Fatigue Behavior, Monotonic Properties

and

Microstructure Data

for

4320, Carburized (Case) Steel

(Iteration No. 50)

By

M. Khalil,

T. H. Topper

Department of Civil Engineering,

University of Waterloo

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TABLE OF CONTENTS

SUMMARY 3

INTRODUCTION 4

EXPERIMENTAL PROCEDURE 4

Specimen Preparation 4

Test Equipment and Procedure 4

RESULTS 5

A) Microstructure Data 5

B) Strain-Life Data 6

C) Cyclic Stress-Strain Curves 6

D) Mechanical Properties 7

REFERENCES 7

SUMMARY

The required chemical analysis, microstructure data, mechanical properties, cyclic stress-strain data and strain-controlled fatigue data for 4320 Carburized (Case) steel (Iteration # 50) have been obtained. The material was provided by the American Iron and Steel Institute (AISI) in the form of 2.5" bars. These bars were machined into smooth axial fatigue specimens. The specimens were heat treated by the AISI group to reach a hardness of about Rc 60. Two monotonic tensile tests were performed to measure the yield strength, the tensile strength and the reduction of area. A monotonic compressive test was also performed to document the difference in mechanical properties between tension and compression for 4320 Carburized Steel. Eighteen specimens were fatigue tested in laboratory air at room temperature to establish a strain-life curve.

INTRODUCTION

This report presents the results of tensile and fatigue tests performed on a group of 21, 4320 Carburized (Case) steel samples. The material was provided by the American Iron and Steel Institute.

The objectives of this investigation were to obtain the chemical analysis, and microstructural data, mechanical properties, cyclic stress-strain data and strain-life fatigue data requested by the AISI bar group.

EXPERIMENTAL PROCEDURE

Specimen Preparation

The material for the study was received in the form of bars. Smooth cylindrical fatigue specimens, shown in Figure 1, were machined from the metal bars. The gauge sections of the fatigue specimens were mechanically polished in the loading direction using 240, 400, 500, and 600 emery paper. After polishing, a thin band of M-coat D acrylic coating was applied along the central gauge section. The purpose of the M-coat D application was to prevent scratching of the smooth surface by the knife-edges of the strain extensometer, thus reducing the incidence of knife-edge failures. In total, 18 fatigue data points were generated.

Test Equipment and Procedure

Two monotonic tension tests were performed to determine the yield strength, the tensile strength, the percent of elongation and the percent reduction of area. Hardness tests were performed on the surface of three fatigue specimens using a Rockwell C scale. The hardness measurements were repeated three times for each specimen and the average value was recorded.

All fatigue tests were carried out in a laboratory environment at approximately 25 ^{o}C using an MTS servo-controlled closed loop electrohydraulic testing machine. A process control computer, controlled by FLEX software [1] was used to output constant strain and stress amplitudes in the form of a sinusoidal wave.

Axial, constant amplitude, fully reversed (R=-1) strain-controlled fatigue tests were performed on smooth specimens. The stress-strain limits for a given cycle of each specimen were recorded at logarithmic intervals throughout the test via a peak reading oscilloscope. Failure of a specimen was defined as a 50 percent drop in tensile peak load from the peak load observed at one half the expected specimen life. For fatigue lives greater than 100,000 reversals, the specimens were tested in stress-control once the stress-strain loops had stabilized. For the stress-controlled tests, failure was defined as the separation of the smooth specimen into two pieces. For strain-controlled tests the loading frequency varied from 0.03 Hz to 5 Hz while in stress-controlled tests the frequency used was up to 110 Hz.

The first reversal of each fatigue test was recorded on a x-y plotter, allowing the elastic modulus (E) and the monotonic yield strength to be determined.

RESULTS

A) Microstructure Data

Figure 2 presents the martensite microstructure of the 4320 Carburized (Case) steel. A Type D series inclusion severity level of 1 was obtained based on ASTM E45 (Method A). Inclusions of types A, B and C were not observed. Figure 3 shows the inclusions observed in the 4320 Carburized (Case) steel. The inclusion area was measured using a JAVA image analysis system. The chemical composition of 4320 Carburized (Case) steel was provided by the MacSteel Company, and is shown in Table 1.

B) Strain-Life Data

The fatigue test data for 4320 Carburized (Case) steel obtained in this investigation are given in Table 2. The stress amplitude corresponding to each strain-amplitude was calculated from the peak load amplitude at the specimen half-life.

