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# CYCLIC STRESS-STRAIN CURVE DETERMINATION FOR D6AC STEEL BY THREE METHODS

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16 Abstract

The room temperature cyclic stress-strain curve was determined for D6AC low alloy steel by three different methods. The method that involves the use of a single specimen monotonic tension test after cyclic straining provided the best agreement with the accepted basic method which requires a number of companion specimen tests. The single specimen test is also the simplest to conduct.

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# CYCLIC STRESS-STRAIN CURVE DETERMINATION

# FOR D6AC STEEL BY THREE METHODS

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## SUMMARY

The room temperature cyclic stress-strain curve was determined for D6AC low alloy steel by three different methods. The first method, the accepted basic method of strain cycling several companion specimens, each at a different completely reversed strain range, is used as the basis of comparison for the other two. The other two methods are the single specimen incremental step test and the monotonic tension test made after cyclic straining. The cyclic stress-strain curves generated by the three methods are compared and mathematical expressions describing these curves are determined. Inasmuch as the curve obtained from the monotonic tension test after cyclic straining lies nearest to the data obtained with the companion specimen tests (accepted basic method) and requires the least amount of programming equipment, the monotonic tension test after cyclic straining is considered to be the simplest for this material.

## INTRODUCTION

Designers and engineers have become increasingly aware of the value of the cyclic stress-strain curve in analyzing low-cycle fatigue problems. The cyclic and monotonic stress-strain curves may differ considerably because of the hardening or softening of the material caused by cyclic plastic straining. Testing procedures for generating the room temperature cyclic-stress-strain curve for a material are discussed in reference 1. Three of these, the companion specimen tests (the accepted basic method), the single specimen incremental step test, and the monotonic tension test following strain cycling, (procedures discussed in ref. 1) were used in the low cycle fatigue program at the NASA-Lewis Research

Center to determine the cyclic stress-strain curve for the cyclic strain softening low alloy steel, D6AC (AMS 6431). The cyclic-stress-strain curves generated by the three testing procedures are compared and mathematical expressions describing these curves were determined.

This work was conducted using the customary U.S. system of units. Conversion to the International System of Units (SI) was made for reporting purposes only.

## MATERIALS, APPARATUS AND TEST PROCEDURES

### Specimens

Heat treated stock of the low alloy steel, D6AC, was provided for the program by the Grumman Aerospace Corporation. The chemical composition, heat treatment schedule, and mechanical properties are given in tables I, II, and III, respectively. The machined specimens had a 0.635 cm (0.250 in.) minimum diameter hourglass test section with button head ends for attachment to the testing machine loading columns. Specimen details are shown in figure 1.

### Apparatus and Test Procedure

The specimens were tested in a strain controlled closed-loop electrohydraulically actuated fatigue testing machine. The details of this machine and its associated equipment are described in reference 2. The feedback signal in the closed loop came from the diametral extensometer that sensed test section diametral displacement produced by cyclic axial loading. The cyclic loads were those required to produce the test section diametral displacement programmed by a function generator. For these tests the programmed signal was a triangular wave form. The cycling frequency for low strain range tests was as high as 1.0 Hz whereas for the largest strain range test the frequency was as low as 0.0833 Hz.

All tests were conducted in ambient air at room temperature.

Companion specimen tests. - The accepted basic method for obtaining the cyclic stress-strain curve for a material is by connecting the tips of the stable hysteresis loops from several companion specimens, each at a different controlled strain range. Load and diametral displacement of the minimum test section diameter were recorded with strip charts moving at a specified rate as well as with an X-Y plotter. Stabilized values of the tensile and compressive stress and strain amplitude at the tips of the hysteresis loop in the vicinity of the half life number of cycles were observed for each test. A plot of the stress amplitude versus the corresponding completely reversed strain amplitude for each specimen forms a representation of the cyclic stress-strain curve which is used as the basis of comparison with the other two methods.

