Characterization of Cyclic Inelastic Strain Behavior On Properties of A572 Gr. 50 and A913 Gr. 50 Rolled Sections

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Final Report
to
American Institute of Steel Construction

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ACKNOWLEDGEMENT

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I. INTRODUCTION

In a series of cracking incidents that have occurred during fabrication with rolled column shapes [1] it was found that the cracking originated in the k-area of the column. It was also found that the mechanical properties in this area were substantially changed as a result of the rotary straightening process now widely used in manufacturing rolled shapes. The cold deformation introduced in the web near the web-flange intersection (k-area) during rotary straightening of the section was found to have markedly elevated the yield and tensile strength with concomitant decreases in ductility and fracture toughness [2]. The local elevation in strength and reduction in ductility and toughness in the k-area was believed to have been a key factor in the cause for the cracking. Beyond the fabrication precautions which have now been implemented to mitigate future cracking in this region [3] the subsequent service performance, particularly severe service as occurs in earthquakes, of rolled sections containing these low ductility and toughness regions also needed to be examined. The study reported herein is one of four studies initiated by the American Institute of Steel Construction to address these needs.

I.1 RESEARCH OBJECTIVE AND APPROACH

The objective of the current study was to examine the basic mechanical properties of inelastically strained A572 Gr. 50, A913 Gr. 50 and A36 steel sections to provide test data that could be used to assess the effects of manufacturing straightening procedures on the notch toughness and ductility of the k-region of rolled shapes. An A36 section was included in the study to compare the inelastic strain behavior of a section produced earlier by integrated mills to sections produced by current manufacturing practices. The studies included tensile and Charpy-V-notch properties (ASTM E8 and E23) of the as-rolled sections and at three levels of monotonic pre-strain (2%, 8%,12%). Although the strain conditions introduced in the k-area during rotary straightening are a combination of tensile, compressive, and shear deformation, quantitative simulation of these complex conditions in the laboratory is not readily achievable. Consequently, monotonic tensile straining was chosen to approximate these conditions and to compare the steels and observe trends at different strain levels. The cyclic inelastic strain behavior of the materials was also studied using standard strain controlled fatigue test methodologies (ASTM E606). Limited studies of the effects of strain aging were also conducted. The contemporary Gr.50 sections were W14 X 176 sections produced by three different mills. Two sections were A572 Gr. 50 and the third was A913 Gr. 50. The A36 steel was a W36 X 260 section manufactured prior to 1984 and was believed to be produced by an integrated mill.

I.2 BACKGROUND

The strain hardening of structural steel has been shown to produce changes in the hardness, strength, ductility, and toughness of the steel. The phenomena of strain aging can produce additional changes in these properties. The effect of these processes on the mechanical properties of steel is illustrated in Figure 1. If, after initial inelastic deformation to Point A on the stress-strain curve of a steel specimen the load is removed a certain amount of permanent deformation remains as a pre-strain. If reloaded immediately the specimen loads elastically to Point A again and continues to extend as if it had not been unloaded. If the specimen is unloaded and aged at room temperature or at moderately elevated temperatures the lower yield point and lower yield extension returns again but at an elevated stress than occurred upon immediate reloading (Point A). Subsequent extension to failure will often be accompanied by a slight increase in tensile strength and reduction in total elongation of the specimen. Straining followed by subsequent aging not only results in increased yield point and reduction in tensile ductility in some steels but also affects the notch toughness of the steel. Reductions in absorbed energy and upward shifts in transition temperature occur in steels as a result of straining often with further changes following aging.

The potential for increases in yield and tensile strength along with decreases in ductility and toughness after monotonic straining have been demonstrated in A572, A588A, A588B, A737B and A737C plates [4]. In this study cold strain at the level of 5 to 10% increased yield strengths of the steels by over 200% and subsequent aging at 370 C raised them another 25%. Cold strain increased the 34 J Charpy V-notch transition temperature by 25-50 F with aging increasing the transition temperature modestly above the as-strained level.

More recently, limited studies of rotary straightened structural members has demonstrated that the k-area of some wide flange shapes have substantially increased hardness, yield and tensile strengths with accompanied decreases in tensile ductility and notch toughness. Hardness as high as RB 97 and notch toughness as low as 4J at room temperature have been reported in this region [2].

II. EXPERIMENTAL PROGRAM

II.1 PROPERTIES OF AS-ROLLED SECTIONS

The as-rolled properties of the A572 Gr. 50, A913 Gr.50 and A36 rolled sections as well as the mill report test results are summarized in Table 1. Standard 0.505 in. round specimens located at the web mid-thickness and centerline of the section were prepared for each section. In general, the tensile properties of the A572 Gr. 50 steel (Steels A and C) were consistent with the mill certificates, however, the A913 Gr. 50 steel (Steel B) provided somewhat lower strengths which can be attributed to the mid-thickness positioning of the 0.505 in. test specimen compared to the full thickness coupon tested by the mill.

Chemical composition of the steels including residual elements are given in Table 2. The analyses show that the steels satisfy their respective specification requirements within product anlaysis tolerances. Residual element levels in Steels A, B, and C are at typical levels found in modern day structural steel sections. The very low residual element levels measured in the A36 section (Steel D) provided additional evidence of its integrated mill origin.

II.2 EFFECT OF INELASTIC PRE-STRAINING ON TENSILE PROPERTIES

II.2.1 Test Procedure

To study the effects of inelastic strain on the mechanical properties of the various steels large

(33"x 4") full web thickness tensile coupons were prepared located near the web centerline of the sections. For each of the four rolled sections coupons were monotonically pre-strained to three different levels of strain (2%, 8%, and 12%) from which longitudinal 0.505 in. tensiles and L-T and T-L oriented Charpy V-notch specimens were then fabricated. Additional coupons were prepared from Steel A and prestrained to an intermediate strain (8%) for subsequent aging (10 hours) at 200 F and 400 F.

II.2.2 Test Results

Figures 2A through 2D show the stress-strain behavior obtained for the four steels (A, B, C, and D) initially (as-rolled) and at the various pre-strains. The results are summarized in Figure 3 and 4 which shows that all of the steels followed the same trend. With increasing pre-strain the yield point increased by 20-40% approaching the tensile strength of the steel while tensile elongation decreased by about the same magnitude. At 12 % pre-strain, close to strain at ultimate tensile strength in the as-rolled condition, yield points and tensile strengths were nearly identical as the strain hardening capacity of the steel was fully exhausted by the pre-strain.

II.2.3 Strain Aging Effects

Aging of Steel A pre-strained to 8% strain resulted in only a small additional increase in strength (~2%). Considering the low carbon (0.067%) and nitrogen (0.0032%) levels measured in this steel it is not surprising that its strain aging response was small. It is interesting that low nitrogen levels were found in all of the steels (see Table 2) and well below the A992 manufacturer's limit of 0.012%. A588 plate steels with higher nitrogen levels (0.011-0.012) studied by Herman et al [4] showed greater effect of strain aging particularly on CVN properties.

II.3 EFFECT OF INELASTIC PRE-STRAINING ON CVN PROPERTIES

II.3.1 Test Procedure

Standard Charpy V-notch specimens were fabricated from the same large pre-strained coupons as the tensile specimens. Eighteen L-T and T-L oriented test specimens were each fabricated for the three pre-strain levels and in the as-rolled condition. The specimens were tested in triplicate over a range of temperatures within the transition temperature range for the material.

II.3.2 Test Results

Results of Charpy V-notch (CVN) tests over the transition temperature range are shown for the as-rolled and variously pre-strained sections in Figures 5A through 5H. All three contemporary sections (Steels A,B, and C) exhibited upper shelf behavior at room temperature in the as-rolled condition whereas the earlier produced A36 (Steel D) showed room temperature toughness in the transition temperature range. Pre-straining resulted in progressive reductions in absorbed energy and an upward shift in transition temperature. A summary of the shift in the 15 ft-lb transition temperature relative to the as-rolled condition ($\Delta T_{transition}$) is provided in Figure 6. For the three contemporary steel sections a pre-strain of 2% was found to shift the 15 ft-lb transition temperature 10-20 F. At 12% pre-strain the shift ranged from 40-70 F. Transverse oriented specimens consistently experienced a larger shift in transition temperature at all pre-strain levels ranging from 25-100 F.