A fatigue strain-life curve for the 4320 Carburized (Case) steel is shown in Figure 4, and is described by the following equation:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

where

$\frac{\Delta\varepsilon}{2}$	= True total strain amplitude
$2N_f$	= Number of reversals to failure
σ'_f	= Fatigue strength coefficient
b	= Fatigue strength exponent
ε'_f	= Fatigue ductility coefficient
c	= Fatigue ductility exponent

Where σ'_f = 4221 MPa, b = -0.113, ε'_f = 0.0051 and c = -0.338. These values of the strain-life parameters were determined from fatigue testing over the range: $0.0035 < \frac{\Delta\varepsilon}{2} < 0.010$.

C) Cyclic Stress-Strain Curves

Stabilized and half-life stress data obtained from strain-life fatigue tests were used to obtain the companion cyclic stress-strain curve shown in Figure 5. The cyclic stress-strain curve is described by the following equation:

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}}$$

where

ε	= True total strain amplitude
σ	= Cyclically stable true stress amplitude
K'	= Cyclic strength coefficient
n'	= Cyclic strain hardening exponent

Where K' = 9855 MPa and n' = 0.222.

D) Mechanical Properties

The engineering monotonic stress-strain curve is given in Figure 6. The monotonic and cyclic properties are included in Appendix 1. The Hardness of the 4320 Carburized (Case) steel was taken as the average of three randomly chosen fatigue specimens and is given in Appendix 1. The individual hardness measurements are also given in Table 2. The true monotonic and true cyclic stress-strain curves plotted together are given in Figure 7.

REFERENCES

[1] Pompetzki, M.A., Saper, R.A., and Topper, T.H., "Software for High Frequency Control of Variable Amplitude Fatigue Tests," Canadian Metallurgical Quarterly, Vol. 25, No. 2, pp. 181-194, 198.

[2] J. A. Bannantine, J. J. Comer, and J. L. Handrock (1990), In :Fundamentals of Metal Fatigue Analysis, Prentice Hall, London.