Single specimen incremental step test. - This method was considered because it requires that only one specimen need be tested. In accordance with this testing procedure a single specimen was subjected to blocks of gradually increasing and decreasing strain amplitudes as illustrated in figure 2. The programmed signal was obtained by slowly modulating the amplitude of the high frequency triangular waveform signal from a function generator by passing the signal through a Research Incorporated Datatrak before it was introduced into the servo controller. Blocks of linearly increasing the decreasing amplitude of 6-minute duration were obtained with the Datatrak programmer. Load and diametral displacement were recorded on strip charts as well as with an X-Y plotter to produce a series of superimposed hysteresis loops of increasing and decreasing size. The locus of the loop tips trace out a cyclic strain curve such as shown in figure 3.

Monotonic tension test after strain cycling. - This method further simplified the procedure for determining the cyclic stress-strain curve by eliminating the need for the Datatrak to modulate the programming signal from a function generator. A single specimen was stabilized by strain cycling. A total of 335 cycles at an inelastic strain range of 0.0048 was sufficient to achieve a stable hysteresis loop. The strain range was gradually reduced to zero before the specimen was monotonically loaded in tension to failure. A plot of applied load vs. diametral displacement of the specimen test section was obtained during the monotonic tensile test with the X-Y plotter, from which a stress-strain curve was constructed.

## RESULTS AND DISCUSSION

The test results from each method were reduced to cyclic stress amplitude and cyclic strain amplitudes so that the cyclic stress-strain curves could be plotted and compared using the following equations.

$$\Delta\epsilon_p = \frac{2\ \Delta d_p}{d} \tag{1}$$

where

| | |
|---|---|
| $\Delta\epsilon_p$ | inelastic strain range |
| $\Delta d_p$ | inelastic diametrial displacement |
| d | initial diameter of test section |

$$\Delta\epsilon_{el} = \frac{\Delta\sigma}{E} \tag{2}$$

where

| | |
|---|---|
| $\Delta\epsilon_{el}$ | elastic strain range |
| $\Delta\sigma$ | stress range |
| E | elastic modulus |

$$\Delta\epsilon_t = \Delta\epsilon_p + \Delta\epsilon_{el} \tag{3}$$

where

| | |
|---|---|
| $\Delta\epsilon_t$ | total strain range |

For each of the companion specimen tests, the stabilized values of the tensile and compressive stress and inelastic strain amplitude at the tips of the hysteresis loop in the vicinity of the half life number of cycles were plotted on a log-log grid.

The curved, inelastic strain portion of the locus of the tips of the hysteresis loops generated by the single specimen incremental step test shown in figure 3 was analyzed by selecting 32 stations equally spaced on the strain axis (16 on the tension side, 16 on the compression side) along the curve. Stress amplitudes were determined from measurements of vertical distances from the zero load line to the stations. Inelastic strain amplitudes were determined from measurements of horizontal distances from the straight line extension of the elastic modulus line to the stations. The stress amplitude and inelastic strain amplitude for each station were plotted on a log-log grid. The monotonic tensile stress-strain curve for cyclically strained material was also plotted in the above manner.

Individual best-fit-by-eye straight lines were drawn through the plotted points for the tension side and for the compression side of the cycles, and equations representing these lines were obtained. The equations for the tension and compression lines passing through the plotted data for the individual companion specimen tests are given in SI units and are:

$$\sigma^t = 2689 \left(\frac{\Delta\epsilon_p^t}{2}\right)^{0.113} \qquad \text{tension} \qquad (4)$$

$$\sigma^c = 2992 \left(\frac{\Delta\epsilon_p^c}{2}\right)^{0.119} \qquad \text{compression} \qquad (5)$$

For comparison the equations for the lines passing through the single specimen incremental test data are:

$$\sigma^t = 2835 \left(\frac{\Delta\epsilon_p^t}{2}\right)^{0.108} \qquad \text{tension} \qquad (6)$$

$$\sigma^c = 3149 \left(\frac{\Delta\epsilon_p^c}{2}\right)^{0.122} \qquad \text{compression} \qquad (7)$$

and for the line passing through the plotted points for the monotonic tension test after cyclic straining, the equation is:

$$\sigma^t = 3172 \, (\epsilon_p)^{0.131} \qquad \text{tension} \qquad (i)$$

The data that was plotted and used to obtain the above equations are listed in table IV.

