Revised

# Fatigue Behavior, Monotonic Properties and Microstructure Data for Controlled Cooled 1070M (C-70) Steel (Iteration No. 43)

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## SUMMARY

The required chemical analysis, microstructure data, mechanical properties, cyclic stress-strain data and strain-controlled fatigue data for 1070M (C-70), Controlled Cooled steel (Iteration No. 43) have been obtained. The material was provided by the American Iron and Steel Institute (AISI) in the form of 2" bars. These bars were machined into smooth axial fatigue specimens. The specimens were tested as received having a hardness of about 241 BHN. Two monotonic tensile tests were performed to measure the yield strength, the tensile strength and the reduction of area. 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 18 Controlled Cooled 1070M (C-70) 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 80% Pearlite and 20% Ferrite microstructure of the 1070M (C-70) Controlled Cooled steel. A Type A inclusion severity level of 1/2 was obtained based on ASTM E45 (Method A). Inclusions of types B, C and D were not observed. Figure 3 shows the inclusions observed in the 1070M (C-70), Controlled Cooled steel. The inclusion area was measured using a JAVA image analysis system. The chemical composition of 1070M (C-70), Controlled Cooled steel was provided by the USS KOBE Steel Company, and is shown in Table 1.

### B) Strain-Life Data

The fatigue test data for 1070M (C-70), Controlled Cooled 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 1070M (C-70), Controlled Cooled 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 |
| $\sigma'_f$ | = Fatigue strength coefficient |
| b | = Fatigue strength exponent |
| $\varepsilon'_f$ | = Fatigue ductility coefficient |
| c | = Fatigue ductility exponent |

Where $\sigma'_f = 1561$ MPa, b = -0.105, $\varepsilon'_f = 0.471$ and c = -0.56. These values of the strain-life parameters were determined from fatigue testing over the range: $0.0017 < \frac{\Delta\varepsilon}{2} < 0.01$.

**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 true cyclic stress-strain curve is described by the following equation:

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

where

| | |
|---|---|
| $\varepsilon$ | = True total strain amplitude |
| $\sigma$ | = Cyclically stable true stress amplitude |
| $K'$ | = Cyclic strength coefficient |
| $n'$ | = Cyclic strain hardening exponent |

Where $K' = 1528$ MPa and $n' = 0.158$.

**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 1070M (C-70), Controlled Cooled steel 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.

