Effect of Strain and Strain Rate on the Bauschinger Effect Response of Three Different Steels

K. HAN, C.J. VAN TYNE, and B.S. LEVY

The Bauschinger behavior after a strain reversal was evaluated for samples with microstructures representative of production sheets for a low-carbon (LC) steel, a high-strength low-alloy (HSLA) steel, and a dual-phase (DP) steel. The microstructures were produced in the samples by laboratory hot rolling and heat treatment. Bauschinger tests were run at strain rates of 0.0001, 0.001, and 0.01 s^{-1}, with tensile prestrains between 1 and 7 pct. After the reversal, the samples were strained 2 pct in compression. The Bauschinger effect is described by a Bauschinger effect parameter (BE), which is the difference between the steel strength at reversal and the 0.05 pct offset yield strength on the reversal, normalized by the steel strength at reversal. It is found that the Bauschinger effect is a continuous increasing function of the strength of the steel, provided the steel is prestrained at least 2.5 pct or beyond the yield point elongation. A single trend line describes the Bauschinger effect variation with steel strength, for all three steels in the present study and for an aluminum-killed drawing quality (AKDQ) steel from a previous investigation. No strain rate influence on the BE was found, due to the limited strain rate range and data uncertainty.

I. INTRODUCTION

THE Bauschinger effect is normally associated with conditions where the yield strength of a metal decreases when the direction of strain is changed. It is a general phenomenon found in most polycrystalline metals.[1,2]

The basic mechanism for the Bauschinger effect is related to the dislocation structure in the cold-worked metal. As deformation occurs, the dislocations will accumulate at barriers and produce dislocation pileups and tangles. Based on the cold work structure, two types of mechanisms are generally used to explain the Bauschinger effect.[3,4,5] First, local back stresses may be present in the material, which assist the movement of dislocations in the reverse direction. Thus, the dislocations can move easily in the reverse direction and the yield strength of the metal is lower. The pile-up of dislocations at grain boundaries and Orowan loops around strong precipitates are two main sources of these back stresses. Second, when the strain direction is reversed, dislocations of the opposite sign can be produced from the same source that produced the slip-causing dislocations in the initial direction. Dislocations with opposite signs can attract and annihilate each other. Since strain hardening is related to an increased dislocation density, reducing the number of dislocations reduces strength. The net result is that the yield strength for strain in the opposite direction is less than it would be if the strain had continued in the initial direction.

In processes such as sheet stamping, the imposed strain path during deformation can be quite complex, especially on a local scale. For example, as a steel sheet slides through a draw bead, the metal near the bottom surface of the sheet is initially stretched at the first bend, then compressed as it passes over the top of the draw bead, and finally stretched again at the final bend as it leaves the draw bead. The metal on the top surface of the sheet also experiences complex straining involving compression, tension, and subsequent compression. As this example shows, strain reversals are quite common on a local scale. Since the Bauschinger effect occurs when metal experiences a strain reversal, it is a factor in sheet metal forming.

Springback can be a major problem in producing sheet metal parts for a variety of applications, such as automotive panels, appliances, *etc*. Springback occurs due to the elastic recovery when the part is removed from the constraints of the die. As the strength of the metal increases, the elastic recovery increases so that springback and its associated problems become greater. The accurate prediction of springback requires that the local stress state in the sheet needs to be known before elastic recovery. As residual stresses are rebalanced when a part is removed from a die, local plastic deformation is also possible. Such plastic deformation can have a significant effect on sheet springback. There are various constitutive models presently being used in computer codes for the modeling of springback after a metal forming process. The present study provides experimental data that can be used to evaluate these constitutive models for steel behavior.

The purpose of the present study was to investigate the Bauschinger effect as a function of three primary variables—microstructure, strain, and strain rate. Bauschinger tests were conducted on steels with microstructures typical of low-carbon (LC), high-strength low-alloy (HSLA), and dual-phase (DP) steels. Samples were prestrained with tension of 1 to 7 pct prior to reversal. Strain rates of 0.01 s^{-1}, 0.001 s^{-1}, and 0.0001 s^{-1} were used. The strength of the steel before reversal and the yield strength on reversal were both measured. A Bauschinger effect parameter was then calculated based on these strengths. Variations in the Bauschinger effect parameter were subsequently used to determine how the primary variables (microstructure, strain, and strain rate) affected the Bauschinger behavior.