II.3.3 Strain Aging Effects

As with tensile properties the effect of an elevated temperature aging treatment on notch toughness was also small. An increase in transition temperature of about 15 F was observed for Steel A at the higher aging temperature of 400 F compared to 68 F increase observed by Herman et al [4].

II.4 CYCLIC STRAIN BEHAVIOR

II.4.1 Test Procedure

Cyclic strain tests following ASTM E606 [5] methodology were carried out on all four materials. The 0.375 in. dia. round test specimen design utilized is shown in Figure 7. The surface finish of the reduced section of the test specimens was a 16 micron finish. Figure 8 shows a test specimen installed in the 55 kip servohydraulic load frame used with a 1 in. G.L. extensometer attached to the reduced section of the test specimen. Tests were conducted at four strain range levels of 2%, 4%, 6% and 8%. Each test consisted of 10 tension-compression cycles at a single strain range. The specimens were loaded at a constant displacement rate of 0.005 in./min. to the specified strain range. A typical strain-time plot for a single test is shown in Figure 9.

II.4.2 Test Results

Figures 10A through 10D show a composite plot of the four individual tests performed at each strain range for the four steels. All four materials cyclically strain hardened similarly. The similarity in the cyclic strain hardening characteristics of the steels is also shown in Figure 11. The stabilized cyclic stress-strain test data for each strain range is plotted and fitted to an equation of the form $\sigma = K\,\varepsilon^n$ where n is the cyclic strain hardening exponent. Also shown are the corresponding monotonic stress-strain curves for comparison. Steels A, B, and C yielded nearly the same value for n ranging from 0.096-0.111. Steel D exhibited a higher value for n of 0.150. In general, materials with greater ductility and higher cyclic strain hardening exponents show greater low cycle fatigue resistance. The test results shown in Figure 10 also show that at the lowest strain range of 2% cyclic stabilization occurred within 4-5 cycles. At the higher strain ranges all four steels cyclically stabilized within 2-3 cycles. The majority of the strain hardening appears to occur during the first strain cycle which suggests that the monotonic pre-strains used to measure effects on properties likely represents the bulk of the strain damage.

II.4.3 Low Cycle Fatigue Tests

No visual indications of cracking was observed in any of the materials within the ten applied cycles. To obtain some information on crack initiation behavior several additional tests were performed where cycling was continued until initiation of fatigue cracking. Three tests were conducted at a strain range of 2%, 6% and 8% using Steel C. Cracking developed within several hundred cycles at the lowest applied strain range and within 25 cycles at 8% strain range. A strain - life plot of the results is shown in Figure 12. Extrapolating the curve to shorter fatigue life suggests that cracking could be expected in the range of 5-10 cycles normally applied in rotary straightening at applied strain ranges of 13-18%.

III. SUMMARY AND CONCLUSIONS

1. The behavior of contemporary A 572 Gr. 50 and A913 Gr.50 rolled sections under inelastic straining was found to be similar. Inelastic strains ranging from 2-12% resulted in significant changes in tensile and notch toughness properties in all three contemporary steels studied. Yield and tensile strengths increased by 20-60% and 5-20%, respectively, with concomitant reductions in tensile elongations of 15-50%. Elevation of CVN transition temperature ranged from 20-70 F over the range of strains studied. Larger shifts in transition temperature were observed transverse to the strain direction ranging from 25-100 F.

2. Strain aging effects were found to be small in A572 Gr. 50 steel. For 8% strain a 2% increase in strength and 15 F increase in transition temperature was observed. Carbon and nitrogen levels were low in all four steels studied which may account for the small strain aging response.

3. The cyclic inelastic strain behavior of all three contemporary Gr. 50 steels was also similar. Cyclic stabilization was achieved after 2-3 applied strain cycles for strain ranges above 2%. The cyclic inelastic behavior of historical A36 steel indicates a higher low cycle fatigue resistance consistent with its lower strength and higher ductility.

4. Low cycle fatigue cracking was not observed in any of the steels examined at strain ranges as high as 8 % in 10 applied cycles. Limited tests using A572 Gr. 50 suggests that strain ranges of 13-18% are necessary for crack initiation to occur in 5-10 cycles normally applied in rotary straightening.

5. Test results suggest that the k-region properties of rotary straightened sections possess properties comparable to monotonic pre-strains of 8-12%.

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5. ASTM E606-92 "Standard Practice for Strain-Controlled Fatigue Testing", Vol. 03.01, ASTM, 2000.

TABLE 2 CHEMICAL COMPOSITIONS

Element	Composition, wt%			
	Steel A	Steel B	Steel C	Steel D
C	0.067	0.085	0.072	0.17
Mn	1.51	1.20	1.48	0.75
P	0.022	0.023	0.014	0.020
S	0.005	0.020	0.016	0.024
Si	0.28	0.18	0.21	0.05
Cr	0.028	0.11	0.061	0.044
Ni	0.23	0.11	0.13	0.031
Mo	0.065	0.072	0.086	0.038
Al	0.032	0.002	0.002	0.002
Cu	0.31	0.22	0.29	0.021
Co	<0.001	0.010	0.008	0.004
Nb	0.003	0.008	0.003	0.002
Ti	0.002	0.001	0.001	<0.001
V	0.15	0.005	0.057	0.004
W	<0.001	<0.001	<0.001	<0.001
Pb	0.006	0.003	0.011	0.003
Sn	0.004	0.013	0.013	0.002
As	0.003	0.011	0.007	0.005
Zr	0.001	0.001	0.001	<0.001
Ca	<0.001	<0.001	<0.001	<0.001
Sb	0.0034	0.0044	0.0047	<0.0001
B	<0.0001	0.0002	<0.0001	<0.0001
N	0.0032	0.0033	0.0040	<0.0005
Fe	97.3	97.9	97.5	98.8

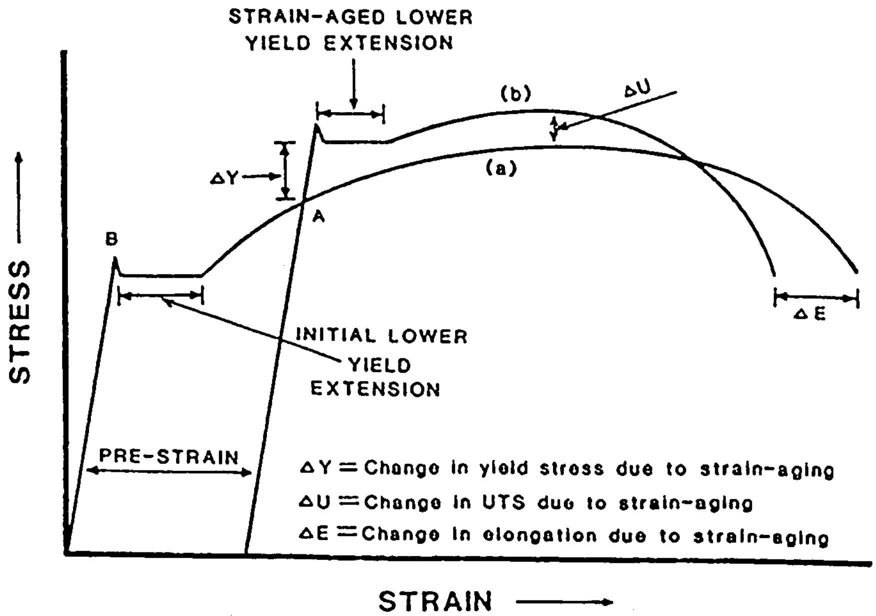

Figure 1 Effect of Straining and Aging on Tensile Properties of Steel.[4]