Cyclic stress and strain amplitudes for each of the methods were also plotted on rectangular coordinates as shown in figure 4. Differences in the cyclic stress-strain curves for the three test methods are relatively small. The single specimen incremental step test had the highest stresses for a given inelastic strain amplitude. The stress-strain curve generated by the monotonic tensile test after strain cycling lies nearest to the data from the five companion specimen tests. Since this method required the least amount of programming equipment, it is also the simplest.

## CONCLUDING REMARKS

Room temperature cyclic stress-strain curves are determined for D6AC low allow steel by three different methods. The accepted basic method of conducting strain cycling tests to failure with several companion specimens, each at a different completely reversed strain range is used as the basis of comparison for the other two. The other two methods are the single specimen incremental step test and the single specimen monotonic tension test after cyclic straining.

The cyclic stress-strain curves generated by the three methods are compared and mathematical expressions describing these curves are determined Inasmuch as the curves obtained from the monotonic tension test after cyclic straining lies nearest to the data obtained with the companion specimen tests (accepted basic method) and requires the least amount of programming equipment, the monotonic tension test after cyclic straining is considered to be the simplest method for determining the cyclic stress-strain curve for D6AC low alloy steel. Further tests with other alloys would have to be made to confirm whether this conclusion holds true for the other materials as well.

## REFERENCES

1. Landgraf, R. W.; Morrow, JoDean; and Endo, T.: Determination of the Cyclic Stress-Strain Curve. ASTM Journal of Materials, vol. 4, no. 1, Mar. 1969, pp. 176-188.

2. Hirschberg, M. H.: A Low Cycle Fatigue Testing Facility. Manual on Low Cycle Fatigue Testing, Test. Mater., Spec. Tech. Publ. 465, 1969, pp. 67-86.

TABLE IV - SUMMARY OF DATA FROM METHODS USED TO MAKE CYCLIC STRESS-STRAIN PLOTS

(a) Companion specimen tests

| Spec no | Loading mode | Stress amplitude | | Longitudinal cyclic inelastic strain amplitude | Longitudinal cyclic total strain amplitude |
|---|---|---|---|---|---|
| | | ksi | $MN/m^2$ | | |
| 51 | Tension | 230 4 | 1588 | 0 0095 | 0 0174 |
| | Compression | 248 8 | 1715 | 0091 | 0176 |
| 52 | Tension | 151 5 | 1045 | 0002 | 0054 |
| | Compression | 160 0 | 1103 | 0002 | 0057 |
| 53 | Tension | 203 6 | 1403 | 0029 | 0099 |
| | Compression | 216 2 | 1491 | 0027 | 0100 |
| 54 | Tension | 176 7 | 1218 | 0007 | 0067 |
| | Compression | 178 4 | 1230 | 0008 | 0069 |
| 62 | Tension | 117 7 | 812 | ****** | 0043 |
| | Compression | 110 1 | 759 | ****** | 0040 |

