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Author(s): N. Shi, U. T. S. Pillai, R. J. Arsenault

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THE BAUSCHINGER EFFECT IN A SiC/AL COMPOSITE

N. Shi¹, U.T.S. Pillai² and R.J. Arsenault²

¹ MS H805, LANSCE, Los Alamos National Lab., Los Alamos, NM 97545

² Metallurgical Materials Laboratory, Dept. of Materials & Nuclear Engineering
University of Maryland, College Park, MD 20742-2115

Abstract

SiC/Al composites have interesting mechanical properties, the tensile yield stress is less than the compressive yield stress, whereas, the apparent modulus in tension is greater than that in compression. The Bauschinger effect of SiC/Al composites is also asymmetric with regard to loading directions. Quantitative measurements of the asymmetry of composite Bauschinger Effect was made in this research. An investigation was undertaken to determine the origin of the asymmetrical Bauschinger effect. We have successfully reconstructed the observed asymmetry using an internal stress model based on the development of internal stresses, conveniently referred to as the "back stress", and work hardening.

Introduction

Since the Bauschinger effect (BE) [1] was first reported about a century ago and had been studied extensively up to the 70's, a logical conclusion could be that nothing remains to be discovered about the BE.

However, not only is there a lack of agreement as to what constitutes the BE, but also there has been no single parameter that satisfactorily quantifies the BE. Most investigators have chosen to define the BE in terms of a reduction in the magnitude of the flow stress for the reverse deformation cycle [2,3], while others preferred a more general definition, such as a certain dependence of the flow stress and rate of work hardening on the strain history or they simply referred to the existence of different stress-strain curves by loading in the reverse direction [4,5]. Orowan [6] considered only the transient softening of materials on stress reversal as the BE, whereas others [7,8] included permanent softening as part of the effect. We will use a simple and effective definition, that is, the magnitude of BE is defined as the Bauschinger stress factor (BSF) as shown in Figure 1, the difference in the flow stress between the forward and the reverse cycles.

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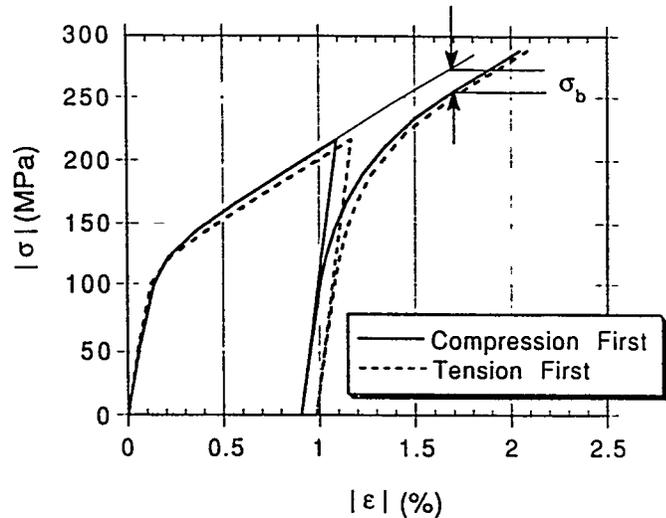


Fig.1 Typical stress-strain responses from Bauschinger tests predicted by FEM. The dotted line represents results from tension first, and the solid line represents results from compression first. The BSF is defined by σ_b .

In the case of monolithic Al, the direction of initial loading, tensile or compressive, has a small influence on the BE. SiC/Al composites, however, exhibit a remarkable characteristic, the flow stress drop during reverse cycle is larger when the composite is deformed in a compression-tension sequence than vice versa [9]. This difference in the composite constitutive response is generally referred to as the asymmetric composite BE.

It is generally believed that the BE in discontinuously reinforced metal matrix composites (DMMC) results from the development of the internal matrix-reinforcement interaction stresses in the matrix [9-14]. Numerical models [10-11] have shown that even without considering the intrinsic BE of the matrix material, a significant BE exists in the corresponding composites reinforced with ceramic particles, such as SiC.

Arsenault and Wu suggested that the thermal residual stress (TRS) is responsible for the asymmetry of the composite BE [9]. The TRS results from cooling during which a thermal mismatch is generated from a difference in the coefficient of thermal expansion between the SiC and Al. Further evidence from finite element method (FEM) modeling indicates that by incorporating the composite thermal history, the composite BE is asymmetric [11]. Without including TRS in the FEM, the sense of initial loading is predicted to have no influence on the composite BE [12]. Withers et al. recently performed a parametric study of the composite BE using the mean field theory [13]. They rationalized a relationship between the influence of the TRS on the monotonic loading and on the composite BE.

