifically, Vucko et al. discussed how the deformation of dislocation cells leads to a decrease of residual stresses which in turn allows to reduce strain energy [26].

In figure 4, the microstructures at different stages of deformation in the tension-compression test with an increased maximum tensile strain are shown.

**Figure 4.** TEM micrographs of the AA1050 sheet material at different stages of a tension-compression test with a maximum tensile strain of 2 %. After tensile straining to 2 %, we observe a higher dislocation density on parallel slip planes (a) compared to smaller tensile strains (see figure 3a). Additional slip systems are activated after load reversal (b). After strains of 4 % in compression, we observe the beginning of the formation of substructures (c). In the cell interiors, some of the dislocation segments formed earlier can still be detected. The stress-strain-curve in (d) highlights the stages of deformation where samples for TEM analysis were taken out.
Figure 4a shows a representative microstructure after loading to a maximum tensile strain of 2 %. The dislocation density appears to be increased compared to figure 3a, and dislocations can be observed throughout the entire grain. In the vicinity of impurities or precipitates, dislocation loops, where the dislocations are not able to pass the obstacles, can be observed. The stress fields of these Orowan loops can also be directly related to the occurrence of a Bauschinger effect. Figure 4b shows the microstructure after load reversal and early yielding under compression. Instead of an annihilation of dislocations (as observed for smaller maximum tensile strains, see figure 3b), the bright field image in figure 4b indicates the activation of a new family of parallel slip systems, where straight dislocation segments seem to cross the other sets of dislocations (formed earlier during tensile deformation). This leads to an increase in the dislocation density already immediately after load reversal and may also lead to an increase of internal stresses that further promote Bauschinger effects. Subsequent compression leads to a further increase in dislocation density, and to the formation of substructures that are more favorable concerning strain energy, figure 4c. These microstructural observations represent only the beginning of the formation of substructures; in the interior of several cell structures we still observe some conventional dislocations. Such remains of the earlier dislocation network are likely to be reduced during the ongoing formation of dislocation cells when the material is strained even further.

4. Summary and conclusions
This investigation focused on both mechanical and microstructural investigations of Bauschinger effects in an AA1050 sheet material. Our study forms the basis for ongoing research on the effect of uni- and biaxial loading on Bauschinger effects in different sheet materials [27, 28]. We performed uniaxial tension-compression tests with an experimental setup with comb-shaped support plates to avoid buckling of the thin sheet specimens after load reversal. The AA1050 material exhibits distinct Bauschinger effects for different maximum tensile strains in the range of relatively small strains from 0.5 % to 2 % investigated here.

Using transmission electron microscopy, we analyzed the development of the microstructures at different stages of the tension-compression tests for experiments with 0.5 % and 2 % maximum tensile strains, respectively. For the 0.5 % maximum tensile strain condition, we observed annihilation of dislocations after load reversal and the formation of dislocation substructures during subsequent compression. These processes clearly contribute to the Bauschinger effect observed in the corresponding mechanical data. For 2 % maximum tensile strain, we observed the activation of a dominant slip system on parallel slip planes after tensile deformation. After load reversal, additional slip systems are activated, and interaction of dislocations on different slip planes is more pronounced than the annihilation processes observed for smaller maximum tensile strains. The developing stress fields also contribute to the macroscopic Bauschinger effect observed in the sheet material. Further compressive straining results in the formation of dislocation cells. The microstructural observations reported here confirm earlier studies on pure aluminum, and they highlight the dominant microstructural processes that also most likely affect Bauschinger effects during more complex, multi-axial load cases.

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