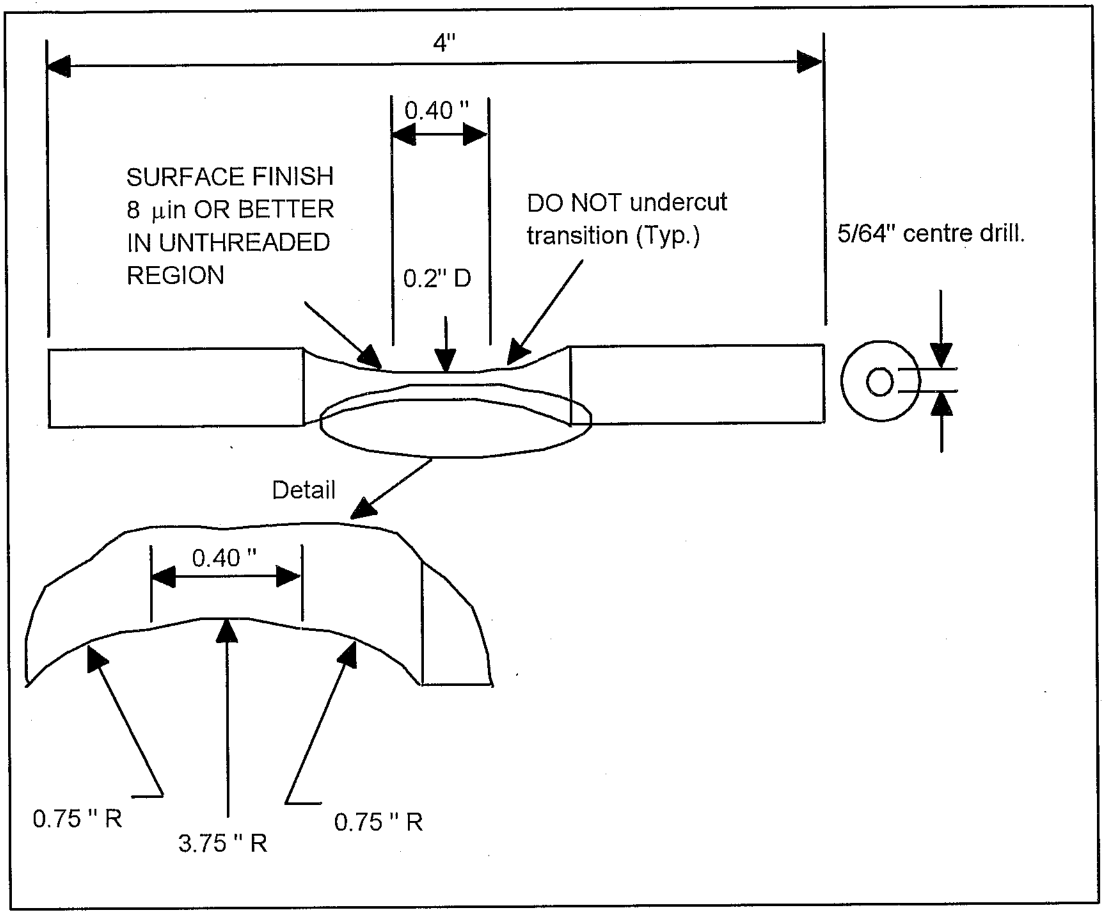
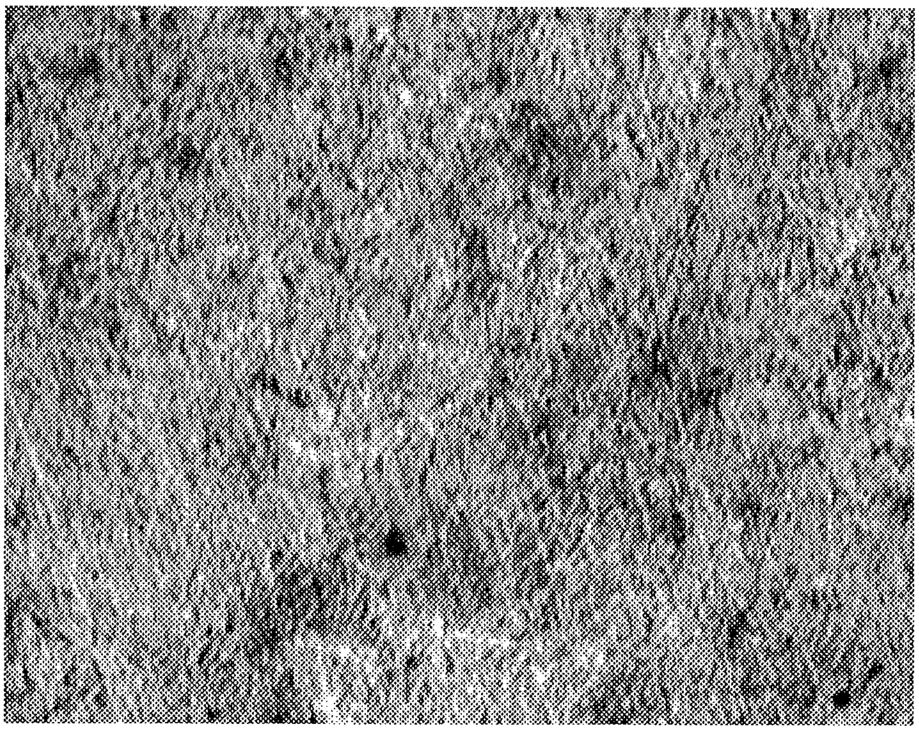
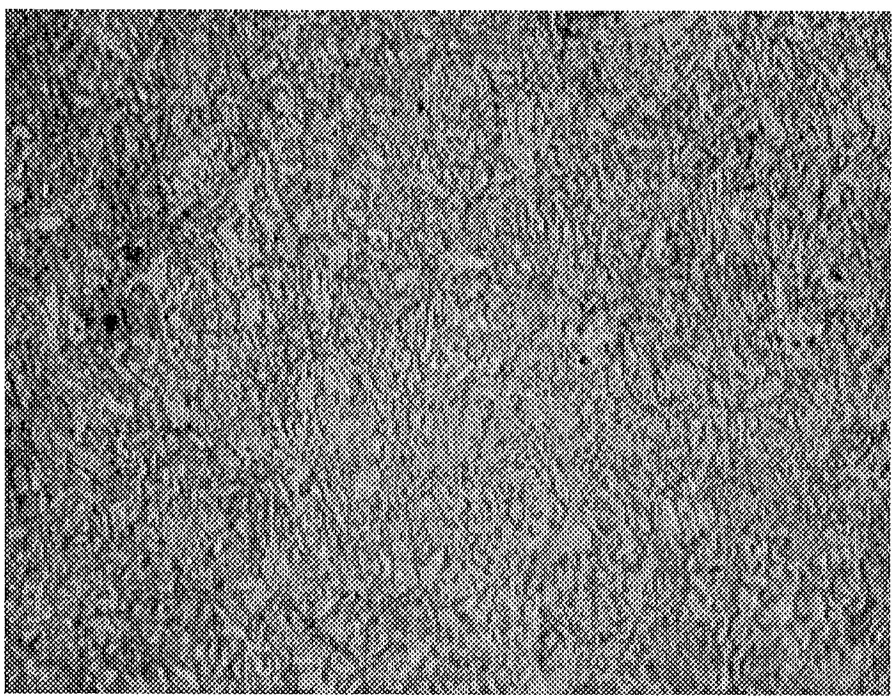


