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Investigation of Cumulative Fatigue Damage for Selected Materials

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TUSKEGEE INSTITUTE
SCHOOL OF ENGINEERING
Tuskegee Institute, Alabama 36088

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FINAL REPORT

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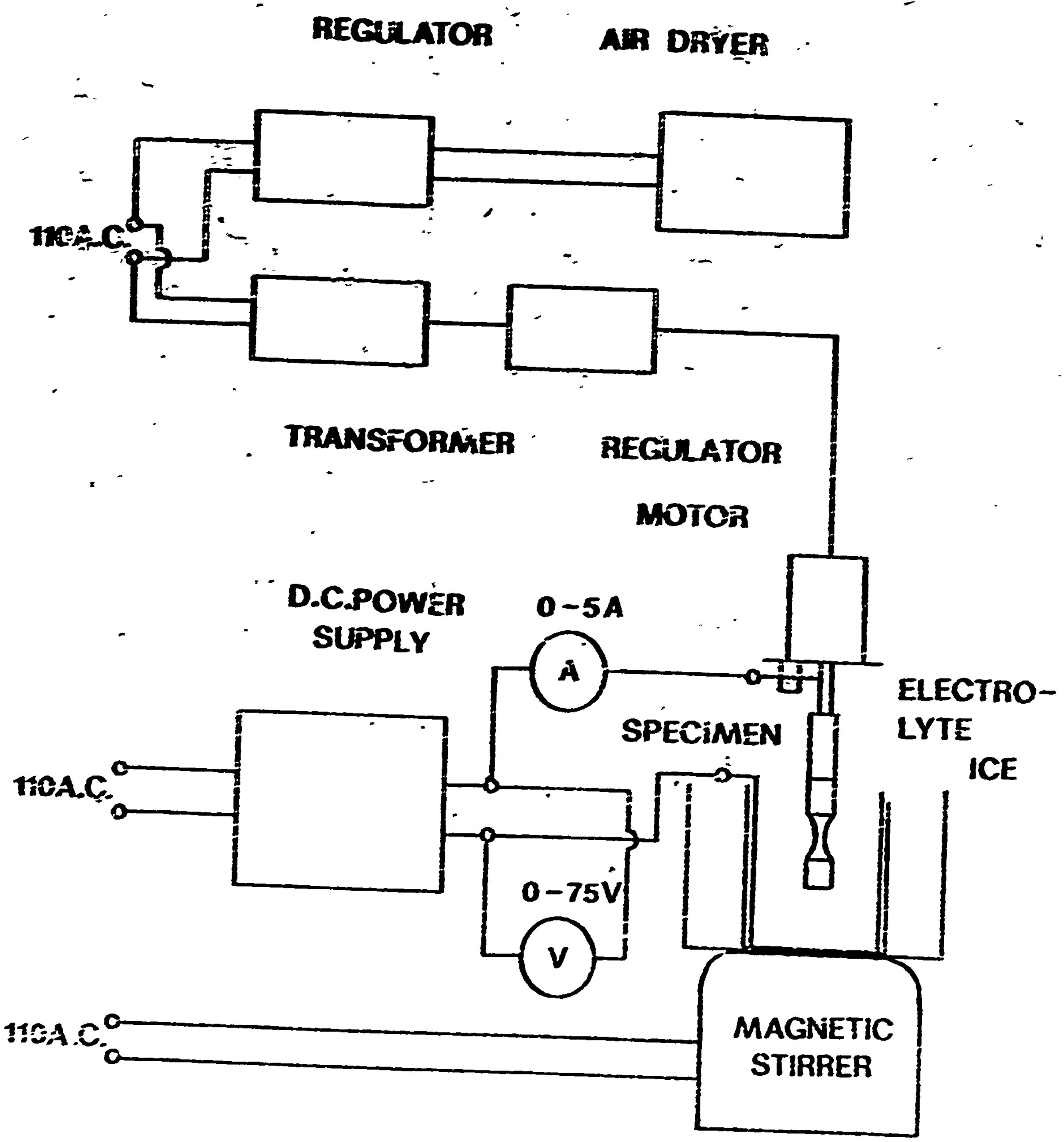

Fig. 4. Block Diagram for Electropolishing.

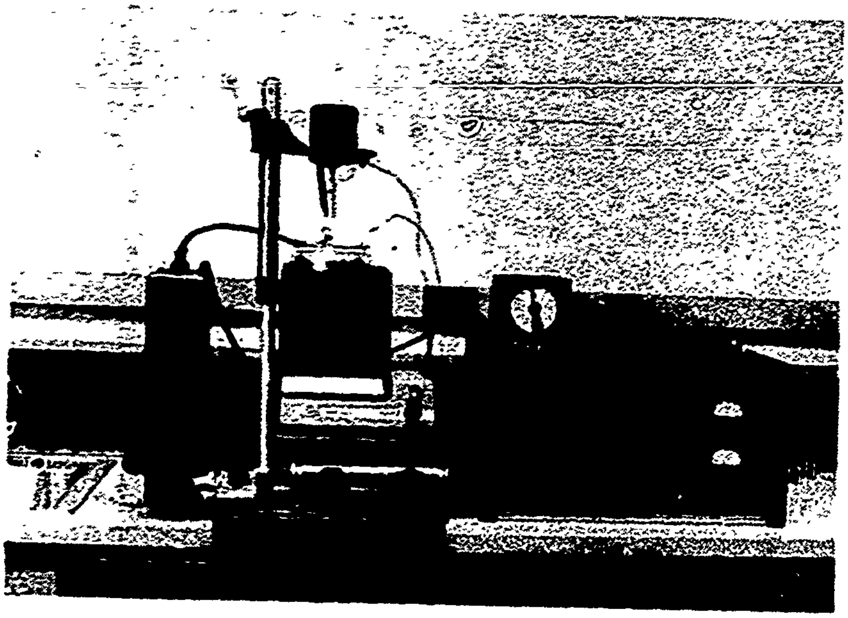

Fig. 5. Electropolishing System.

from the eccentric. Loads of 25, 50, and 75 pounds were applied at the free-end of the arm and the strain indicator adjusted to read the loads directly.