Shi and Arsenault [14] investigated the asymmetric BE in SiC/Al composites by FEM modeling, and a model was constructed based on the "back stress" from the changes in the residual stresses due to loading. A comparison with the FEM results is shown in Figure 2.

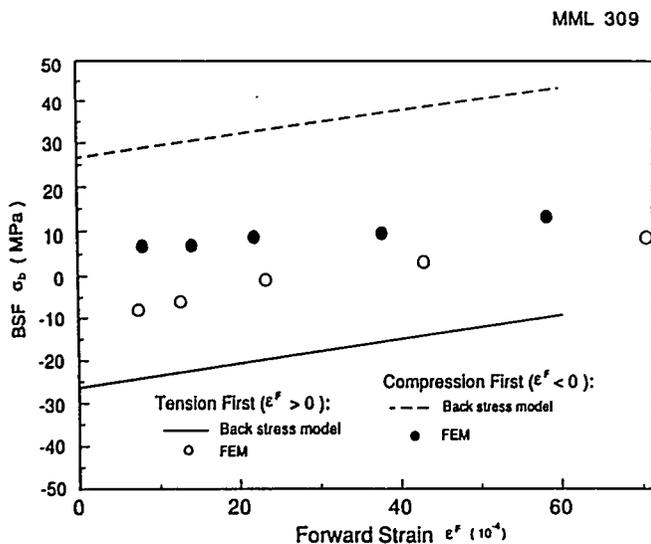


Fig.2 Comparison of the predictions from the Back Stress Model and the FEM. The two models give a good agreement on the slopes and the general trends on the variations of σ_b , while the back stress model predicts a larger σ_b .

In this research, the change in the BSF of both composites and unreinforced alloys with the direction of the initial loading was experimentally determined. The BSF of the SiC/Al composite was compared with the Al alloys. The experimental results were rationalized using an improved "back stress" model.

Experimental Procedure

Three different materials were tested, 1100, 6061 Al alloys and a 20v% SiC (whisker)/6061 Al alloy composite. The 1100 alloy and the 6061 Al alloys were commercially obtained rods with a diameter of 12.5 mm. The 20v% SiC (whisker)/6061 Al composite was purchased from ARCO Silag in the form of an extruded rod with a diameter of 12.5 mm. The morphology of the SiC whisker has been described elsewhere [15,16]. The sample geometry is shown in Figure 3. The samples, when held by a special gripping arrangement [9], enables BE tests with uninterrupted tension-compression transition. The machined samples were annealed for 12 hrs at 810 K and then furnace cooled.

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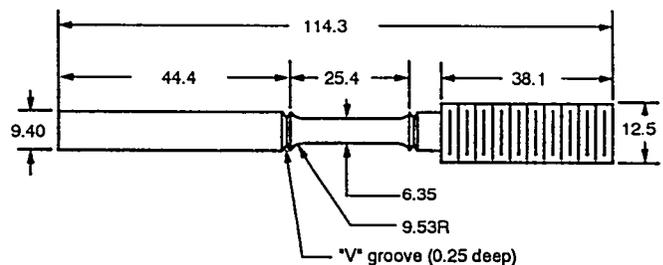


Fig.3 Tension-compression sample. All dimensions are in millimeters.

The testing was performed in a standard screw driven machine at a cross head speed of $1.6 \times 10^{-2} \text{ mm}^3 \cdot \text{sec}^{-1}$. The maximum misalignment was 0.014° and would result in a maximum misalignment stress of 0.2% of the applied compressive stress. In order to improve the alignment, the top grip was replaced by an aligned bored hole, and the sample diameter was $2.5 \times 10^{-2} \text{ mm}$ smaller than the bored hole in the grip. The sample was held in place by a set of 4 opposing screws. It was believed that this arrangement resulted in a smaller misalignment stress during the compression test [9]. Also, to further minimize the effect of misalignment, the total strain in compression was limited to 0.01 to 0.02. The strain measurements were obtained with an extensometer attached in the "V" grooves, shown in Fig.3, the correlation between the extension measured by extensometer mounted in the "V" grooves and the actual extension has been determined previously [17].

