INFORMATION TO USERS

The most advanced technology has been used to photograph and reproduce this manuscript from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.
Prediction of fatigue life in relation to surface finish parameters

Abdulrahim, Abdallah Adel, Ph.D.

Rice University, 1989
RICE UNIVERSITY

PREDICTION OF FATIGUE LIFE
IN RELATION TO SURFACE FINISH PARAMETERS

by

Abdallah A. Abdulrahim

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

APPROVED, THESIS COMMITTEE:

J.E. Merwin, Director
Professor in the Department of Civil Engineering

A.J. Durrani,
Associate Professor of Civil Engineering

G.M. Pharr
Associate Professor of Materials Science

Houston, Texas
May, 1988
ABSTRACT

One can safely claim that not one single surface roughness parameter, in terms of completely characterizing a surface, can be exhaustive. This study is both an experimental and theoretical study of characterizing surface finish in relation to fatigue; and the role of this finish in fatigue initiation.

A total of forty-two samples, comprising three different groups that exhibited different surface finish properties, were fatigued using constant amplitude loading. The S-N curves for these groups were established. A correlation between surface finish parameters and fatigue initiation was established. The parameters of importance were expected to be the deepest scratch and the rms valley curvature (sharpness) of the measured surfaces. The product of both parameters showed a reasonable degree of correlation with fatigue initiation at different stress levels. This product became a basis of establishing the functional relationships between surface finish parameters and fatigue failure. A number of specimens were prepared having a single scratch that varied in depth from 0.004 inches to 0.02 inches. The scratches had a fixed radius of curvature of 0.003 inches. The specimens were fatigued and the resulting S-N curves were grouped into one spectrum. The single scratch spectrum utilizing the deepest scratch and sharpness was used as a basis to predict fatigue failure. First-passage criteria were used to predict the deepest scratch in longer sampling lengths. The product of the predicted deepest scratches and curvature were used with the single scratch spectra to predict fatigue failure. The predicted life was within the 95% confidence bands of the S-N curves generated from fatiguing the specimens.
ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation and gratitude to Professor John E. Merwin, under whose supervision, guidance and encouragement this work was accomplished.

The author also wishes to acknowledge the following individuals:
- Mr. Hugh L. Hales for his help with the test set-up and sample preparation;
- Dr. George M. Pharr for helping in the metalurgical aspects of the study, and for serving on the thesis committee;
- Dr. Ahmad Durrani, for accepting to serve as a replacement on the thesis committee, under short notice;
- Ms. Rhonda Moore for typing this thesis.

Finally, to my dear mother and family who have been supportive and patient all these years.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td></td>
<td>ACKNOWLEDGEMENTS</td>
<td>ii</td>
</tr>
<tr>
<td></td>
<td>TABLE OF CONTENTS</td>
<td>iii</td>
</tr>
<tr>
<td></td>
<td>LIST OF SYMBOLS</td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td></td>
<td>LIST OF FIGURES</td>
<td>viii</td>
</tr>
<tr>
<td>I</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>BACKGROUND</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2.1 Characterization of surface profiles</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2.2 Surface profiles and their measurement</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2.3 The filtering process</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>2.4 Statistical properties</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2.5 Preliminary concepts in fatigue</td>
<td>22</td>
</tr>
<tr>
<td>III</td>
<td>EXPERIMENTAL PROCEDURE</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>3.1 Test specimens</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>3.2 Test set-up</td>
<td>25</td>
</tr>
<tr>
<td>IV</td>
<td>EXPERIMENTAL RESULTS AND ANALYTICAL PREDICTIONS</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>4.1 Analysis of the measured surfaces</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>4.2 Fatigue test results</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>4.3 Correlation of roughness and initiation</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>4.4 Analytical predictions</td>
<td>35</td>
</tr>
<tr>
<td>V</td>
<td>THEORETICAL PREDICTIONS OF CYCLES TO FAILURE</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>5.1 Gaussian assumptions and justifications</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>5.2 Predictions using the First-Passage Criteria</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>5.3 Predictions using the Method of Moments</td>
<td>84</td>
</tr>
<tr>
<td>Chapter</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>VI</td>
<td>CONCLUSIONS</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>REFERENCES.</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>APPENDICES.</td>
<td>111</td>
</tr>
<tr>
<td></td>
<td>A. Surface roughness profiles</td>
<td>111</td>
</tr>
<tr>
<td></td>
<td>B. Computer programs</td>
<td>135</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation or Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x(\xi)$</td>
<td>surface form</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>root mean square</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>root mean square of first derivative of $x(\xi)$</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>root mean square of second derivative of $x(\xi)$</td>
</tr>
<tr>
<td>$\nu_0^+$</td>
<td>rate of zero up-crossings</td>
</tr>
<tr>
<td>$\nu_b^+$</td>
<td>rate of up-crossings at level b</td>
</tr>
<tr>
<td>$n_p^+$</td>
<td>rate of occurrence of positive peaks</td>
</tr>
<tr>
<td>$\lambda_{AV}$</td>
<td>Average Wavelength of $x(\xi)$</td>
</tr>
<tr>
<td>$\lambda_{rms}$</td>
<td>Rms Wavelength of $x(\xi)$</td>
</tr>
<tr>
<td>$\sigma^*_3$</td>
<td>Rms Valley Curvature of $x(\xi)$</td>
</tr>
<tr>
<td>$V_D$</td>
<td>Deepest Scratch</td>
</tr>
<tr>
<td>$V_D^*$</td>
<td>predicted deepest scratch</td>
</tr>
<tr>
<td>$L_S$</td>
<td>sampling length</td>
</tr>
<tr>
<td>$m_x$</td>
<td>estimated mean</td>
</tr>
<tr>
<td>$a_x$</td>
<td>Estimated Standard deviation</td>
</tr>
<tr>
<td>$t(\alpha/2, n-1)$</td>
<td>$\chi$ distribution</td>
</tr>
<tr>
<td>$N_f$</td>
<td>Number of cycles to failure</td>
</tr>
<tr>
<td>$N_i$</td>
<td>Number of cycles to initiation</td>
</tr>
<tr>
<td>$\varepsilon_p$</td>
<td>Plastic strain</td>
</tr>
<tr>
<td>erf(·)</td>
<td>Error function</td>
</tr>
<tr>
<td>erfc(·)</td>
<td>Complimentary error function</td>
</tr>
<tr>
<td>Symbol</td>
<td>Explanation or Definition</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>( r(\cdot) )</td>
<td>Gamma function</td>
</tr>
<tr>
<td>( S_r )</td>
<td>Stress range</td>
</tr>
<tr>
<td>( K,m )</td>
<td>Constants related to fatigue material properties</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table 4-1</th>
<th>Mannesmann Pipe Surface Profile Statistical Properties.</th>
<th>43</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 4-2</td>
<td>Mannesmann Pipe Surface Profile Statistical Properties (Filtered at $T_0 = 5\lambda_{av}$)</td>
<td>44</td>
</tr>
<tr>
<td>Table 4-3</td>
<td>24 Grit Ground Surface Profile Statistical Properties</td>
<td>45</td>
</tr>
<tr>
<td>Table 4-4</td>
<td>24 Grit Ground Surface Profile Statistical Properties (Filtered at $T_0 = 5\lambda_{av}$)</td>
<td>46</td>
</tr>
<tr>
<td>Table 4-5</td>
<td>Regression Lines for Tested Specimens</td>
<td>62</td>
</tr>
<tr>
<td>Table 4-6</td>
<td>Cycles to Initiation and Failure for Mannesmann Pipe Specimens</td>
<td>63</td>
</tr>
<tr>
<td>Table 4-7</td>
<td>Cycles to Initiation and Failure for Ground (24 Grit) Specimens</td>
<td>64</td>
</tr>
<tr>
<td>Table 4-8</td>
<td>Cycles to Initiation and Failure for Single Scratch Specimens</td>
<td>65</td>
</tr>
<tr>
<td>Table 4-9</td>
<td>Correlation of Deepest Scratch with Fatigue Initiation.</td>
<td>66</td>
</tr>
<tr>
<td>Table 4-10</td>
<td>Predicted Values for the Mannesmann Pipe Specimens from the Single Scratch Spectra</td>
<td>77</td>
</tr>
<tr>
<td>Table 4-11</td>
<td>Predicted Values for the Ground (24 Grit) Specimens from the Single Scratch Spectra</td>
<td>78</td>
</tr>
<tr>
<td>Table 5-1</td>
<td>Mannesmann Surface Profile Average of Peak Moments Using Positive Peak Extrema</td>
<td>88</td>
</tr>
<tr>
<td>Table 5-2</td>
<td>Mannesmann Surface Profile Average of Peak Moments Using Positive Peak Extrema Filtered at $T_0 = 5\lambda_{av}$</td>
<td>89</td>
</tr>
<tr>
<td>Table 5-3</td>
<td>Ground (24 Grit) Surface Profile Average of Peak Moments Using Positive Peak Extrema</td>
<td>90</td>
</tr>
<tr>
<td>Table 5-4</td>
<td>Ground (24 Grit) Surface Profile Average of Peak Moments Using Positive Peak Extrema Filtered at $T_0 = 5\lambda_{av}$</td>
<td>91</td>
</tr>
<tr>
<td>Table 5-5</td>
<td>Predicted Life Using the Single Scratch Spectra</td>
<td>92</td>
</tr>
<tr>
<td>Table 5-6</td>
<td>Estimated Values Using the Method of Moments</td>
<td>99</td>
</tr>
<tr>
<td>Table 5-7</td>
<td>Predicted Life for Estimators of (Table 5-6) Using Single Scratch Spectra</td>
<td>100</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Profile of a Rounded Tip Stylus</td>
<td>11</td>
</tr>
<tr>
<td>2-2</td>
<td>Measured Surface Characteristics of a Ground Specimen G2521</td>
<td>13</td>
</tr>
<tr>
<td>2-3</td>
<td>Measured Surface Characteristics of a Ground Specimen GF2521 (Filtered)</td>
<td>14</td>
</tr>
<tr>
<td>2-4</td>
<td>Characteristics of Five Pole Butterworth Filter</td>
<td>16</td>
</tr>
<tr>
<td>2-5</td>
<td>Kurtosis Variations</td>
<td>18</td>
</tr>
<tr>
<td>3-1</td>
<td>Typical Specimen Dimensions</td>
<td>26</td>
</tr>
<tr>
<td>3-2</td>
<td>Stress-Strain Diagram for Mannesmann FG57T Steel Riser Pipe</td>
<td>27</td>
</tr>
<tr>
<td>3-3</td>
<td>Measured Surface Characteristics of Various Single Scratch Specimens</td>
<td>28</td>
</tr>
<tr>
<td>3-4</td>
<td>Test Fixture</td>
<td>29</td>
</tr>
<tr>
<td>4-1</td>
<td>Cumulative Distribution of Peaks (Specimen SNF3)</td>
<td>38</td>
</tr>
<tr>
<td>4-2</td>
<td>Measured Surface Characteristics of a Mannesmann Specimen SN3</td>
<td>39</td>
</tr>
<tr>
<td>4-3</td>
<td>Measured Surface Characteristics of a Mannesmann Specimen SNF3 (Filtered)</td>
<td>40</td>
</tr>
<tr>
<td>4-4</td>
<td>Measured Surface Characteristics of a Mannesmann Specimen G2426</td>
<td>41</td>
</tr>
<tr>
<td>4-5</td>
<td>Measured Surface Characteristics of a Mannesmann Specimen GF2426 (Filtered)</td>
<td>42</td>
</tr>
<tr>
<td>4-6</td>
<td>Mannesmann Riser Pipe, S-N Curve</td>
<td>47</td>
</tr>
<tr>
<td>4-7</td>
<td>Ground with 24 Grit, S-N Curve</td>
<td>48</td>
</tr>
<tr>
<td>4-8</td>
<td>Single Scratch 0.004 Inches Deep, S-N Curve</td>
<td>49</td>
</tr>
<tr>
<td>4-9</td>
<td>Single Scratch 0.006 Inches Deep, S-N Curve</td>
<td>50</td>
</tr>
<tr>
<td>4-10</td>
<td>Single Scratch 0.010 Inches Deep, S-N Curve</td>
<td>51</td>
</tr>
<tr>
<td>4-11</td>
<td>Single Scratch 0.015 Inches Deep, S-N Curve</td>
<td>52</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4-12</td>
<td>Single Scratch 0.020 Inches Deep, S-N Curve</td>
<td>53</td>
</tr>
<tr>
<td>4-13</td>
<td>Fatigue Crack Initiation vs. Deepest Scratch Stress Range = 80 ksi.</td>
<td>54</td>
</tr>
<tr>
<td>4-14</td>
<td>Fatigue Crack Initiation vs. Deepest Scratch Stress Range = 70 ksi.</td>
<td>55</td>
</tr>
<tr>
<td>4-15</td>
<td>Fatigue Crack Initiation vs. Deepest Scratch Stress Range = 65 ksi.</td>
<td>56</td>
</tr>
<tr>
<td>4-16</td>
<td>Fatigue Crack Initiation vs. Deepest Scratch Stress Range = 45 ksi.</td>
<td>57</td>
</tr>
<tr>
<td>4-17</td>
<td>Fatigue Crack Initiation vs. Deepest Scratch x Curvature Stress Range = 80 ksi</td>
<td>58</td>
</tr>
<tr>
<td>4-18</td>
<td>Fatigue Crack Initiation vs. Deepest Scratch x Curvature Stress Range = 70 ksi</td>
<td>59</td>
</tr>
<tr>
<td>4-19</td>
<td>Fatigue Crack Initiation vs. Deepest Scratch x Curvature Stress Range = 65 ksi</td>
<td>60</td>
</tr>
<tr>
<td>4-20</td>
<td>Fatigue Crack Initiation vs. Deepest Scratch x Curvature Stress Range = 45 ksi</td>
<td>61</td>
</tr>
<tr>
<td>4-21</td>
<td>Fatigue Life (Failure) Single Scratch Data S-N Curves</td>
<td>67</td>
</tr>
<tr>
<td>4-22</td>
<td>Fatigue Life (Initiation) Single Scratch Data S-N Curves.</td>
<td>68</td>
</tr>
<tr>
<td>4-23</td>
<td>Determination of Single Scratch Coefficients</td>
<td>69</td>
</tr>
<tr>
<td>4-24</td>
<td>Single Scratch Coefficients for Initiation</td>
<td>70</td>
</tr>
<tr>
<td>4-25</td>
<td>Single Scratch Failure Spectra</td>
<td>71</td>
</tr>
<tr>
<td>4-26</td>
<td>Single Scratch Initiation Spectra</td>
<td>72</td>
</tr>
<tr>
<td>4-27</td>
<td>Fatigue Life (Failure), Mannesmann Specimens, Predicted Life from Single Scratch Spectra</td>
<td>73</td>
</tr>
<tr>
<td>4-27A</td>
<td>Mannesmann Riser Pipe (Initiation), S-N Curve</td>
<td>74</td>
</tr>
<tr>
<td>4-28</td>
<td>Fatigue Life (Failure), Ground 24 Grit, Predicted Life from Single Scratch Spectra</td>
<td>75</td>
</tr>
<tr>
<td>4-28A</td>
<td>Ground 24 Grit (Initiation), S-N Curve</td>
<td>76</td>
</tr>
<tr>
<td>5-1</td>
<td>Cumulative Distribution of Specimen SNF62 (Filtered) in Comparison with a Gaussian Distribution</td>
<td>87</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>5-2</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Ls = 2 Inches, Ground Specimens.</td>
<td>93</td>
</tr>
<tr>
<td>5-3</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Ls = 2 Inches, Mannesmann Specimens.</td>
<td>94</td>
</tr>
<tr>
<td>5-4</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Ls = 40 ft., Mannesmann Specimens.</td>
<td>95</td>
</tr>
<tr>
<td>5-5</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Ls = 40 ft., Ground Specimens.</td>
<td>96</td>
</tr>
<tr>
<td>5-6</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Ls = 1000 ft., Mannesmann Specimens</td>
<td>97</td>
</tr>
<tr>
<td>5-7</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Ls = 1000 ft., Ground Specimens.</td>
<td>98</td>
</tr>
<tr>
<td>5-8</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Using Method of Moments, Ls = 2 Inches, Mannesmann Specimens.</td>
<td>101</td>
</tr>
<tr>
<td>5-9</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Using Method of Moments, Ls = 2 Inches, Ground Specimens.</td>
<td>102</td>
</tr>
<tr>
<td>5-10</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Using Method of Moments, Ls = 40 ft., Mannesmann Specimens.</td>
<td>103</td>
</tr>
<tr>
<td>5-11</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Using Method of Moments, Ls = 40 ft., Ground Specimens.</td>
<td>104</td>
</tr>
<tr>
<td>5-12</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Using Method of Moments, Ls = 1000 ft., Mannesmann Specimens.</td>
<td>105</td>
</tr>
<tr>
<td>5-13</td>
<td>Predicted Life from Single Scratch Spectra Using First Passage Criteria, Using Method of Moments, Ls = 1000 ft., Ground Specimens.</td>
<td>106</td>
</tr>
</tbody>
</table>
CHAPTER I
INTRODUCTION

Surface finish or roughness has been recognized as being important in various engineering problems [1]. In particular, surface finish is known to have a considerable influence on fatigue life [1,2]. A geometrical description of surface roughness would be useful in attempting to correlate the physical geometry of surfaces with the measured surface properties (Chapter II). It is well established that fatigue cracks, in most cases, initiate at the surface grains. The quality of this surface would then have an effect on its fatigue life.