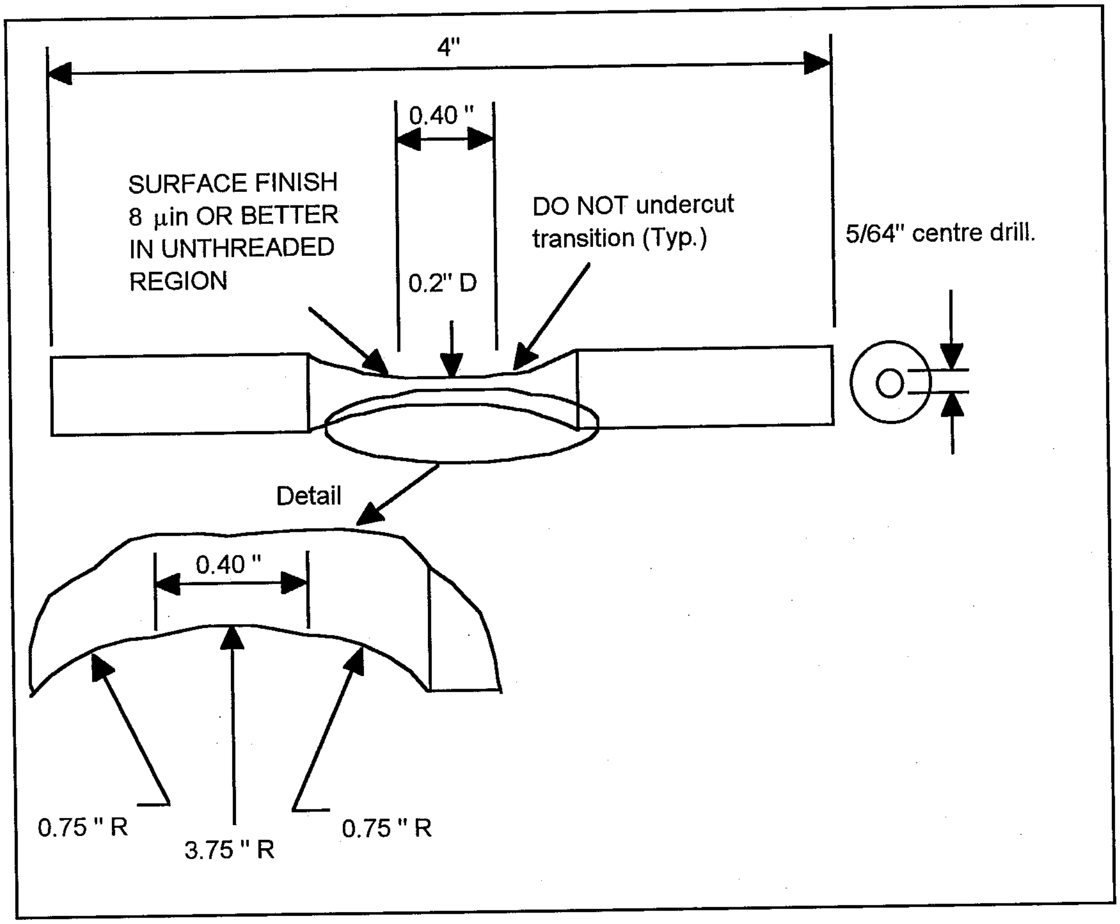


Fig. 1 Smooth cylindrical fatigue specimen

(a) Longitudinal Direction

(b) Transverse Direction

Fig. 2 Photomicrographs of 1070M (C-70), Controlled Cooled (X100)

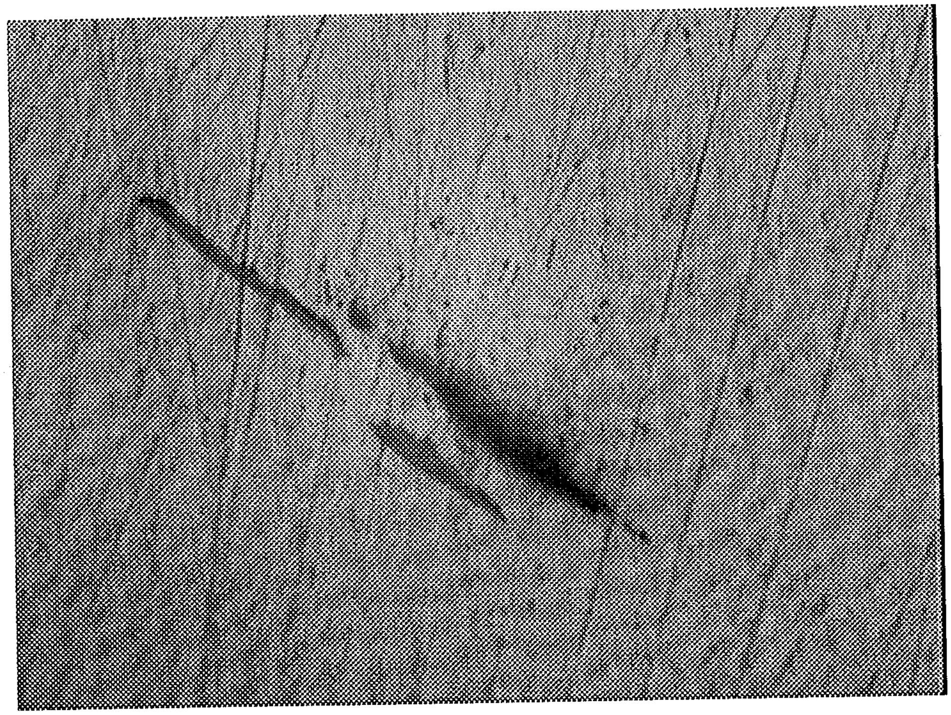

Fig. 3 Inclusions photomicrograph of 1070M (C-70), Controlled Cooled (X500)