Numerous tests to different total strains were conducted with all three types of materials to determine the possible effect of the allowed misalignment. The results of these tests indicated that if the deformation was confined to 0.01-0.02, there was no indication of measurable misalignment with the alignment tolerance set as stated above. The alignment was also

checked by examining the initial loading portion of the load vs displacement curve, and misalignment is detected by the curve having an unusual "S" shape. The misalignment can be more readily be detected in compression. Also, the unloading-reloading portion of the load-displacement curve was examined for non-uniform changes. A final check was to examine the sample after testing in compression to determine how straight they remained. All of these checks indicated that alignment was good, i.e., no misalignment could be detected.

Results

We will start our discussion of the results with the composite sample. Figure 4 is a plot of the tensile and compressive stresses ($\pm\sigma$) vs total strain ($\pm\epsilon_T$). The sample was first tested in tension to a total forward strain (ϵ_{TF}) of 0.011 and then unloaded followed by compression. The data in Figure 4 is replotted in Figure 5 as the absolute value of stress ($|\sigma|$) vs that of total strain ($|\epsilon_T|$). The dashed line extension of the tension portion of the curve is based on a fit of the test results with a polynomial expression and is used to approximate the extension of the forward stress-strain curve. Following our definition of BE, we have:

$$\sigma_b = \sigma_f^F - \sigma_f^R \quad (1)$$

where σ_f^F and σ_f^R are the flow stresses for the forward and reverse loading cycles. σ_b is BSF.

In a BE test, the BSF in Eq.1 is uniquely defined when the work hardening rate of the forward and the reverse loading cycle does not differ as shown in Fig.1, i.e., the flow curves of the forward and the reverse loading cycles are in parallel. In the present BE tests this flow curve parallelism cannot be achieved when strains were capped within 0.01 to 0.02 in each loading cycle. For example, the magnitude of the BSF at A is 146 MPa in Fig.5 and continues to decrease with increasing strain increment in the reverse loading cycle ($\Delta\epsilon = |\epsilon_T| - |\epsilon_{TF}|$), at D, the BSF equals 90 MPa.

A single $\Delta\epsilon$ was chosen for all BE tests at which the BSF was measured as shown in Fig.6a. A sufficiently large $\Delta\epsilon$ was chosen such that the reverse flow stress is well beyond the macroscopic yield. In the present investigation, we chose $\Delta\epsilon$ as 0.002. The variation of the flow stress from a number of repeat tests is ± 3 MPa. This translates into a maximum error limit of ± 6 MPa for the BSF, however, the statistical error limit will be ± 4 MPa.

The difference in BSF is significant for the composite as shown in Figs. 6a and 6b. When the test was initiated with strain 0.001 in tension BSF = - 20 MPa (Fig.6a), whereas, when the test was initiated with the same forward plastic

strain in compression BSF = 53 MPa. The BSF is greater for a test in compression-tension sequence, regardless of the magnitude of ϵ_{TF} .

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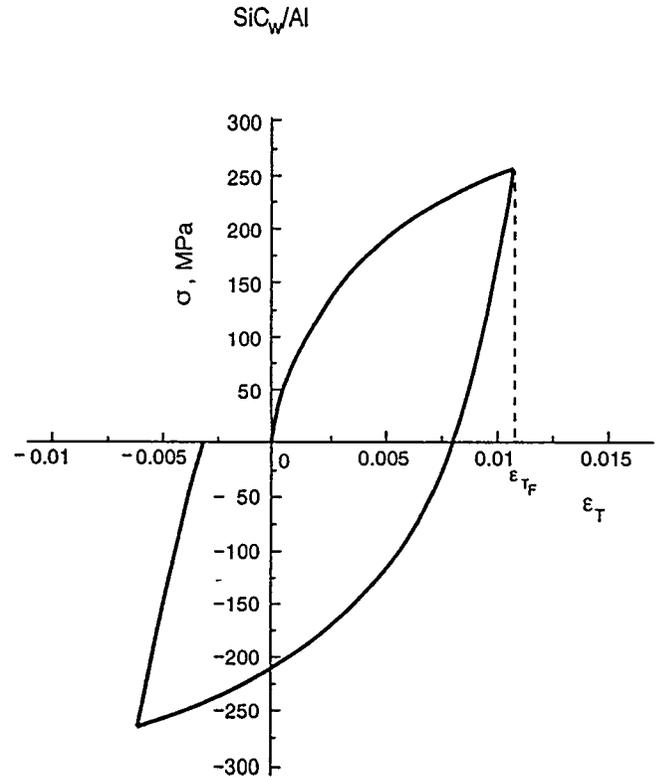


Fig.4 Tensile and compressive stresses vs total strain of one of the composite samples for a BE test begun in tension, strain to a forward strain of 0.011 and then unloaded and followed by compression without any interruption.