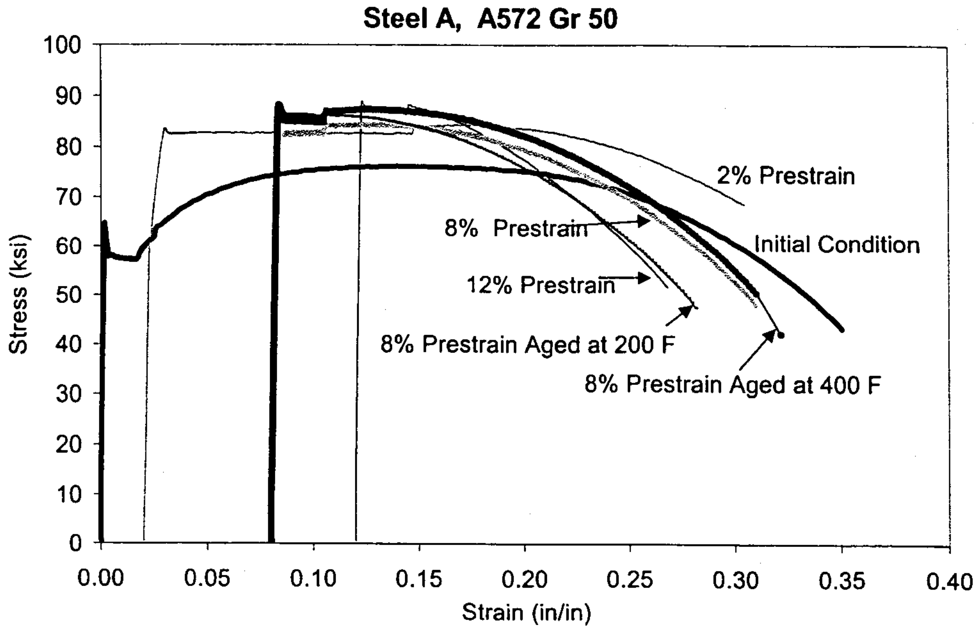

Figure 2A Stress-Strain Curves for Steel A For Various Pre-strain Conditions.

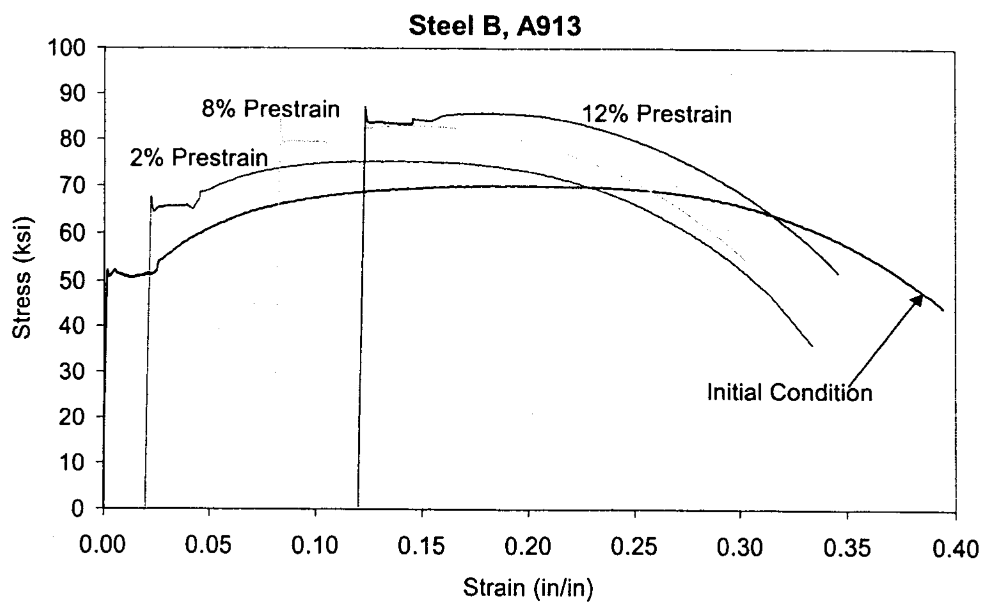

Figure 2B Stress-Strain Curves for Steel B For Various Pre-strain Conditions.

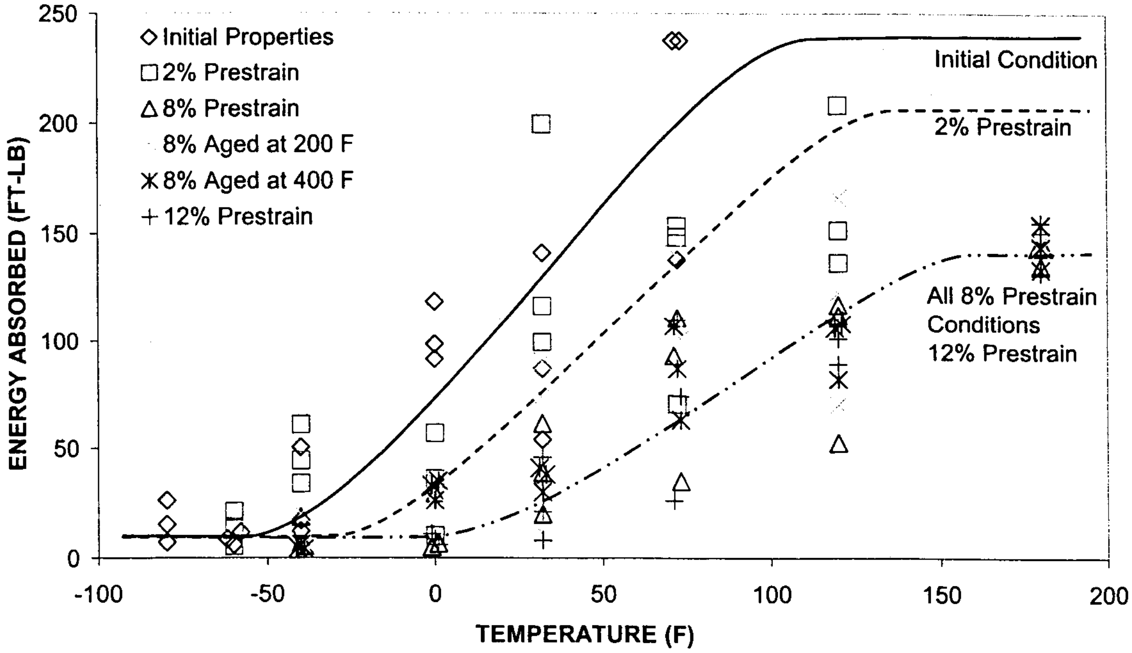

Figure 5A CVN Transition Curves (TL) For Steel A For Various Pre-strain Conditions.

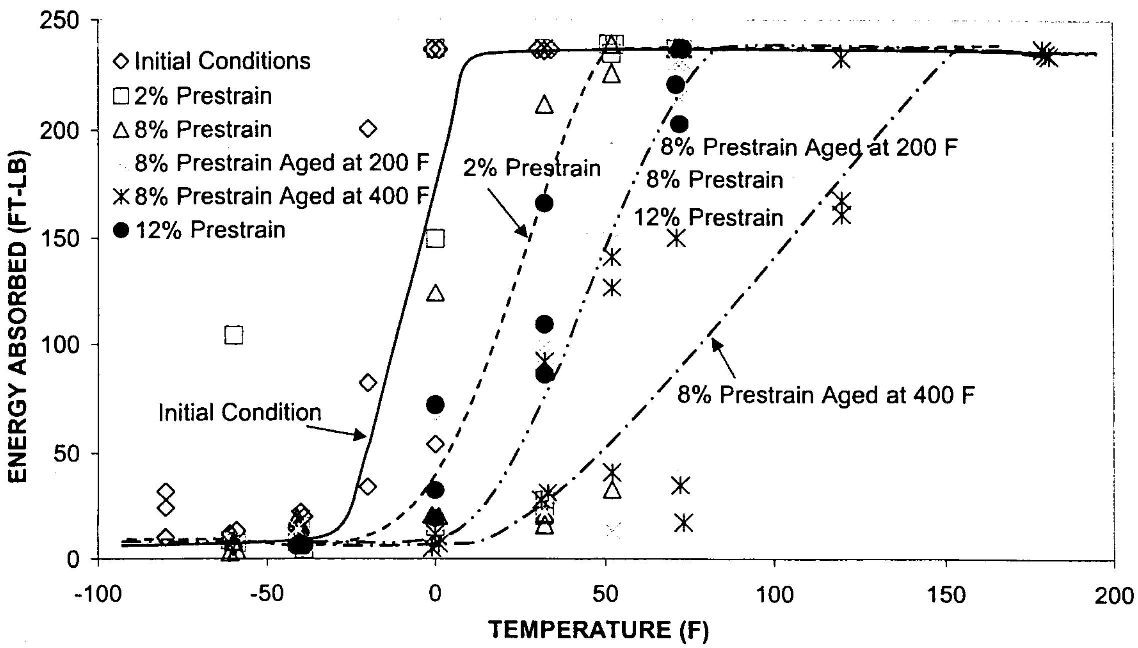

Figure 5B CVN Transition Curves (LT) For Steel A For Various Pre-strain Conditions.

