



ESTIMATION OF FATIGUE PROPERTIES OF 35NCDV12 ALLOY STEEL UNDER CHROMIUM COATING USING THE STAIRCASE METHOD

Dr. Nabil N. Swadi *

ABSTRACT:

In this paper, the experimental estimation of the fatigue strength and the standard deviation for the 35NCDV12 alloy steel have been found using the *Staircase* (up and down) method. The specimens divided into two groups. The first group contains 15 non-chromium specimens and the second group contains 15 hard chromium specimens. The thickness of the chrome is about (100 to 120 microns). The fatigue or endurance limit has been determined for each group and then compared with that estimated from S-N (Wöhler) curve for the 35NCDV12 alloy steel. The results show that the endurance limit of the chromium specimens is decreased to a ratio about 60 % from those non-chromium specimens. This proves that the chromium plating increases the wear and corrosion resistance of the metals and decreases the fatigue strength and endurance limit of those metals. In addition, the results show that the staircase method is very useful testing compared with S-N curve for estimation the endurance limit without a large number of specimens.

(35NCDV12)

:

35NCDV12

(Staircase)

15

15

120 100

.(60 %)

*Dept. of Machines & Equipments.

INTRODUCTION:

Many different fatigue procedures have been devised to provide information suitable for meeting a variety of different objectives. In this study we desired to obtain strength distribution data at a constant life level. Therefore, the **staircase** method outlined in this study to determine the fatigue strength of the 35NCDV12 alloy steel for constant life level of 5×10^6 cycles for chromium and non-chromium specimens made from this steel alloy. Those specimens are subjected to repeated forces of specified magnitudes while the cycles or stress reversals are counted to destruction. The most widely used fatigue-testing machine is the R.R. Moore high-speed rotating bending machine, Budynas et al 2008. This machine subjects the specimen to pure bending by means of weights. The specimens are very carefully machined and polished, with a final polishing in an axial direction to avoid circumferential scratches.

The objective of the fatigue strength test (also called the fatigue limit test, the strength test, or the response test) is to estimate a statistical distribution of the fatigue strength at a specific high – cycle fatigue life. Among many fatigue strength test methods, the **staircase** method (often referred to as the up – and – done method) is the most popular one that has been adopted by many standards (e.g., Japanese Society of Mechanical Engineers 1981, L'association Francaise de Normalisation 1991, MPIF, 2000) to assess statistical properties of a fatigue limit.

In this method (staircase), the mean fatigue limit has to be first estimated, and a fatigue life test is then directed at a stress level a little higher than the estimated mean. If the specimen fails earlier to the life of interest, the next specimen has to be tested at a lower stress level. If the specimen does not fail within this life of interest, a new test has to be directed at a higher stress level. Therefore, each test is dependent on the previous test results, and the test continuous with a stress level increased or decreased.

COLLINS 1993, and PETER et al 2005, recommends that the test be run with at least 15 specimens while VALIM et al 2009, was applied the staircase method on a group of 12 compressor blades.

Two typical data reduction techniques, the Dixon et al 1948 and the Zhang et al 1998 methods, can be used to determine the statistical parameters of the test. The details of the two methods can be found elsewhere, LIN et al 2001. The latter method has been used in this work because it is easy to use and often provides conservative results.

ANALYSES PROCEDURE:

The procedure for analyzing up-and-down data is as follow (COLLINS 1993, and YUNG et al 2005):

1. Estimate the mean fatigue strength μ_S corresponding to the life level of interest.
2. Estimate the standard deviation σ_S for the material, based on experience.
3. Test the first specimen at a stress level $(\mu_S + d)$, where d is the step size. Continue the test at this stress level until the specimen either fails or runs out at the prescribed life of interest.
4. If the first specimen fails, test the second specimen at a stress level one-increment d *lower* than the previous stress level (μ_S) . If the first specimen runs out, test the second specimen at a stress level one-increment d *higher* than the previous stress level $(\mu_S + 2d)$.
5. Continue the test sequentially until at least 15 to 30 specimens have been tested.
6. When the test has been completed, determine whether failures or run outs are the less frequent event. Only the less frequent event is used in the analysis.
7. Tabulate the results as follows in a five column table:

- In column II the number 0 is assigned to the lowest level, 1 is assigned to the next higher stress level, etc., until all stress levels are numbered in order of increasing magnitude. Name this column by i .
- In column III list the number of times the event occurred at each stress level, name this column by n_i .
- In column IV tabulate the product of column II times column III, $i*n_i$.
- In column V tabulate the product of the square of column II times column III, i^2*n_i .

8. From the tabulation of step 7, sum column III and set the sum equal to N , $N = \sum n_i$.

Also from the tabulation, sum column IV and set the sum equal to A , $A = \sum i*n_i$.

Also from the tabulation, sum column V and set the sum equal to B , $B = \sum i^2 *n_i$.

9. Calculate the statistical estimate of mean fatigue strength at the prescribed life from (COLLINS 1993, and YUNG et al 2005):

$$\mu_S = S_o + d * \left[\frac{A}{N} \pm \frac{1}{2} \right] \quad (1)$$

where μ_S = statistical estimate of mean fatigue strength at prescribed life.

S_o = lowest stress level at which the less frequent event occurred.

d = step size,

N = total number of less frequent events.

The plus sign (+) is used if the less frequent event is run out, and the minus sign (-) is used if the less frequent event is failure.

10. Calculate the statistical estimate of the population standard derivation from (COLLINS 1993, and YUNG et al 2005):

$$\sigma_S = 1.62 * d * \left[\frac{NB - A^2}{N^2} + 0.029 \right],$$

$$\text{if } \frac{NB - A^2}{N^2} \geq 0.3 \quad (2)$$

$$\sigma_S = 0.53 * d,$$

$$\text{if } \frac{NB - A^2}{N^2} < 0.3 \quad (3)$$

where σ_S = statistical estimate of standard deviation.

d = step size.

$$B = \sum i^2 * n_i$$

11. With the mean μ_S and standard deviation σ_S determined for a normal distribution, the lower – bound value associated with reliability and confidence levels can be determined by one – side lower – bound tolerance limit K factor, LIEBERMAN 1958, as follows:

$$S_{e,R,C} = \mu_S - K * \sigma_S \quad (4)$$

where the K factors for one – side tolerance limit for a normal distribution are given in (YUNG et al 2005). The lower – bound fatigue limit $S_{e,R,C}$ means that with a confidence level of $C\%$, $R\%$ of the tested fatigue limit might be expected to exceed the $S_{e,R,C}$ level.

ESTIMATED S-N CURVE OF A COMPONENT BASED ON ULTIMATE TENSILE STRENGTH AT ROOM TEMPERATURE:

STEEL UNDER CHROMIUM COATING USING THE STAIRCASE METHOD

In the event that experimental S-N data are not available, methods for estimating the S-N behavior of a component becomes useful and important for the design process.

Through many years of experience and testing, empirical relationships that relate fatigue strength data and the ultimate tensile strength, R_m , have been developed. These relationships are not scientifically based but are simple and useful engineering tools to estimate the fatigue lives of components in the high-cycle fatigue region. Thus, the estimated fatigue strength corresponding to the two fatigue lives (e.g., 10^3 cycles and 10^6 cycles) for the baseline test specimens are discussed in this section. It is necessary to adjust or modify the baseline S-N curve when a component or loading condition deviates from the standard test. Such adjustments are accomplished through the use of modifying factors.

Figure 1 illustrates the effects of modifying factors on a baseline S-N curve, YUNG et al, 2005.