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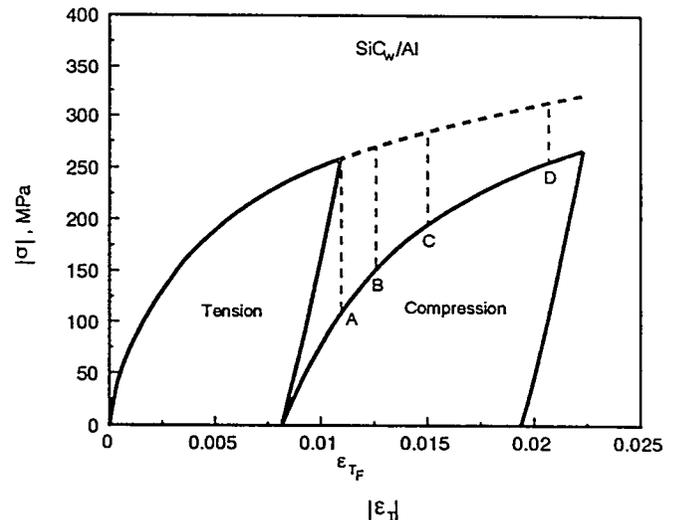


Fig.5 The absolute value of the stress vs absolute total strain for same test data as showed in Fig.4.

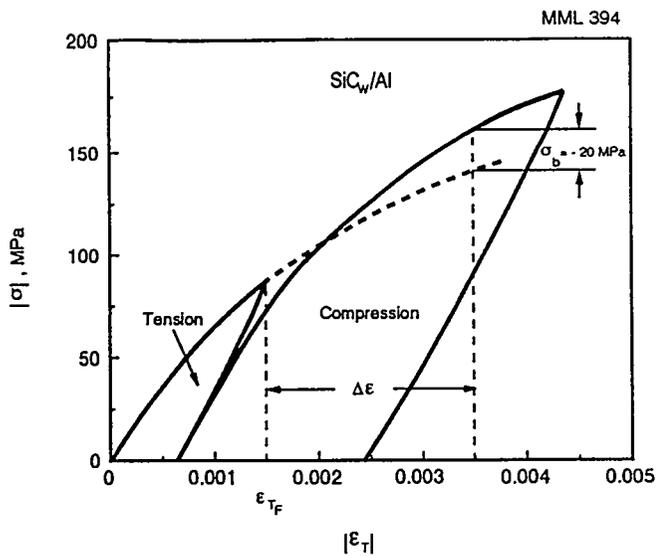


Fig.6a The absolute stress vs absolute total strain of composite sample in which the test was conducted first in tension to a total forward strain of 0.0015, followed by unloading and continued in compression without interruption.

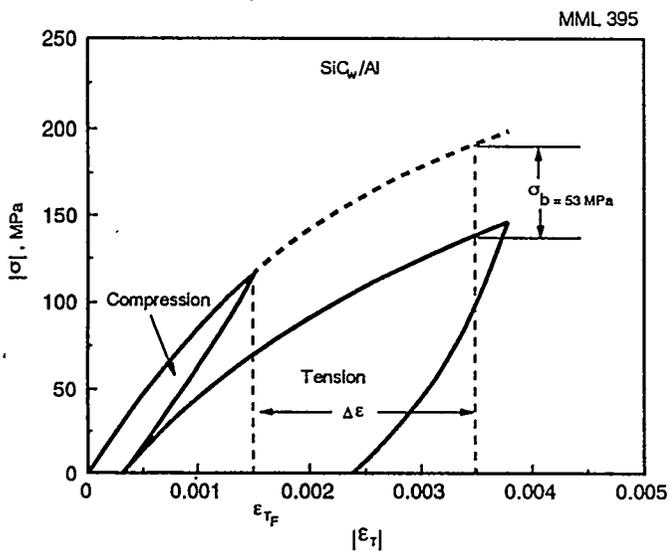


Fig.6b The same as Figure 6a except the test starts in compression.