In Chapter IV of this study, two surface roughness parameters were studied in relation to fatigue crack initiation. The parameters chosen were either height descriptors such as depth, or texture descriptors, such as curvature. These properties or parameters of the measured surfaces were then correlated with fatigue life initiation of the specimens they were measured from. It turns out that the height descriptors or texture descriptors, on their own, would not make good candidates for a good correlation; whereas, a combination of both descriptors showed a promising avenue. The product of the deepest scratch with the root mean square valley curvature (sharpness) of the measured surfaces showed a considerable degree of correlation with fatigue initiation at the different stress ranges. This combination of depth and "sharpness" was then chosen to be the surface roughness parameter with which the functional relations between fatigue initiation and surface finish were established.
A number of specimens were prepared having a single scratch that varied in depth from 0.004 inches to 0.02 inches. These scratches had a fixed radius of curvature, of approximately 0.003 inches (Chapter III). The specimens were then fatigued and the corresponding S-N curves were obtained. These S-N curves were then combined into one spectrum which was used as a basis of prediction in this study.

Two other groups of specimens were prepared. These specimens had ground surfaces which exhibited different surface characteristics. The surfaces of these specimens were traced and the values of the deepest scratch and "sharpness" were obtained from the measured surfaces of every specimen. The specimens were then fatigued and the respective initiation life and number of cycles to failure were recorded. The products of the deepest scratch and curvature, for every specimen, were used to predict the specimens initiation and failure life from the single scratch spectra. The predicted results from the single scratch spectra were within the 95% confidence bands of the S-N curves generated from fatiguing the specimens. In other words, by knowing the deepest scratch and "sharpness" of a measured surface, fatigue life could be predicted by utilizing the single scratch spectra.

In the second phase of the study, Chapter V, the object was to be able to predict the deepest scratch in longer sampling lengths, based on the information available from the 2 inch sampling lengths of the specimens. The assumption made was that the surface irregularities had a Gaussian distribution. This assumption was then justified, by two methods, for the measured surfaces. First-passage criteria were used to predict the deepest scratch in sampling lengths
of 40 feet and 1000 feet. The product of depth and "sharpness" was used again to predict fatigue life from the single scratch spectra. The results also fell in the 95% confidence bands of the S-N curves of the tested specimens. The predicted cycles were lower than the actual cycles to failure in most of the cases.

The product of the deepest scratch and curvature was established as a characteristic of surface roughness that can be utilized to predict fatigue failure.
CHAPTER II

BACKGROUND

This chapter will serve as a brief review of the concepts utilized in the study of fatigue crack initiation in relation to surface finish parameters. Section 2.1 describes and defines the types of surface finish descriptors and how surface profiles are characterized. Section 2.2 deals with the measurement techniques of such profiles. The use of data filtering is discussed in Section 2.3. In Section 2.4 the statistical properties that are fundamental and essential to this study are reviewed. Finally, Section 2.5 addresses the preliminary concepts in structural fatigue.

2.1 CHARACTERIZATION OF SURFACE PROFILES

A surface by definition is the boundary that separates an object from its surroundings. The shape of an object or what is usually represented on a drawing is referred to as the nominal surface; moreover, a measured surface is the surface representation obtained by a surface measuring instrument. The shape of a specified section through the surface is what we call a profile and the average distance between the irregularities on the surface profile is called the spacing. Surface texture is those irregularities that tend to form a pattern on the surface. Surface texture has two components; namely, roughness, sometimes referred to as the primary texture, and waviness, or the secondary texture. The primary texture is the high frequency component of surface texture which results from the manufacturing process. It is important to note that the "roughness" of a surface encompasses both the size and shape of irregularities. Waviness, on the other
hand, is the low frequency component of surface texture. Waviness usually results from inconsistencies in machining or grinding [6].

It has been established that no list of roughness parameters can be exhaustive, but references to a reasonably comprehensive list can be found [4]. Whitehouse and Archand [7] showed that the statistical geometry of many profiles can be represented by only two parameters namely, the root mean square and the correlation length (defined in Section 2.4). It was later shown by Nayak [8], that this two parameter representation was a special case where the measured surface could be adequately represented by the first three even moments of the power spectrum of the surface profile. This was also confirmed experimentally by Sayles [9]. Unfortunately, it turns out that none of these parameters is a property of the real surface [10]. Surface roughness parameters are divided into three categories; height descriptors, which give an average value of the behavior of a profile in a plane normal to the surface; extreme value height descriptors, these depend on isolated critical events; and texture descriptors, which describe the variation of the profile in a horizontal plane. All height descriptors such as CLA, $\sigma_1$...etc. (defined later in this section) depend on the high pass filter cut-off and for many surfaces their values increase as the square root of the cut-off [11]. The height descriptor considered in this study is $\sigma_1$ the (standard deviation). Moreover, extreme-value height descriptors, such as $R_{\text{max}}$ (maximum peak to valley height) and $V_D$ (deepest valley), depend on the sampling length. For example, if the sampling length is decreased, the likelihood of missing a maximum or minimum increases and hence
could change the value of both \( R_{\text{max}} \) and \( V_D \). Most texture parameters such as slope and curvature, on the other hand, depend on the low pass cut-off. It can be shown that for many surfaces the mean slope decreases as the square root of the sampling length, while the mean peak radius of curvature increases as the 3/2 power [11]. The texture descriptors considered in this study are, \( \lambda_{\text{rms}} \) (root mean square wavelength), \( \sigma_2 \) (root mean square slope) and \( \sigma_3 \) (root mean square curvature). It must not be overlooked that roughness parameters, being imperfect statistical representations of surfaces that are man made, are more conducive than many other physical measurements to scatter. It is unreasonable to argue differences of one or two percent when sampling error can amount to 20\%-50\% [12].

In general, a surface profile is described mathematically by a Fourier series [13].

\[
F(x) = \frac{A_0}{2} + \sum_{k=1}^{N-1} \left( A_k \cos \frac{2\pi k x}{L} + B_k \sin \frac{2\pi k x}{L} \right) + A_N \cos \frac{2\pi N x}{L} \quad (2-1)
\]

where \( A_0, A_k, B_k, (k = 1, 2, \ldots, N-1) \) and \( A_N \) are the Fourier coefficients. The Fourier coefficients are given by:

\[
A_0 = \frac{2}{L} \int_0^L F(x) \, dx \quad (2-2)
\]

\[
A_k = \frac{2}{L} \int_0^L F(x) \cos \frac{2\pi k x}{L} \, dx \quad (2-3)
\]

\[
B_k = \frac{2}{L} \int_0^L F(x) \sin \frac{2\pi k x}{L} \, dx \quad (2-4)
\]

\[
A_N = \frac{2}{L} \int_0^L F(x) \cos \frac{2\pi N x}{L} \, dx \quad (2-5)
\]
The surface roughness parameters of interest in this study are defined as follows:

The average depth of surface irregularities, sometimes referred to as the Center Line Average (CLA), is

\[ \text{CLA} = \frac{1}{L} \int_{0}^{L} |F(x)| \, dx \]  \hspace{1cm} (2-6)

The root-mean-square for the profile is

\[ \sigma_1 = \frac{\frac{1}{L} \int_{0}^{L} [F(x)]^2 \, dx}{\int_{0}^{L} [F'(x)]^2 \, dx} \] \hspace{1cm} (2-7)

The average wavelength [14] is

\[ \lambda_{av} = 2\pi \frac{\int_{0}^{L} |F(x)| \, dx}{\int_{0}^{L} |F'(x)| \, dx} \] \hspace{1cm} (2-8)

and the rms wavelength is

\[ \lambda_{rms} = 2\pi \frac{\left( \frac{1}{L} \int_{0}^{L} [F(x)]^2 \, dx \right)^{1/2}}{\left( \int_{0}^{L} [F'(x)]^2 \, dx \right)^{1/2}} \] \hspace{1cm} (2-9)

from equations (2-7) and (2-9) it follows that

\[ \sigma_2 = \frac{1}{L} \int_{0}^{L} [F'(x)]^2 \, dx \] \hspace{1cm} (2-10)

or

\[ \sigma_2 = 2\pi \frac{\sigma_1}{\lambda_{rms}} \] \hspace{1cm} (2-11)

where \( \sigma_2 \) is the rms of the first derivative of the measured surface.

Another useful geometrical parameter that indicates the sharpness or degree of curvature of the "peaks" and "valleys" is \( \sigma_3 \), the rms
of the second derivative of the profile defined by

$$\sigma_3 = \left( \frac{1}{L} \int_0^L [F''(x)]^2 \, dx \right)^{1/2}$$  \hspace{1cm} (2-12)

It turns out that a combination of surface roughness parameters, $\sigma_1$, $\sigma_2$, $\sigma_3$ and $V_D$, is of importance to the scope of this study.

2.2 SURFACE PROFILES AND THEIR MEASUREMENT

In this study surface texture is measured along a cross-section normal to the direction of the predominant surface pattern; which results from the production process. Since the irregularities of the surface profile are minute in depth, it is necessary to have graphical representations of them shown with a considerable degree of magnification for the vertical and horizontal scales. In this study, graphical representation of the surfaces are presented with a magnification of approximately one thousand times for the vertical scale and four times for the horizontal scale. Basically, the measurement of surface texture is a problem in three dimensional geometry [15]. In practice, it is reduced to a problem in two dimensional geometry by confining measurement of the profiles to plane sections taken through the surface. The combined effect of roughness and waviness will then constitute the surface texture. To maximize the contribution of roughness and minimize the contribution of waviness; it is necessary to define an appropriate sampling length; referred to in practice as the meter cut-off. In particular, a study at Rice [3] showed the need of using a sampling length longer than 0.0625 inches in order to obtain better representation of the measured surface. A sampling length of this size was not enough to make any distinction
between waviness and mere bias in the profile datum. A more recent study [5] indicates that a sampling length of 0.4 inches is sufficient to make that distinction. A total of 2650 equally spaced digitized data points were used and a good representation of both the nominal and measured surfaces was achieved. In this study a sampling length of 2 inches is used and 14,000 data points define the surface profile. This choice is based on the experimental need to have specimens of a reasonable size to fit the fatigue testing criteria where the section of the specimens under pure bending is 3 inches long. These sections are traced by a "Talysurf" surface measuring instrument manufactured by Taylor-Hobson. The "Talysurf" makes use of a sharply pointed diamond stylus with a $5 \times 10^{-5}$ inch tip radius and stylus force of 0.1 grams. The pick-up carrying the stylus and skid, is traversed across the surface by means of a motorized drive unit. The up and down movements of the stylus are converted into changes in electric voltage by the use of an inductive transducer. These voltage changes are amplified and an HP9000 model 236 computer with an A to D board is utilized to store this transducer output. The surface irregularities of a typical diamond-turned surface, having a CLA of 36 micro-inches, is traced to check the calibration of the "Talysurf". The transducer output is matched and a conversion factor shows an equivalent of 535 micro-inches for every one volt measured. The "Talysurf" is limited to a sampling length of 0.4 inches. To achieve a sampling length of 2 inches, a motor and gear mechanism was used to drive the specimen at a constant speed underneath the pick-up which was kept stationary.

There are two limitations on the response acquired by the stylus
and skid. The stylus, no matter how small in radius can not have a mathematically sharp point. The profile of a stylus having a rounded tip is shown in figure (2-1). If the valley in the profile is deep enough, the stylus can not reach the bottom. The full depth of the groove is reduced by an amount "b" and the measured surface is smoothed out over the sharp corners. Other than the reduction in the total depth, this shortcoming is practically unnoticeable when looking at the nominal surface, with the horizontal scale compressed relative to the vertical scale. This reduction in depth and sharpness may be fully offset in an "average" reading. The loss in the valley may be compensated by the gain resulting from the rounding of a peak. On the other hand, this error becomes more important and noticeable, in the measured surface, when the spacing between irregularities is much smaller than the deep valleys. Fortunately in this study, the spacing between irregularities is in the order of 20,000 micro-inches and the valleys considered range from 800 micro-inches in the case of the 24 grit ground specimens to 4000 micro-inches for the specimens from the Mannesmann pipe (Section 3.1). To offset some of these measurement problems, the following measures are taken. When it comes to curvature, instead of using the curvature of the deepest scratch as a measure of sharpness, which could be misleading, the use of an average curvature is more appropriate. Hence the rms valley curvature is chosen to represent the measure of sharpness in the profile. To compensate for the loss in depth, the cumulative distribution of peaks is obtained and a new datum, other than the center line, is used as a reference. This datum would be exceeded by approximately 5 percent
Relationship of stylus point to the actual profile of the surface

Behaviour of the stylus when traversing ridges and grooves

FIGURE 2-1 - Profile of a Rounded Tip Stylus
of the peaks. This practice is more reasonable than using the range (the distance between the highest peak and the lowest valley) as a measure since there would be some surface extrusions that need to be accounted for.

2.3 THE FILTERING PROCESS

To remove the undesired bias and waviness in the nominal and measured surface, digital filtering of the data is mandatory. The effect of filtering is very clear in figures (2-2 and 2-3). The nominal surface (shape) of the surface profile looks totally different and the measured surface exhibits different statistical properties. A filter period of five times the average wavelength is used. This translates to filter periods ranging from three to five percent of the sampling length, which seems reasonable when compared with the spacing between irregularities. The filtered outputs were used to make the adjustments discussed in Sec. 2.2 on the measured surfaces.