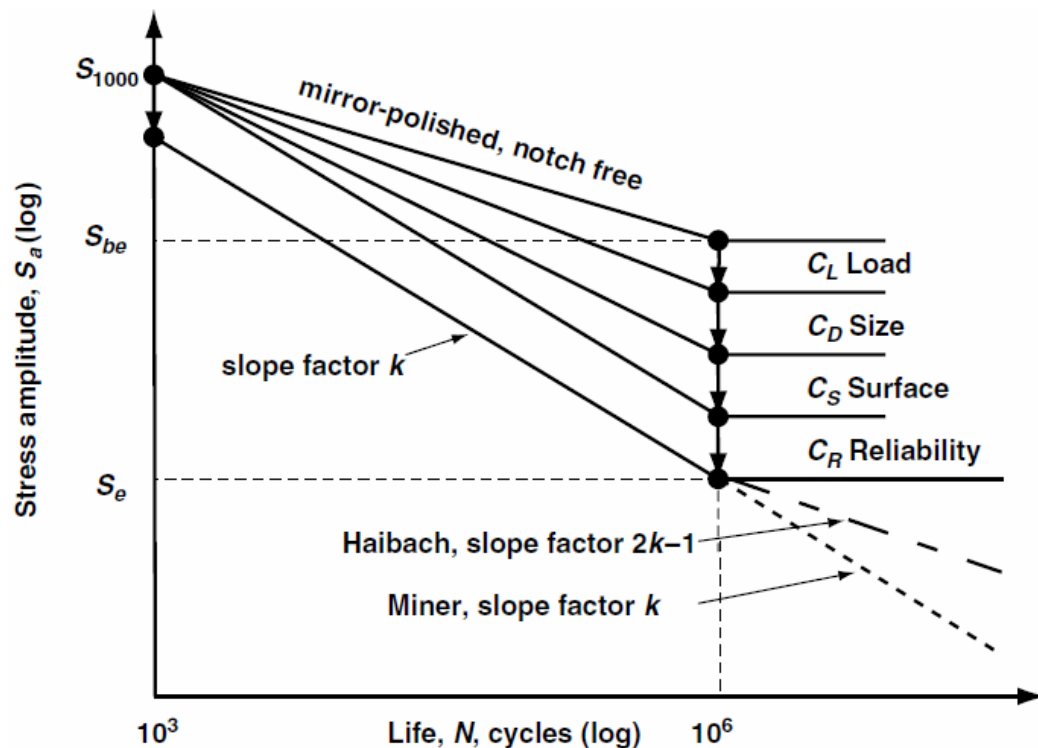


Figure 1: Modified S-N curves for smooth components made of steels.

To generate a baseline S-N curve for a component, the ultimate strength of that given material must first be known. Once determine the fatigue strengths at 10^3 cycles and at the fatigue limit, life can be approximated using the ultimate strength. These strength values can be later

modified to include the effects of other factors such as loading, surface finish, size, and reliability on the S-N curve.

The fatigue strength for unnotched specimen at 10^3 cycles (S_{1000}) depends on the reliability level and the type of loading, YUNG et al 2005.

$$S_{1000,R} = S_{1000} * C_R \quad (5)$$

Where S_{1000} = is the fatigue strength at 10^3 cycles based on the standard test specimens.

C_R = is the modifying factor at a specified reliability level.

$$S_{1000} = 0.90 * R_m \quad (\text{for bending}) \quad (6)$$

For 90% reliability, YUNG et al, 2005:

$$C_R = 0.897$$

The bending fatigue limit (endurance limit), S_{be} , at 10^6 cycles for steels (JUVINALL et al, 2000) is:

$$S_{be} = (0.25 \text{ to } 0.60) * R_m \quad (7)$$

Or $S_{be} = 0.6 * R_m$ (for steel)