The BE results of the 1100 Al alloy samples are shown in Fig.7. Compared with Fig.6, the magnitude of BSF in Fig.7 is much smaller. There is only a slight tendency for BSF to be larger if the BE test was initiated in compression. However, the magnitude of the difference in the flow curve, though consistent, is within the error limit of ± 4 MPa. Additional tests were conducted as a function of the forward strain $|\epsilon_{TF}|$. The same procedure was followed for the 6061 Al alloy samples.

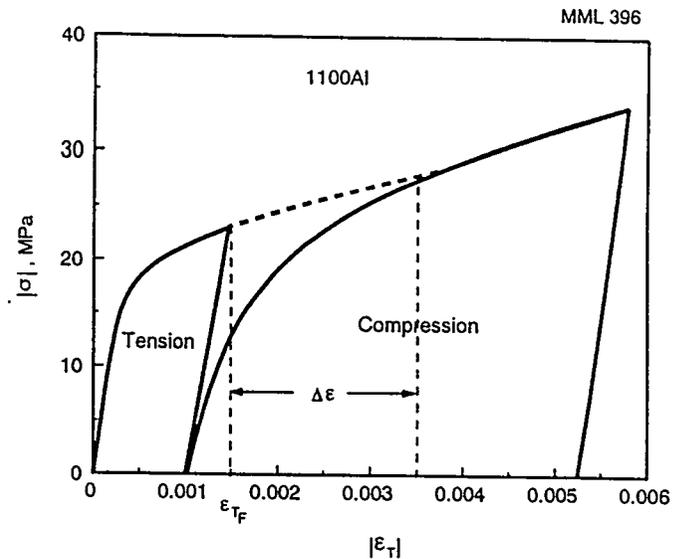


Fig.7a The absolute stress vs absolute total strain of a 1100 Al alloy sample in which the test starts in tension to a total strain of 0.0015, followed by unloading and continued in compression without interruption.

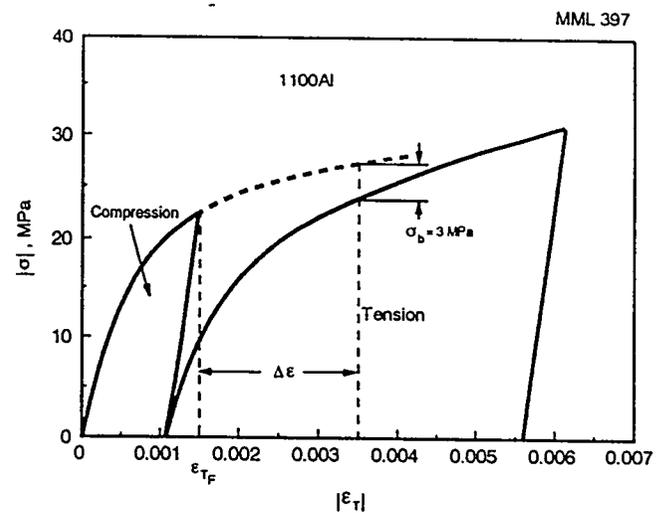


Fig.7b Same material as Figure 7a, except the test starts in compression.

The results of the tests for both the composite and the alloys are summarized in Table I and Figure 8. The values listed in Table I are average values with an error limit of ± 4 MPa. Based on the experimental results, the following is apparent:

- For the composite with a small forward strain $|\epsilon_{TF}|$, the BSF is negative for test begun in tension, and positive when begun in compression.
- The magnitude of BSF of the composite at a given value of ϵ_{TF} is much greater (in absolute terms) than that of the alloys, approximately an order of magnitude larger.
- The BSF for the composite is greater for a BE test in compression-tension sequence than vice versa. For the Al

alloys, the extent of this difference is much less, arguably within the error limits.