A low-pass filter is a device that passes signals of low frequencies and rejects those of high frequencies. The frequencies that pass constitute the passbands and those that are rejected make up the stopbands of the filter. The performance of a filter may be measured by its amplitude response "|H(T)|" versus the period "T". H(T) is the ratio of the filter output amplitude to input amplitude (A/A₀) when both input and output are harmonic terms with period "T₀". There are a number of types of low pass filters; one of the most commonly used is the Butterworth type. By definition, a filter that approximates the ideal low pass with a so-called maximally flat passband characteristic is the 5th order Butterworth filter [16]. Its amplitude
FIGURE 2-2 Measured Surface Characteristics of a Ground Specimen G3521

PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 376 microinches
STANDARD DEVIATION (rms) = 493 microinches
SKEWNESS = .088
KURTOSIS = 3.742
NUMBER OF ZERO CROSSINGS = 451
TOTAL NUMBER OF PEAKS & VALLEYS = 2309
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1414
BAND WIDTH PARAMETER (ALPHA) = .195
THE FREQUENCY OF POSITIVE PEAKS = .612
THE RMS SLOPE = .3317
THE AVERAGE WAVE LENGTH = .00991 inches
THE RMS WAVE LENGTH = .00934 inches
THE RMS CURVATURE = .001286 1/inches
THE RMS VALLEY CURVATURE = .001334 1/inches
THE MINIMUM VALLEY CURVATURE = -0.011450 1/inches or .059 inches
THE CURVATURE OF DEEPEST SCRATCH = .000766 1/inches or 1.389 inches
THE RANGE = 3692 microinches
THE DEEPEST VALLEY = -1712 microinches
THE MAXIMUM PEAK = 1980 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 6.310 x 1.399 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = .822
THIRD MOMENT M3 = 1.975
FIFTH MOMENT M5 = 10.317
SEVENTH MOMENT M7 = 76.703
NINTH MOMENT M9 = 703.956
FIG. 2-3 Filtered Measured Surface Characteristics of a Ground Specimen GF2521

PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 139 microinches
STANDARD DEVIATION (rms) = 179 microinches
SKEWNESS = -.177
KURTOSIS = 3.729
NUMBER OF ZERO CROSSINGS = 1262
TOTAL NUMBER OF PEAKS & VALLEYS = 2583
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1874
BAND WIDTH PARAMETER (ALPHA) = .488
THE FREQUENCY OF POSITIVE PEAKS = .725
THE RMS SLOPE = .3311
THE AVERAGE WAVE LENGTH = .00365 inches
THE RMS WAVE LENGTH = .0034 inches
THE RMS CURVATURE = 1286 1/inches
THE RMS VALLEY CURVATURE = 1246 1/inches
THE MINIMUM VALLEY CURVATURE = -11449 1/inches @ .059 inches
THE CURVATURE OF DEEPEST SCRATCH = 361 1/inches @ 1.169 inches
THE RANGE = 1577 microinches
THE DEEPEST VALLEY = -787 microinches
THE MAXIMUM PEAK = 789 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = .752 @ 1.168 inches

AVERAGE OF PEAK MOMENTS USING POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .951
THIRD MOMENT M3 = 2.682
FIFTH MOMENT M5 = 16.553
SEVENTH MOMENT M7 = 163.398
NINTH MOMENT M9 = 2118.137
response is given by:

\[
|H(T)| = \frac{G}{1 + (T/T_c)^{2n}} \quad n = 1, 2, 3, \ldots
\]

(2-13)

where \( n \) is the order of the filter, and \( T_c \) is the period at which \(|H(T)|\) is 1/2 times its maximum value \( G \). As \( n \) increases the response more nearly approximates the ideal case.

The maximum value of the amplitude \(|H(T)|\) of the filters transfer function \( H(T) \) is unity, and the order of the filter is a fifth order. The filter is applied twice (i.e., forward and backward) to balance the phase and to achieve symmetry. To measure the performance of the filter, sine waves of the form shown below in equation (2-14) are filtered by varying \( T_0 \). The resulting amplitude response is plotted against the output periods \( T \).

\[
Q(I) = \sin (2\pi * T_0 * I/14000); I = 1, 2, 3, \ldots 14000
\]

(2-14)

Filtering will eliminate some of the waviness and error of form present in the surface profiles; hence giving a better understanding of the true roughness of the surface.

The response obtained from the digital filters at selected points using equation (2-14) is shown in figure (2-4) along with the response given by equation (2-13). As can be seen, the responses match very well.

2.4 STATISTICAL PROPERTIES

The statistical parameters of the measured surface, such as the mean and standard deviation can be found in any standard text in statistics [17]. Other statistical parameters are:
Figure 2-4 CHARACTERISTICS OF FIVE POLE BUTTERWORTH FILTER

- Stopband
- Passband

\( \frac{I}{I_0} \) vs. \( \frac{R}{R_0} \)
Kurtosis, a measure of the sharpness of the Probability Density Function (PDF), can be utilized to quantitatively describe the randomness of a profile's shape relative to that of a perfectly Gaussian random surface which has a kurtosis of 3. A PDF with a kurtosis value greater than 3 is considered to be sharp. Figure (2-5) shows some surface profiles with the corresponding PDF's and kurtosis values. Kurtosis is defined as:

\[ \text{Kurtosis} = \frac{1}{\sigma_1^4} \frac{1}{N_1} \sum_{i=1}^{N_1} Y_i^4 \]  \hspace{1cm} (2-14)

where \( Y_i \) = the profile ordinates

\( N_1 \) = the number of ordinates chosen in a profile record length

\( \sigma_1 \) = the root mean square

Skewness, on the other hand, is a measure of symmetry of the profile about the centerline. Negative skewness values indicate that the profile is shifted more to the negative side of the centerline. A zero skewness would mean that the profile is symmetric about the centerline. Skewness would be a good indicator of the effectiveness of filtering when it comes to the error of form or bias in the nominal surface.

\[ \text{Skewness} = \frac{1}{\sigma_1^3} \frac{1}{N_1} \sum_{i=1}^{N_1} Y_i^3 \]  \hspace{1cm} (2-15)

Assume that the surface form \( x(\xi) \) is an ergodic process with zero mean. A random process is said to be ergodic if its statistical averages from any sample are the same as the statistical ensemble averages, where an ensemble is the collection of all possible samples in the process. Often it is assumed that \( x(\xi) \) is a normal Gaussian
FIG. 2-5 Kurtosis Variations
process; this assumption prescribes a certain form for the PDF and simplifies a lot of the statistical parameters. Some of the resulting expressions which are particularly pertinent to our problem are listed hereunder. The rate at which \( x(\xi) \) crosses its constant mean value (with positive slope) \([18]\) is

\[
\nu_0^+ = \frac{1}{2\pi} \frac{\sigma_2}{\sigma_1}
\]  

(2-16)

The rate of occurrence of peaks (local maxima) of \( x(\xi) \) is

\[
\eta_P = \frac{1}{2\pi} \frac{\sigma_3}{\sigma_2}
\]  

(2-17)

The irregularity factor \([19]\), which is defined as \( \frac{\nu_0^+}{\eta_P} \) then becomes

\[
\alpha = \frac{\sigma_2}{\sigma_1 \sigma_3}
\]  

(2-18)

The factor \( \alpha \) can be shown to be a measure of the extent to which \( x(\xi) \) is dominated by a small band of frequency components. Hence \( \alpha \) is also referred to as a band width parameter. A process \( x(\xi) \) is said to be a narrow band process; when \( \alpha \) approaches unity. When \( \alpha \) approaches zero the process \( x(\xi) \) becomes a broad band process.

The spectral width parameter \( \varepsilon \) is

\[
\varepsilon = \sqrt{1 - \alpha^2}
\]  

(2-19)

S.O. Rice derived an expression for the distribution of peaks in a normal Gaussian process \([17]\)

\[
F_p(U) = \frac{1}{2} \text{erfc} \left( \frac{-u}{\sqrt{2\varepsilon \sigma_1}} \right) - \frac{\alpha}{2} \exp\left( \frac{-u^2}{2\sigma_1^2} \right) \text{erfc} \left( \frac{-\alpha u}{\sqrt{2\varepsilon \sigma_1}} \right)
\]  

(2-20)
where \( \text{erfc} \) denotes the complementary error function and

\[
\text{erfc}(u) = \frac{2}{\sqrt{\pi}} \int_u^\infty \exp(-\mu^2) \, d\mu \quad (2-21)
\]

and

\[
\text{erfc}(-u) = 2 - \text{erfc}(u) \quad (2-22)
\]

\( F_p(U) \) is the fraction of all peaks which have a value less than \( u \). The cumulative distribution \( F_p(U) \) includes negative as well as positive peaks. The fraction of positive peaks which are less than \( u \) is:

\[
F_p^+(U) = \frac{1}{1+\alpha} \left[ \text{erfc}(-\frac{u}{\sqrt{2\sigma_1}}) - \alpha \exp(-\frac{u^2}{2\sigma_1^2}) \text{erfc}(-\frac{\alpha u}{\sqrt{2\sigma_1}}) + \alpha - 1 \right] \quad (2-23)
\]

note that when \( \alpha \) tends to unity the peak distribution \( F_p(U) \) tends to the well known Rayleigh distribution

\[
F_p(U) = 1 - \exp(-\frac{u^2}{2\sigma_1^2}) \quad (2-24)
\]

The fraction of peaks which are positive is \( \frac{1+\alpha}{2} \) and the rate of occurrence of positive peaks is:

\[
\eta_p^+ = \frac{1+\alpha}{2} \eta_p \quad \text{(positive peaks/unit displacement)} \quad (2-24)
\]

or

\[
\eta_p^+ = \frac{1+\alpha}{4\pi} \frac{\sigma_3}{\sigma_2} \quad (2-25)
\]

The integral for the average value (expected value) of the mth power of a peak is
\[ I(m, \alpha) = \int_0^\infty u^m \frac{dF^+}{du} \]  \hspace{1cm} (2-26)

It is numerically evaluated for \( F^+_p(U) \) given by equation (2-23) with \( \alpha \) ranging from 0 to 1 and \( m = 1, 3, 5, 7, 9 \). As noted previously when \( \alpha = 1 \), equation (2-24) and (2-26) yield

\[ I(m, 1) = (2)^{m/2} \sigma_1^m \Gamma(1 + \frac{m}{2}) \]  \hspace{1cm} (2-27)

where \( \Gamma \) is the Gamma function which gives a recursive relationship of

\[ I(m+2, 1) = (m+2)\sigma_1^2 I(m, 1) \]  \hspace{1cm} (2-28)

In the other limiting situation where \( \alpha = 0 \), the peak distribution gives a one-sided normal form

\[ \frac{dF_p}{du} = \sqrt{\frac{2}{\pi}} \frac{\exp(-u^2/2\sigma_1^2)}{\sigma_1} \]  \hspace{1cm} (2-29)

using equations (2-29) and (2-26)

\[ I(m, 0) = \frac{2^{m/2}}{\sqrt{\pi}} \sigma_1^m \Gamma(1 + \frac{m}{2}) \]  \hspace{1cm} (2-30)

equations (2-27) and (2-30) will be used to calculate the average \( m \)th power of a peak. Those moments will be compared to the average peak moments for the surface form \( x(\xi) \). These moments are

\[ m_i = \frac{1}{n_p} \sum \frac{A_i}{\sigma_1^i} i = 1, 3, 5, 7, 9 \]  \hspace{1cm} (2-31)

where \( A = \) the peak amplitude in \( x(\xi) \).
Since S.O. Rice assumed a Gaussian process in his derivation for the expression of peak distribution, it would be reasonable to conclude that, if the average of peak moments, from equations (2-27), (2-30) and (2-31) match, then \( x(\xi) \) would be a Gaussian process. Moreover, the cumulative distribution of peaks for \( x(\xi) \) will be also compared with \( F_p(u) \). Finally the kurtosis values for \( x(\xi) \) will be compared to those of a Gaussian process and if the kurtosis of \( x(\xi) \) is close to 3 then one can draw the same conclusion.

2.5 PRELIMINARY CONCEPTS IN FATIGUE

Fatigue life predictions are generally based on a known or assumed S-N curve for the specimens where \( S \) denotes a constant cyclic stress range, and \( N \) denotes the number of cycles to failure. Empirical data of this type can be approximated usually by the following relationship [26].

\[
N = KS^{-m}
\]

(2-32)

where \( K \) and \( m \) are constants. Many materials give results which differ significantly from equation (2-32). Moreover, equation (2-32) ignores the existence of any fatigue limit (endurance limit) which would give a minimum range to cause damage. Non-ferrous materials generally do not exhibit an endurance limit.

Since surface roughness affects only fatigue initiation \( N_i \), it would be meaningful to obtain a correlation between the measured surface roughness parameters and \( N_i \). When the strain range is held constant and only the surface roughness parameter is varied in fatigue tests, the relation between \( N_i \) and the geometrical parameter (which enhances
the strain at the crack tip) is assumed to be of the following form [28]:

\[ N_i = A (\text{surface roughness parameter})^{-\alpha} \quad (2-33) \]

where \( A \) and \( \alpha \) are constants.

Equation (2-33) is based on the Coffin-Manson relation for crack initiation [28,29]:

\[ N_i = A(\Delta \varepsilon_p)^{-\alpha} \quad (2-34) \]

where \( \Delta \varepsilon_p \) is the plastic strain range. When \( \Delta \varepsilon_p \) is held constant and only surface roughness increases, the effect of surface roughness may be considered to enhance the strain concentration at the crack tip [27], which depends on the surface roughness characteristics, as in equation (2-33). Based on the correlation factor of linear regression for limited data, the surface roughness parameters which correlate most with \( N_i \) will be the basis of our study to establish the functional relationships between surface roughness parameters and fatigue crack initiation.
CHAPTER III

EXPERIMENTAL PROCEDURE

This chapter describes the experimental program (i.e., specimens, set-up and test procedures). Section 3.1 gives a background on the specimens used in the fatigue study. In Section 3.2 the test set-up and procedure are discussed.

3.1 TEST SPECIMENS

All the specimens tested were taken from one piece of 18 inch riser pipe manufactured by Mannesmann. These specimens were made from FG57T Grade K80 steel. The specimens were nominally 1 inch wide by 5/8 inch thick by 10 inches long, see figure (3-1). The lengths of the specimens were oriented in the longitudinal direction of the riser pipe. A reduced section 3/4 inches wide was milled in the central portion. Standard 0.505" tension specimens were tested to determine the yield stress and ultimate stress. The yield stress and ultimate stress were determined to be 101 ksi and 112 ksi respectively, figure (3-2).

A total of 42 specimens were prepared. The surfaces and characteristics of these specimens were as follows:

(1) Fifteen specimens had the surface characteristics of the Mannesmann riser pipe.

(2) Twenty-one specimens were polished and had single scratches at mid-span of the section in bending. These single scratches were prepared using a sharp cutter and were traced by the "Talysurf" after preparation to ensure accuracy. The depths of the prepared single scratch specimens were 0.004, 0.006, 0.010, 0.015 and 0.020 inches.
The measured surfaces of these specimens were in agreement with the preparation procedure up to a depth of 0.06 inches, see figure (3-3). Due to the limitations of the "Talysurf" discussed in Chapter 3, the measured depths of scratches greater than 0.06 inches were less than the anticipated values. However, based on the preparation technique used, it was assumed that the deeper scratches had the desired values. A microscopic examination of a sample with various scratch depths verified that the desired depths were achieved in the sample. Moreover, this examination showed that the scratches had a radius of curvature on the average of 0.003 inches.

It was intended in the scope of the study to vary the depths of the scratches while maintaining a constant radius of curvature at the tip of the scratch.

(3) The last six specimens were polished and ground with a 24 grit surface. All specimens were fatigued under different stress ranges and their respective S-N curves were obtained.