CUMULATIVE FATIGUE DAMAGE IN 2011-T3 ALUMINUM ALLOY

Figure 6 is the fatigue strength versus life (S-N) diagrams for stress ratios of $R=-1$, $-\frac{1}{2}$, and 0 plotted from the test data shown in Tables 1, 2, and 3 (Appendix B). Figure 7 is the constant fatigue life diagram obtained from the S-N diagrams.

Table 4 (Appendix B) shows the cumulative fatigue data low-high stress sequence. Table 5 (Appendix B) shows the cumulative fatigue data for low-high mixed stress sequence. The last two columns in both Tables 4 and 5 show a comparison between the theoretical and experimental values of the number of cycles required for failure to occur in the last (fourth) stage. It can be seen that there is a close agreement between the theoretical and experimental values.

Table 6 (Appendix B) shows the cumulative fatigue damage for low-high stress sequence, while Table 7 (Appendix B) shows the cumulative fatigue damage for low-high mixed stress sequence. It can be seen that Miner's equation is more conservative than that proposed by Kramer.

A set of sample calculations and the computer program used for computations are shown in Appendix C and Appendix D, respectively.

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ABSTRACT

A direct tension-compression fatigue testing machine Model DS-600 HLM is procured, installed, and calibrated for the generation of data to study the cumulative fatigue damage in selected materials. An apparatus and step-by-step procedure are developed to electropolish the fatigue machine.

Experimental data are generated using 2011-T3 aluminum alloy specimens under completely reversed condition for low-high and low-high mixed stress cycles.

Analysis of the data has indicated that the predicted cumulative fatigue damage and fatigue life are in complete agreement with the experimental values.

ACKNOWLEDGEMENTS

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Gratitude is also expressed to Dr. B. Z. Jarkowski and Dr. I. R. Karmer for their consultations throughout this research.

Finally, the authors express their thanks to the Department of the Navy, Naval Air Systems Command, Washington, DC, for providing financial support for this research through their grant No. N00019-79-C-0421.

INTRODUCTION

A research program to investigate the cumulative fatigue damage for selected materials was initiated in 1977 in the Department of Mechanical Engineering at Tuskegee Institute, Tuskegee Institute, Alabama. The Department of the Navy, Naval Air Systems Command, Washington, DC, supported the research program with an initial grant of $30,000 through contract # N00019-78-C-0034 for the period 11/28/77 - 9/2/78.

The research activity under the above contract consisted of:

1. Development of appropriate computer program to test the equation proposed by Kramer (1), and
2. Collection of experimental data from industrial sources for comparison with the predicted values obtained from Kramer's equation.

A satisfactory computer program was developed. It was concluded that the predicted cumulative fatigue damage was in good agreement with the experimental data generated by Kramer (1,2).

Various organizations suggested by the Department of Navy were contacted for the procurement of the experimental data on cumulative fatigue damage. Attempts were also made by the Naval Air Systems Command's personnel to assist the investigators in obtaining the information. Unfortunately, only limited experimental data was obtained. Consequently, comparison of the predicted values on cumulative fatigue damage with the comprehensive experimental data could not be done.

Therefore, it was decided to develop an experimental facility at Tuskegee Institute to generate experimental data for selected metals subjected to cumulative fatigue under variable cyclic stresses.

The Department of Navy renewed the support of the research program by granting $41,175 through Contract No. N00019-79-C-0421 for the period February 1, 1979 - April 30, 1980. Since experimental data on cumulative fatigue damage could not be obtained from industrial sources, the investigators directed their efforts toward the development of the experimental facility.

This report describes the research activity during the second phase from February 1, 1979 through April 30, 1980.

INSTALLATION AND CALIBRATION OF THE FATIGUE MACHINE

A tension-compression fatigue machine, Model DS 600 HLM, was purchased from Fatigue Dynamics and installed as shown in Figure 1. The machine is equipped with an automatic hydraulic load maintainer which adjusts the pre-load continuously to the pre-set value as the specimen yields. The machine is provided with a loading arm which has a capacity of 600 pounds. The arm is connected to the specimen at point A while end C is connected to an eccentric which is adjusted manually to adjust the cyclic load.