There have been a number of equations suggested to quantify the Bauschinger effect.[6–9] In the present work, the Bauschinger effect parameter (BE) is defined as the strength

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Table I. Chemical Compositions of Experimental Steels (Weight Percent)

Material	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Sn	V	Al	Nb	Ti	N
LC	0.062	1.20	0.018	0.006	0.020	0.094	0.048	0.022	0.014	—	0.003	0.026	—	0.008	0.009
HSLA and DP	0.1	1.06	0.005	0.31	0.27	0.39	0.16	0.09	0.047	0.011	0.001	0.003	0.021	—	0.015

difference on reversal, normalized by the strength before reversal. Increased values of Bauschinger effect parameter indicate large Bauschinger effects.

II. EXPERIMENTAL PROCEDURES

A. *Materials*

Materials representative of three classes of sheet steels were chosen for study. These include a low carbon (LC) steel, a high strength low alloy (HSLA) steel, and a dual phase (DP) steel. Since these materials are normally produced as sheet products that are too thin for the compressive part of the testing used in this project, a systematic methodology was developed to produce "bulk" plate steels with microstructures that simulated production sheet materials. The LC steel was received as a 63-mm-thick plate. An HSLA steel from wide-flanged beams was chosen to be used without laboratory processing as the HSLA steel for this study. The HSLA wide-flanged beam was also used for the DP steel after appropriate heat treatment to produce a ferrite-martensite microstructure. The compositions of the two steels are summarized in Table I. The steels are not as clean as would be expected of a sheet product, but since the investigation was focused on the behavior at yield and just beyond yield, the steels are good surrogates of sheet steels within this region of mechanical behavior under study.

The LC steel was hot rolled to 12.5 mm on a Fenn rolling mill. The specimens were then normalized using controlled cooling that simulates the cooling history of a large production coil. The DP steel was annealed in the intercritical region at 750 °C for 30 minutes, and water quenched to obtain about 20 pct martensite. The microstructures of the three steels are presented in Figure 1. Base material properties were obtained by uniaxial tensile testing performed on a screw-driven MTS frame at displacement rates of 0.282, 0.0282, and 0.00282 mm/s, which corresponded to engineering strain rates of 0.01 s^{-1}, 0.001 s^{-1}, and 0.0001 s^{-1}. The strain hardening exponent, n, was determined over the range of 5 pct plastic strain to uniform strain. Duplicate tests were run for each strain rate.

B. *Bauschinger Test Specimen Geometry*

For the Bauschinger tests, the specimen geometry was based on work of Johnson *et al*.[10] and is shown in Figure 2. This geometry was used for the HSLA and DP steels. Since the LC steel came from a slightly thinner plate, the outside diameter of the thread region was 11.11 mm, instead of 12.70 mm. Samples for the Bauschinger tests and tensile tests were oriented in the rolling direction of the original steel plates.

C. *Bauschinger Test Conditions*

Prestrain was accomplished by tensile deformation to five different levels (1, 2.5, 4, 5.5, and 7 pct). After prestraining, the specimen was subjected to a reversal in compression of

(*a*) (*b*) (*c*)