3.2 THE TEST SET-UP

The specimens were loaded in a test fixture providing four point beam loading with the overall span being 9 inches and with a pure moment span of 3 inches. One inch diameter hardened steel rollers were used to transmit loads to the specimens. The test fixture is shown in figure (3-4). This test fixture was used in an MTS 22 kip load frame with servo-hydraulic loop control. All specimens were tested in the load control mode with constant amplitude. The control signal was sinusoidal and was generated using an HP 9000 model 236 computer with an HP 59501B digital to analog power supply. All of
Figure 3-2 Stress-Strain Diagram for Mannesmann FG57T Steel Riser Pipe

Yield Stress = 101 ksi
Ultimate Stress = 112 ksi
Elastic Modulus = 28,400 ksi
FIGURE 3-3 Measured Surface Characteristics of Various Single Scratch Specimens
Figure 3-4 Test Fixture
the tests were run with an R ratio of 0.1, the HP computer was also used to monitor the tests using an analog to digital board, as an aid for detecting crack initiation. The static stiffness of the specimens was checked periodically. At predetermined intervals of cycles, the sinusoidal loading was stopped, static loads equal to the minimum load and 90% of the maximum were applied, and the corresponding deflections were measured and recorded. Since it was important to achieve rather precise measurements, the control signal for the static loads was adjusted on the basis of the average of ten samples of the feedback signal until the average was within a desired fraction of the load. Ten samples were taken of the deflection feedback signal and averaged before continuing the sinusoided testing. Tests were terminated when the deflection exceeded four times the deflection at the start of a test. The change in the average of the static deflections was monitored, and initiation was established on that basis. The test accuracy of an MTS load cell is typically better than 0.1% of the full scale load range. For the tests conducted, the range used was 4 kips and hence, the accuracy of the load measurement was \( \pm 4 \text{ lbs} \). The corresponding accuracy of the nominal stresses was 0.1 ksi. The computer program and a typical output can be found in the Appendix.
CHAPTER IV
EXPERIMENTAL RESULTS
AND ANALYTICAL PREDICTIONS

All the experimental results are presented in this chapter. Section 4.1 is an analysis of the measured surfaces; namely, the Mannesmann pipe specimens and the Ground (24 grit) specimens. In Section 4.2, the results of all the fatigue tests are presented and analyzed. A correlation is established in Section 4.3 between surface finish parameters and fatigue initiation. Section 4.4 deals with the analytical predictions arising from the test results.

4.1 ANALYSIS OF THE MEASURED SURFACES

The surfaces of the Mannesmann pipe specimens and the ground (24 grit) specimens were traced by the "Talysurf". The surface profiles for these specimens can be found in Appendix A. The resulting measured surfaces were manipulated to obtain the statistical parameters, see Tables (4-1) and (4-3). The height descriptors, such as the CLA and $\sigma_1$, did not show a consistent behavior. They were doubled at times from one sample to another. The extreme height descriptors such as $V_D$ and $R_{max}$ also varied in the same fashion; on the other hand the texture descriptors $\sigma_2$ and $\sigma_3$ seemed to be consistent. To minimize this inconsistency in the height descriptors, the measured surfaces were filtered at a filter period equal to five times the average wave length (Section 2-3), the outcome did not only affect the nominal surface (shape) as shown in figures (2-2 and 2-3), it also affected most of the parameters in the measured surface, see Tables (4-2) and (4-4). The extreme height descriptor $R_{max}$ was reduced from 8126 micro-
inches to 4770 microinches for sample SN61, and the deepest scratch \( V_D \) was also reduced from 4546 microinches to 2819 microinches. The value of \( \sigma_1 \) dropped from 1790 microinches to 645 microinches. These changes were due to the elimination of some of the waviness and error of form. Moreover, the filtering did not affect the average of the texture descriptors \( \sigma_2 \) and \( \sigma_3 \). Since we are more interested in valleys than peaks, the rms valley curvature (\( \sigma_3^* \)), see Sec. (2-2), would be our choice to represent the texture descriptors. The deepest scratch \( V_D \) would be the parameter of interest from the extreme height descriptors.

The cumulative distribution of peaks for all measured surfaces was obtained and a new datum, other than the centerline, was used as reference. This datum would be exceeded by approximately five percent of the peaks; a typical output of that cumulative distribution of peaks for SNF3 is shown in figure (4-1). A line at 1.5 standard deviations or 563 microinches, Table (4-2), would be exceeded by approximately five percent of the peaks. This adjustment was necessary to ensure that the full depth of a valley was accounted for. These adjustments for \( V_D (V_D^*) \) are shown in tables (4-2 and 4-4). Therefore, the surface roughness parameters of choice would be \( V_D^* \) and \( \sigma_3^* \). Typical surface traces (filtered and unfiltered) and their statistical properties are presented in figures (4-2 through 4-4), the profiles of the other surfaces can be found in the Appendix.

4.2 FATIGUE TEST RESULTS

Constant amplitude fatigue tests were run at different load levels to determine the basic S-N curves for the Mannesmann pipe specimens,
ground (24 grit) specimens and the single scratch specimens. The load ranges in kips were (2.8 - 0.28), (2.5 - 0.25), (1.7 - 0.17) and (1.2 - 0.12) for the Mannesmann pipe specimens. The ground (24 grit) specimens had load ranges from (2.8 - 0.28), (2.5 - 0.25), (2.2 - 0.22). The load ranges for the single scratch specimens varied from 2.5 kips on the high side to 1.4 kips on the low side. A linear regression analysis resulted in the expressions for the S-N curves shown in Table (4-5). Tables (4-6), (4-7), and (4-8) show the different test specimens and their cycles to initiation and failure. Moreover, the S-N curves for the Mannesmann, ground, and single scratch specimens are presented in figures (4-6 through 4-12). In table (4-5), the ground specimens showed a lower coefficient of linear correlation when compared with the other specimens. Furthermore, from the 97\% confidence line factor (2.7) one can conclude that the data were not well grouped. On the other hand, the single scratch specimens and the Mannesmann pipe specimens had larger coefficients of linear correlation and narrower 95\% confidence bands; therefore, better grouping. One should also notice the trend in the indicies of the S-N relationships. The Mannesmann specimens were behaving like an SS(0.015), although the deepest scratch in the Mannesmann measured surfaces did not exceed 5000 microinches. Upon comparing the curvatures of both, the average curvature of the Mannesmann specimens was 0.000832 compared to 0.000333 for the SS(0.015); this means that the Mannesmann specimens were on the average about 2.5 times "sharper" than the SS(0.015) specimens. Moreover, examining tables (4-2) and (4-6) and considering samples Sn_1 and Sn_3, the Sn_3 specimen failed at 79,000
cycles compared to SN\textsubscript{1} which failed at 114,400 cycles. Both specimens were tested at the same stress range, although SN\textsubscript{1} had a deeper scratch, V\textsubscript{D}, of 2631 microinches compared to 1694 microinches for SN\textsubscript{3}. SN\textsubscript{3} failed at a lower number of cycles. The rms valley curvatures, on the other hand, were 0.001124 for SN\textsubscript{3} compared to 0.000885 for SN\textsubscript{1}. SN\textsubscript{3} was about 1.27 times "sharper" than SN\textsubscript{1}. It seems that in this case it was the effect of depth and sharpness that contributed to failure rather than depth alone. Similarly, upon comparing SN\textsubscript{5} and SN\textsubscript{4} one would reach the same conclusion.

4.3 CORRELATION OF ROUGHNESS WITH INITIATION

It has been established that surface roughness has an effect on fatigue initiation. In this section, the correlation coefficient for linear regression between the deepest scratch and fatigue initiation (at a certain stress range) will be established. Moreover, the same is also established for the product of the rms valley curvature (c\textsubscript{3}) with the deepest scratch (V\textsubscript{D}). Table (4-9) shows those correlation coefficients together with the regression relationships for cycles to failure versus the roughness parameters. Figures (4-13 through 4-20) provide the plots of these relationships at different stress levels.

Studying Table (4-9), one can see that both the product (V\textsubscript{D} x c\textsubscript{3}) and (V\textsubscript{D}), had a high degree of correlation with fatigue initiation at the upper stress ranges. This was expected since the specimens, at those upper stress levels, would be close to their yield stress of 101 ksi. The material properties of those high stress levels would be the contributing factor to cause failure, and not the surface
characteristics. At a stress level of 65 ksi, it became more apparent
that the product continued to exhibit a high coefficient of correlation,
whereas the deepest scratch had poor correlation with initiation.
Furthermore, at the 65 ksi level, specimens from all groups were
represented, see figures (4-15 and 4-19). There were two samples
from the single scratch specimens, two samples from the Ground (24
grit) specimens and one sample from the Mannesmann pipe specimens.
At the 45 ksi level, the deepest scratch has a positive coefficient
of correlation with initiation, figure (4-16). This is contradictory
with the expected behavior. Cycles to failure are expected to decrease
with increasing depth. On the other hand, the product \((V_D^* \times \sigma_3^*)\)
continued to exhibit a good correlation with initiation. Moreover,
the 95% confidence bands for the product were narrower in three of
the four stress ranges. Therefore, one can conclude that the product
of the deepest scratch \((V_D^*)\) and the rms valley curvature \((\sigma_3^*)\)
showed better correlation with fatigue initiation and hence should be used
as the basis to develop the functional relationships that relate surface
finish to fatigue initiation. Furthermore, the geometric interpretation
of using \((V_D^* \times \sigma_3^*)\) is also logical; the deepest scratch being an extreme
height descriptor, which is usually normal to the governing pattern
of the nominal surface, when combined with the rms valley curvature,
a texture descriptor, parallel to the governing pattern, the combination
would then comprise a plane that better represents the characteristics
of surface roughness.

4.4 ANALYTICAL PREDICTIONS

The S-N curves for the single scratches were grouped into one
single spectrum, see figures (4-21, 4-22). To arrive at the equations
that generate this spectrum, the indices (slopes) and constants of
the S-N relationships were plotted against the product \((V_D^* \times \sigma_3^*)\) as
shown in figures (4-23, 4-24). A quadratic expression seemed to be
a best fit for the plotted points. The relations obtained are:

\[
N_i = A_i S_r^{B_i} \tag{4-1}
\]

where

\[
A_i = 18.94 - 1.95 (V_D^* \times \sigma_3^*) + 0.089 (V_D^* \times \sigma_3^*)^2
\]

\[
B_i = 7.37 - 0.88 (V_D^* \times \sigma_3^*) + 0.036 (V_D^* \times \sigma_3^*)^2
\]

and

\[
N_F = A_F S_r^{B_F} \tag{4-2}
\]

\[
A_F = 19.88 - 2.72 (V_D^* \times \sigma_3^*) + 0.171 (V_D^* \times \sigma_3^*)^2
\]

\[
B_F = 7.86 - 1.31 (V_D^* \times \sigma_3^*) + 0.081 (V_D^* \times \sigma_3^*)^2
\]

The best fit curves coincided with the original S-N curves. After
crack initiation, the crack propagation is assumed to be uniform for
the additional cycles to failure. So, the next step would be to predict
fatigue failure.

Using equations (4-1) and (4-2), and varying the product of depth
and curvature, one can obtain the single scratch failure and initiation
spectra, see figures (4-25, 4-26). Using figure (4-25) or the equa-
tions, one can predict the number of cycles to failure at any stress
level if \((V_D^* \times \sigma_3^*)\) is provided. These spectra were used to predict
failure in the Mannesmann pipe specimens and the ground (24 grit)
specimens. The results of these predictions are available in Tables
(4-10 and 4-11). The predicted values were then plotted on the S-N
curves of the original data, see figures (4-27 and 4-28). In the case of the Mannesmann pipe specimens, the predicted values for cycles to failure fell within the 95% confidence band of the tested data, except for two values. These values were at stress levels of 35.96 ksi and 36.46, and the cycles to failure were 1,545,129 cycles and 1,810,370, respectively. For design purposes one would like the predicted values of cycles to failure to be less than the measured ones. The above values missed the mean line by factors of 1.996 and 2.454, respectively, where the upper confidence line factor is 1.804. All predicted values for the ground (24 grit) surface, on the other hand, fell within the 95% confidence band of the tested data. These predictions strengthen the belief in \((V_D^2 \times \sigma_3^2)\) as a surface roughness parameter that helps predicting fatigue failure.
FIGURE 4-2 Measured Surface Characteristics of a Mannesmann Specimen SN3

PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 570 microinches
STANDARD DEVIATION (rms) = 708 microinches
SKEWNESS = -.245
KURTOSIS = 2.625
NUMBER OF ZERO CROSSINGS = 346
TOTAL NUMBER OF PEAKS & VALLEYS = 2773
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1538
BAND WIDTH PARAMETER (ALPHA) = .124
THE FREQUENCY OF POSITIVE PEAKS = .554
THE RMS SLOPE = .2737
THE AVERAGE WAVE LENGTH = .0175 inches
THE RMS WAVE LENGTH = .0162 inches
THE RMS CURVATURE = .001130 1/inches
THE RMS VALLEY CURVATURE = .001162 1/inches
THE MINIMUM VALLEY CURVATURE = -.005251 1/inches @ .655 inches
THE CURVATURE OF DEEPEST SCRATCH = .003009 1/inches @ 1.358 inches
THE RANGE = 3550 microinches
THE DEEPEST VALLEY = -1548 microinches
THE MAXIMUM PEAK = 2001 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 4.393 @ .416 inches

AVERAGE OF PEAK MOMENTS USING POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = .763
THIRD MOMENT M3 = 1.248
FIFTH MOMENT M5 = 3.629
SEVENTH MOMENT M7 = 14.396
NINTH MOMENT M9 = 72.034
FIGURE 4-3 Measured Surface Characteristics of a Mannesmann Specimen SNF3 (Filtered)

PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 272 microinches
STANDARD DEVIATION (rms) = 352 microinches
SKEWNESS = -.278
KURTOSIS = 3.383
NUMBER OF ZERO CROSSINGS = 814
TOTAL NUMBER OF PEAKS & VALLEYS = 3361
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1934
BAND WIDTH PARAMETER (ALPHA) = .242
THE FREQUENCY OF POSITIVE PEAKS = .575
THE RMS SLOPE = .2711
THE AVERAGE WAVE LENGTH = .00842 inches
THE RMS WAVE LENGTH = .00815 inches
THE RMS CURVATURE = 1124 1/inches
THE RMS VALLEY CURVATURE = 1124 1/inches
THE MINIMUM VALLEY CURVATURE = -5232 1/inches \& .855 inches
THE CURVATURE OF DEEPEST SCRATCH = 270 1/inches \& 1.739 inches
THE RANGE = 2450 microinches
THE DEEPEST VALLEY = -1319 microinches
THE MAXIMUM PEAK = 1131 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 2.084 \& .065 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = .795
THIRD MOMENT M3 = 1.791
FIFTH MOMENT M5 = 8.186
SEVENTH MOMENT M7 = 53.131
NINTH MOMENT M9 = 425.799
FIGURE 4-4 Measured Surface Characteristics of a Ground Specimen G2426

PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 401 microinches
STANDARD DEVIATION (rms) = 535 microinches
SKEWNESS = -.315
KURTOSIS = 3.513
NUMBER OF ZERO CROSSINGS = 497
TOTAL NUMBER OF PEAKS & VALLEYS = 2219
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1394
BAND WIDTH PARAMETER (ALPHA) = .223
THE FREQUENCY OF POSITIVE PEAKS = .628
THE RMS SLOPE = .3303
THE AVERAGE WAVE LENGTH = .0108 inches
THE RMS WAVE LENGTH = .0102 inches
THE RMS CURVATURE = .001279 1/inches
THE RMS VALLEY CURVATURE = .001364 1/inches
THE MINIMUM VALLEY CURVATURE = -.000212 1/inches @ 1.628 inches
THE CURVATURE OF DEEPEST SCRATCH = .001134 1/inches @ 1.126 inches
THE RANGE = 3402 microinches
THE DEEPEST VALLEY = -1842 microinches
THE MAXIMUM PEAK = 1560 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 6.271 @ 1.136 inches