*Negligible

(b) Single specimen incremental step test

| Station no | Loading mode | Stress amplitude | | Longitudinal inelastic strain amplitude | Longitudinal total strain amplitude |
|---|---|---|---|---|---|
| | | ksi | $MN/m^2$ | | |
| 1 | Tension | 163 1 | 1125 | 0 0002 | 0 0058 |
| 2 | | 185 8 | 1281 | 0005 | 0068 |
| 3 | | 198 5 | 1369 | 0010 | 0078 |
| 4 | | 208 5 | 1438 | 0016 | 0087 |
| 5 | | 213 9 | 1475 | 0022 | 0095 |
| 6 | | 217 5 | 1500 | 0028 | 0102 |
| 7 | | 224 7 | 1549 | 0034 | 0111 |
| 8 | | 230 2 | 1587 | 0041 | 0120 |
| 9 | | 233 8 | 1612 | 0048 | 0128 |
| 10 | | 235 7 | 1625 | 0054 | 0134 |
| 11 | | 238 3 | 1643 | 0061 | 0142 |
| 12 | | 240 2 | 1656 | 0067 | 0149 |
| 13 | | 242 9 | 1675 | 0074 | 0157 |
| 14 | | 244 7 | 1687 | 0081 | 0165 |
| 15 | | 246 5 | 1700 | 0088 | 0172 |
| 16 | | 247 4 | 1706 | 0095 | 0179 |
| 17 | Compression | 156 8 | 1081 | 0001 | 0055 |
| 18 | | 180 4 | 1244 | 0005 | 0067 |
| 19 | | 195 7 | 1349 | 0009 | 0076 |
| 20 | | 208 4 | 1437 | 0014 | 0085 |
| 21 | | 217 5 | 1500 | 0020 | 0094 |
| 22 | | 223 8 | 1543 | 0026 | 0102 |
| 23 | | 230 2 | 1587 | 0032 | 0111 |
| 24 | | 235 7 | 1625 | 0038 | 0118 |
| 25 | | 239 3 | 1650 | 0045 | 0127 |
| 26 | | 242 9 | 1675 | 0051 | 0133 |
| 27 | | 245 6 | 1693 | 0058 | 0142 |
| 28 | | 249 3 | 1719 | 0065 | 0151 |
| 29 | | 251 9 | 1737 | 0071 | 0157 |
| 30 | | 253 8 | 1750 | 0078 | 0165 |
| 31 | | 255 6 | 1762 | 0085 | 0172 |
| 32 | | 258 3 | 1781 | 0091 | 0179 |

(c) Monotonic tension test after strain cycling

| Station no | Stress amplitude | | Longitudinal inelastic strain | Longitudinal total strain |
|---|---|---|---|---|
| | ksi | $MN/m^2$ | | |
| 1 | 80 5 | 555 | 0 | 0 0028 |
| 2 | 151 0 | 1041 | 0003 | 0055 |
| 3 | 191 2 | 1318 | 0011 | 0076 |
| 4 | 209 3 | 1443 | 0025 | 0101 |
| 5 | 221 4 | 1526 | 0038 | 0114 |
| 6 | 230 7 | 1591 | 0052 | 0130 |
| 7 | 238 3 | 1643 | 0067 | 0148 |
| 8 | 242 7 | 1674 | 0081 | 0164 |
| 9 | 246 8 | 1702 | 0095 | 0180 |
| 10 | 251 6 | 1735 | 0111 | 0197 |

TABLE I. - CHEMICAL COMPOSITION OF D6AC STEEL*

Weight percent

| Carbon | Manganese | Silicon | Vanadium | Nickel | Chromium | Molybdenum | Iron |
|---|---|---|---|---|---|---|---|
| 0.47 | 0.75 | 0.20 | 0.12 | 0.55 | 1.1 | 1.0 | Balance |

*Supplied by Grumman Aerospace Corporation.

TABLE II. - HEAT TREATMENT OF D6AC STEEL

1. Austenitize at 927 ±14° C, heat 125 minutes in air or 30 minutes in salt bath and hold an additional 60 minutes.
2. Transfer piece to a furnace set at 518 ±6° C and allow to cool to this temperature within 2 hours.
3. Quench piece in agitated oil bath at 60° C to 121° C until equalized.
4. Air cool to below 60° C.
5. Temper immediately to 552° C and air cool.
6. Retemper a second time.