The fatigue limit, S_e can be estimated by modifying the bending fatigue limit (S_{be}) with the four factors for the type of loading (C_L), surface finish (C_S), size (C_D), and reliability level (C_R), from BUDYNAS, 2008:

$$S_{e,R} = S_{be} * C_L * C_S * C_D * C_R \quad (8)$$

For bending load condition, YUNG et al, 2005:

$$C_L = 1.0$$

For mirror polishing specimen, JAAP, 2009:

$$C_S = 1.0$$

For the diameter of the specimen, $d < 8$ mm, HORGGER, 1965:

$$C_D = 1.0$$

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The general formulas to determine S_e and S'_{1000} for the notched shaft made of steel, BUDYNAS, 2008 are:

$$S_{e, \text{notched}} = S_{be} * C_L * C_S * C_D * C_R / K_f \quad (9)$$

And

$$S'_{1000, \text{notched}} = S_{1000} * C_R / K'_f \quad (10)$$

Where K_f and K'_f are the fatigue strength reduction factors for a component at 10^3 cycles and the fatigue limit at 10^6 cycles respectively.

$$K_f = 1 + (K_t - 1) * q \quad (11)$$

$$K'_f = 1 + (K_f - 1) * q'_{1000} \quad (12)$$

$$q = 1 / (1 + a/r) \quad (13)$$

Based on JAAP, 2009:

$$K_t = \sigma^0 / S_{\text{nominal}} \quad (14)$$

Where σ^0 = maximum elastic notch stress

Where r is the notch radius

For bending loading, PETERSON, 1959:

$$a = 0.0254 * (2079 / R_m)^{1.8} \quad (15)$$

MACHINE AND SPECIMEN USED:

The rotating bending machine of constant bending moment type is described schematically (HENRI 1982), as shown in Figure 2. With this type of device the region of rotating beam between the supports is subjected to a constant bending moment all its along length. While under the influence of this constant moment, the specimen is caused to rotate with the drive spindles about a longitudinal axis. Any point on the surface is thereby subjected to a completely reversed stress-time pattern, HEARN, 2001. Figure 3 illustrates some kinds of the rotating bending machine, CAZAUD et al, 1969.

The applied bending moment and bending stress distribution along the specimen body is shown in Figure 4.

The configuration and dimensions of the specimen used in this study is presented in Figure 5. It is made from 35NCDV12 alloy steel in two groups; the first group includes 15 of non-chromium specimens while the second group includes 15 chromium specimens. The thickness of the chromium layer is about 100 to 120 microns.

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF THE SPECIMEN MATERIAL:

The specimen made of 35NCDV12 steel of chemical composition and basic mechanical properties within the range shown in table 1 and 2 respectively:

Table 1: Chemical compositions of 35NCDV12 alloy steel.

Material %	<i>C</i>	<i>S</i>	<i>P</i>	<i>Mn</i>	<i>Si</i>	<i>Ni</i>	<i>Cr</i>	<i>Mo</i>	<i>V</i>	<i>Cu</i>	<i>Al</i>
35NCDV12	0.33	.002	.006	0.42	0.27	3.35	1.35	0.51	0.61	0.04	0.01

Table 2: Mechanical properties of 35NCDV12 alloy steel.

Properties	Y. strength R _{0.2} (Mpa)	U. strength R _m (Mpa)	Elongation A %	K _{cu} J/cm ²	K _v J
Value	1200 - 1230	1300 - 1350	12 - 14	60 - 80	30

THE HEAT TREATMENT:

1. 875 C°, water quenched
2. Tempered 570 to 580 C° at 30 min.

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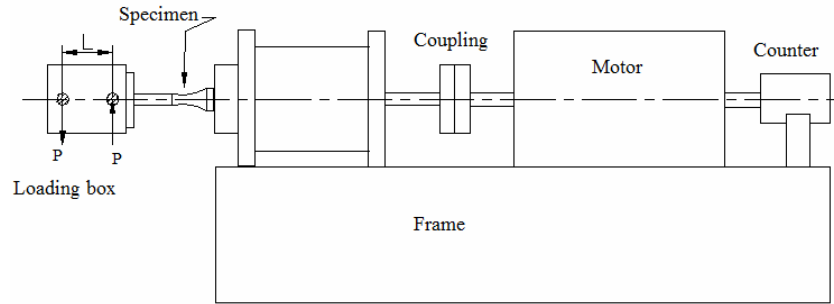


Figure 2: Schematic diagram of the rotating bending machine.