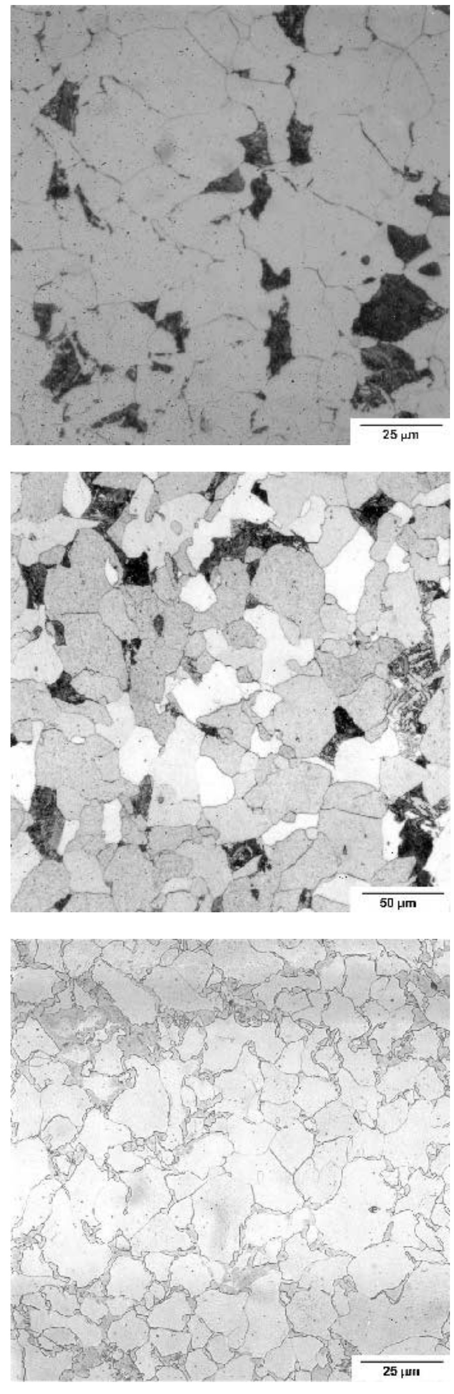

Fig. 1—Microstructures of (*a*) LC steel, (*b*) HSLA steel, and (*c*) DP steel.

2 pct strain. Tests were conducted on a 20 kips MTS servohydraulic system. Strain was measured by a 12.7-mm extensometer with a range of ±8 pct strain. These tests were performed on specimens with the three different microstructures. Each test condition was run at least twice. Bauschinger

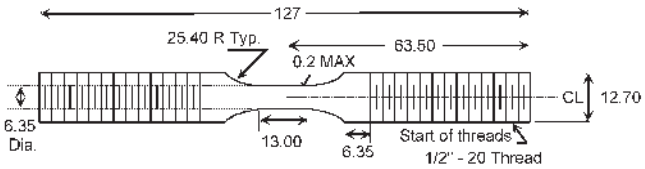

Fig. 2—Geometry of the Bauschinger test specimen (units in millimeters, except for thread designation).

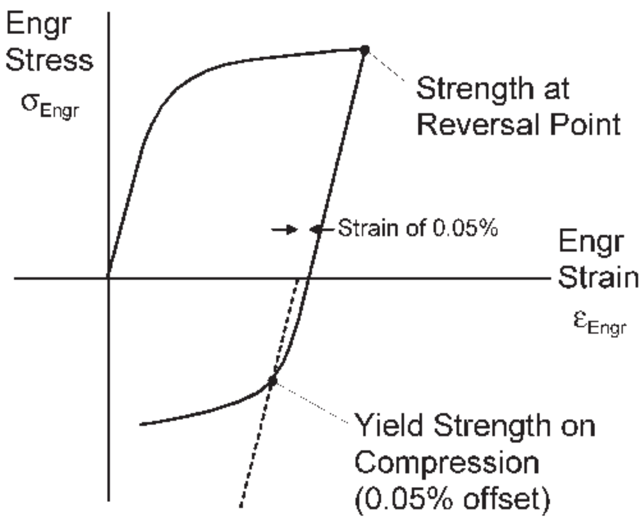

Fig. 3—Schematic for the description of the Bauschinger effect.

testing has been done at engineering strain rates of 0.01 s^{-1}, 0.001 s^{-1}, and 0.0001 s^{-1}.

D. *Analysis Methods*

For the reversal from initial tension to compression, a Bauschinger effect parameter (BE) is used as a quantitative measure of the Bauschinger behavior. In equation form,

$$BE = \frac{\sigma_{\text{at Reversal Point}} - |\sigma_{\text{Yield on Compression}}|}{\sigma_{\text{at Reversal Point}}} \quad [1]$$

Figure 3 gives a schematic that illustrates the specific strength values used in Eq. [1]. Equation [1] is the strength difference upon reversal, normalized with respect to the strength of the material at the reversal point. The BE is equivalent to the Bauschinger effect factor of Jamison and Hood.[6] As shown in Figure 3, a 0.05 pct offset strain was used to determine the yield strength on compression, because it provided a better correlation of the test data than the conventional 0.2 pct offset yield strength.

III. RESULTS

A. *Initial Microstructures and Mechanical Properties*

The microstructure of the LC steel consists of a ferrite grain size of about 19 μm, with regions of pearlite. The microstructure of the HSLA steel consists of a mix of ferrite and pearlite, with an average ferrite grain size of about 15 μm. The microstructure of the DP steel consists of a mixture of ferrite and about 20 pct martensite, with an average ferrite grain size of about 10 μm. It should be noted that in all three steels, the predominant phase is ferrite.