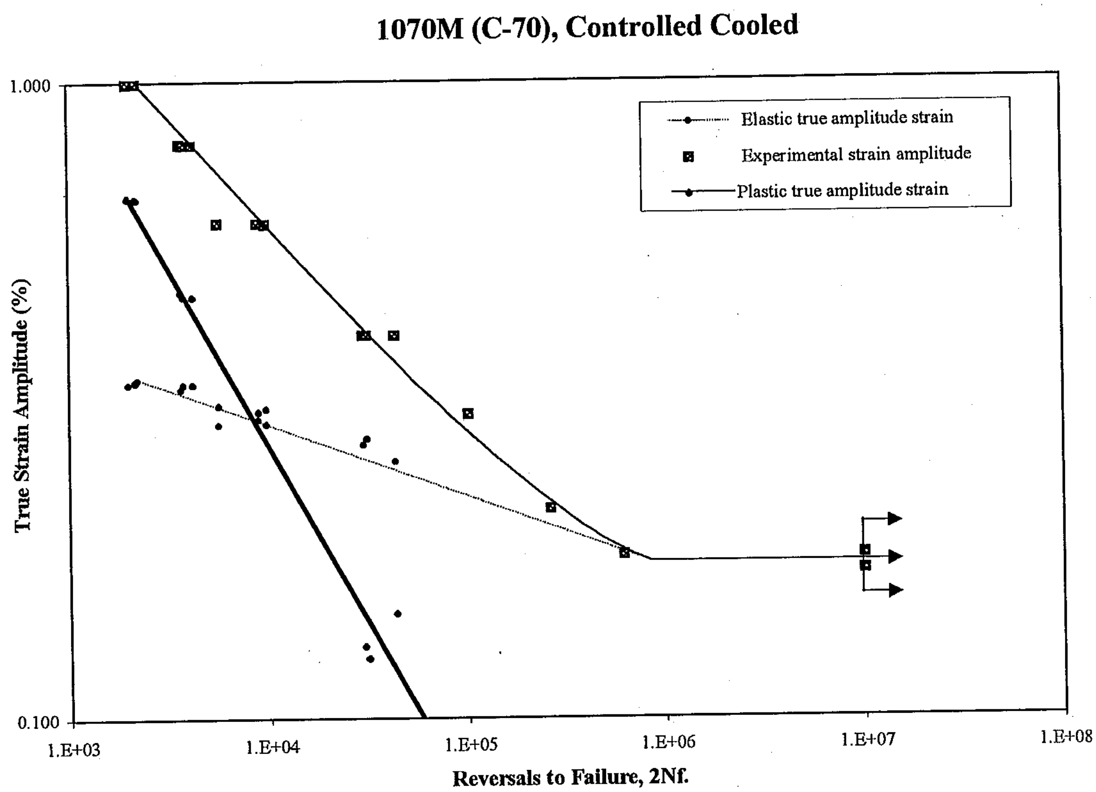


Figure 4. Constant amplitude fully reversed strain-life curve for 1070M (C-70), Controlled Cooled steel.