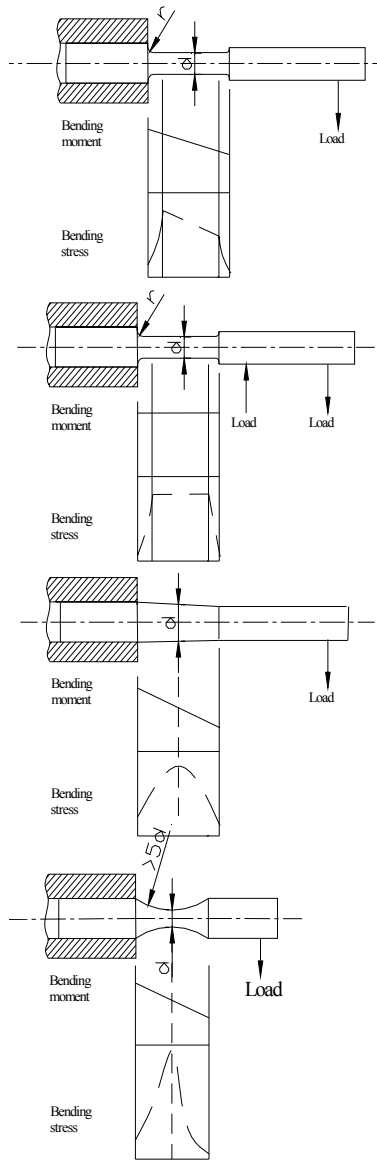


Figure 3: Different types of the rotating bending machine.

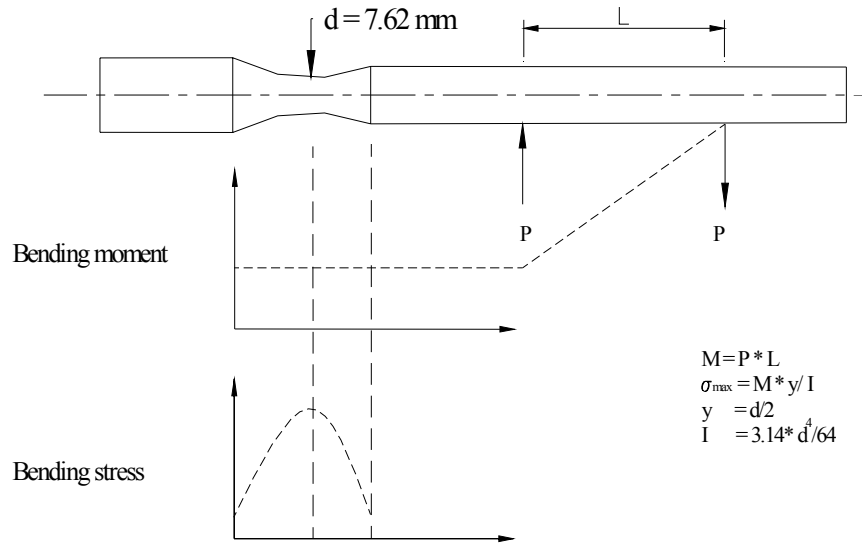
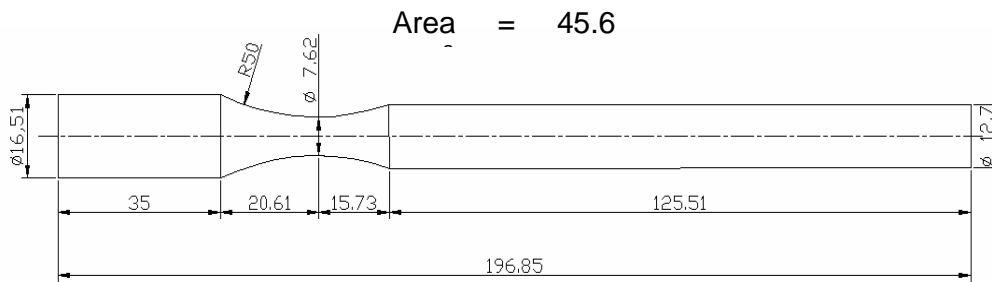


Figure 4: The bending moment and bending stress applied to the critical section of the specimen.