Fig. 1 Smooth cylindrical fatigue specimen



(a) Longitudinal Direction



(b) Transverse Direction

Figure 2. Photomicrographs of 4320 Carburized (Case) steel (X500)

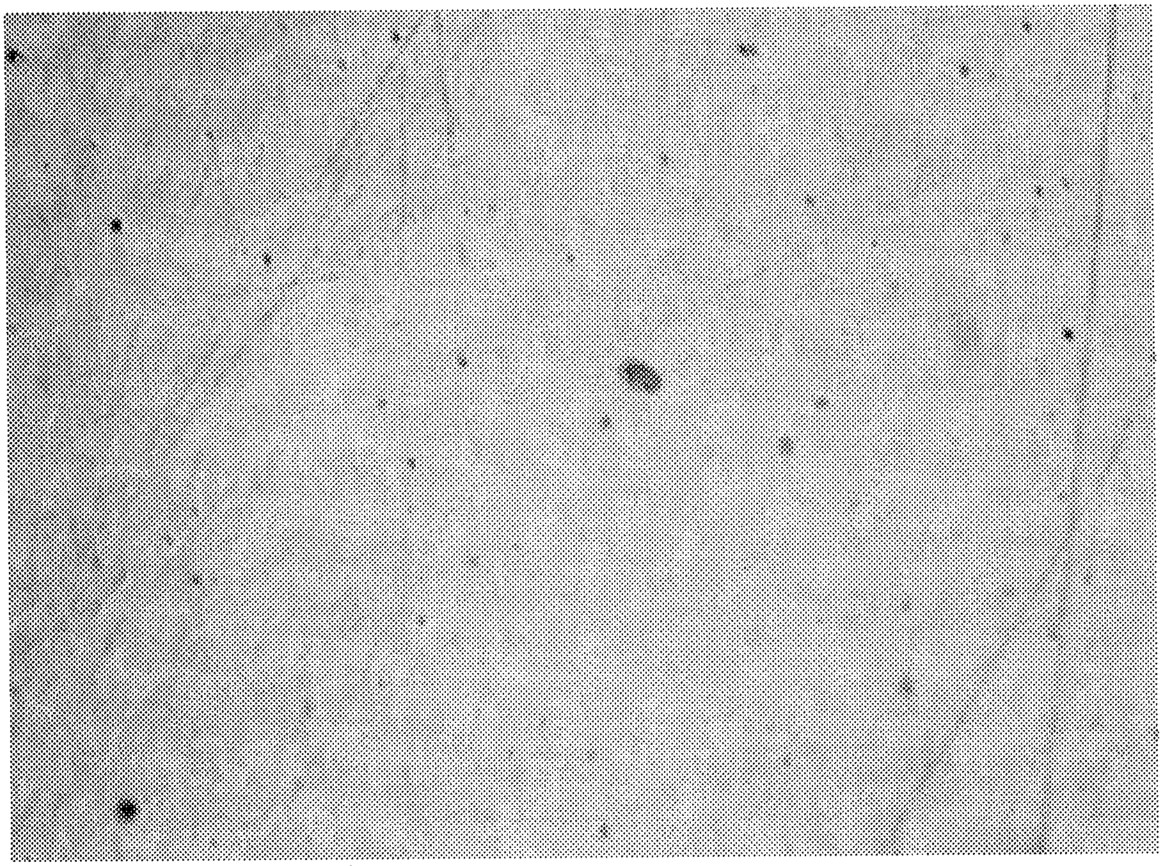


Figure 3. Inclusions photomicrograph of 4320 Carburized (Case) steel (X100)