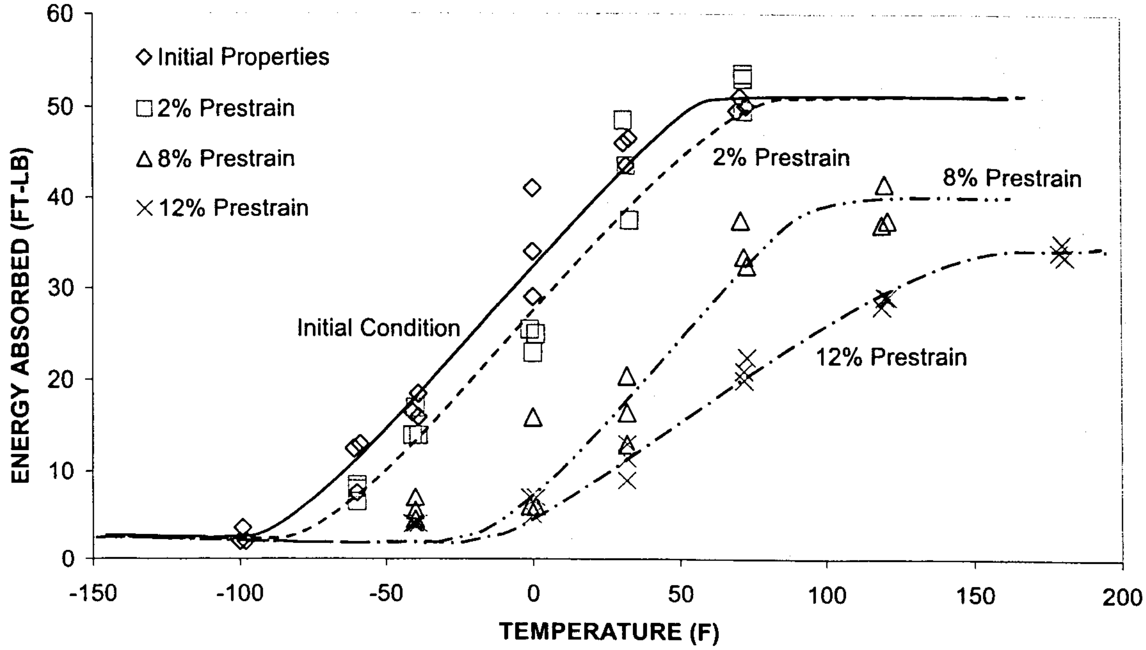

Figure 5C CVN Transition Curves (TL) For Steel B For Various Pre-strain Conditions.

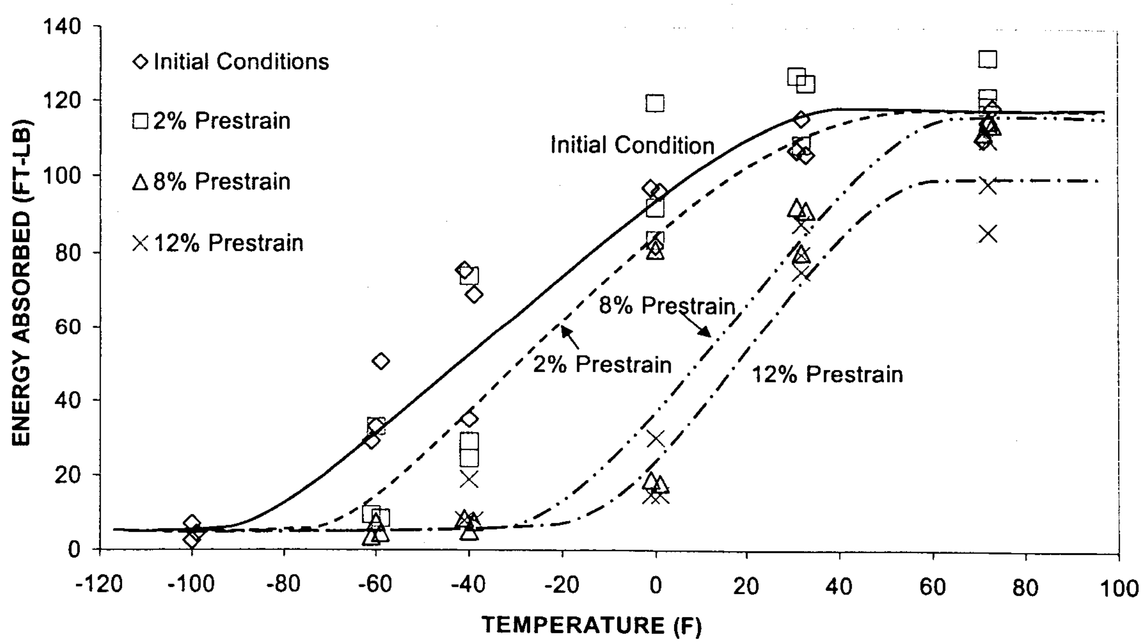

Figure 5D CVN Transition Curves (LT) For Steel B in the LT For Various Pre-strain Conditions.

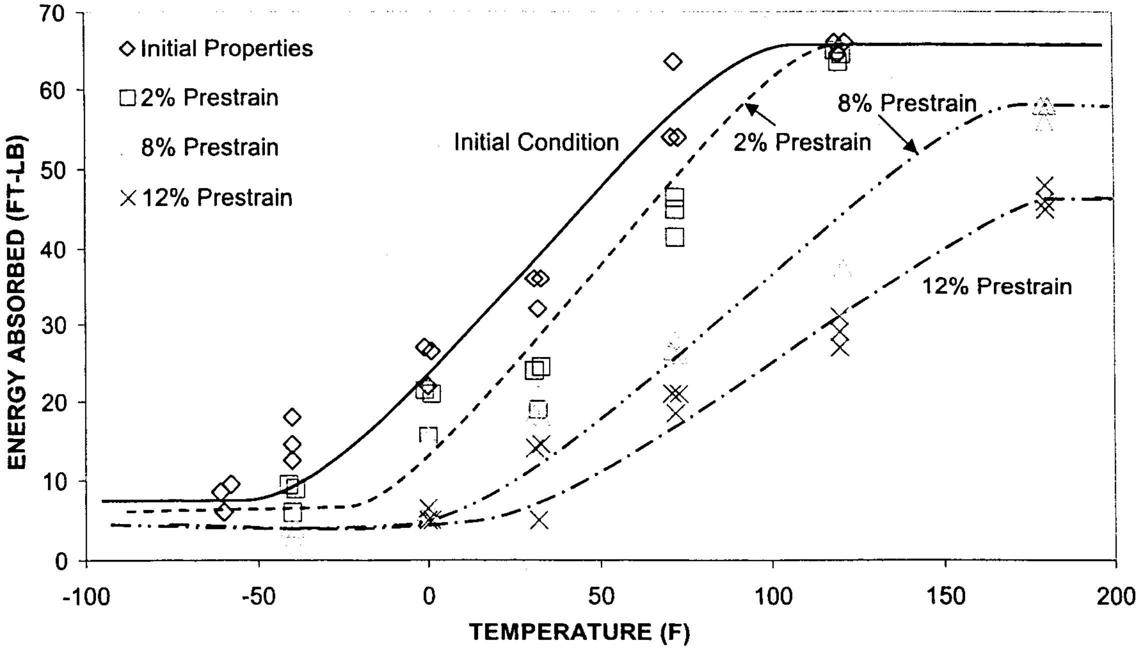

Figure 5E CVN Transition Curves (TL) For Steel C For Various Pre-strain Conditions.