AVERAGE OF PEAK MOMENTS USING POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = .787
THIRD MOMENT M3 = 1.97
FIFTH MOMENT M5 = 9.555
SEVENTH MOMENT M7 = 59.074
NINTH MOMENT M9 = 417.99
FIGURE 4-5 Measured Surface Characteristics of a Ground Specimen GF2426 (Filtered)

PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 121 microinches
STANDARD DEVIATION (rms) = 162 microinches
SKEWNESS = -.138
KURTOSIS = 4.108
NUMBER OF ZERO CROSSINGS = 1387
TOTAL NUMBER OF PEAKS & VALLEYS = 2469
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1856
BAND WIDTH PARAMETER (ALPHA) = .561
THE FREQUENCY OF POSITIVE PEAKS = .751
THE RMS SLOPE = .3299
THE AVERAGE WAVE LENGTH = .00325 inches
THE RMS WAVE LENGTH = .00508 inches
THE RMS CURVATURE = .1279 1/inches
THE RMS VALLEY CURVATURE = .1286 1/inches
THE MINIMUM VALLEY CURVATURE = .8214 1/inches @ 1.528 inches
THE CURVATURE OF DEEPEST SCRATCH = 2.084 1/inches @ 1.364 inches
THE RANGE = .0344 microinches
THE DEEPEST VALLEY = -605 microinches
THE MAXIMUM PEAK = .739 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = .999 @ 1.628 inches

AVERAGE OF PEAK MOMENTS USING POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .952
THIRD MOMENT M3 = 3.073
FIFTH MOMENT M5 = 20.919
SEVENTH MOMENT M7 = 209.612
NINTH MOMENT M9 = 2655.25
<table>
<thead>
<tr>
<th></th>
<th>SN1</th>
<th>SN2</th>
<th>SN3</th>
<th>SN4</th>
<th>SN5</th>
<th>SN6</th>
<th>SN61</th>
<th>SN62</th>
<th>SN63</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLA ((\mu''))</td>
<td>613</td>
<td>626</td>
<td>570</td>
<td>552</td>
<td>779</td>
<td>852</td>
<td>1423</td>
<td>1213</td>
<td>1195</td>
</tr>
<tr>
<td>(\sigma_1 (\mu''))</td>
<td>765</td>
<td>763</td>
<td>708</td>
<td>698</td>
<td>975</td>
<td>1039</td>
<td>1790</td>
<td>1579</td>
<td>1554</td>
</tr>
<tr>
<td>SKEWNESS</td>
<td>-0.60</td>
<td>-0.76</td>
<td>-0.25</td>
<td>-0.69</td>
<td>-0.60</td>
<td>-0.59</td>
<td>-0.27</td>
<td>-0.53</td>
<td>-0.70</td>
</tr>
<tr>
<td>KURTOSIS</td>
<td>2.92</td>
<td>3.14</td>
<td>2.63</td>
<td>3.17</td>
<td>2.91</td>
<td>2.70</td>
<td>2.65</td>
<td>3.19</td>
<td>3.29</td>
</tr>
<tr>
<td>(v_0)</td>
<td>244</td>
<td>158</td>
<td>346</td>
<td>435</td>
<td>198</td>
<td>210</td>
<td>89</td>
<td>113</td>
<td>96</td>
</tr>
<tr>
<td>(N_{pv})</td>
<td>2371</td>
<td>2015</td>
<td>2773</td>
<td>2508</td>
<td>2258</td>
<td>2031</td>
<td>1013</td>
<td>931</td>
<td>1094</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>0.10</td>
<td>0.08</td>
<td>0.12</td>
<td>0.17</td>
<td>0.09</td>
<td>0.10</td>
<td>0.12</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>(\lambda_{AV} (''))</td>
<td>0.026</td>
<td>0.025</td>
<td>0.018</td>
<td>0.019</td>
<td>0.033</td>
<td>0.028</td>
<td>0.058</td>
<td>0.048</td>
<td>0.047</td>
</tr>
<tr>
<td>(\sigma_2)</td>
<td>0.2166</td>
<td>0.2365</td>
<td>0.2737</td>
<td>0.2534</td>
<td>0.2124</td>
<td>0.2792</td>
<td>0.2334</td>
<td>0.2320</td>
<td>0.2401</td>
</tr>
<tr>
<td>(\sigma_3 (1/''))</td>
<td>846</td>
<td>878</td>
<td>1130</td>
<td>794</td>
<td>837</td>
<td>981</td>
<td>568</td>
<td>557</td>
<td>682</td>
</tr>
<tr>
<td>(\sigma_3 (1/''))</td>
<td>895</td>
<td>976</td>
<td>1162</td>
<td>835</td>
<td>927</td>
<td>1084</td>
<td>640</td>
<td>646</td>
<td>808</td>
</tr>
<tr>
<td>(v_D (\mu''))</td>
<td>2501</td>
<td>2938</td>
<td>1548</td>
<td>2597</td>
<td>2787</td>
<td>2780</td>
<td>4546</td>
<td>4511</td>
<td>2720</td>
</tr>
<tr>
<td>(R_{MAX} (\mu''))</td>
<td>3931</td>
<td>4111</td>
<td>3550</td>
<td>3811</td>
<td>4270</td>
<td>4215</td>
<td>8126</td>
<td>7499</td>
<td>7546</td>
</tr>
<tr>
<td></td>
<td>SNF1</td>
<td>SNF2</td>
<td>SNF3</td>
<td>SNF4</td>
<td>SNF5</td>
<td>SNF6</td>
<td>SNF61</td>
<td>SNF62</td>
<td>SNF63</td>
</tr>
<tr>
<td>------------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>$\text{CLA}[\mu&quot;]$</td>
<td>243</td>
<td>272</td>
<td>272</td>
<td>392</td>
<td>384</td>
<td>372</td>
<td>476</td>
<td>537</td>
<td>373</td>
</tr>
<tr>
<td>$\sigma_1[\mu&quot;]$</td>
<td>363</td>
<td>391</td>
<td>352</td>
<td>510</td>
<td>513</td>
<td>496</td>
<td>645</td>
<td>702</td>
<td>510</td>
</tr>
<tr>
<td>$\text{SKEWNESS}$</td>
<td>-0.22</td>
<td>-0.70</td>
<td>-0.28</td>
<td>-0.91</td>
<td>-0.90</td>
<td>-0.44</td>
<td>-0.56</td>
<td>-0.41</td>
<td>-0.74</td>
</tr>
<tr>
<td>$\text{KURTOSIS}$</td>
<td>6.82</td>
<td>4.92</td>
<td>3.40</td>
<td>3.85</td>
<td>4.30</td>
<td>4.22</td>
<td>4.14</td>
<td>3.53</td>
<td>5.18</td>
</tr>
<tr>
<td>$\nu_0$</td>
<td>658</td>
<td>557</td>
<td>814</td>
<td>463</td>
<td>429</td>
<td>412</td>
<td>243</td>
<td>196</td>
<td>316</td>
</tr>
<tr>
<td>$N_{pv}$</td>
<td>1669</td>
<td>2407</td>
<td>3361</td>
<td>2534</td>
<td>2324</td>
<td>2407</td>
<td>1133</td>
<td>1004</td>
<td>1188</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.23</td>
<td>0.23</td>
<td>0.24</td>
<td>0.18</td>
<td>0.18</td>
<td>0.17</td>
<td>0.21</td>
<td>0.19</td>
<td>0.27</td>
</tr>
<tr>
<td>$\lambda_{av}[^\mu&quot;]$</td>
<td>0.010</td>
<td>0.011</td>
<td>0.008</td>
<td>0.014</td>
<td>0.017</td>
<td>0.012</td>
<td>0.019</td>
<td>0.021</td>
<td>0.015</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>0.2178</td>
<td>0.2349</td>
<td>0.2711</td>
<td>0.2532</td>
<td>0.2122</td>
<td>0.2767</td>
<td>0.2309</td>
<td>0.2308</td>
<td>0.2387</td>
</tr>
<tr>
<td>$\sigma_3[1/\mu&quot;]$</td>
<td>849</td>
<td>878</td>
<td>1130</td>
<td>794</td>
<td>847</td>
<td>981</td>
<td>568</td>
<td>557</td>
<td>682</td>
</tr>
<tr>
<td>$\sigma_3^*[1/\mu&quot;]$</td>
<td>885</td>
<td>960</td>
<td>1124</td>
<td>828</td>
<td>935</td>
<td>1049</td>
<td>608</td>
<td>607</td>
<td>773</td>
</tr>
<tr>
<td>$V_D[\mu&quot;]$</td>
<td>1905</td>
<td>1921</td>
<td>1131</td>
<td>2055</td>
<td>2100</td>
<td>2137</td>
<td>2819</td>
<td>3622</td>
<td>2782</td>
</tr>
<tr>
<td>$R_{max}[\mu&quot;]$</td>
<td>3553</td>
<td>3245</td>
<td>2450</td>
<td>3245</td>
<td>3426</td>
<td>4085</td>
<td>4770</td>
<td>4710</td>
<td>4271</td>
</tr>
<tr>
<td>Adjusted by</td>
<td>2631</td>
<td>2781</td>
<td>1694</td>
<td>3177</td>
<td>3126</td>
<td>3228</td>
<td>4238</td>
<td>3886</td>
<td>3700</td>
</tr>
</tbody>
</table>

$V_D^*[\mu"]$ (2*RMS) (2.3*RMS) (1.6*RMS) (2.2*RMS) (2.0*RMS) (2.2*RMS) (2.2*RMS) (1.8*RMS) (1.8*RMS)
<table>
<thead>
<tr>
<th></th>
<th>G26</th>
<th></th>
<th>G21</th>
<th></th>
<th>G48</th>
<th></th>
<th>G27</th>
<th></th>
<th>G23</th>
<th></th>
<th>G34</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CLA (μ&quot;)</strong></td>
<td>401</td>
<td></td>
<td>376</td>
<td></td>
<td>452</td>
<td></td>
<td>333</td>
<td></td>
<td>508</td>
<td></td>
<td>440</td>
<td></td>
</tr>
<tr>
<td><strong>σ₁ (μ&quot;)</strong></td>
<td>535</td>
<td></td>
<td>493</td>
<td></td>
<td>550</td>
<td></td>
<td>456</td>
<td></td>
<td>630</td>
<td></td>
<td>553</td>
<td></td>
</tr>
<tr>
<td><strong>SKEWNESS</strong></td>
<td>-0.32</td>
<td></td>
<td>-0.09</td>
<td></td>
<td>-0.26</td>
<td></td>
<td>-0.42</td>
<td></td>
<td>0.05</td>
<td></td>
<td>-0.26</td>
<td></td>
</tr>
<tr>
<td><strong>KURTOSIS</strong></td>
<td>3.51</td>
<td></td>
<td>3.74</td>
<td></td>
<td>2.43</td>
<td></td>
<td>3.68</td>
<td></td>
<td>2.67</td>
<td></td>
<td>2.74</td>
<td></td>
</tr>
<tr>
<td><strong>ν₀</strong></td>
<td>497</td>
<td></td>
<td>451</td>
<td></td>
<td>355</td>
<td></td>
<td>635</td>
<td></td>
<td>306</td>
<td></td>
<td>427</td>
<td></td>
</tr>
<tr>
<td><strong>N_{pv}</strong></td>
<td>2219</td>
<td></td>
<td>2309</td>
<td></td>
<td>2451</td>
<td></td>
<td>2392</td>
<td></td>
<td>2341</td>
<td></td>
<td>2763</td>
<td></td>
</tr>
<tr>
<td><strong>α</strong></td>
<td>0.22</td>
<td></td>
<td>0.20</td>
<td></td>
<td>0.14</td>
<td></td>
<td>0.27</td>
<td></td>
<td>0.13</td>
<td></td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td><strong>λ_{AV} (&quot;</strong>)</td>
<td>0.011</td>
<td></td>
<td>0.010</td>
<td></td>
<td>0.011</td>
<td></td>
<td>0.010</td>
<td></td>
<td>0.015</td>
<td></td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td><strong>σ₂</strong></td>
<td>0.3303</td>
<td></td>
<td>0.3317</td>
<td></td>
<td>0.3360</td>
<td></td>
<td>0.2934</td>
<td></td>
<td>0.2972</td>
<td></td>
<td>0.3136</td>
<td></td>
</tr>
<tr>
<td><strong>σ₃ (1/&quot;</strong>)</td>
<td>1279</td>
<td></td>
<td>1286</td>
<td></td>
<td>1318</td>
<td></td>
<td>1204</td>
<td></td>
<td>1216</td>
<td></td>
<td>1277</td>
<td></td>
</tr>
<tr>
<td><strong>σ₃ (1/&quot;</strong>)</td>
<td>1364</td>
<td></td>
<td>1334</td>
<td></td>
<td>1290</td>
<td></td>
<td>1187</td>
<td></td>
<td>1225</td>
<td></td>
<td>1216</td>
<td></td>
</tr>
<tr>
<td><strong>V_D (μ&quot;)</strong></td>
<td>1842</td>
<td></td>
<td>1712</td>
<td></td>
<td>1547</td>
<td></td>
<td>1285</td>
<td></td>
<td>1965</td>
<td></td>
<td>1570</td>
<td></td>
</tr>
<tr>
<td><strong>R_{max} (μ&quot;)</strong></td>
<td>3402</td>
<td></td>
<td>3692</td>
<td></td>
<td>3156</td>
<td></td>
<td>2731</td>
<td></td>
<td>3525</td>
<td></td>
<td>3245</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G26</td>
<td>G21</td>
<td>G48</td>
<td>G27</td>
<td>G23</td>
<td>G34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLA($\mu''$)</td>
<td>121</td>
<td>139</td>
<td>139</td>
<td>109</td>
<td>106</td>
<td>119</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_1(\mu''$)</td>
<td>162</td>
<td>179</td>
<td>183</td>
<td>140</td>
<td>144</td>
<td>153</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SKEWNESS</td>
<td>-0.14</td>
<td>-0.18</td>
<td>0.19</td>
<td>-0.50</td>
<td>-0.20</td>
<td>-0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KURTOSIS</td>
<td>4.10</td>
<td>3.73</td>
<td>4.66</td>
<td>5.79</td>
<td>4.41</td>
<td>4.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_0$</td>
<td>1387</td>
<td>1262</td>
<td>1359</td>
<td>1452</td>
<td>1656</td>
<td>1395</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{pv}$</td>
<td>2469</td>
<td>2583</td>
<td>2788</td>
<td>2754</td>
<td>2499</td>
<td>2743</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.56</td>
<td>0.49</td>
<td>0.49</td>
<td>0.53</td>
<td>0.56</td>
<td>0.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda_{av}(\mu'')$</td>
<td>0.003</td>
<td>0.004</td>
<td>0.004</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>0.3299</td>
<td>0.3311</td>
<td>0.3355</td>
<td>0.2979</td>
<td>0.3282</td>
<td>0.3132</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_3(1/\mu''$)</td>
<td>1286</td>
<td>1286</td>
<td>1318</td>
<td>1209</td>
<td>1279</td>
<td>1277</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_3^*(1/\mu''$)</td>
<td>1279</td>
<td>1246</td>
<td>1201</td>
<td>1118</td>
<td>1266</td>
<td>1211</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{D}(\mu''$)</td>
<td>605</td>
<td>787</td>
<td>685</td>
<td>582</td>
<td>575</td>
<td>574</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RANGE($\mu''$)</td>
<td>1344</td>
<td>1577</td>
<td>1611</td>
<td>1180</td>
<td>1263</td>
<td>1433</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
FATIGUE LIFE, N (CYCLES)