All dimensions are in mm.

Figure 5: Geometry of the rotating bending specimen.

RESULTS AND DISCUSSION:

1. Non chromium specimens:

$N_f = 5 * 10^6$ cycles.

Frequency: 28 Hz (1680 RPM)

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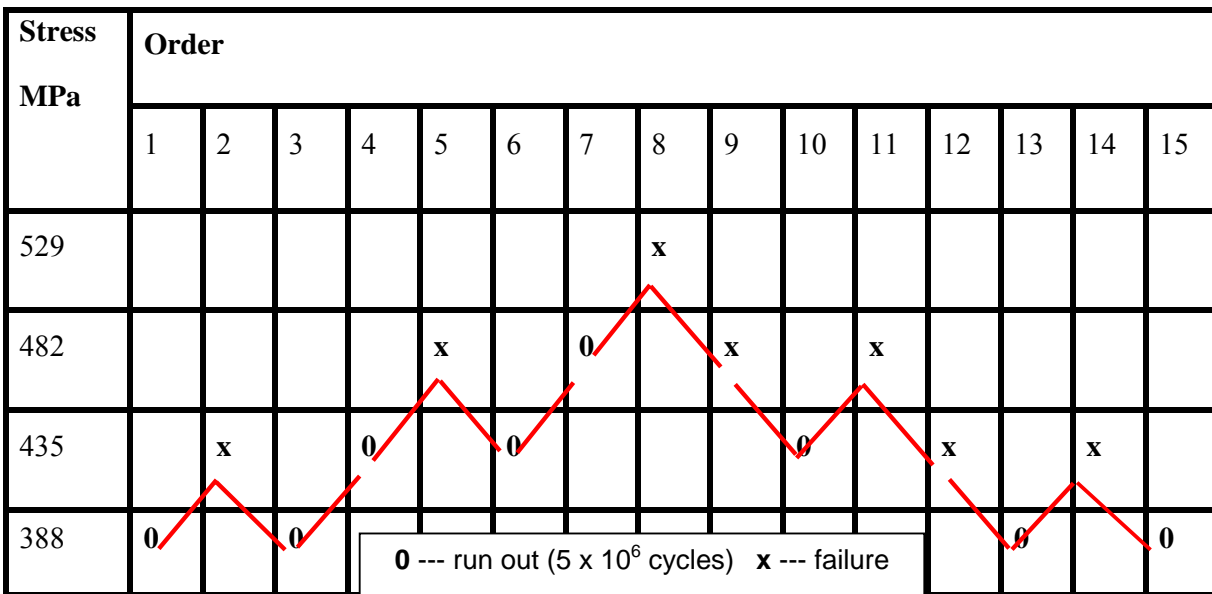


Figure 5: Staircase fatigue test used to determine mean fatigue strength at 5×10^6 cycles for 35NCDV12 steel alloy **non-chromium** specimens.

Table 3: Tabular information required for computing mean and standard deviation from staircase test data for **non-chromium** specimens.

<i>I</i>	<i>II</i>	<i>III</i>	<i>IV</i>	<i>V</i>
	<i>i</i>	<i>n_i</i>	<i>i</i> * <i>n_i</i>	<i>i</i> ² * <i>n_i</i>
388	0	4	0	0
435	1	3	3	3
482	2	1	2	4
529	3	0	0	0
		<i>N</i> = 8	<i>A</i> = 5	<i>B</i> = 7

From Figure 5, the failures are used in this non – chromium specimens test because they are the less frequent event. Thus, from table 4, $N = 8$, $A = 5$, $B = 7$, and $d = 47$ MPa, the fatigue strength can be calculated from eq (1) as follows: $\mu_S = 393.875$ MPa.