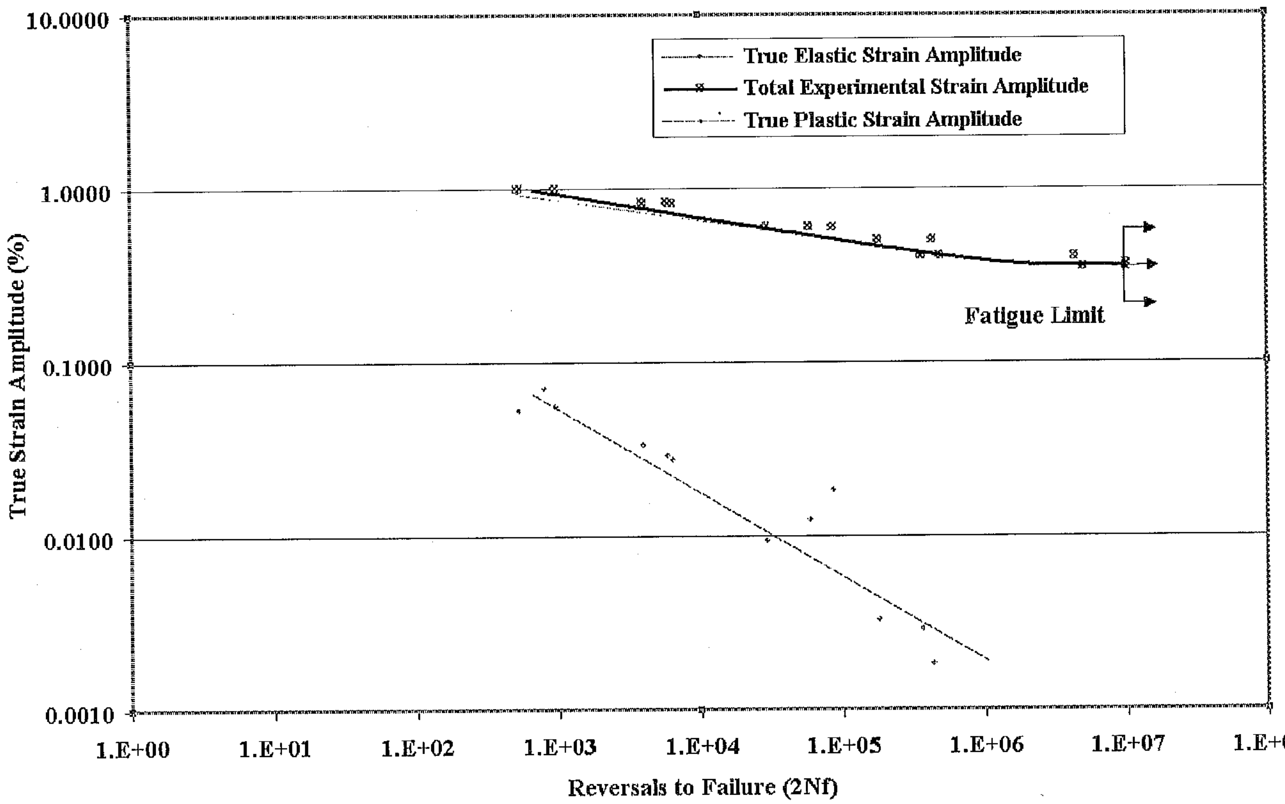


Figure 4. Constant amplitude fully reversed strain-life curve for 4320 Carburized (Case) steel.