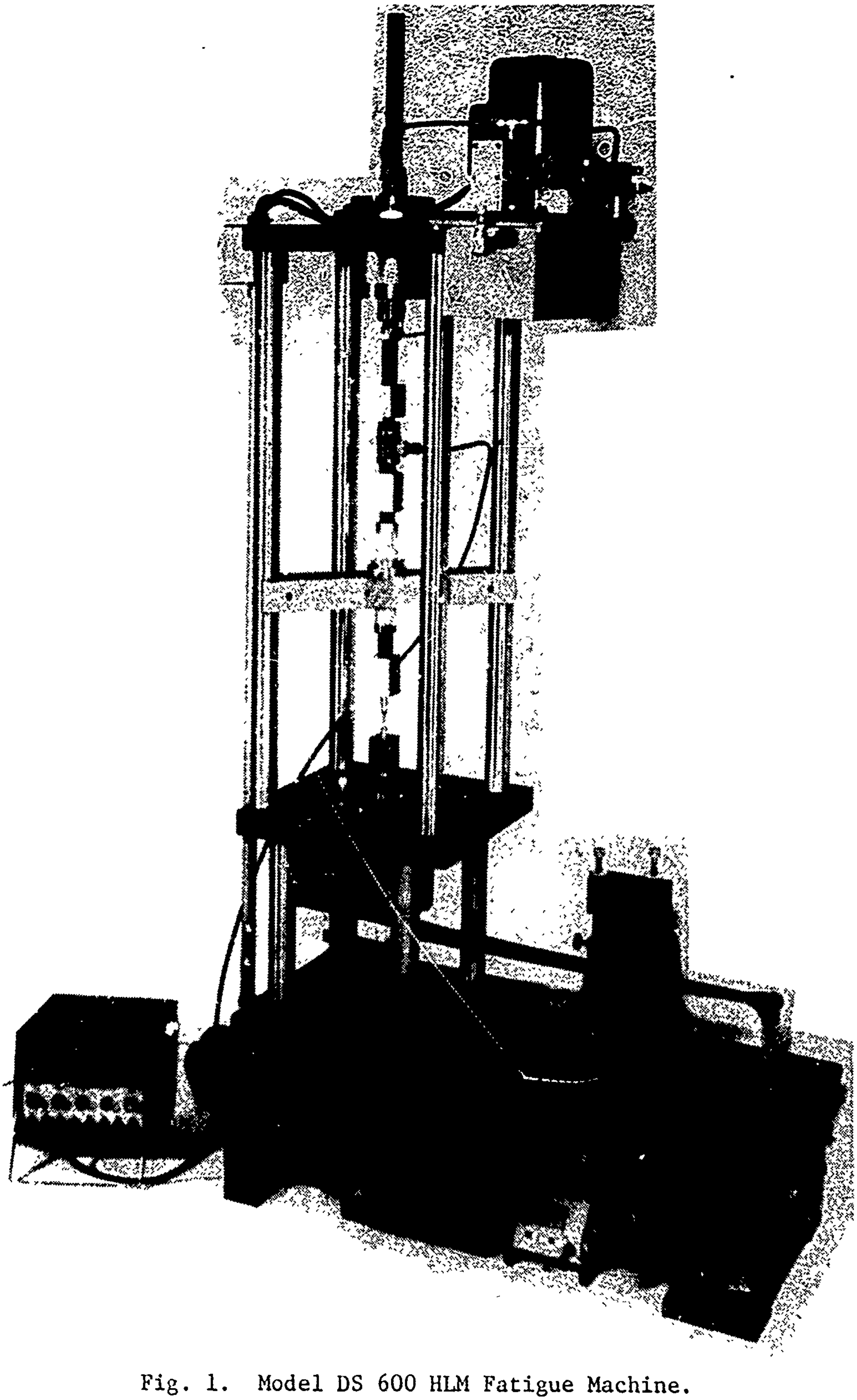


Fig. 1. Model DS 600 HLM Fatigue Machine.

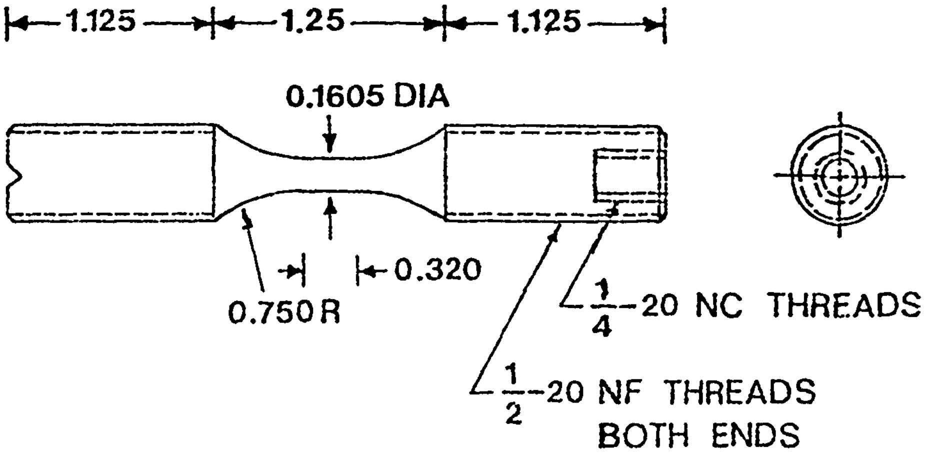
SPECIMEN PREPARATION

Figure 2 shows the specimen designed for this investigation. The threaded ends of the specimen were made long enough to accommodate lock nuts to avoid any slackening at the grips. The specimen grips on the fatigue machine were custom designed to hole the specimen ends firmly. The length to diameter ratio of the gauge section of the specimen was chosen as 2:1 to avoid buckling during compression.

After careful machining the surface of the specimen was pre-polished with grade 600 and 800 silicon carbide papers to reduce the circular grooves and other tool marks. This was followed by electro-polishing to eliminate completely any surface irregularity.

Figures 3, 4, and 5 show the electropolishing device designed for polishing the specimen. It consists of an anode rotated by a lab stirrer at a predetermined speed. The pre-polished specimen is attached to the anode. The cathode consists of a 25 gauge stainless steel bent cylindrically to maintain uniform anode-cathode distance. The glass container is filled with the electrolyte which is a mixture of 59% methanol, 35% butyl cellosolve, and 6% perchloric acid. The container is placed on a magnetic stirrer which is used to stir the electrolyte to ensure uniform strength throughout. Step-by-step procedure for polishing the specimen is shown in the appendix A.