TABLE III. - MECHANICAL PROPERTIES OF D6AC

| Ultimate tensile strength | | Yield strength | | Elongation percent | Reduction of area, percent | Elastic modulus | | Fracture strength | |
|---|---|---|---|---|---|---|---|---|---|
| $MN/m^2$ | ksi | $MN/m^2$ | ksi | | | $MN/m^2$ | ksi | $MN/m^2$ | ksi |
| 1629 | 236.2 | 1472 | 213.5 | 11.2 | 36.9 | $202\times10^3$ | $29.3\times10^3$ | 2116 | 306.9 |

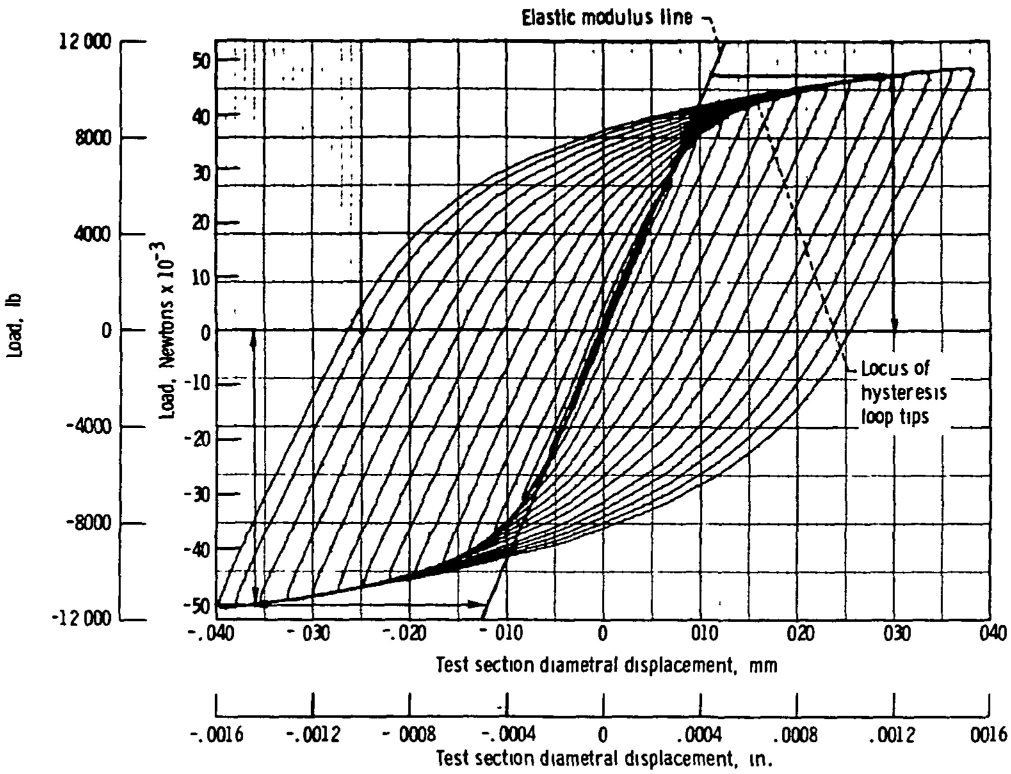


Figure 3 - Cyclic load versus diametral displacement curve traced by hysteresis loop tips in single specimen incremental step test of D6AC steel showing two sample stations on inelastic portion for which cyclic stresses and inelastic strains were calculated.