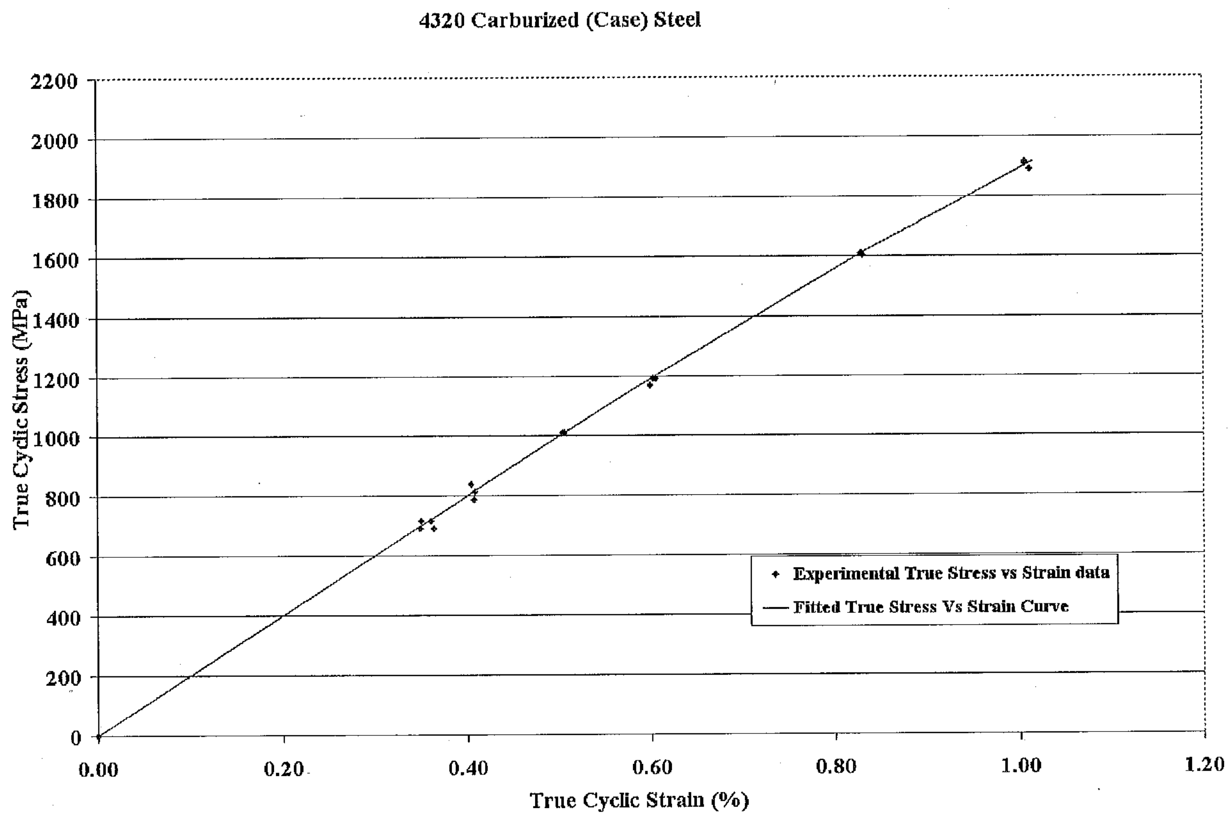


Figure 6. Cyclic stress-strain curve for 4320 Carburized (Case) steel.

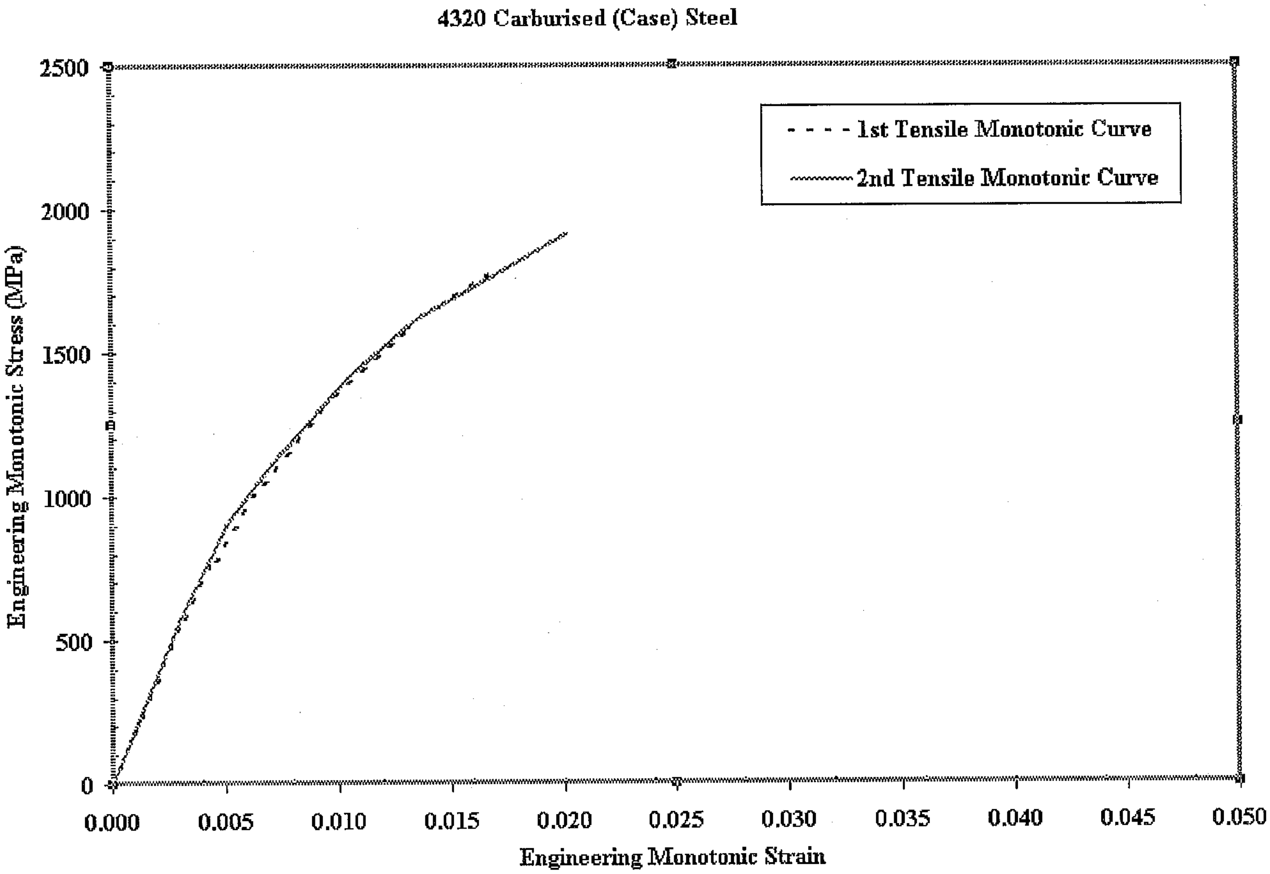


Figure 5. Monotonic stress-strain curves for two 4320 Carburized (Case) steel specimens.