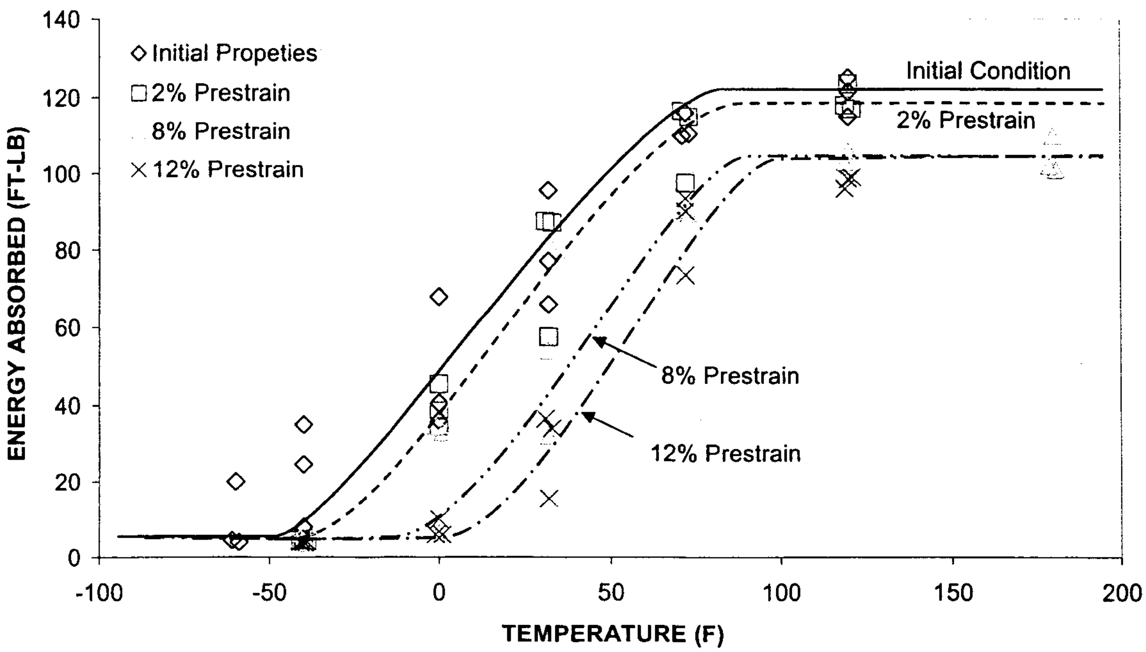

Figure 5F CVN Transition Curves (LT) For Steel C For Various Pre-strain Conditions.

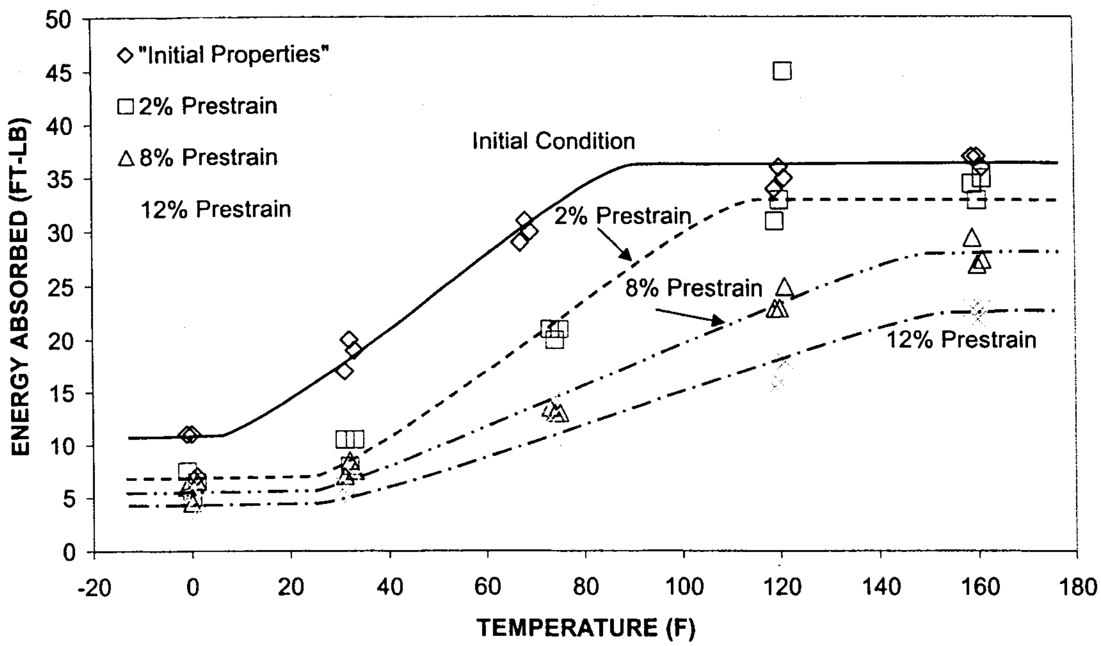

Figure 5G CVN Transition Curves (TL) For Steel D For Various Pre-strain Conditions.

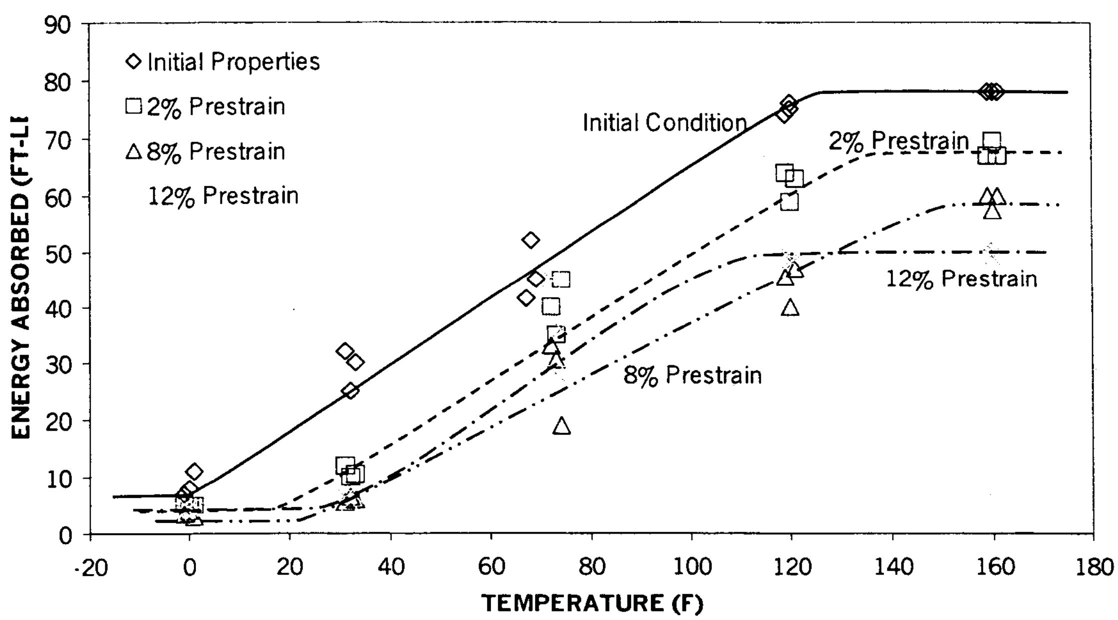

Figure 5H CVN Transition Curves (LT) For Steel D For Various Pre-strain Conditions.