The fatigue machine is equipped with a load cell Model GSE 5410-1K. The four lead wires coming out of the load cell were connected to the strain indicator HW1-D of strain cert. The loading arm was disconnected



ALL DIMENSIONS IN INCHES

Fig. 2. Fatigue Specimen.

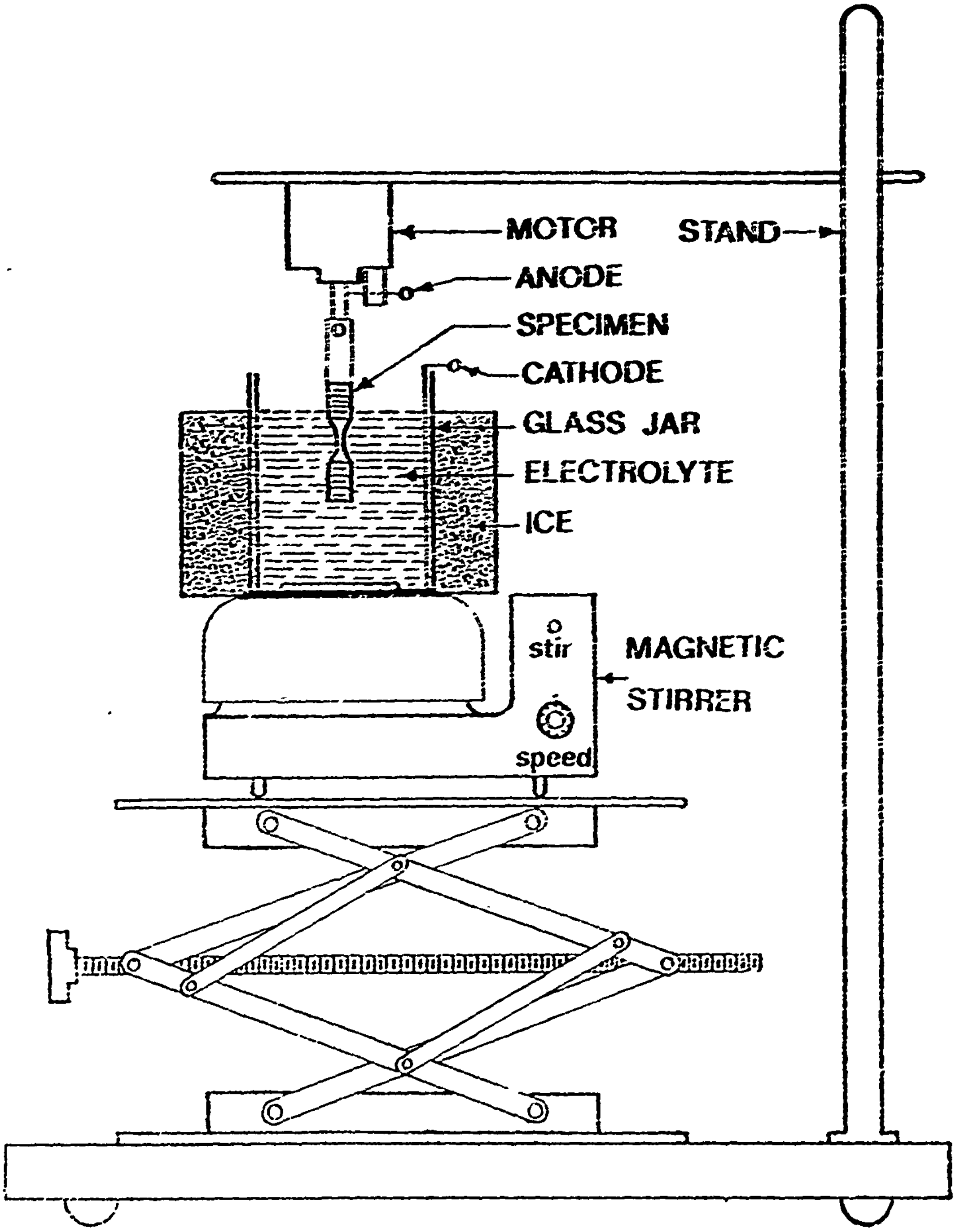


Fig. 3. Electropolishing Apparatus.

TABLE 6

CUMULATIVE FATIGUE DAMAGE FOR LOW-HIGH STRESS SEQUENCE (R=-1)

S. No.	Kramer's Equation	Miner's Equation
1	0.881	1.011
2	0.994	1.187
3	0.974	1.124
4	0.963	1.111
5	0.963	1.111
6	0.994	1.187
7	0.911	1.058
8	0.975	1.133
9	1.018	1.184
10	0.971	1.145
11	1.020	1.208
12	1.000	1.183
13	1.006	1.267
14	0.997	1.253
15	1.011	1.274
16	1.008	1.263
17	1.004	1.257
18	0.992	1.239