Table 1 Chemical composition of 4320 Carburized (Case) steel.

Carbon, C	0. 18%
Manganese, Mn	0.48%
Phosphorous, P	0.006%
Sulfur, S	0.02%
Silicon, Si	0.26%
Copper, Cu	0.17%
Nickel, Ni	1.74%
Chromium, Cr	0.58%
Molybdenum, Mo	0.17%
Sn	NA
Al	NA
Vanadium, Va	NA
N	NA
Ti	NA
N2	NA
V	0.002%
Cb	NA
Te	NA

Table 2 Tensile and Fatigue Test Data for 4320 Carburized (Case) steel.

Meas Calc.

Sp#	Total Strain Amplitude(%)	Stress Amplitude (MPa)	Plastic Strain Amplitude(%)	Elastic Strain Amplitude(%)	(50% load drop) Fatigue Life (Reversals, 2Nf)	MONOTONIC Young's Modulus(GPa)	Hardness (Rc)
5	1.012	1890	0.072	0.940	794	200	62
4	1.006	1908	0.057	0.949	952	202	62
2	1.006	1914	0.054	0.952	522	203	64
7	0.831	1602	0.034	0.797	3968	193	64
8	0.828	1608	0.028	0.800	6334	204	60
15	0.829	1608	0.029	0.800	5864	201	60
9	0.605	1192	0.012	0.593	58772	197	62
10	0.602	1192	0.009	0.593	29018	198	59
6	0.600	1168	0.019	0.581	85384	195	62
14	0.505	1010	0.003	0.502	178952	200	63
13	0.504	1010	0.002	0.502	421988	200	62
11	0.409	816	0.003	0.406	354562	200	60
1	0.407	790	0.000	0.407	474468	202	60
12	0.404	840	0.000	0.404	4324504	208	60
2*	0.364	691	0.000	0.364	10000000	205	60
7*	0.361	719	0.000	0.361	10000000	199	62
16*	0.350	718	0.000	0.350	10000000	205	60
3	0.349	691	0.000	0.349	4982040	198	60

* Run out

Appendix 1

Monotonic Properties for 4320 Carburized (Case) steel.

Average Elastic Modulus, E	=	201	GPa
Yield Strength	=	1250	MPa
Ultimate tensile Strength	=	NA	MPa
% Elongation	=	2.1	%
% Reduction of Area	=	2.2	%
True fracture strain, $Ln\ (A_i / A_f)$	=	2.2	%
True fracture stress, $\sigma_f = \dfrac{P_f}{A_f}$	=	2060	MPa

Bridgman correction, $\sigma_f = \dfrac{P_f}{A_f} \Big/ \left(1 + \dfrac{4R}{D_f}\right) Ln \left(1 + \dfrac{D_f}{4R}\right)$ =NA MPa

Monotonic strength coefficient, K	=	6856	MPa
Monotonic strain hardening exponent, n	=	0.273	
Hardness, Rockwell C (Rc)	=	60	
Hardness, Brinell	=	600	

Cyclic Properties for 4320 Carburized (Case) steel.

Cyclic Yield Strength, (0.2% offset)= $K'(0.002)^{n'}$	=	2480	MPa
Cyclic strength coefficient, K'	=	9855	MPa
Cyclic strain hardening exponent, n'	=	0.222	
Fatigue Strength Coefficient, σ'_f	=	4221	MPa
Fatigue Strength Exponent, b	=	-0.113	
Fatigue Ductility Coefficient, ε'_f	=	0.0051	
Fatigue Ductility Exponent, c	=	-0.338	

P_f:	Load at fracture.
A_i and A_f:	Specimen cross-section area before and after fracture.
R:	Specimen neck radius.
D_f	Specimen diameter at fracture.