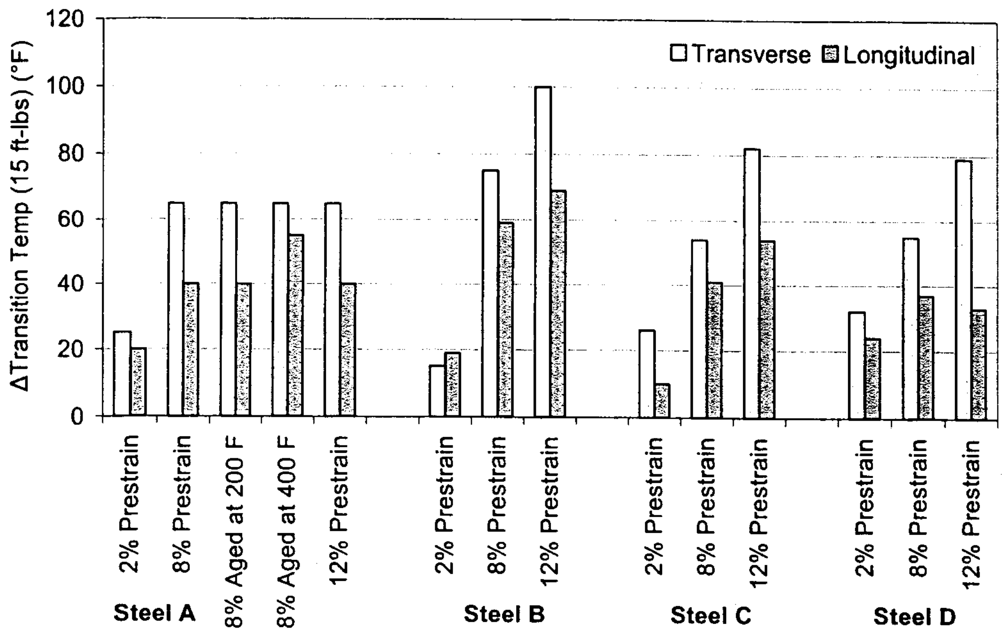

Figure 6 $\Delta T_{transition}$ at 15 ft-lbs from As-rolled Condition For Various Pre-strain Conditions.

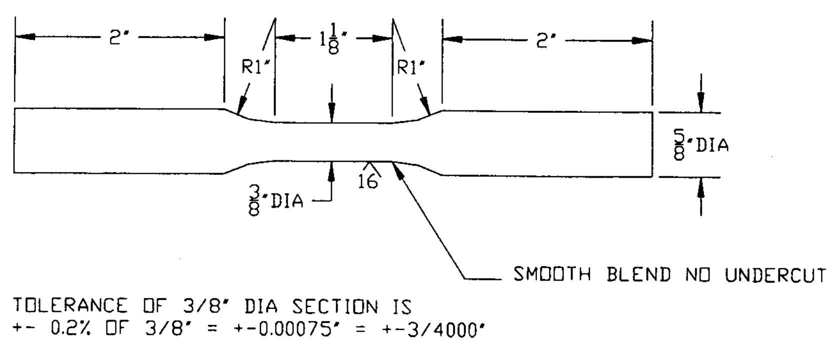

Figure 7 Cyclic Strain Test Specimen (ASTM E606).

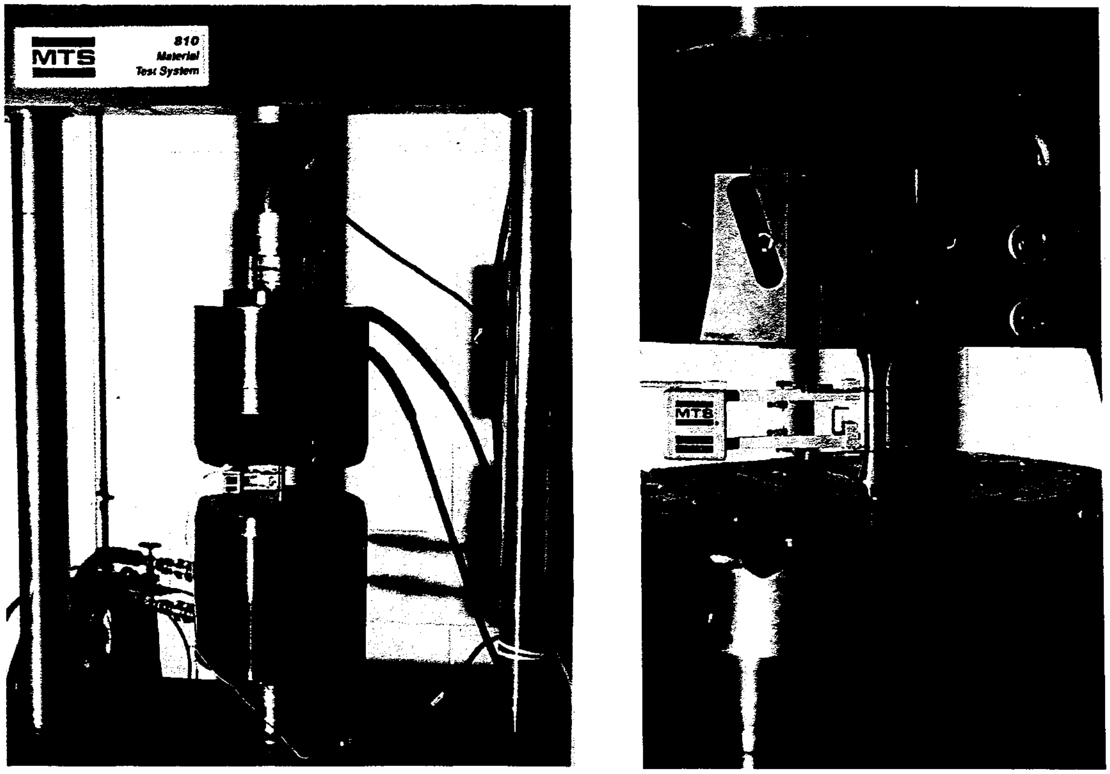

Figure 8 Cyclic Strain Test Set-up.

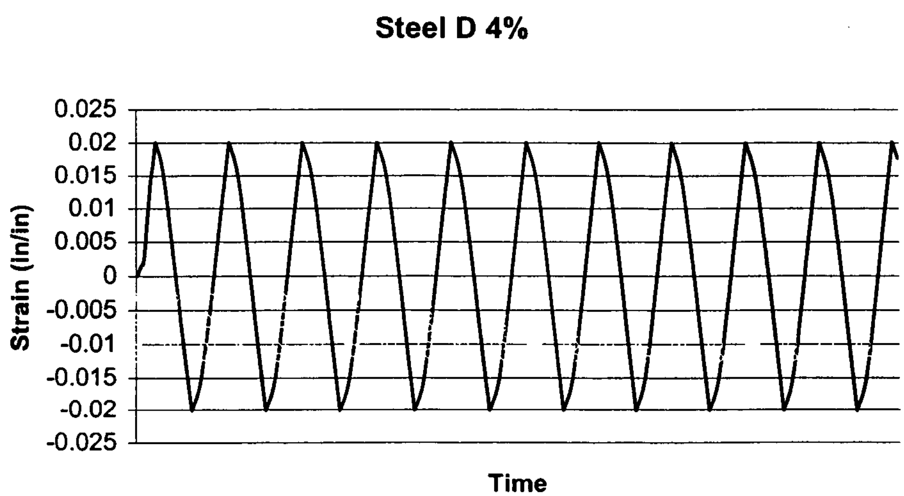

Figure 9 Typical Strain-Time Plot for a Single Cyclic Strain Test.