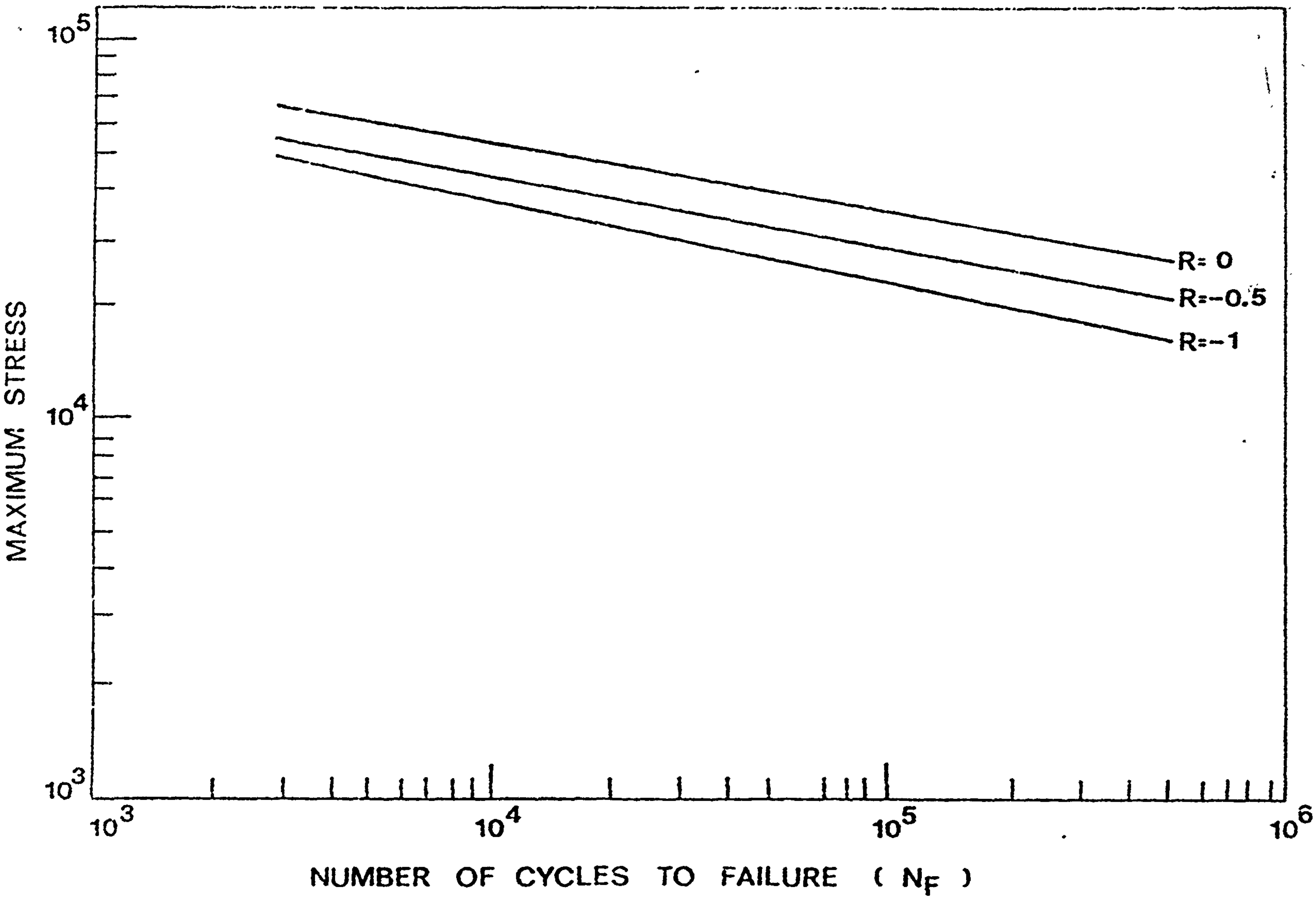


Fig. 6. S-N Diagrams for 2011-T3 Aluminum Alloy.