Since, $\frac{NB-A^2}{N^2} = 0.4843 > 0.3$, the standard deviation can be estimated from eq. (2) as follows: $\sigma_S = 39.088$ MPa. Assuming that the fatigue limit follows a normal distribution, the *R90C90* lower

bound fatigue limit value can be found from eq. (4) as follows: $S_{e,0.9,0.9} = 307.137$ MPa, where K is obtained as 2.219 from (LIEBERMAN, 1958) with $N = 8$.

2. Chromium specimens:

$N_f = 5 * 10^6$ cycles.

Frequency: 28 Hz (1680 RPM)

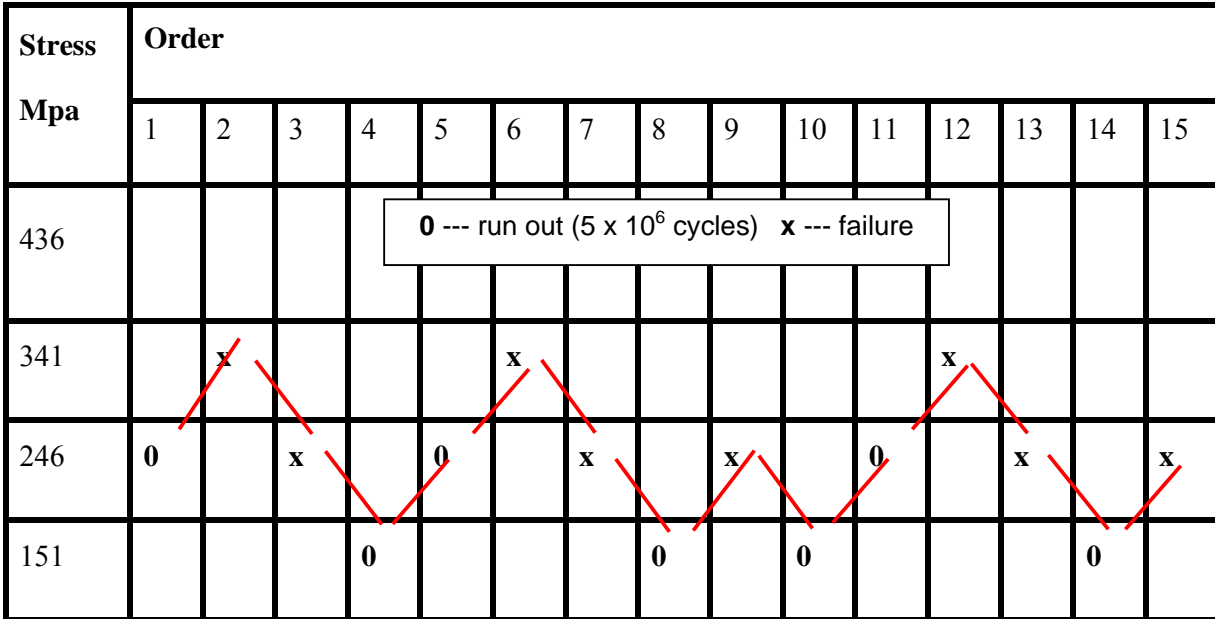


Figure 6: Staircase fatigue test used to determine mean fatigue strength at 5×10^6 cycles for 35NCDV12 steel alloy **chromium** specimens.

Table 4: Tabular information required for computing mean and standard deviation from staircase test data for **chromium** specimens.

<i>I</i>	<i>II</i>	<i>III</i>	<i>IV</i>	<i>V</i>
	<i>i</i>	<i>n_i</i>	<i>i*n_i</i>	<i>i²*n_i</i>
151	0	4	0	0
246	1	3	3	3
341	2	0	0	0
436	3	0	0	0
		<i>N = 7</i>	<i>A = 3</i>	<i>B = 3</i>

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From Figure 6, the survivals are used in this chromium specimens test because they are the less frequent event. Similarly, the fatigue strength, standard deviation and the lower bound of fatigue limit can be respectively calculated as follows:

$\mu_S = 239.214$ MPa, $\sigma_S = 50.35$ MPa (eq. (3)), and $S_{e,0.90,0.90} = 121.74$ MPa, where K is obtained as 2.333 from (LIEBERMAN, 1958) with $N = 7$.