Table II gives the averaged mechanical property values from the duplicate tensile tests at each strain rate. For all strain rates, the LC steel exhibited yield point elongation (YPE) up to 3 pct, the HSLA steel had YPE up to 2 pct, and the DP steel had continuous yielding. A small strain rate effect is observed, but since the range of strain rates was limited, property values averaged over all strain rates are shown in Table II. As expected, yield strength and ultimate tensile strength increase from LC to HSLA to DP. Since the primary testing focus is on the strain region below the uniform elongation, the total elongation data are not included. The strain-hardening exponent (*n*) and the strength coefficient (*K*) values were determined over the range of 5 pct plastic strain to the uniform elongation strain. The measured values shown in Table II are similar to what would be expected from sheet steels of comparable strength.

B. *Bauschinger Tests*

For all of the Bauschinger tests, as the reverse strain was applied, the yield strength for the material on compression was lower than would be expected if the material work hardened in an isotropic manner. The values for the BE parameter as a function of strength just before the reversal were extracted from the Bauschinger test curves, and the values are given in Tables III(a), (b), and (c) for the LC, HSLA, and DP steels, respectively. Figure 3 provides a schematic of how the points were selected from the Bauschinger test curves.

Plots of the BE *vs* prestrain before reversal are shown in Figure 4 for the three steels. The data points in the figure are for the samples prestrained to 1, 2.5, 4, 5.5, or 7 pct, and then reversed to 2 pct compression at all three strain rates. It was found that as the prestrain increases, BE increases, indicating that the Bauschinger effect increases with increasing amount of prior deformation. These observations are consistent with the results of other studies.[4,6,11]

For all three steels, no significant or consistent trends were found with strain rate. Because no consistent trend was observed with respect to strain rate, a single curve has been shown in Figure 4 to indicate how the BE data vary with prestrain.

IV. DISCUSSION

Figure 4 shows that BE increases with prestrain. Since increasing prestrain increases the strength of the material due to strain hardening, BE increases with the strength of the material. Figure 4 also shows that BE is larger for the microstructures associated with the higher strength steels. These observations suggest that a relationship between BE and the strength of the material, regardless of whether the strength increase is due to microstructure or strain hardening, exists. The strength of the material at the reversal point is a measure of the combined microstructural and strain hardening effects.

It was observed that some degree of prestrain was needed to have a regular relationship between BE and strength. The necessity of a minimum prestrain is expected if one considers

Table II. Tensile Properties of Experimental Steels

Material	Strain Rate (s^{-1})	0.2 Pct YS (MPa)	UTS (MPa)	n Value	K Value (MPa)	Uniform Elongation (Pct)
LC	0.0001	263	374	0.209	648	35.8
	0.001	287	386	0.214	675	38.4
	0.01	305	396	0.227	712	38.8
	Average	285 ± 21.1	385 ± 11.0	0.217 ± 0.009	678 ± 32.1	37.6 ± 1.63
HSLA	0.0001	405	532	0.160	848	26.4
	0.001	420	549	0.158	869	27.7
	0.01	427	545	0.158	867	26.3
	Average	417 ± 11.2	542 ± 8.9	0.159 ± 0.001	861 ± 11.6	26.8 ± 0.78
DP	0.0001	507	858	0.089	1178	10.2
	0.001	499	877	0.095	1222	11.0
	0.01	494	859	0.101	1211	12.8
	Average	500 ± 6.6	865 ± 10.7	0.095 ± 0.006	1204 ± 22.9	11.3 ± 1.33

Note: Uncertainty for average values is ±1 standard deviation.

Table IIIa. Bauschinger Effect Values for LC Steel at Reversal Point

		0.01 s^{-1}		0.001 s^{-1}		0.0001 s^{-1}	
Material	Prestrain	Reversal Point (MPa)	BE	Reversal Point (MPa)	BE	Reversal Point (MPa)	BE
LC	1 pct	280	0.210	268	0.268	263	0.215
		290	0.234	274	0.196	262	0.226
		—	—	263	0.284	—	—
	2.5 pct	293	0.332	280	0.286	260	0.240
		291	0.339	270	0.324	276	0.318
	4 pct	313	0.382	297	0.296	296	0.394
		314	0.374	284	0.349	295	0.410
		—	—	302	0.366	—	—
	5.5 pct	338	0.424	320	0.380	311	0.420
		338	0.413	332	0.404	317	0.410
	7 pct	357	0.438	326	0.409	332	0.431
		358	0.414	336	0.396	329	0.404