Discussion

Table I
Bauschinger Stress Factor at Various Total Forward Strains

Material	$ \epsilon_{TF} $	Compression First σ_b (MPa)	Tension First σ_b (MPa)
Al-SiC _w	0.0015	53	-20
	0.002	59	21
	0.055	83	62
	0.011	127	109
Al-1100	0.0015	3	0
	0.002	0	0
	0.055	8	4
	0.011	8	0
Al-6160	0.0015	8	0
	0.002	4	3
	0.055	13	10
	0.011	18	13

In a previous publication by Shi and Arsenault [14], two methods or models were used to predict the changes of the BSF as a function of both the magnitude and the direction of the total forward strain, $|\epsilon_{TF}|$. One model is based on FEM and the other from the concept of "back stress" or "mean field", to account for the internal stress development. The results of these two models are shown in Figure 2. If we compare the modeling (Fig.2) with the experimental results (Fig.8), the general trends in the BSF change for composites are in agreement. That is, (1) the magnitude of BSF is greater for the BE test begun in compression; (2) BSF is negative at small ϵ_{TF} for BE test in tension-compression sequence; (3) the magnitude of the BSF increases with increasing ϵ_{TF} regardless of initial loading direction.

The physical basis for the observed effect, as modeled by Shi and Arsenault [14], is as follows: The average matrix TRS in the composite prior to testing is in tension [18]. A tensile matrix thermal residual stress biases the macroscopic yielding such that the yield stress in tension is lower than that in compression. In the context of BE tests, the yield stress in the forward deformation cycle of a compression-tension BE test is always algebraically larger than vice versa. The fact that the matrix residual stress is modified by the external load will further bias the yielding during the reverse loading. The matrix tensile residual stress along the loading direction is reported to increase with a compressive plastic strain and decrease with a tensile plastic strain [18]. That is, the state of the matrix residual stress after unloading from the forward loading (modified by the forward loading) always tends to lower the yield stress during the subsequent reverse loading, i.e., an increasing matrix tensile residual stress following compression reduces the subsequent tensile yield stress in the reverse loading cycle, and vice versa. The corollary is that the BSF is larger for a compression-tension test, and BSF is larger at higher $|\epsilon_{TF}|$. These trends are consistent with both predictions (Fig.2) and experiments (Fig.8). However, following small forward strains, the effect of tensile matrix residual stress is not erased by the applied load. Because the remaining of tensile matrix residual stress and little strain hardening in the forward cycle, the compressive yield stress in the reverse cycle is higher than the tensile flow stress in the forward deformation cycle, giving rise to a negative BSF (Figs.2 and 8).

Although the changes in residual stress have been successfully used to explain the asymmetry of BE in composites, the magnitude of the measured BSF is greater than predictions (Figs.2 and 8), and the range of the negative BSF predicted by the back stress model [14] is larger than

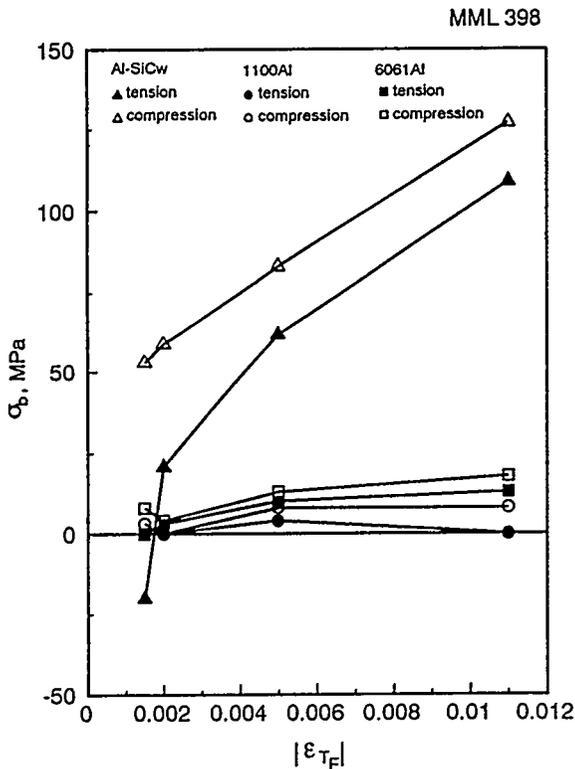


Fig.8 The Bauschinger stress factor vs the absolute total forward strain of the composite and the 1100 and 6061 Al alloy.

that from the experiment (Figs. 2 and 8).