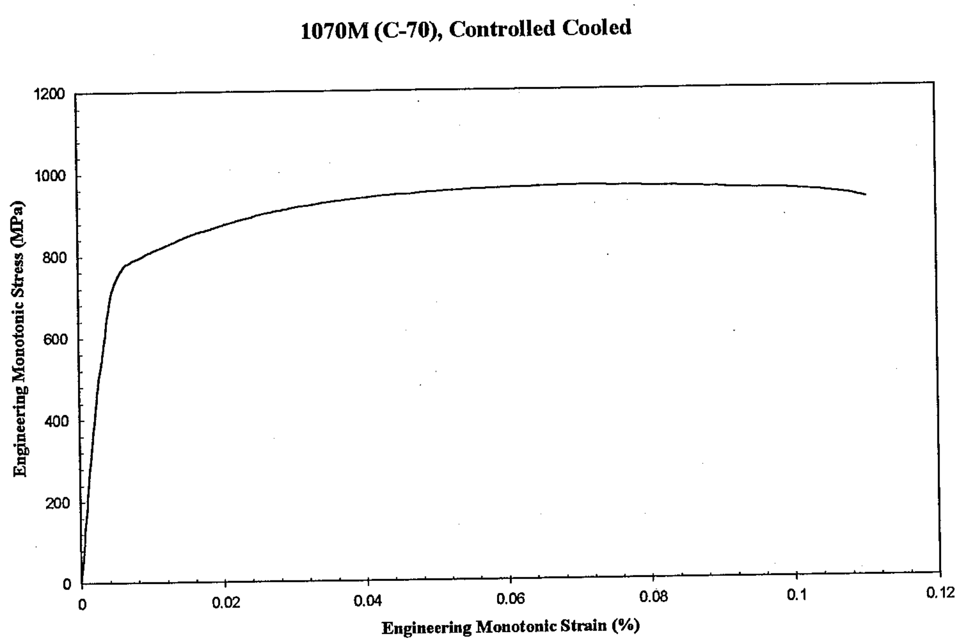


Figure 5. Monotonic stress-strain curve for 1070M (C-70), Controlled Cooled steel.

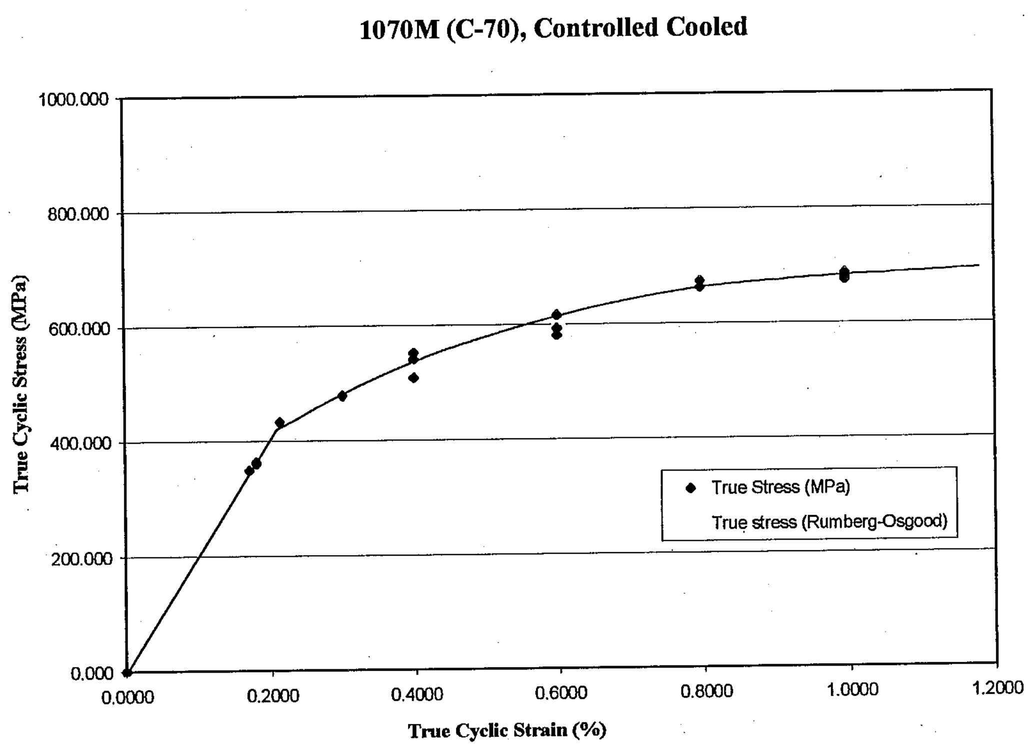


Figure 6. Cyclic stress-strain curve for 1070M (C-70), Controlled Cooled steel.