Table IIIb. Bauschinger Effect Values for HSLA Steel at Reversal Point

		0.01 s^{-1}		0.001 s^{-1}		0.0001 s^{-1}	
Material	Prestrain	Reversal Point (MPa)	BE	Reversal Point (MPa)	BE	Reversal Point (MPa)	BE
HSLA	1 pct	406	0.398	405	0.315	396	0.380
		405	0.385	401	0.392	391	0.417
	2.5 pct	440	0.438	429	0.457	408	0.467
		450	0.491	423	0.427	394	0.426
		—	—	—	—	407	0.420
	4 pct	467	0.471	464	0.526	439	0.496
		474	0.498	476	0.494	427	0.507
	5.5 pct	502	0.497	502	0.523	476	0.525
		508	0.568	497	0.505	489	0.505
		514	0.508	—	—	—	—
	7 pct	529	0.564	521	0.507	514	0.526
		520	0.519	528	0.534	498	0.466
		530	0.530	—	—	—	—
		533	0.529	—	—	—	—

dislocation morphology and the need to develop a back stress of sufficient magnitude to cause a decrease in yielding upon reverse loading. From an analysis of the experimental data, it was determined that a prestrain of 2.5 pct or a prestrain greater than the yield point elongation is needed. Figure 5 shows the relationship between BE and strength at reversal for the data that meet these criteria. The figure also includes data for a hot-rolled AKDQ steel[12] that was used in another study.

Figure 5 provides a general relationship between BE and the strength at the reversal point for the four different steels. Since the common metallurgical feature of the four steels in the figure is a predominant ferrite microstructure, the relationship suggests that the various second phases in the steels

Table IIIc. **Bauschinger Effect Values for DP Steel at Reversal Point**

		$0.01\ s^{-1}$		$0.001\ s^{-1}$		$0.0001\ s^{-1}$	
Material	Prestrain	Reversal Point (MPa)	BE	Reversal Point (MPa)	BE	Reversal Point (MPa)	BE
DP	1 pct	588	0.523	593	0.504	540	0.542
		568	0.515	595	0.499	561	0.474
	2.5 pct	693	0.646	720	0.658	729	0.674
		786	0.660	695	0.630	664	0.645
		702	0.655	—	—	—	—
	4 pct	795	0.706	767	0.637	689	0.623
		839	0.699	784	0.673	730	0.679
		773	0.659	—	—	750	0.668
	5.5 pct	845	0.691	818	0.680	804	0.686
		811	0.732	864	0.686	747	0.667
		817	0.710	—	—	770	0.689
	7 pct	841	0.634	856	0.695	793	0.698
		882	0.715	810	0.698	791	0.698
		851	0.664	—	—	—	—

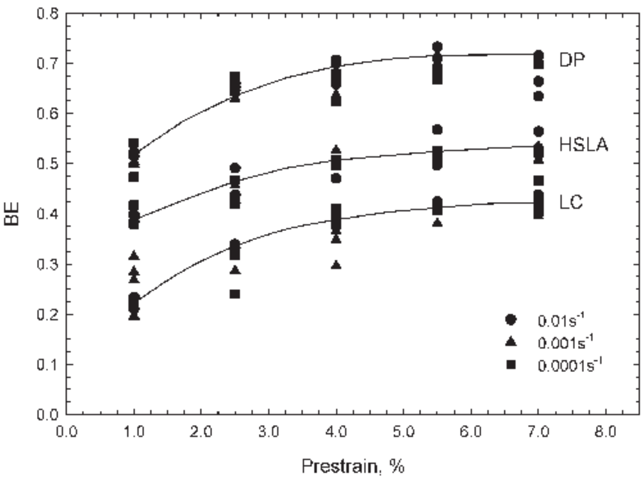

Fig. 4—BE for the three steels at various strain rates.

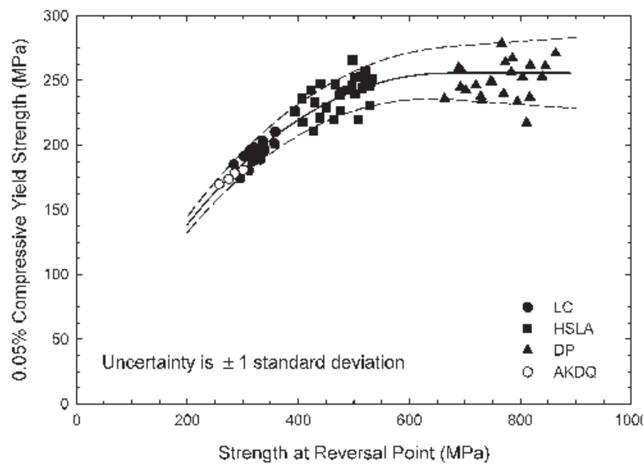

Fig. 6—Compressive 0.05 pct yield strength as a function of the steel strength before reversal.