Mannesmann Riser Pipe

\[ N = 1.87 \times 10^{11} \times S_r^{-3.46} \]
FATIGUE LIFE, N (CYCLES)

Ground With 24 Grit

$N = 5.79 \times 10^{19} \cdot Sr^{-7.77}$
Figure 4-8  Single Scratch 0.004 inches deep

\[ N = 2.98 \times 10^{16} S_r^{-6.21} \]
Figure 4-9: Single Scratch 0.006 inches deep

$N = 1.83 \times 10^5 \text{ Sr} = 5.66$

Stress Range SF (KSI)
FATIGUE LIFE, N (CYCLES)

STRESS RANGE Sr (KSI)

FIGURE 4-11 Single Scratch 0.015 inches deep

\[ N = 3.49 \times 10^{10} S_r^{-3.32} \]
FATIGUE LIFE, N (CYCLES)

FIGURE 4-12 Single Scratch 0.020 inches deep

\[ N = 3.31 \times 10^9 S_r^{-2.82} \]
FIGURE 4-13 Fatigue Initiation, $N_i$ (Cycles)

Fatigue Crack Initiation vs. Deepest Scratch

$$N_i = 5.14 \times 10^6 \, S_c^{.61}$$

Stress Range $= 80 \, ksi$

<table>
<thead>
<tr>
<th>Scratch Microinches</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>25000</td>
</tr>
<tr>
<td>6000</td>
<td>29000</td>
</tr>
<tr>
<td>10000</td>
<td>16000</td>
</tr>
<tr>
<td>10000</td>
<td>14500</td>
</tr>
<tr>
<td>4000</td>
<td>42500</td>
</tr>
<tr>
<td>4000</td>
<td>31500</td>
</tr>
<tr>
<td>575</td>
<td>92000</td>
</tr>
</tbody>
</table>

Number of samples $= 7$

$X_{mean} = 3.65$

$Y_{mean} = 4.47$

Variance of $X = .154$

Variance of $Y = .063$

Covariance $S_{XY} = -.0943$

Correlation $R_{xy} = .958$

$RMS = .0774$
Figure 4-14  Fatigue Crack Initiation vs. Deepest Scratch

\[ N_1 = 2.47 \times 10^7 \quad \text{Sc} \leq 77 \]

Stress Range = 70 ksi

<table>
<thead>
<tr>
<th>Deepest Scratch Microinches</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>15000</td>
<td>16500</td>
</tr>
<tr>
<td>20000</td>
<td>11100</td>
</tr>
<tr>
<td>2631</td>
<td>78100</td>
</tr>
<tr>
<td>1694</td>
<td>64000</td>
</tr>
<tr>
<td>605</td>
<td>182000</td>
</tr>
</tbody>
</table>

Number of samples = 5
Xmean = 3.58
Ymean = 4.64
Variance of X = .332
Variance of Y = .202
Covariance of SXY = -.255
Correlation Rxy = -.985
RMS = .0872
Fatigue Crack Initiation vs. Deepest Scratch

\[ N_i = 2.5 \times 10^6 \sqrt{c}^{0.37} \]

Stress Range = 65 ksi

<table>
<thead>
<tr>
<th>Deepest Scratch</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microinches</td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>135000</td>
</tr>
<tr>
<td>4000</td>
<td>174000</td>
</tr>
<tr>
<td>2781</td>
<td>74000</td>
</tr>
<tr>
<td>787</td>
<td>184000</td>
</tr>
<tr>
<td>582</td>
<td>300000</td>
</tr>
</tbody>
</table>

Number of samples = 5
Xmean = 3.26
Ymean = 5.2
Variance of X = 1.29
Variance of Y = .0407
Covariance SXY =-.0475
Correlation Rxy =-.655
RMS = .17
Stress Range = 45 ksi

<table>
<thead>
<tr>
<th>Deepest Scratch (Microinches)</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000</td>
<td>268000</td>
</tr>
<tr>
<td>10000</td>
<td>227000</td>
</tr>
<tr>
<td>3126</td>
<td>167000</td>
</tr>
<tr>
<td>3228</td>
<td>160000</td>
</tr>
<tr>
<td>3700</td>
<td>375000</td>
</tr>
</tbody>
</table>

Number of samples = 5
Xmean = 3.71
Ymean = 5.36
Variance of X = .055
Variance of Y = .0187
Covariance of SXY = .00984
Correlation Rxy = .307
RMS = .146
Fatigue Initiation, $N_1$ (Cycles)

Figure 4-17 Fatigue Crack Initiation vs. Deepest Scratch x Curvature

$N_1 = 5.71 \times 10^4 (S_0 x C_r)^{-1.12}$

Stress Range = 80 ksi

<table>
<thead>
<tr>
<th>Deepest Scratch</th>
<th>Curvature 1/microinches</th>
<th>Product</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>0.00033300</td>
<td>2.00</td>
<td>25000</td>
</tr>
<tr>
<td>6000</td>
<td>0.00033300</td>
<td>2.00</td>
<td>25000</td>
</tr>
<tr>
<td>10000</td>
<td>0.00033300</td>
<td>3.33</td>
<td>16000</td>
</tr>
<tr>
<td>10000</td>
<td>0.00033300</td>
<td>3.33</td>
<td>14500</td>
</tr>
<tr>
<td>4000</td>
<td>0.00033300</td>
<td>1.33</td>
<td>42500</td>
</tr>
<tr>
<td>4000</td>
<td>0.00033300</td>
<td>1.33</td>
<td>31500</td>
</tr>
<tr>
<td>575</td>
<td>0.00127900</td>
<td>.74</td>
<td>92000</td>
</tr>
</tbody>
</table>

Number of Samples = 7

Xmean = .252
Ymean = 4.47
Variance of X = .0474
Variance of Y = .063
Covariance SXY = -.0533
Correlation Rxy = -.976
RMS = .0592
Figure 4-18 Fatigue Crack Initiation vs. Deepest Scratch \times Curvature

\[ N_i = 1.56 \times 10^5 \ (Sc \times Cr)^{1.33} \]

Stress Range = 70 ksi

<table>
<thead>
<tr>
<th>Deepest Scratch</th>
<th>Curvature \ (1/\text{microinches})</th>
<th>Product</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>15000</td>
<td>.00033300</td>
<td>4.99</td>
<td>16500</td>
</tr>
<tr>
<td>20000</td>
<td>.00033300</td>
<td>6.66</td>
<td>11100</td>
</tr>
<tr>
<td>2631</td>
<td>.00088500</td>
<td>2.33</td>
<td>78100</td>
</tr>
<tr>
<td>1694</td>
<td>.00112400</td>
<td>1.90</td>
<td>64000</td>
</tr>
<tr>
<td>605</td>
<td>.00128600</td>
<td>.78</td>
<td>182000</td>
</tr>
</tbody>
</table>

Number of samples = 5
X mean = .412
Y mean = 4.64
Variance of X = .108
Variance of Y = .202
Covariance SXY = -.144
Correlation Rxy = -.977
RMS = .108
Figure 118 Fatigue Crack Initiation vs. Deepest Scratch \times Curvature

\[ N_1 = 2.03 \times 10^5 \ (S_{0x} \text{Cr})^{1.04} \]

Stress Range = 65 ksi

<table>
<thead>
<tr>
<th>Deepest Scratch</th>
<th>Curvature 1/microinches</th>
<th>Product</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000</td>
<td>.00033300</td>
<td>1.33</td>
<td>135000</td>
</tr>
<tr>
<td>4000</td>
<td>.00033300</td>
<td>1.33</td>
<td>174000</td>
</tr>
<tr>
<td>2781</td>
<td>.00096000</td>
<td>2.67</td>
<td>74000</td>
</tr>
<tr>
<td>787</td>
<td>.00128600</td>
<td>1.01</td>
<td>184000</td>
</tr>
<tr>
<td>582</td>
<td>.00120900</td>
<td>.70</td>
<td>308000</td>
</tr>
</tbody>
</table>

Number of samples = 5
Xmean = .106
Ymean = 5.2
Variance of X = .0361
Variance of Y = .0407
Covariance SXY = -.0375
Correlation of Rxy = -.98
RMS = .045
FATIGUE INITIATION, $N_i$ (CYCLES)

Figure 4-20 Fatigue Crack Initiation vs. Deepest Scratch x Curvature

$$N_i = 2.05 \times 10^7 (S_c x C_r)^{-2.76}$$

Stress Range = 45 ksi

<table>
<thead>
<tr>
<th>Deepest Scratch</th>
<th>Curvature</th>
<th>Product</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000 microinches</td>
<td>.00033300</td>
<td>3.33</td>
<td>268000</td>
</tr>
<tr>
<td>10000 microinches</td>
<td>.00033300</td>
<td>3.33</td>
<td>227000</td>
</tr>
<tr>
<td>3228 1/microinches</td>
<td>.00107600</td>
<td>3.47</td>
<td>160000</td>
</tr>
<tr>
<td>3700 1/microinches</td>
<td>.00077300</td>
<td>2.86</td>
<td>375000</td>
</tr>
</tbody>
</table>

Number of samples = 4
Xmean = .511
Ymean = 5.39
Variance of X = .00103
Variance of Y = .0178
Covariance of SXY = -.00388
Correlation $R_{xy} = -.987$
RMS = .0648
### Table (4-5)

**Regression Lines for Tested Specimens**

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Correlation Coefficient</th>
<th>97.5% Confidence Line (Factor)</th>
<th>S-N Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mannesmann</td>
<td>-0.969</td>
<td>1.804</td>
<td>$N = 1.87 \times 10^9 \text{ Sr}^{-3.46}$</td>
</tr>
<tr>
<td>Ground (24 Grit)</td>
<td>-0.929</td>
<td>2.700</td>
<td>$N = 5.79 \times 10^{19} \text{ Sr}^{-7.77}$</td>
</tr>
<tr>
<td>SS(0.004)</td>
<td>-0.978</td>
<td>1.402</td>
<td>$N = 2.98 \times 10^{16} \text{ Sr}^{-6.21}$</td>
</tr>
<tr>
<td>SS(0.006)</td>
<td>-0.994</td>
<td>1.298</td>
<td>$N = 1.83 \times 10^{15} \text{ Sr}^{-5.66}$</td>
</tr>
<tr>
<td>SS(0.010)</td>
<td>-0.997</td>
<td>1.207</td>
<td>$N = 5.15 \times 10^{12} \text{ Sr}^{-4.40}$</td>
</tr>
<tr>
<td>SS(0.015)</td>
<td>-1.00</td>
<td>1.000</td>
<td>$N = 3.49 \times 10^{10} \text{ Sr}^{-3.32}$</td>
</tr>
<tr>
<td>SS(0.020)</td>
<td>-1.00</td>
<td>1.000</td>
<td>$N = 3.31 \times 10^{9} \text{ Sr}^{-2.82}$</td>
</tr>
</tbody>
</table>

† SS stands for single scratch, quantity in parenthesis is the depth in inches.
### TABLE (4-6)

**CYCLES TO INITIATION AND FAILURE FOR MANNESMANN PIPE SPECIMENS**

<table>
<thead>
<tr>
<th>SPECIMEN DESIGNATION</th>
<th>STRESS RANGE (KSI)</th>
<th>$N_i$ (CYCLES)</th>
<th>$N_f$ (CYCLES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN1</td>
<td>68.03</td>
<td>78,100</td>
<td>114,400</td>
</tr>
<tr>
<td>SN2</td>
<td>63.62</td>
<td>74,000</td>
<td>105,000</td>
</tr>
<tr>
<td>SN3</td>
<td>68.15</td>
<td>64,000</td>
<td>79,000</td>
</tr>
<tr>
<td>SN4</td>
<td>46.64</td>
<td>262,000</td>
<td>322,000</td>
</tr>
<tr>
<td>SN5</td>
<td>47.92</td>
<td>167,000</td>
<td>196,000</td>
</tr>
<tr>
<td>SN6</td>
<td>46.47</td>
<td>160,000</td>
<td>168,000</td>
</tr>
<tr>
<td>SN61</td>
<td>35.96</td>
<td>957,000</td>
<td>1,135,500</td>
</tr>
<tr>
<td>SN62</td>
<td>36.46</td>
<td>1,116,000</td>
<td>1,170,100</td>
</tr>
<tr>
<td>SN63</td>
<td>43.90</td>
<td>375,000</td>
<td>399,400</td>
</tr>
<tr>
<td>SN64</td>
<td>82.94</td>
<td>25,300</td>
<td>36,300</td>
</tr>
<tr>
<td>SN65</td>
<td>81.32</td>
<td>37,700</td>
<td>48,280</td>
</tr>
<tr>
<td>SN66</td>
<td>82.30</td>
<td>29,200</td>
<td>40,760</td>
</tr>
<tr>
<td>SN67</td>
<td>82.94</td>
<td>25,000</td>
<td>35,600</td>
</tr>
</tbody>
</table>

*SN - denotes Mannesmann pipe specimens*
<table>
<thead>
<tr>
<th>SPECIMEN DESIGNATION</th>
<th>STRESS RANGE (KSI)</th>
<th>$N_i$ (CYCLES)</th>
<th>$N_F$ (CYCLES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G26</td>
<td>73.61</td>
<td>182,000</td>
<td>212,200</td>
</tr>
<tr>
<td>G23</td>
<td>82.34</td>
<td>92,000</td>
<td>111,000</td>
</tr>
<tr>
<td>G21</td>
<td>64.70</td>
<td>184,000</td>
<td>217,200</td>
</tr>
<tr>
<td>G27</td>
<td>64.70</td>
<td>308,000</td>
<td>308,000</td>
</tr>
<tr>
<td>G48</td>
<td>54.46</td>
<td>---</td>
<td>3,195,000†</td>
</tr>
<tr>
<td>G34</td>
<td>54.46</td>
<td>---</td>
<td>2,155,000†</td>
</tr>
</tbody>
</table>

G denotes Ground (24 Grit) specimens.
†Samples G48 and G34 did not fail.
<table>
<thead>
<tr>
<th>SPECIMEN DESIGNATION</th>
<th>STRESS RANGE (KSI)</th>
<th>$N_i$ (CYCLES)</th>
<th>$N_f$ (CYCLES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS$_1$(0.004)</td>
<td>80.65</td>
<td>42,500</td>
<td>53,500</td>
</tr>
<tr>
<td>SS$_2$(0.004)</td>
<td>56.58</td>
<td>---</td>
<td>--- Junk</td>
</tr>
<tr>
<td>SS$_3$(0.004)</td>
<td>63.51</td>
<td>135,000</td>
<td>181,200</td>
</tr>
<tr>
<td>SS$_4$(0.004)</td>
<td>64.52</td>
<td>174,000</td>
<td>197,100</td>
</tr>
<tr>
<td>SS$_5$(0.004)</td>
<td>79.39</td>
<td>31,500</td>
<td>40,300</td>
</tr>
<tr>
<td>SS$_1$(0.006)</td>
<td>78.85</td>
<td>25,000</td>
<td>31,500</td>
</tr>
<tr>
<td>SS$_2$(0.006)</td>
<td>79.23</td>
<td>29,000</td>
<td>37,000</td>
</tr>
<tr>
<td>SS$_3$(0.006)</td>
<td>54.09</td>
<td>216,000</td>
<td>256,000</td>
</tr>
<tr>
<td>SS$_4$(0.006)</td>
<td>54.23</td>
<td>258,000</td>
<td>328,000</td>
</tr>
<tr>
<td>SS$_1$(0.010)</td>
<td>79.00</td>
<td>16,000</td>
<td>24,900</td>
</tr>
<tr>
<td>SS$_2$(0.010)</td>
<td>79.54</td>
<td>14,500</td>
<td>23,000</td>
</tr>
<tr>
<td>SS$_3$(0.010)</td>
<td>56.66</td>
<td>66,000</td>
<td>88,200</td>
</tr>
<tr>
<td>SS$_4$(0.010)</td>
<td>44.86</td>
<td>268,000</td>
<td>318,100</td>
</tr>
<tr>
<td>SS$_5$(0.010)</td>
<td>44.39</td>
<td>227,000</td>
<td>288,400</td>
</tr>
<tr>
<td>SS$_1$(0.015)</td>
<td>70.11</td>
<td>16,500</td>
<td>25,400</td>
</tr>
<tr>
<td>SS$_2$(0.015)</td>
<td>50.99</td>
<td>58,000</td>
<td>73,100</td>
</tr>
<tr>
<td>SS$_1$(0.020)</td>
<td>70.20</td>
<td>11,100</td>
<td>21,000</td>
</tr>
<tr>
<td>SS$_2$(0.020)</td>
<td>50.71</td>
<td>30,000</td>
<td>51,400</td>
</tr>
<tr>
<td>SS$_1$(0.0)</td>
<td>82.13</td>
<td>216,000</td>
<td>245,200</td>
</tr>
<tr>
<td>SS$_2$(0.0)</td>
<td>73.42</td>
<td>244,000</td>
<td>276,800</td>
</tr>
</tbody>
</table>