3. Estimated S-N (Wöhler) Curve at room temperature:

- a. Case 1: For mirror polished, no reliability and unnotched specimens:

$$S_{1000} = 1170 \text{ MPa}$$

$$S_{be} = 780 \text{ MPa}$$

- b. Case 2: For mirror polished, 90% reliability and unnotched specimens:

$$S_{1000,R} = 1049.49 \text{ MPa}$$

$$S_{e,R} = 686 \text{ MPa}$$

- c. Case 3: For mirror polished, 90% reliability and notched specimens:

$$S'_{1000, \text{notched}} = 646.237 \text{ MPa}$$

$$S_{e, \text{notched}} = 305 \text{ MPa}$$

COMPARISON OF THE RESULTS:

Type of test	d (Mpa)	S_o (Mpa)	S_e (Mpa)	Specimens
Non chromium specimen	47	388	307.137	15
Chromium specimen	95	151	121.74	15
Estimated S-N (Wöhler) Curve	-	-	305	-

Figure 7 represents the comparison between the endurance limit obtained from **staircase** method and from generalized **Wöhler** curve.

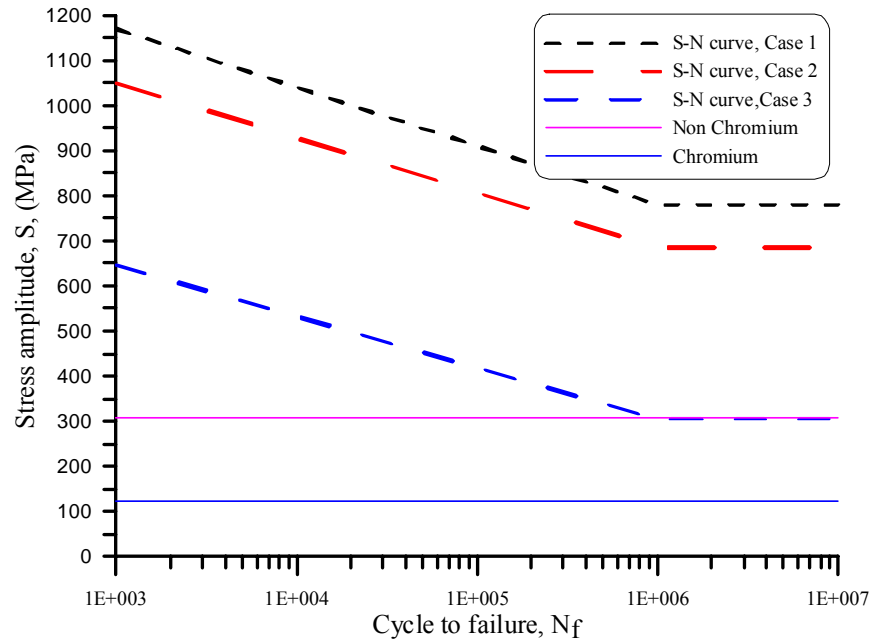


Figure 7: Estimated S-N curve and staircase results with 90% reliability for mirror polishing notched 35NCDV12 alloy steel under rotating bending loadings.

CONCLUSION:

1. The staircase method is very useful testing for estimation the mean fatigue strength, endurance limit and the standard deviation at any specified life without a large number of specimens are required. This makes the staircase method not costly and less time consuming.
2. The great advantage to the staircase method is that the statistical analysis is quite simple under certain conditions.
3. The chromium plating decreases the fatigue strength and the endurance limit of the metallic component to at least 60 % depending to the chromium thickness.
4. The chromium plating can be used for performing the wear and corrosion resistance of the components.
5. When the number of the tested specimens increased, the better result can be obtained for the same level of confidence and reliability.

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