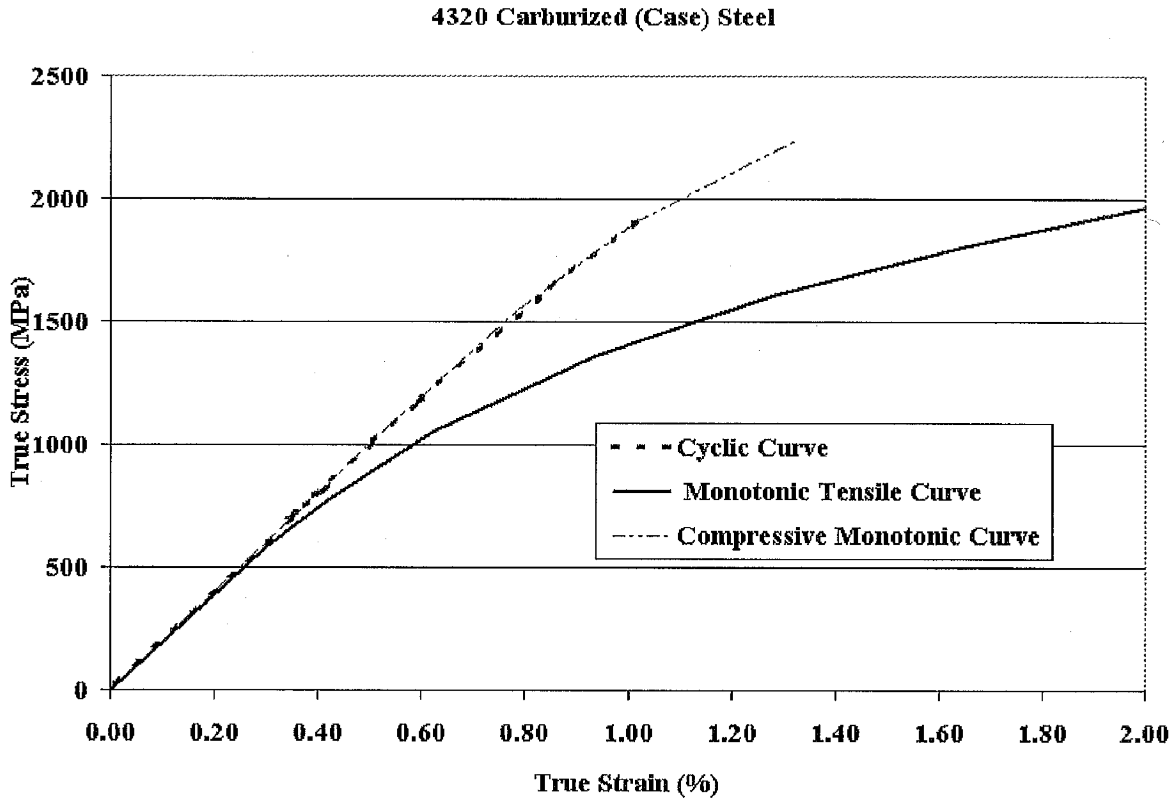


Fig. 7 Monotonic and Cyclic stress-strain curves for 4320 Carburized (Case) steel.

D-U-N-S 04-166-0445 STEEL DIVISION

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TIMKEN ORDER: 24245-A BOL: 554726 PLANT: 13 SHIP FROM: CANTON, OH DIST CODE: 2001 INVOICE NUMBER: 11-00176
CARRIER: R & L TRANSFER TARP: Y SHPG TYPE: COMTRUCK SELL TERM: FOB CANTON, OH
CUST PO: AISI FATIGUE TEST SPEC CUST PART: ALLOTMENT: INVOICE DATE: 2000/11/07
CUST TYPE/QUAL: 4320*CQ TYPE CODE: 3800 CUST CODE: DIR CUST: 536 SHIPPING DATE: 2000/11/06
PAINT INST: BOL DESC: STEEL BARS DISTRICT: 05 DIVISION: 1
COND: HR-TEMP-STR MSDS NMBR: 11459 CAR NMBR: FRT: PPD

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63.50	0.00	0.00	0.00	MM

SHAPE: RD
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LENGTH				
MIN:	5 FT	0.000 IN	1,524.000	MM
MAX:	5 FT	0.000 IN	1,524.000	MM
MULTS:	0 FT	0.000 IN	0.000	MM
SHORTS:	0 FT	0.000 IN	0.000	MM

TERMS: CIA-NET CURRENCY: $USD

BUNDLE NUMBER	HEAT NUMBER	NUMBER OF BNDLS	NUMBER OF PIECES	PCT	LENGTH FEET	LENGTH METERS	WEIGHT POUNDS	WEIGHT KILOGRAMS	PRICE / UOM	AMOUNT
0153929	28453	1	10		0.0000	0.000	780	353.8		
BASE TOTALS		1	10		0.0000	0.000	780	353.8	NO CHARGE	
NET SALES							AMOUNT TO BE USED IN COMPUTING DISCOUNT			0.00

FREIGHT ADJUSTMENTS DESCRIPTION

PLUS FRT TO DESTINATION 39.51

INVOICE TOTAL 39.51

Item 49 + 50

COMMENTS NO CHARGE FOR MATERIALS

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HEAT	C	MN	P	S	SI	CR	NI	MO	CU	V	CAST
28453	0.18	0.48	0.006	0.020	0.26	0.58	1.74	0.26	0.17	0.002	STRAN

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