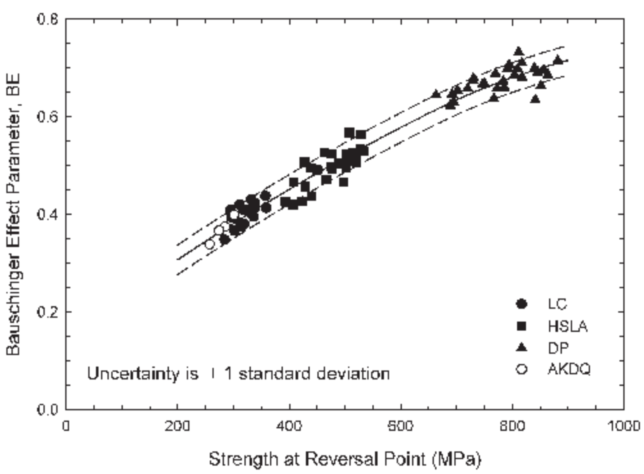

Fig. 5—BE as a function of steel strength before reversal.

do not affect the initial yielding on reversal. It is likely and would be expected that the second phases have a significant effect on the subsequent strain hardening behavior of the steel.

The trend line given in Figure 5 could be of high interest from an engineering perspective. This indicates that for a number of steels over a wide range of strength, the initial yield strength on reverse straining is dependent on the strength before reversal. For modelers of sheet forming processes, such a trend can be used in the material constitutive equation. Most finite-element models can track the local strength of the sheet (*i.e.*, local stress in the sheet) as it deforms. When the deformation is reversed and the Bauschinger effect becomes important, the single trend line of Figure 5 can be used to determine the stress level at which reverse plastic deformation would begin.

Figure 6 shows the 0.05 pct yield strength in compression as a function of the strength of the steel just prior to the strain reversal. The yield strength predicted from the trend line that is given in Figure 5 is also plotted in Figure 6. The uncertainty range in Figure 6 is obtained from the calculated uncertainty limits that are shown in Figure 5. The reverse yield strength increases as the strength of the steel before reversal increases. This increasing trend occurs until the strength of the steel before reversal reaches about 700 MPa. For higher strengths, the reverse yield strength seems to saturate at a constant value of about 250 MPa. The implication of this plot is that the 0.05 pct reverse yield strength in steels with predominantly ferrite microstructures has a maximum or limiting value.

Zhonghua and Haicheng[4] indicate that the ferrite and the martensite phases in the DP steel deform differently because they have different mechanical properties, such as strength and ductility. After plastic deformation, local residual stresses can develop in such DP materials. They indicate that the residual stress may also contribute to the reduced yield strength on compression. This explanation for the Bauschinger effect is also used for steels with inclusions or second phases just like DP.[13] If the residual stress contributes to the Bauschinger response, then multiphase steels would behave differently from the single-phase steel during reverse deformation. Since a single trend line for the LC, HSLA, and DP steels was found in the present investigation, our results seem to be contradictory to these other investigations.[4,13] The reason for the apparent discrepancy is that these other authors did not study initial yielding explicitly; their results are for the subsequent strain hardening rather than for the initial yielding of the material. In the present work, only the initial yield point on reversal was studied.

If the 1 pct prestrain data for all three steels and the 2.5 pct data for the LC steel, which has a YPE of 3 pct, are added to Figure 5, they would appear below the trend line. These results indicate that some minimum prestrain is needed to establish the trend line and the necessary prestrain increases as YPE increases.

V. CONCLUSIONS

The major conclusions drawn from the present investigation are as follows.

1. A single trend line describes the Bauschinger effect parameter (BE) for the reversal in terms of the strength just prior to the reversal, providing prestrains are at least 2.5 pct or beyond the yield point elongation. The trend line accounts for the data from all three steels in the present study, and the data from an AKDQ steel from another investigation. The trend line indicates that the higher the strength of the steel, the greater the BE.
2. There is no consistent effect of strain rate on BE. Since the strain-rate range is limited and the experimental uncertainty is significant, it was not possible to determine if strain rate hardening influences the Bauschinger effect.

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