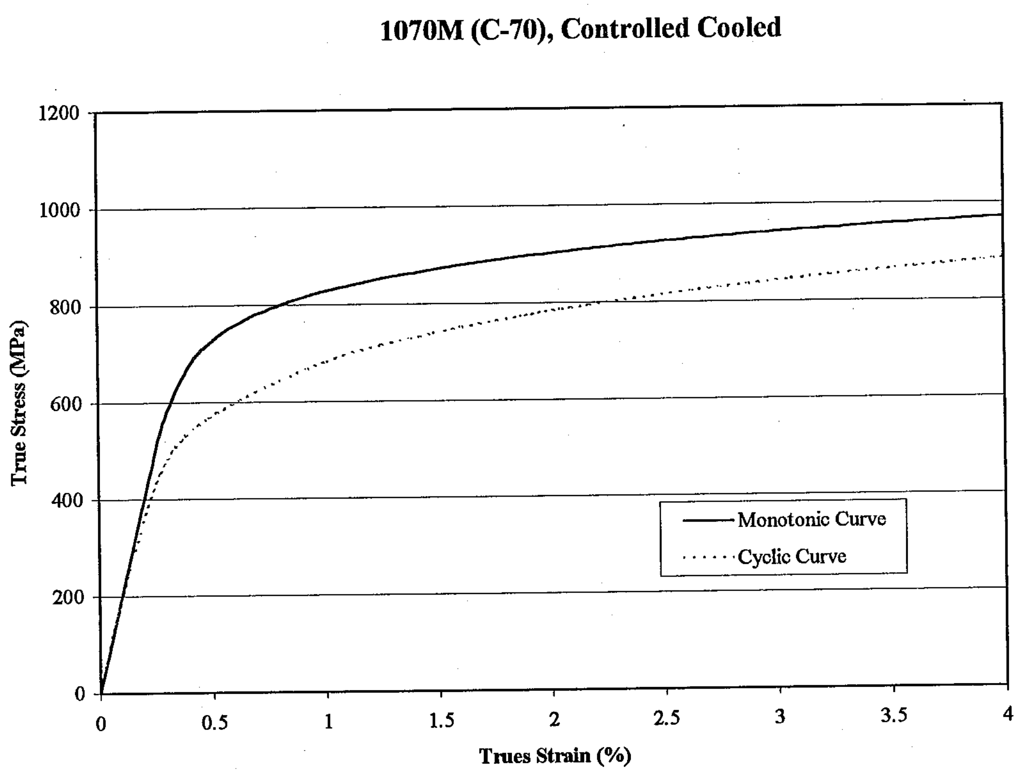


Fig. 7 Monotonic and Cyclic stress-strain curves for 1070M (C-70), Controlled Cooled steel.

Table 1 Chemical composition of 1070M (C-70), Controlled Cooled steel.

| | |
|---|---|
| Carbon, C | 0. 7% |
| Manganese, Mn | 0.98% |
| Phosphorous, P | 0.014% |
| Sulfur, S | 0.024% |
| Silicon, Si | 0.28% |
| Copper, Cu | 0.015% |
| Nickel, Ni | 0.01% |
| Chromium, Cr | 0.11% |
| Molybdenum, Mo | 0.049% |
| Sn | |
| Al | 0.031% |
| Vanadium, Va | |
| N | 33 PPM |
| Ti | |
| B | |
| Zn | |
| Pb | |
| Co | |