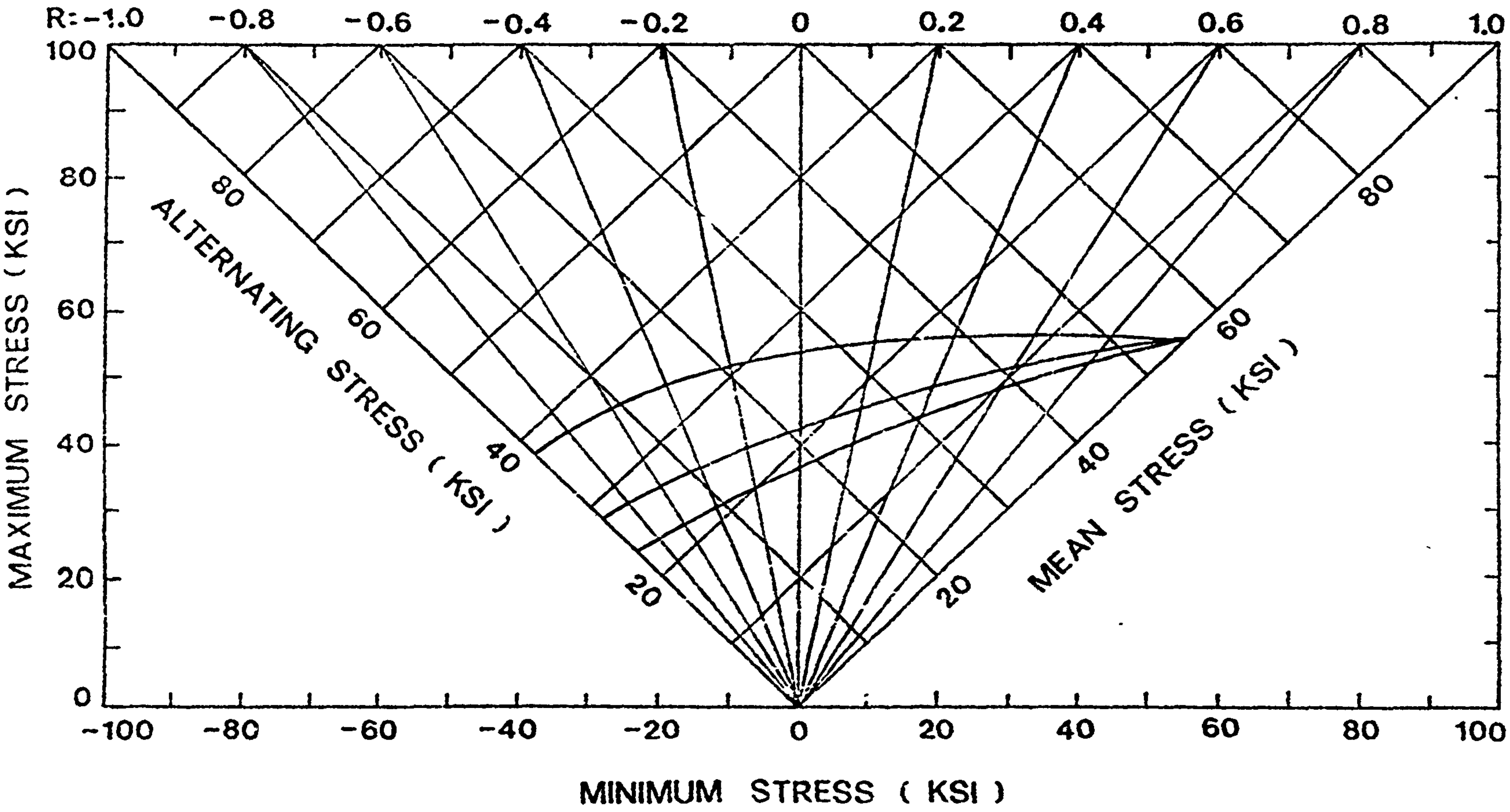


Fig. 7. Constant Fatigue Life Diagram for 2011-T3 Aluminum Alloy.

CONCLUSIONS AND RECOMMENDATIONS

1. The experimental set-up seems to be quite adequate for the generation of experimental data on fatigue damage.
2. The procedure of specimen preparation and operation of the fatigue machine is quite simple.
3. The experimental data generated using 2011-T3 aluminum alloy specimens indicates that there is a close agreement between the experimental and theoretical values of fatigue life and cumulative fatigue damage. Kramer's equation predicts less conservative and more realistic cumulative fatigue damage than the popularly used Miner's rule.

It is suggested that the tests be continued to generate fatigue data on 2011-T3 aluminum alloy specimens for $R=0$ and $-\frac{1}{2}$. It is also recommended that this investigation be continued for other alloys of practical use.

APPENDICES

APPENDIX A

SPECIMEN PREPARATION

1. The specimen is to be machined as per the specifications in the drawing.
2. The tool marks on the surface where the polishing is to be done should be cleaned using the finest grade of silicon carbide and sand paper.
3. The specimen should be heat-treated and tempered back to the pre-machining metalurgical conditions of the metal used (2011-T3).
4. The surface to be polished should be washed with methanol and dried.
5. The specimen should be examined using a microscope for circumferential scratches or tool marks on the surface to be polished. If any scratches are found they should be removed.
6. Attach the specimen to the shaft of the stirrer.
7. The electrolyte should be prepared by using 59% methanol, 35% butyl cellosolve, and 6% perchloric acid.
8. The electrolyte temperature should be kept at 15°C.
9. Adjust the speed of the magnetic stirrer at 4.5.
10. Start the motor holding the specimen and the magnetic stirrer. Care should be taken to see that the specimen rotates in the direction opposite to that of the magnetic stirrer.
11. Immerse the specimen in the electrolyte, by raising the platform, until the surface which is to be polished is completely immersed. Allow the specimen to cool in the electrolyte for 20 seconds.

12. Set the voltage at 15-20 volts (1.2 - 1.5 amps) and adjust the timer for 2 minutes. Turn on the power to start the polishing.

13. At the end of 2 minutes, turn off the power and lower the platform. Stop the motor and remove the specimen.

14. Rinse the specimen with hot water and methanol and dry it in the air dryer.

15. After drying, the specimen should be carefully examined under the microscope at 10 X magnification to see if all the surface irregularities are removed. If any irregularities are still observed, the whole process should be repeated again starting from step 5.

16. If no irregularities are found, the specimen should be carefully wrapped in cotton and stored in the desicator.

APPENDIX B

TABLES

TABLE 1

EXPERIMENTAL DATA FOR S-N CURVE (R=-1)

No.	Max. Stress (PSI)	No. of Cycles to Failure (N)
1	42300	4100
2	36800	8000
3	34600	11400
4	32100	20500
5	30800	34700
6	28800	42800
7	26800	72600
8	23900	81600
9	22100	147000
10	19100	289000

TABLE 2

EXPERIMENTAL DATA FOR S-N CURVE (R=-½)

No.	Max. Stress (PSI)	No. of Cycles to Failure (N)
1	46000	6800
2	42800	12300
3	41100	15500
4	38400	25500
5	35800	28200
6	31800	59500
7	29400	76600
8	24900	211000

TABLE 3

EXPERIMENTAL DATA FOR S-N CURVE (R=0)

No.	Max. Stress (PSI)	No. of Cycles to Failure (N)
1	47700	17000
2	44300	57000
3	44300	28500
4	38300	72800
5	33800	101000
6	29800	270000
7	26900	340000
8	26900	640000

TABLE 4

CUMULATIVE FATIGUE DATA FOR LOW-HIGH STRESS SEQUENCE (R=-1)