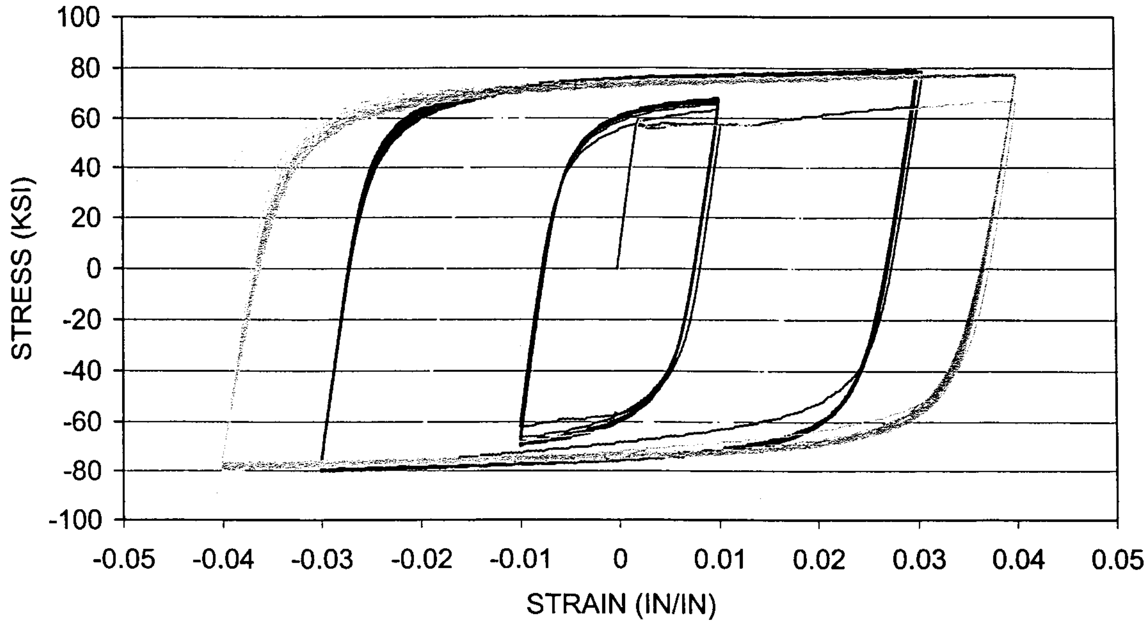

Figure 10A Cyclic Strain Behavior of Steel A (10 cycles at 2%, 4%, 6%, and 8% Strain Range).

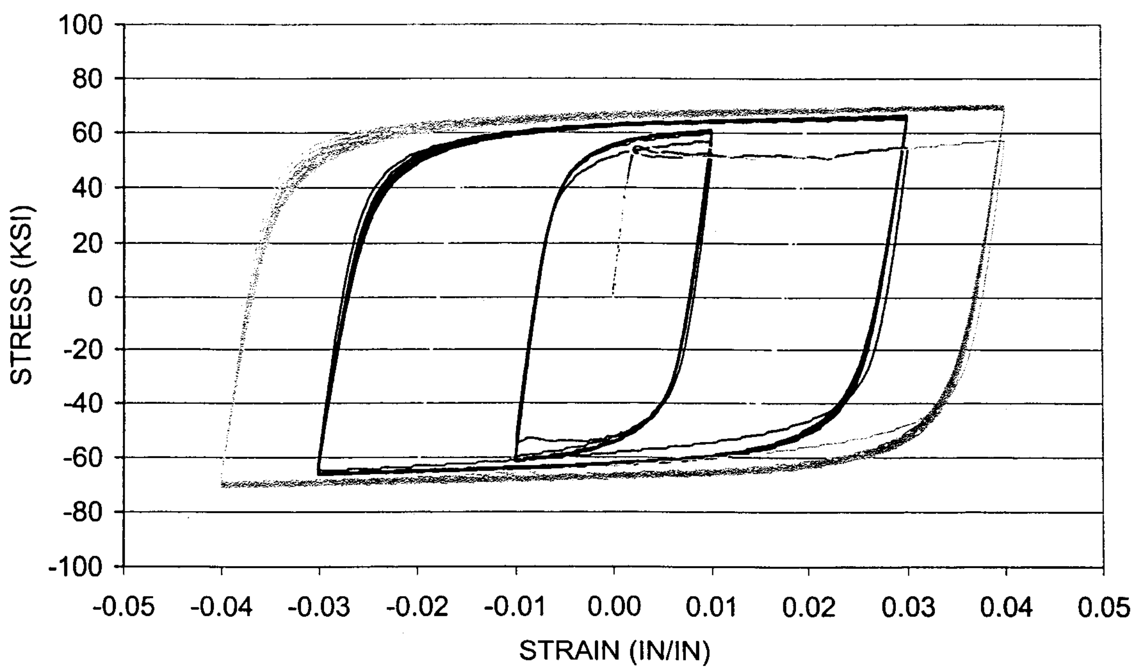

Figure 10B Cyclic Strain Behavior of Steel B (10 cycles at 2%, 4%, 6% and 8% Strain Range).

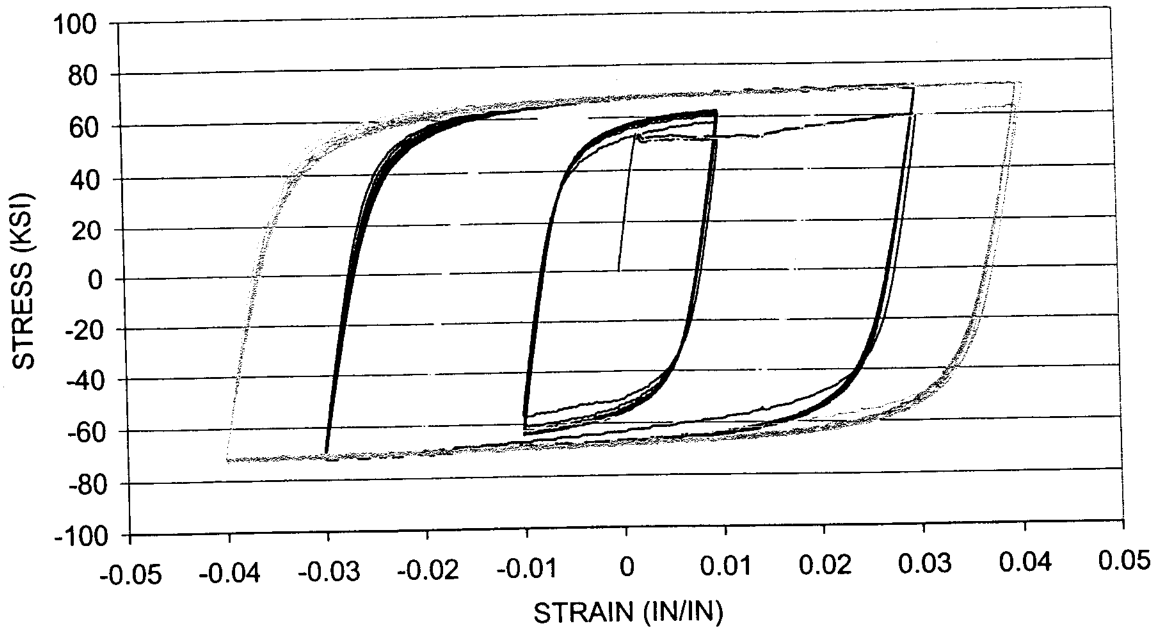

Figure 10C Cyclic Strain Behavior of Steel C (10 cycles at 2%, 4%, 6% and 8% Strain Range).