SS stands for single scratch, quantity in parenthesis is the scratch depth in inches
### TABLE (4-9)

**CORRELATION OF DEEPEST SCRATCH WITH FATIGUE INITIATION**

<table>
<thead>
<tr>
<th>STRESS RANGE (KSI)</th>
<th>CORRELATION COEFFICIENT</th>
<th>97.5% CONFIDENCE LINE (FACTOR)</th>
<th>REGRESSION LINES</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>-0.958</td>
<td>1.418</td>
<td>$N_i = 5.14 \times 10^6 \ (v_D)^{-0.61}$</td>
</tr>
<tr>
<td>70</td>
<td>-0.985</td>
<td>1.482</td>
<td>$N_i = 2.47 \times 10^7 \ (v_D)^{-0.77}$</td>
</tr>
<tr>
<td>65</td>
<td>-0.655</td>
<td>2.154</td>
<td>$N_i = 2.50 \times 10^6 \ (v_D)^{-0.37}$</td>
</tr>
<tr>
<td>*45</td>
<td>+0.307</td>
<td>1.933</td>
<td>$N_i = 4.92 \times 10^4 \ (v_D)^{0.18}$</td>
</tr>
</tbody>
</table>

**CORRELATION OF CURVATURE x DEEPEST SCRATCH WITH FATIGUE INITIATION**

<table>
<thead>
<tr>
<th>STRESS RANGE (KSI)</th>
<th>CORRELATION COEFFICIENT</th>
<th>97.5% CONFIDENCE LINE (FACTOR)</th>
<th>REGRESSION LINES</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>-0.976</td>
<td>1.306</td>
<td>$N_i = 5.71 \times 10^4 \ (v_D \times \sigma_3^{*})^{-1.12}$</td>
</tr>
<tr>
<td>70</td>
<td>-0.977</td>
<td>1.628</td>
<td>$N_i = 1.56 \times 10^5 \ (v_D \times \sigma_3^{*})^{-1.33}$</td>
</tr>
<tr>
<td>65</td>
<td>-0.980</td>
<td>1.225</td>
<td>$N_i = 2.03 \times 10^5 \ (v_D \times \sigma_3^{*})^{-1.04}$</td>
</tr>
<tr>
<td>45</td>
<td>-0.907</td>
<td>1.340</td>
<td>$N_i = 2.05 \times 10^7 \ (v_D \times \sigma_3^{*})^{-3.76}$</td>
</tr>
</tbody>
</table>
Figure 4-24 Single Scratch Coefficients for Initiation
Figure 4-25 Single Scratch Failure Spectra
Figure 4-26 Single Scratch Initiation Spectra

Depth × Curvature
FATIGUE LIFE, N (CYCLES)
Mannesmann Riser Pipe

\[ N = 1.87 \times 10^{11} \left( \frac{\text{Sr}}{\text{m}} \right)^{-3.46} \]

* Denotes Predicted Life From Single Scratch Spectra
Figure 4-27A Crack Initiation, Ni (Cycles) Mannesmann Riser Pipe

$N = 2.21 \times 10^{12} \text{ Sr}^{-4.14}$

Stress Range $S_p (KSI)$
**FIGURE 4-28**

**FATIGUE LIFE, N (CYCLES)**

Ground With 24 Grit

\[ N = 5.79 \times 10^{19} \cdot S_r^{-7.77} \]

* Denotes Predicted Life From Single Scratch Spectra
FIGURE 4-28A  CRACK INITIATION, \( N_i \) (CYCLES)

Ground With 24 Grit

\[ N = 1.30 \times 10^{12} S_r^{-3.71} \]
TABLE (4-10)

PREDICTED VALUES
FOR THE MANNESMAN PIPE SPECIMENS
FROM THE SINGLE SCRATCH SPECTRA

<table>
<thead>
<tr>
<th>SPECIMEN DESIGNATION</th>
<th>STRESS RANGE (KSI)</th>
<th>V_D^* (µ&quot;)</th>
<th>σ_D^* (µ&quot;)</th>
<th>σ_D^* x V_D^*</th>
<th>PREDICTED N_i (CYCLES)</th>
<th>MEASURED N_i (CYCLES)</th>
<th>PREDICTED N_f (CYCLES)</th>
<th>MEASURED N_f (CYCLES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN1</td>
<td>68.03</td>
<td>2631</td>
<td>0.000885</td>
<td>2.007</td>
<td>54,485</td>
<td>78,100</td>
<td>70,481</td>
<td>114,400</td>
</tr>
<tr>
<td>SN2</td>
<td>63.62</td>
<td>2781</td>
<td>0.000960</td>
<td>2.220</td>
<td>64,613</td>
<td>74,000</td>
<td>83,463</td>
<td>105,000</td>
</tr>
<tr>
<td>SN3</td>
<td>68.15</td>
<td>1694</td>
<td>0.001124</td>
<td>1.878</td>
<td>68,951</td>
<td>64,000</td>
<td>86,919</td>
<td>79,000</td>
</tr>
<tr>
<td>SN4</td>
<td>46.64</td>
<td>3177</td>
<td>0.000828</td>
<td>2.687</td>
<td>344,429</td>
<td>262,000</td>
<td>400,088</td>
<td>322,000</td>
</tr>
<tr>
<td>SN5</td>
<td>47.92</td>
<td>3126</td>
<td>0.000935</td>
<td>3.203</td>
<td>239,706</td>
<td>167,000</td>
<td>281,033</td>
<td>196,000</td>
</tr>
<tr>
<td>SN6</td>
<td>46.47</td>
<td>3228</td>
<td>0.001076</td>
<td>4.661</td>
<td>189,457</td>
<td>160,000</td>
<td>220,825</td>
<td>168,000</td>
</tr>
<tr>
<td>SN61</td>
<td>35.96</td>
<td>4238</td>
<td>0.000608</td>
<td>2.900</td>
<td>1,446,640</td>
<td>957,000</td>
<td>1,545,129</td>
<td>1,135,000</td>
</tr>
<tr>
<td>SN62</td>
<td>36.46</td>
<td>3886</td>
<td>0.000607</td>
<td>2.859</td>
<td>1,662,721</td>
<td>1,116,000</td>
<td>1,810,370</td>
<td>1,170,000</td>
</tr>
<tr>
<td>SN63</td>
<td>43.90</td>
<td>3700</td>
<td>0.000773</td>
<td>3.301</td>
<td>394,533</td>
<td>375,000</td>
<td>447,353</td>
<td>399,400</td>
</tr>
<tr>
<td>SPECIMEN DESIGNATION</td>
<td>STRESS RANGE (KSI)</td>
<td>$V_D^*$ (μm)</td>
<td>$\sigma_3^*$ (μm)</td>
<td>ADJUSTED $\sigma_3^* \times V_D^*$ (CYCLES)</td>
<td>PREDICTED $N_i$ (CYCLES)</td>
<td>MEASURED $N_i$ (CYCLES)</td>
<td>PREDICTED $N_F$ (CYCLES)</td>
<td>MEASURED $N_F$ (CYCLES)</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------</td>
<td>--------------</td>
<td>-------------------</td>
<td>------------------------------------------</td>
<td>--------------------------</td>
<td>-------------------------</td>
<td>--------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>G26</td>
<td>73.76</td>
<td>605</td>
<td>0.001286</td>
<td>0.778</td>
<td>85,043</td>
<td>182,000</td>
<td>98,910</td>
<td>212,200</td>
</tr>
<tr>
<td>G21</td>
<td>64.70</td>
<td>787</td>
<td>0.001286</td>
<td>1.012</td>
<td>172,157</td>
<td>184,000</td>
<td>206,850</td>
<td>217,200</td>
</tr>
<tr>
<td>G48</td>
<td>54.46</td>
<td>685</td>
<td>0.001318</td>
<td>0.903</td>
<td>---</td>
<td>Did not fail</td>
<td>---</td>
<td>3,195,000</td>
</tr>
<tr>
<td>G27</td>
<td>64.70</td>
<td>582</td>
<td>0.001209</td>
<td>0.704</td>
<td>216,981</td>
<td>308,000</td>
<td>257,613</td>
<td>342,700</td>
</tr>
<tr>
<td>G23</td>
<td>82.34</td>
<td>575</td>
<td>0.001279</td>
<td>0.735</td>
<td>41,609</td>
<td>92,000</td>
<td>47,201</td>
<td>111,000</td>
</tr>
<tr>
<td>G34</td>
<td>54.46</td>
<td>575</td>
<td>0.001277</td>
<td>0.734</td>
<td>---</td>
<td>Did not fail</td>
<td>---</td>
<td>2,155,000</td>
</tr>
</tbody>
</table>
CHAPTER V
THEORETICAL PREDICTIONS OF CYCLES TO FAILURE

This chapter deals with theoretically predicting the cycles to failure for specimens that have longer sampling lengths, where the surface form \( x(\xi) \) is assumed to be normally distributed. These predictions can be a useful tool to the engineer, giving him an idea about the expected cycles to failure in his engineering application. It will be shown in Section 5.1 that the measured surface distributions, for the Mannesmann pipe specimens and the ground (24 grit) specimens, can be assumed to be normal Gaussian distributions. In Section 5.2, the deepest scratch in sampling lengths of 40 feet and 1000 feet will be predicted using the First-Passage criteria by assuming that the surface form \( x(\xi) \) is normal with standard deviation \( \sigma_1 \), rms slope \( \sigma_2 \) and rms valley curvature \( \sigma_3 \) where \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are values taken from the measured surfaces of the specimens with a sampling length \( L_s = 2 \) inches. After predicting the deepest scratch \( V_D^* \), the single scratch spectra will be used to predict the number of cycles to failure. In Section 5.3, the predicted values of the deepest scratch \( V_D^* \) and rms valley curvature \( \sigma_3^* \) will be averaged for every sampling length, (i.e., \( L_s = 2'' \), \( L_s = 40' \), \( L_s = 1000' \)) using the method of moments. The average values will be used to predict the cycles to failure by utilizing the single scratch spectra. In the case of \( L_s = 2'' \) the average values used are the average values of the measured surface.

5.1 GAUSSIAN ASSUMPTIONS AND JUSTIFICATIONS

The measured surfaces of the surface form \( x(\xi) \) will be tested for normality. A perfectly Gaussian surface has a kurtosis value
of 3. Referring to Tables (4-1, 4-3), the kurtosis values of the measured surfaces, for both the Mannesmann pipe specimens and the ground (24 grit) specimens, are very close to 3. Even after filtering, which tends to sharpen the profile, tables (4-2, 4-4), the kurtosis values would still be acceptable for most of the cases. The kurtosis values for both groups of specimens seem to indicate that their measured surfaces can be assumed to have a normal Gaussian distribution.

S.O. Rice derived an expression for the distribution of peaks in a normal Gaussian process (Sec. 2.4). If the average of peak moments of the surface form $x(\xi)$ reasonably matches with the average of peak moments of the S.O. Rice peak distribution, one can then conclude that the surface form $x(\xi)$ is normally distributed. Referring to Tables (5-1, 5-3), the average of peak moments matches extremely well for specimens SN1, SN4, SN62, SN63, G26, G21, and G27, up to the ninth moment. The rest of the specimens match up to the third moment, which is still a good match. The average of peak moments for the filtered measured surfaces also match up to the third moment. Moreover, Figure (5-1) shows a plot of the cumulative distribution of peaks for sample SNF62 compared to that of a Gaussian distribution. Both distributions seem to be reasonably close. Based on the above justifications, one can assume that the surface form $x(\xi)$ is normally distributed.

5.2 PREDICTIONS USING THE FIRST-PASSAGE CRITERIA

Considering the surface form $x(\xi)$, where $x(\xi)$ is traced over a sampling length $L_s$, resulting with a deepest scratch $V_D^*$, where one is interested in predicting the deepest scratch $V_D^*$ over a sampling
length $\beta L_{5}$. The problem at hand falls under the category of "First-passage" problems [20]. In general such problems are very difficult and an exact solution for the present case is unknown [21]. To visualize the situation, imagine the ensemble of samples $x(\xi)$. Each sample $x(j)$ reaches the value $V_{0}^{*}$ at a distance $r_{j}$ in a sampling length $L_{5}$. The ensemble of these values of $L$ have some kind of a distribution. The problem would be completely solved if this distribution $p(L)$ could be found. Moreover, it would be very helpful if the mean and variance of this distribution could be related to known statistical parameters of the process $x(\xi)$. Some information that bears on the result is available [22]. If the joint probability of $x(\xi)$ and $x_{2}(\xi)$ is known, then the expected number of crossings of the level $x = b$ with positive slope per unit distance is:

$$v_{b}^{+} = \int_{0}^{\infty} x_{2}p(b,x_{2})dx_{2}$$

(5-1)

where $x_{2}$ is the first derivative of $x$.