**Table 2 Tensile and Fatigue Test Data for 1070M (C-70), Controlled Cooled steel.**

√

| 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 (HRC) |
|---|---|---|---|---|---|---|---|
| 2 | 0.995 | 680.5 | 0.656 | 0.339 | 2150 | 197 | 20 |
| 10 | 0.994 | 674.8 | 0.658 | 0.336 | 2000 | 208 | 21 |
| 19 | 0.995 | 686.1 | 0.653 | 0.341 | 2216 | 207 | 23 |
| 5 | 0.798 | 662.1 | 0.468 | 0.329 | 3646 | 194 | 22 |
| 29 | 0.796 | 673.5 | 0.461 | 0.335 | 3772 | 197 | 21 |
| 31 | 0.795 | 673.5 | 0.460 | 0.335 | 4200 | 199 | 25 |
| 21 | 0.598 | 593.0 | 0.303 | 0.295 | 8890 | 202 | 20 |
| 17 | 0.600 | 581.8 | 0.310 | 0.289 | 5634 | 200 | 21 |
| 8 | 0.597 | 615.6 | 0.290 | 0.306 | 9742 | 202 | 24 |
| 6 | 0.399 | 541.1 | 0.130 | 0.269 | 29906 | 203 | 20 |
| 11 | 0.399 | 552.4 | 0.124 | 0.275 | 31254 | 203 | 20 |
| 12 | 0.399 | 508.7 | 0.146 | 0.253 | 43280 | 204 | 23 |
| 9 | 0.300 | 478.6 | 0.000 | 0.300 | 101402 | 200 | 22 |
| 30 | 0.213 | 433.2 | 0.000 | 0.213 | 263274 | 200 | 23 |
| 13* | 0.180 | 360.0 | 0.000 | 0.180 | 10000000 | 201 | 20 |
| 26* | 0.180 | 362.8 | 0.000 | 0.180 | 10000000 | 191 | 25 |
| 4 | 0.180 | 360.0 | 0.000 | 0.180 | 614986 | 199 | 24 |
| 22* | 0.170 | 348.7 | 0.000 | 0.170 | 10000000 | 210 | 23 |

* Run out

# Appendix 1

## Monotonic Properties for 1070M (C-70), Controlled Cooled steel.

| | | | |
|---|---|---|---|
| Average Elastic Modulus, E | = | 201.4 | GPa |
| Yield Strength | = | 765 | MPa |
| Ultimate tensile Strength | = | 964 | MPa |
| % Elongation | = | 14.3 | % |
| % Reduction of Area | = | 16.8 | % |
| True fracture strain, $Ln\ (A_i / A_f)$ | = | 19.7 | % |
| True fracture stress, $\sigma_f = \dfrac{P_f}{A_f}$ | = | 927 | MPa |

Bridgman correction, $\sigma_f = \dfrac{P_f}{A_f} \Big/ \left(1+\dfrac{4R}{D_f}\right) Ln\left(1+\dfrac{D_f}{4R}\right)$ =837 MPa

| | | | |
|---|---|---|---|
| Monotonic strength coefficient, K | = | 1315 | MPa |
| Monotonic strain hardening exponent, n | = | 0.090 | |
| Hardness, Rockwell C (HRC) | = | 23 | |
| Hardness, Brinell | = | 241 | |

## Cyclic Properties for 1070M (C-70), Controlled Cooled steel.

Cyclic Yield Strength, (0.2% offset)= $K'(0.002)^{n'}$ = 572 MPa

| | | | |
|---|---|---|---|
| Cyclic strength coefficient, K' | = | 1528 | MPa |
| Cyclic strain hardening exponent, n' | = | 0.158 | |
| Fatigue Strength Coefficient, $\sigma'_f$ | = | 1561 | MPa |
| Fatigue Strength Exponent, b | = | -0.105 | |
| Fatigue Ductility Coefficient, $\varepsilon'_f$ | = | 0.471 | |
| Fatigue Ductility Exponent, c | = | -0.56 | |

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| | |
|---|---|
| $P_f$: | 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. |