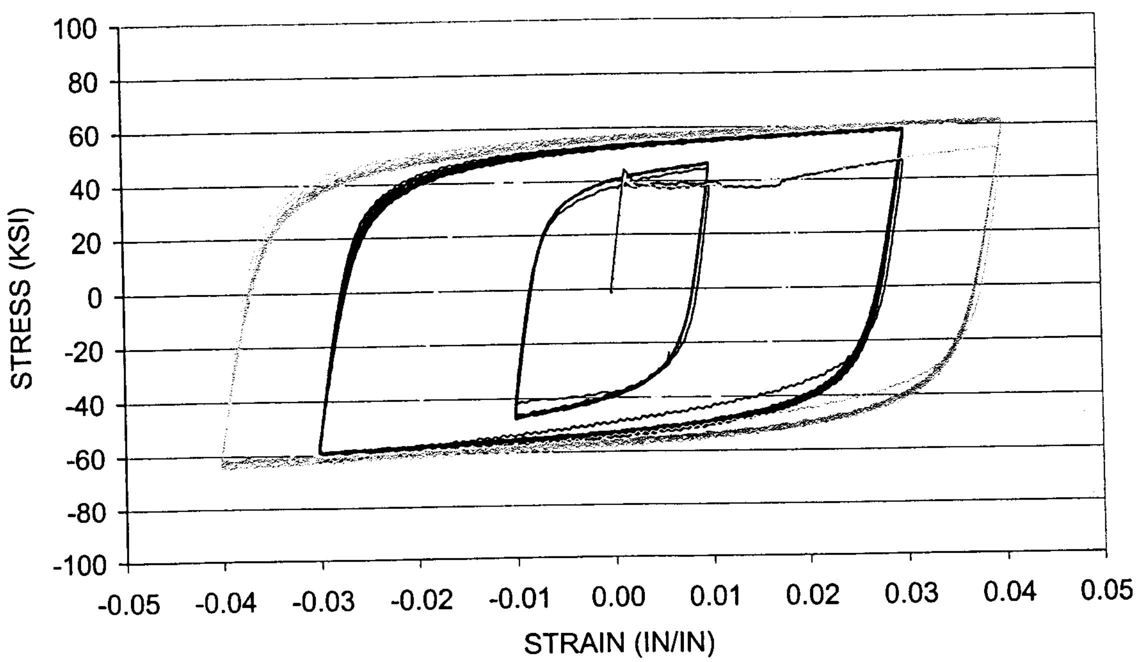

Figure 10D Cyclic Strain Behavior of Steel D (10 cycles at 2%, 4%, 6% and 8% Strain Range).

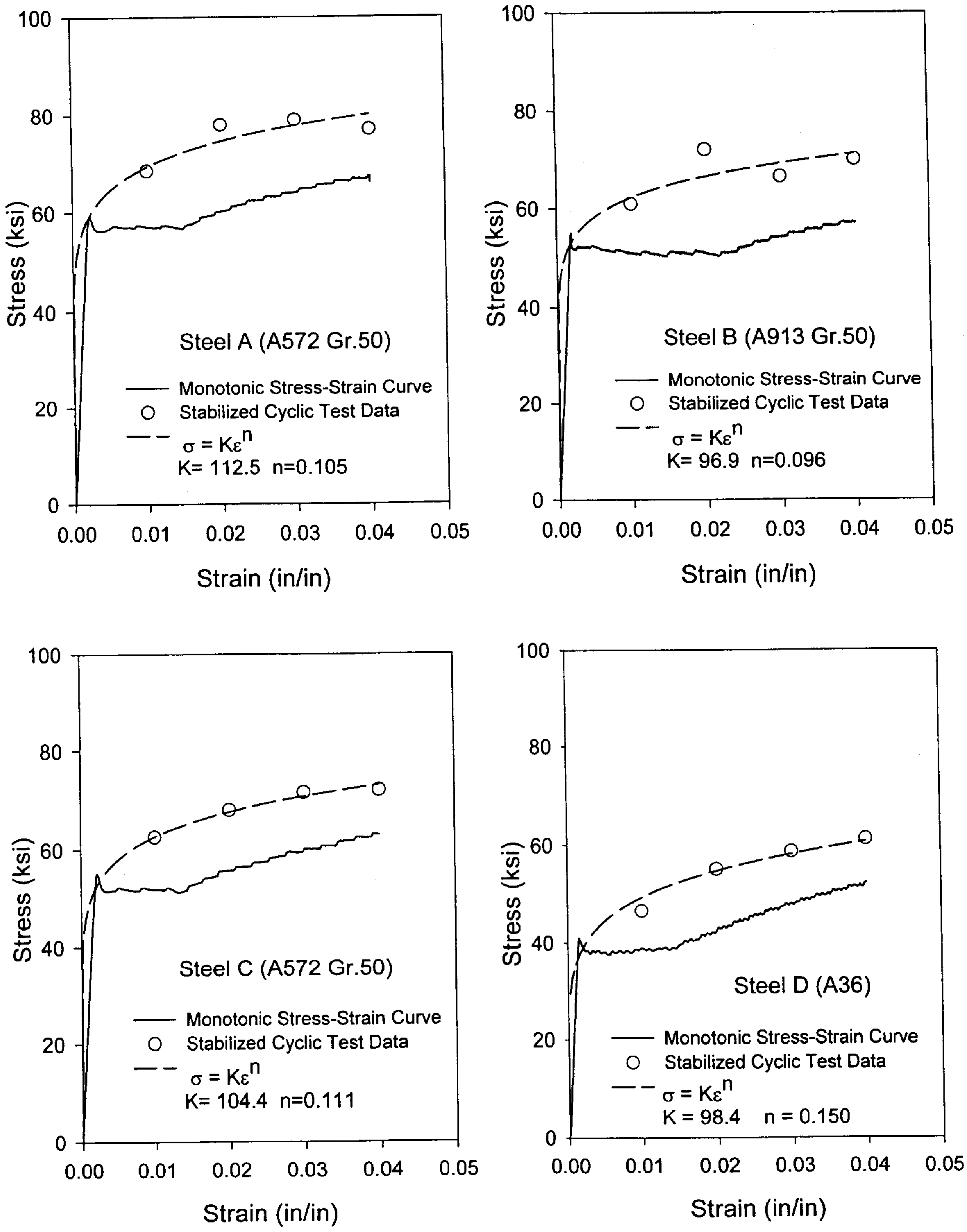

Figure 11 Comparison of Monotonic and Stabilized Cyclic Stress-Strain Behavior of the Four Steels.

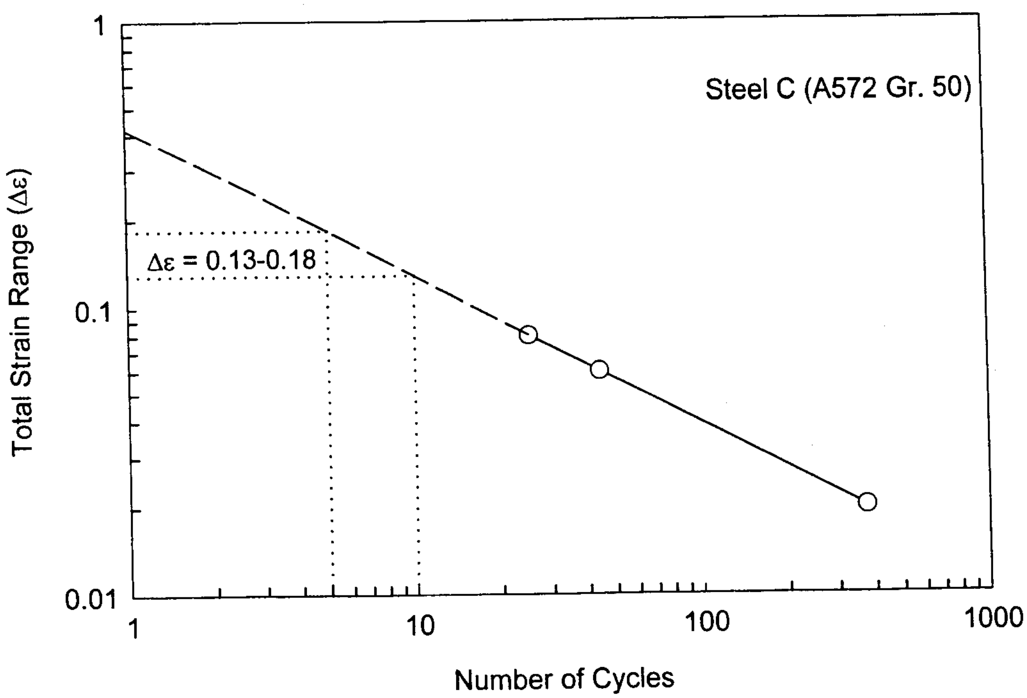

Figure 12 Strain-Life Plot for Steel C (A572 Gr. 50) with Data Extrapolated to Low Fatigue Life.