S. No.		Stage 1 25000 PSI	Stage 2 30000 PSI	Stage 3 35000 PSI	*Stage 4 - 40000 PSI	
					Theoretical	Experimental
1	Numbers of Cycles	20000	8000	4000	2397	1300
2		20000	8000	4000	2397	2400
3		20000	8000	4000	2397	2200
4		20000	8000	4000	2397	2100
5		20000	8000	4000	2397	2100
6		20000	8000	4000	2397	2400
7		30000	10000	3000	1335	500
8		30000	10000	3000	1335	1100
9		30000	10000	3000	1335	1500
10		25000	10000	5000	996	700
11		25000	10000	5000	996	1200
12		25000	10000	5000	996	1000
		20000 PSI	25000 PSI	30000 PSI	35000 PSI	
13		35000	30000	15000	1890	1700
14		25000	30000	15000	1890	1500
15		35000	30000	15000	1890	1800
16		40000	28000	16000	1373	1200
17		40000	28000	16000	1373	1100
18		40000	28000	16000	1373	850

*Specimen is stressed till failure in the 4th stage.

TABLE 5

CUMULATIVE FATIGUE DATA FOR LOW-HIGH MIXED STRESS SEQUENCE (R=-1)

S. No.		Stage 1 25000 PSI	Stage 2 30000 PSI	Stage 3 35000 PSI	*Stage 4 - 40000 PSI	
					Theoretical	Experimental
1	Numbers of Cycles	20000	4000	8000	2689	2700
2		20000	4000	8000	2689	2400
3		20000	4000	8000	2689	3200
4		20000	4000	8000	2689	2800
5		20000	4000	8000	2689	2650
6		20000	4000	8000	2689	2800
7		30000	3000	10000	1161	1200
8		30000	3000	10000	1161	800
9		30000	3000	10000	1161	1300
10		25000	5000	11000	462	900
11		25000	5000	11000	462	600
12		25000	5000	11000	462	1050
		20000 PSI	30000 PSI	25000 PSI	35000 PSI	
13		35000	15000	25000	132	200
14		35000	15000	25000	132	700
15		35000	15000	25000	132	300
16		40000	16000	20000	1551	900
17		40000	16000	20000	1551	1300
18		40000	16000	20000	1551	1650

*Specimen is stressed till failure in the 4th stage.

TABLE 6

CUMULATIVE FATIGUE DAMAGE FOR LOW-HIGH STRESS SEQUENCE (R=-1)

S. No.	Kramer's Equation	Miner's Equation
1	0.881	1.011
2	0.994	1.187
3	0.974	1.124
4	0.963	1.111
5	0.963	1.111
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8	0.975	1.133
9	1.016	1.184
10	0.971	1.145
11	1.020	1.208
12	1.060	1.183
13	1.006	1.267
14	0.997	1.253
15	1.011	1.274
16	1.008	1.263
17	1.004	1.257
18	0.992	1.239

TABLE 7

CUMULATIVE FATIGUE DEMAGE FOR LOW-HIGH MIXED STRESS SEQUENCE (R=-1)

S. No.	Kramer's Equation	Miner's Equation
1	1.002	1.187
2	0.975	1.149
3	1.044	1.250
4	1.01	1.199
5	0.997	1.180
6	1.01	1.199
7	1.003	1.146
8	0.971	1.096
9	1.011	1.159
10	1.033	1.20
11	1.01	1.165
12	1.045	1.222
13	1.003	1.089
14	1.021	1.123
15	1.006	1.096
16	0.985	1.124
17	1.003	1.151
18	1.017	1.175

APPENDIX C

SAMPLE CALCULATIONS

The sample calculations are shown for the following case:

completely reversed (R=-1)

σ_1 = 25,000 psi, N_1 = 20,000 cycles

σ_2 = 30,000 psi, N_2 = 8,000 cycles

σ_3 = 35,000 psi, N_3 = 4,000 cycles

σ_4 = 40,000 psi, N_4 = 2,400 cycles (failure)

Kramer's equation is as follows:

$$N_1\sigma_1 P + N_2\sigma_2 P\left(\frac{\sigma_1}{\sigma_2}\right)^{Pf_1} + N_3\sigma_3 P\left(\frac{\sigma_2}{\sigma_3}\right)^{Pf_2}\left(\frac{\sigma_1}{\sigma_2}\right)^{Pf_2 f_1} + ---- = \frac{\sigma_S^*}{\alpha} = \beta$$

or

$$\frac{N_1\sigma_1 P}{\beta} + \frac{N_2\sigma_2 P}{\beta}\left(\frac{\sigma_1}{\sigma_2}\right)^{Pf_1} + \frac{N_3\sigma_3 P}{\beta}\left(\frac{\sigma_2}{\sigma_3}\right)^{Pf_2}\left(\frac{\sigma_1}{\sigma_2}\right)^{Pf_2 f_1} + ---- = F$$

$f_1, f_2 \ldots$ = Damage prehistories

F = Cumulative fatigue damage

m = Slope of the S-N curve which is of the form

Log Y = m Log x + log c

$N_1, N_2 \ldots$ = No. of cycles applied

P = Material constant = $\frac{1}{m}$

σ_S^* = Critical surface layer stress

$\sigma_1, \sigma_2 \ldots$ = Applied stress

α = Material constant

β = Material constant = $(\log^{-1} C)^P$

Calculation of P & :

$$m = \frac{n.\Sigma\ (\log x.\ \log Y) - \Sigma \log x.\ \Sigma \log Y}{n.\Sigma\ (\log x)^2 - (\Sigma \log x)^2} = -0.2206$$

therefore, $P = \frac{-1}{m} = \frac{-1}{(-0.2206)} = 4.533$

$$\log C = \frac{\Sigma \log Y\ .\ \Sigma(\log x)^2 - \Sigma \log x\ .\ \Sigma(\log x.\ \log Y)}{n.\Sigma\ (\log x)^2 - (\Sigma \log x)^2} \approx 5.4625$$