In the simple back stress model [14], the effects of the "back stress" (i.e., matrix residual stresses) are treated as an invariant. This assumption is accurate when material deforms elastically. With plasticity the state of "back stress" varies with deformation. the modification of the "back stress" by plastic flow can be formulated phenomenologically by means of composite work hardening [12,19]. Combining the contributions from matrix residual stress [14] and plasticity [12,19], we obtained the following:

$$\sigma_b = \Delta\sigma_b^F + \Delta\sigma_b^R + 2\bar{E}_T^C \varepsilon_p \quad (2)$$

where $\Delta\sigma_b^F$ and $\Delta\sigma_b^R$ are contributions from the back stress due to residual stresses during forward and reverse loading cycles [14] and \bar{E}_T^C is a combination of composite Young's and tangent moduli given in [12,19] and ε_p is the forward plastic strain. Employing the results of Shi and Arsenault [14] and Taya et al. [12] we obtain Figure 9. The predicted BSF is now much larger both in magnitude and in the slope with $|\varepsilon_{TF}|$ than predictions by Shi and Arsenault [14], and the general trends remain the same. These results from Eq.2 provides a better agreement with the experiments as shown in Fig.9.

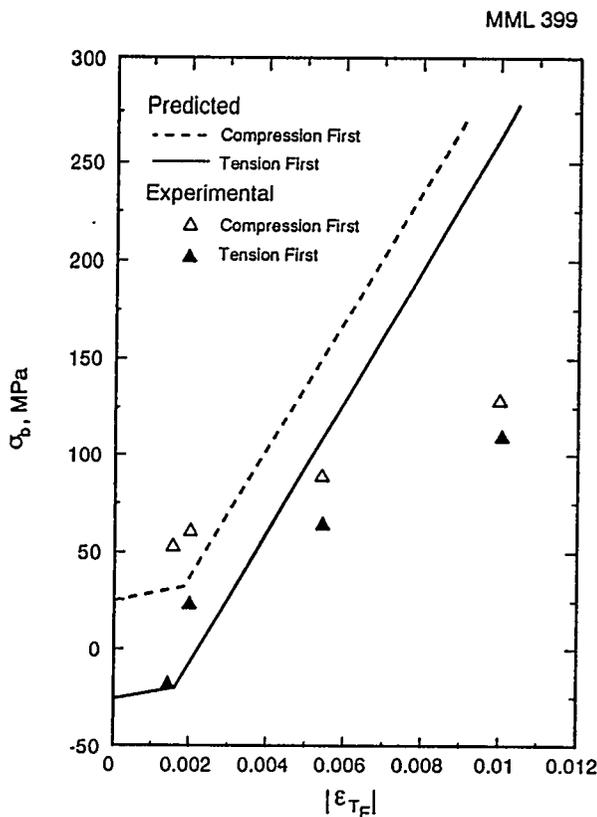


Fig.9 Comparison of the predicted and experimental data of the BSF vs absolute total forward strain for the composite sample.

For the BSF of the 1100 Al alloy, data in Figure 8 and Table I show that the BSF is much smaller than that of the composite. Similar to composite, there is a slight tendency for BSF to be larger in a BE test initiated in compression.

Unmodified theories derived from two phase alloy cannot be readily applied to understand the intrinsic BE in unreinforced alloys. Pederson et al. [8] approached the problem by treating dislocations in a single phase alloy as nonuniformly distributed dislocation clusters. This approximation enables the use of theoretical tools developed for two-phase inhomogeneous alloys. From the Eshelby mean field model, they obtained:

$$\sigma_b \approx K(\alpha_f - \alpha_y) \quad (3)$$

where K is a constant which takes into account volume fraction of dislocation clusters and the Eshelby accommodation factor, α_f is the flow stress at ε_{TF} and α_y is the yield stress. Since the work hardening for Al is generally small, the difference between α_f and α_y is insignificant and therefore the predicted BSF is small. This is in agreement with experimental results.

The BSF of the 6061 Al alloy is approximately a factor of 2 greater than the BSF of the 1100 Al alloy, but is still much smaller than the BSF of the composite. If we apply the same approach as used for the 1100 Al alloy the predicted BSF is larger for the 6061 Al alloy due to a higher work hardening rate for 6061 Al alloy.

Conclusions

- For the composite, the Bauschinger Stress Factor (BSF) is greater when the test starts in compression than vice versa.
- The magnitude of the BSF for the composite is more than an order of magnitude greater than that of 1100 and 6061 Al alloys.
- The asymmetric behavior of the BE in the composites can be accounted for by a model based on the change in the residual stress and the work hardening of the matrix.

Acknowledgement

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