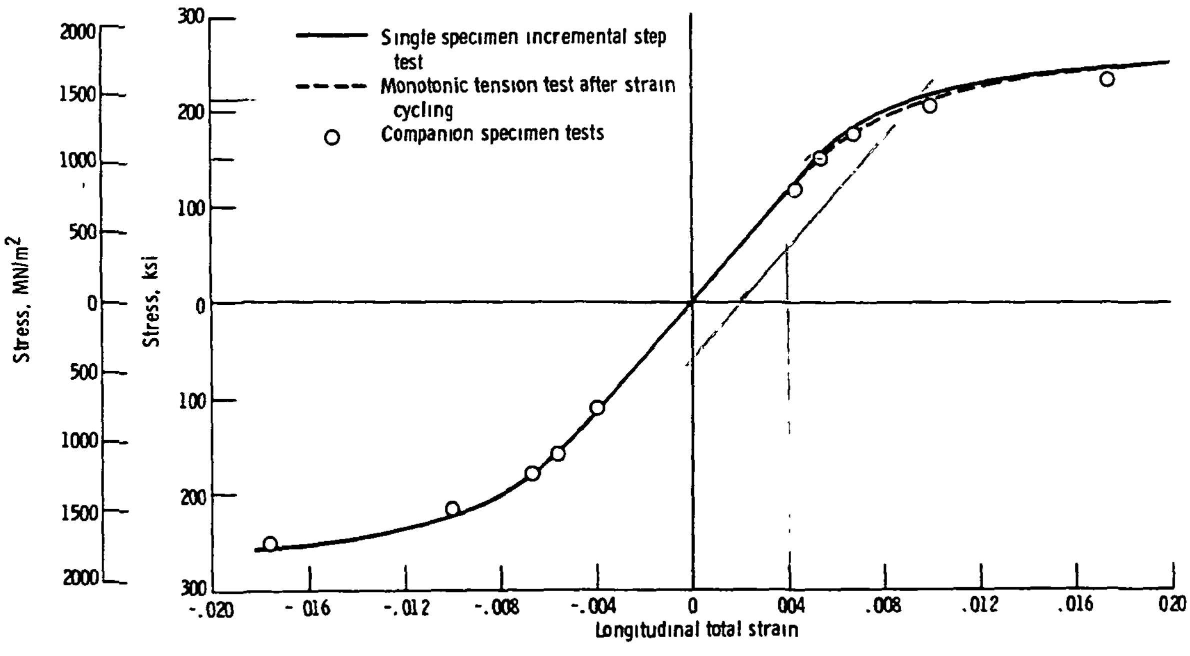


Figure 4. - Comparison of cyclic stress-strain curves for D6AC steel obtained by three different test methods

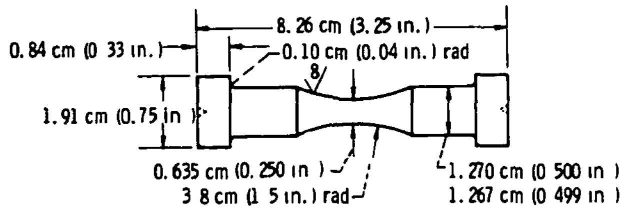


Figure 1. - Test specimen geometry and dimensions.

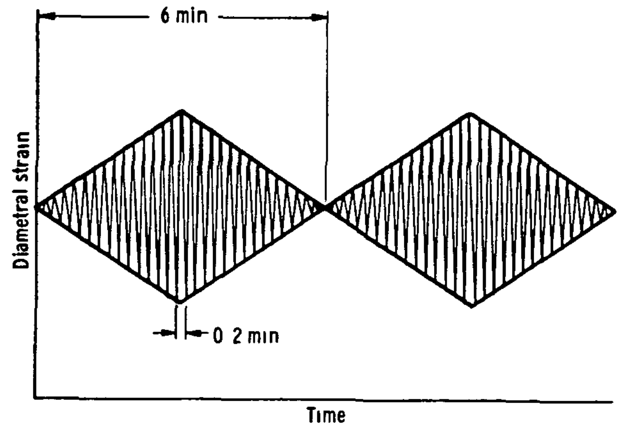


Figure 2. - Programming blocks of linearly increasing-decreasing command signal for incremental step test.

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