$$\beta = (\log^{-1} C)^P = 5.7745 \times 10^{24}$$

Calculation of Fatigue Damage:

$$\frac{N_1\sigma_1{}^P}{\beta} + \frac{N_2\sigma_2{}^P}{\beta}\left(\frac{\sigma_1}{\sigma_2}\right)^{Pf_1} + \frac{N_3\sigma_3{}^P}{\beta}\left(\frac{\sigma_2}{\sigma_3}\right)^{Pf_2}\left(\frac{\sigma_1}{\sigma_2}\right)^{Pf_2f_1} + \ldots.$$

$$f_1 = \frac{N_1\sigma_1{}^P}{\beta} = \frac{20000 \times (25116)^{4.533}}{5.7745 \times 10^{24}} = 0.305$$

$$f_2 = \frac{N_2\sigma_2{}^P}{\beta}\left(\frac{\sigma_1}{\sigma_2}\right)^{Pf_1} = \frac{8000 \times (30090)}{5.7745 \times 10^{24}}\left(\frac{25116}{30090}\right)^{1.383}$$

$$f_3 = \frac{N_3\sigma_3{}^P}{\beta}\left(\frac{\sigma_2}{\sigma_3}\right)^{Pf_2}\left(\frac{\sigma_1}{\sigma_2}\right)^{Pf_2f_1}$$

$$= \frac{4000 \times (35063)^{4.533}}{5.7745 \times 10^{24}}\left(\frac{30090}{35063}\right)^{0.979} \times \left(\frac{25116}{30090}\right)^{0.299}$$

$$= 0.226$$

$$f_4 = \frac{N_4\sigma_4{}^P}{\beta}\left(\frac{\sigma_3}{\sigma_4}\right)^{Pf_3}\left(\frac{\sigma_2}{\sigma_3}\right)^{Pf_3f_2}\left(\frac{\sigma_1}{\sigma_2}\right)^{Pf_3f_2f_1}$$

$$= \frac{2400 \times (39789)^{4.533}}{5.7745 \times 10^{24}}\left(\frac{35063}{39789}\right)^{1.024} \times \left(\frac{30090}{35063}\right)^{0.221} \times \left(\frac{25116}{30090}\right)^{0.067}$$

$$= 0.247$$

Therefore, cumulative fatigue damage $F = f_1 + f_2 + f_3 + f_4$

$$= 0.305 + 0.216 + 0.226 + 0.247$$

$$= 0.994$$

Prediction of Fatigue Life:

The following calculation shows the predictionoof the number of cycles required to cause failure in the last (fourth) stage.

$$f_4 = F - (f_1 + f_2 + f_3) = 1 - (0.305 + 0.216 + 0.226)$$

$$= 1 - 747 = 0.253$$

$$f_4 = \frac{N_4 \sigma_4 P}{} \left(\frac{\sigma_3}{\sigma_4}\right)^{Pf_3} \left(\frac{\sigma_2}{\sigma_3}\right)^{Pf_3 f_2} \left(\frac{\sigma_1}{\sigma_2}\right)^{Pf_3 f_2 f_1}$$

$$0.253 = N_4\ (1.0303 \times 10^{-4})$$

No. of cycles to failure N_4 = 2456 cycles.

APPENDIX D

COMPUTER PROGRAM FOR CALCULATING THE CUMULATIVE FATIGUE DAMAGE AND FATIGUE LIFE

```
10  REM  TUSKEGEE INSTITUTE

20  REM  PREDICTION OF FATIGUE DAMAGE

30  REM  P = -1M,A CONSTT. OBTAINED FROM S-N CURVE

40  REM  B = C^P,A CONSTT.

50  REM  A(I) = APPLIED STRESS

60  REM  N(I) = NO. OF APPLIED CYCLES

70  REM  F(I) = DAMAGE PREHISTORIES

80  REM  D = TOTAL DAMAGE

90  P  = 4.533

100 B  = 5.7745 + 24

110 READ A1, A2, A3, A4, N1, N2, N3, N4

120 F1 = ((A1^P)*N1)/B

130 F2 = ((A2^P)*N2*((A1/A2)^(P*F1)))/B

140 f3 = ((A3^P)*((A2/A3)^(P*F2))*((A1/A2)^(P*F2*F1)))/B

150 L  = (A4^P)*N4*((A3/A4)^(P*F3))*((A2/A3)^(P*F3*F2)

160 M  = (A1/A2)^(P*F3*F2*F1)

170 F4 = (L*M)/B

180 D  = F1 + F2 + F3 + F4

190 PRINT  "F1 = "F1,"F2 = "F2,"F3 = "F3,"F4 = "F4

200 PRINT  "TOTAL DAMAGE D = "D

210 DATA  1,2,3,4,5,6,7,8

220 END
```

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2. Kramer, I. R. 1976. "Prediction of Fatigue Damage." Proceedings of the Second International Conference on Mechanical Behavior of Materials.

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A direct Tension-compression fatigue testing machine Model DS-600 HLM is procured, installed, and calibrated for the generation of data to study the cumulative fatigue damage in selected materials. An apparatus ;and step-by-step procedure are developed to electropolish the fatigue specimen.

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Experimental data are generated using 2011-T3 aluminum alloy specimens under completely reversed condition for Low-High and Low-High-Mixed stress cycles.

Analysis of the data has indicated that the predicted cumulative fatigue damage and fatigue life are in complete agreement with the experimental values.