In particular if the process $x(\xi)$ is a Gaussian process with zero mean then

$$v_{b}^{+} = \frac{1}{2\pi} \frac{\sigma_{2}}{\sigma_{1}} \exp(-\frac{b^{2}}{2\sigma_{1}^{2}})$$

(5-2)

One can proceed a little further on the basis of a conservative assumption that the crossing of the level $x = b$ from below occurs at a sequence of increments $\xi_k$. This would then constitute a very particular random process known as Poisson's process [23]. In particular, the probability density function for first-passage in a Poisson process is an exponential function. This function has a single parameter related to the expected rate of crossings from below $v_{b}^{+}$. 
\[ P(b, L) = \nu_b^+ \exp(-\nu_b^+ L) \quad L \geq 0 \] (5-4)

Based on that assumption the complete solution for the first-passage problem is attainable. The mean and standard deviation for the Poisson distribution would then be

\[ E[L] = \frac{1}{\nu_b^+} \] (5-5)

\[ E[L^2] = \frac{1}{\nu_b^+} \] (5-6)

hence, the probability of having a deepest scratch; \( P(|x| < b) \) in a sampling length \( L_s \) is given by

\[ P(b, L_s) = \int_0^{L_s} p(L) dL \] (5-7)

and

\[ P(b, L_s) = \exp(-\nu_b^+ L_s) \] (5-8)

therefore from equations (5-3) and (5-8):

\[ P(b, L_s) = \exp\left[\frac{-L_s}{2\pi} \frac{\sigma_2}{\sigma_1} \exp(-b^2/2\sigma_1^2)\right] \] (5-9)

Furthermore, Chebyshev's Inequality enables one to find the upper (or lower) bounds for certain probabilities. These bounds, however, are not necessarily close to the exact probabilities and, accordingly, they are only used in theoretical discussions or to get a conservative estimate of the probabilities involved. For a random variable \( x(\xi) \) with standard deviation \( \sigma_1 \) and zero mean; it follows [24] that
P(|x| \geq k\sigma_1) \leq \frac{1}{k^2} \quad k > 0 \quad (5-10)

or equivalently

P(|x| < k\sigma_1) \geq 1 - \frac{1}{k^2} \quad k > 0 \quad (5-11)

If one assumes that this upper (or lower) bound probability is equal to the first-passage probability, then from equations (5-9) and (5-11) it follows that the permissible deepest scratch \( V_D^* \) in a sampling length \( \beta L_s \) is

\[
V_D^* = \{-2\ln \left[ \frac{\lambda_{rms}}{\beta L_s} \right] \}^{1/2} \sigma_1^{1/2} \quad k > 0 \quad (5-12)
\]

where \( \lambda_{rms} \) is the root means square wavelength and

\[
\lambda_{rms} = 2\pi \frac{\sigma_1}{\sigma_2} \quad (5-13)
\]

using equation (5-12), the deepest scratch \( V_D^* \) was predicted for sampling lengths \((L_s = 2" , \ L_s = 40', \ L_s = 1000')\). The deepest scratch \( V_D^* \) was predicted for \( L_s = 2" \) to find out how well this method of prediction works. Since the outcome of the measured surface was known, it was assumed that \( P(b,L_s) = 99.99\% \). Referring to table (5-5) the predicted values for \( V_D^* \) were a bit lower for samples SNF1 and SNF63, but overall the predicted values were within 300 microinches. Moreover, higher predicted values would result in a smaller number of cycles to failure which is a conservative result. Sample SNF63 was predicted to have a deepest scratch of 3407 microinches which is lower than the measured 3700 microinches. All the other predicted values seem to be acceptable.
Using the measured values of the deepest scratch $V_D^*$ and $a_1$ ($L_s = 2''$), one can obtain $k = V_D^* / a_1$. Substituting $k$ in equation (5-12) with $\beta L_s = 40'$ or $\beta L_s = 1000'$, one can predict the new value of $V_D^*$ for ($L_s = 40'$, $L_s = 1000'$). The predicted values are tabulated in table (5-5).

The next step is to predict the number of cycles to failure. Using the value $a_3^*$ from the measured surfaces ($L_s = 2''$) together with predicted values for $V_D^*$ and the single scratch spectra figure (4-25), the number of cycles to failure can be predicted at any stress level. The predicted values of cycles to failure for the different cases are also tabulated in Table (5-5). Figures (5-2 and 5-3) show that the predicted values of cycles to failure ($L_s = 2''$) fall within the 95% confidence bands for both the Mannesmann pipe specimens and the ground (24 grit) specimens (at the same stress ranges). The predicted cycles compared very well with the measured cycles. Moreover, the predicted cycles were on the low side in all the cases except for SN63. Even then, the predicted value was still within the 95% confidence bond. Similarly, figures (5-4, 5-5, 5-6, and 5-7) show that the predicted life was less than the measured life in all the cases. Hence, one can conclude that the theoretical predictions utilizing the First-passage criteria yielded conservative estimates of fatigue life when used with the single scratch spectra.

5.3 PREDICTIONS USING THE METHOD OF MOMENTS

A probabilistic model remains abstract until it has been related to observations. The outcome of these observations (data), yields numerical estimates of the parameters that can be used to verify a proposed model. If the estimation of parameters is based on a practical
sample size, the chances of having a good verification are better. The method of moments [25] employs the moments of the numerical data to match with the moments of the proposed model.

If the surface form \( x(\xi) \) is Gaussian, then the moments of the measured data can be assumed to be the moments of the distribution. Since a Gaussian distribution is defined by its variance and mean, then the estimator \( m_1 \) of \( m_x \) should be the sample mean and the estimator \( \sigma^2_1 \) of \( \sigma^2_x \) should be the variance of the sample, therefore:

\[
m_1 = m_x = \frac{1}{n} \sum_{i=1}^{n} x_i
\]

\[
\sigma^2_1 = \sigma^2_x = \frac{1}{n} \sum_{i=1}^{n} (x_i - m_x)^2
\]

where \( n \) is the number of samples and the sample coefficient of variation is

\[
S = \frac{\sigma_1}{m_1}
\]

Moreover, the derivatives of \( x(\xi) \), \( x'(\xi) \) and \( x''(\xi) \) would be also normally distributed and the estimators of \( \sigma_2 \) and \( \sigma^*_3 \) can be also calculated in the same fashion. Given the parameters in equations (5-14) and (5-15) the engineer can make such statements as the probability is 5 percent that the deepest scratch \( V_D^* \) of any particular sample will be less than \( (m_1 - 1.65\sigma_1) \) where \( m_1 \) is the mean value of all the deepest scratches in the different samples and \( \sigma_1 \) is the standard deviation from that mean.

The average values for \( V_D^* \), \( \sigma_2 \) and \( \sigma^*_3 \) were calculated for the measured depths \( (L_s = 2") \) and the predicted depths \( (L_s = 40', L_s \)
= 1000'). These values are tabulated in table (5-6). Using the single scratch spectra, the number of cycles to failure were predicted for the different cases, table (5-7). The predicted cycles to failure for \( L_s = 2'' \) were generally on the high side when compared with the measured cycles to failure, but they still fell within the 95% confidence bands of the Mannesmann pipe specimens, figure (5-8).

For the ground (24 grit) specimens, the predicted cycles fell on the mean line, figure (5-9). From these results one can conclude that this averaging approach seems to work very well especially in the case of the ground (24 grit) specimens. Moreover, for \( L_s = 40', L_s = 1000' \), the predicted cycles were on the low side and the results were conservative, figures (5-10 through 5-13). The advantages of using this approach are to the engineer who has data from different specimens and would like to make a statement about the behavior of these data. For example, in the Mannesmann pipe specimens case \( L_s = 40' \), the engineer could say that there is a five percent chance that his predicted value for \( V_0^* \) would be less than \( [3786 - 1.65(839)] = 2402\mu'' \). This approach can be utilized with distributions other than the normal distribution, and is one way to completely define a model.
FIGURE 5-1 Cumulative Distribution of Specimen SWF62 (Filtered) in Comparison with a Gaussian Distribution.
### Table (5-1)

**Manesmann Surface Profile**

Average of peak moments using positive peak extrema

Values in parenthesis Eq. [2-27, 2-30]

<table>
<thead>
<tr>
<th></th>
<th>SN1</th>
<th>SN2</th>
<th>SN3</th>
<th>SN4</th>
<th>SN5</th>
<th>SN6</th>
<th>SN61</th>
<th>SN62</th>
<th>SN63</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>0.10</td>
<td>0.08</td>
<td>0.12</td>
<td>0.17</td>
<td>0.09</td>
<td>0.10</td>
<td>0.09</td>
<td>0.12</td>
<td>0.09</td>
</tr>
<tr>
<td>(M_1)</td>
<td>0.811</td>
<td>0.894</td>
<td>0.763</td>
<td>0.805</td>
<td>0.707</td>
<td>0.739</td>
<td>0.804</td>
<td>0.793</td>
<td>0.786</td>
</tr>
<tr>
<td></td>
<td>(0.842)</td>
<td>(0.832)</td>
<td>(0.853)</td>
<td>(0.875)</td>
<td>(0.838)</td>
<td>(0.842)</td>
<td>(0.838)</td>
<td>(0.853)</td>
<td>(0.838)</td>
</tr>
<tr>
<td>(M_3)</td>
<td>1.894</td>
<td>2.185</td>
<td>1.248</td>
<td>1.941</td>
<td>1.375</td>
<td>1.283</td>
<td>1.500</td>
<td>1.809</td>
<td>1.839</td>
</tr>
<tr>
<td></td>
<td>(1.809)</td>
<td>(1.760)</td>
<td>(1.876)</td>
<td>(1.946)</td>
<td>(1.792)</td>
<td>(1.809)</td>
<td>(1.792)</td>
<td>(1.876)</td>
<td>(1.792)</td>
</tr>
<tr>
<td></td>
<td>(7.584)</td>
<td>(7.340)</td>
<td>(7.596)</td>
<td>(8.885)</td>
<td>(7.410)</td>
<td>(7.584)</td>
<td>(7.410)</td>
<td>(7.596)</td>
<td>(7.410)</td>
</tr>
<tr>
<td>(M_7)</td>
<td>49.28</td>
<td>98.49</td>
<td>14.40</td>
<td>58.06</td>
<td>24.46</td>
<td>17.80</td>
<td>16.64</td>
<td>43.16</td>
<td>53.93</td>
</tr>
<tr>
<td></td>
<td>(48.13)</td>
<td>(45.64)</td>
<td>(48.88)</td>
<td>(57.09)</td>
<td>(46.01)</td>
<td>(48.13)</td>
<td>(46.01)</td>
<td>(48.88)</td>
<td>(46.01)</td>
</tr>
<tr>
<td>(M_9)</td>
<td>336.0</td>
<td>1013.80</td>
<td>70.00</td>
<td>446.7</td>
<td>131.1</td>
<td>87.4</td>
<td>71.5</td>
<td>271.9</td>
<td>383.80</td>
</tr>
<tr>
<td></td>
<td>(391.8)</td>
<td>(377.60)</td>
<td>(393.7)</td>
<td>(486.9)</td>
<td>(379.3)</td>
<td>(391.8)</td>
<td>(379.3)</td>
<td>(393.7)</td>
<td>(379.3)</td>
</tr>
<tr>
<td></td>
<td>SNF1</td>
<td>SNF2</td>
<td>SNF3</td>
<td>SNF4</td>
<td>SNF5</td>
<td>SNF6</td>
<td>SNF61</td>
<td>SNF62</td>
<td>SNF63</td>
</tr>
<tr>
<td>-----</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.23</td>
<td>0.23</td>
<td>0.24</td>
<td>0.18</td>
<td>0.18</td>
<td>0.17</td>
<td>0.21</td>
<td>0.19</td>
<td>0.27</td>
</tr>
<tr>
<td>$M_1$</td>
<td>0.7560</td>
<td>0.8150</td>
<td>0.7950</td>
<td>0.8510</td>
<td>0.8050</td>
<td>0.8760</td>
<td>0.8250</td>
<td>0.8750</td>
<td>0.802</td>
</tr>
<tr>
<td></td>
<td>(0.9009)</td>
<td>(0.9009)</td>
<td>(0.9014)</td>
<td>(0.8869)</td>
<td>(0.8869)</td>
<td>(0.8825)</td>
<td>(0.8922)</td>
<td>(0.8834)</td>
<td>(0.9185)</td>
</tr>
<tr>
<td>$M_3$</td>
<td>2.887</td>
<td>2.805</td>
<td>1.781</td>
<td>2.207</td>
<td>2.023</td>
<td>2.443</td>
<td>2.532</td>
<td>2.383</td>
<td>2.717</td>
</tr>
<tr>
<td></td>
<td>(2.103)</td>
<td>(2.103)</td>
<td>(2.125)</td>
<td>(1.992)</td>
<td>(1.992)</td>
<td>(1.969)</td>
<td>(2.058)</td>
<td>(2.014)</td>
<td>(2.191)</td>
</tr>
<tr>
<td>$M_7$</td>
<td>449.81</td>
<td>284.58</td>
<td>53.13</td>
<td>98.01</td>
<td>83.49</td>
<td>164.66</td>
<td>189.63</td>
<td>111.23</td>
<td>532.66</td>
</tr>
<tr>
<td></td>
<td>(61.51)</td>
<td>(61.51)</td>
<td>(62.56)</td>
<td>(56.28)</td>
<td>(56.28)</td>
<td>(56.17)</td>
<td>(59.42)</td>
<td>(57.32)</td>
<td>(65.69)</td>
</tr>
<tr>
<td>$M_9$</td>
<td>8110.2</td>
<td>4398.2</td>
<td>425.8</td>
<td>991.6</td>
<td>830.6</td>
<td>2063.6</td>
<td>2569.4</td>
<td>1151.6</td>
<td>12,274.9</td>
</tr>
<tr>
<td></td>
<td>(530.8)</td>
<td>(530.8)</td>
<td>(540.9)</td>
<td>(480.5)</td>
<td>(480.5)</td>
<td>(470.4)</td>
<td>(510.7)</td>
<td>(490.5)</td>
<td>(571.1)</td>
</tr>
</tbody>
</table>
TABLE (5-3)

GROUND (24 GRIT) SURFACE PROFILE
AVERAGE OF PEAK MOMENTS USING POSITIVE PEAK EXTREMA
VALUES IN PARENTHESIS, EQ. (2-27, 2-30)

<table>
<thead>
<tr>
<th></th>
<th>G26</th>
<th>G21</th>
<th>G48</th>
<th>G27</th>
<th>G23</th>
<th>G34</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.22</td>
<td>0.20</td>
<td>0.14</td>
<td>0.27</td>
<td>0.13</td>
<td>0.15</td>
</tr>
<tr>
<td>$M_1$</td>
<td>0.7870</td>
<td>0.8220</td>
<td>0.8770</td>
<td>0.7720</td>
<td>0.8610</td>
<td>0.8280</td>
</tr>
<tr>
<td></td>
<td>(0.8966)</td>
<td>(0.8878)</td>
<td>(0.8611)</td>
<td>(0.9185)</td>
<td>(0.8567)</td>
<td>(0.8655)</td>
</tr>
<tr>
<td>$M_3$</td>
<td>1.970</td>
<td>1.975</td>
<td>1.728</td>
<td>1.74</td>
<td>1.768</td>
<td>1.755</td>
</tr>
<tr>
<td></td>
<td>(2.081)</td>
<td>(2.036)</td>
<td>(1.903)</td>
<td>(2.191)</td>
<td>(1.881)</td>
<td>(1.925)</td>
</tr>
<tr>
<td>$M_7$</td>
<td>59.07</td>
<td>76.70</td>
<td>23.46</td>
<td>55.85</td>
<td>28.87</td>
<td>33.04</td>
</tr>
<tr>
<td></td>
<td>(60.46)</td>
<td>(58.37)</td>
<td>(52.26)</td>
<td>(65.69)</td>
<td>(51.20)</td>
<td>(53.25)</td>
</tr>
<tr>
<td>$M_9$</td>
<td>418.0</td>
<td>703.7</td>
<td>115.3</td>
<td>369.9</td>
<td>158.2</td>
<td>191.3</td>
</tr>
<tr>
<td></td>
<td>(520.7)</td>
<td>(500.6)</td>
<td>(441.3)</td>
<td>(571.1)</td>
<td>(434.1)</td>
<td>(451.7)</td>
</tr>
<tr>
<td></td>
<td>G26</td>
<td>G21</td>
<td>G48</td>
<td>G27</td>
<td>G23</td>
<td>G34</td>
</tr>
<tr>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>α</td>
<td>0.56</td>
<td>0.49</td>
<td>0.49</td>
<td>0.53</td>
<td>0.66</td>
<td>0.51</td>
</tr>
<tr>
<td>$M_1$</td>
<td>0.962</td>
<td>0.951</td>
<td>0.9000</td>
<td>0.9850</td>
<td>0.9550</td>
<td>0.9810</td>
</tr>
<tr>
<td></td>
<td>(1.0454)</td>
<td>(1.0146)</td>
<td>(1.0146)</td>
<td>(1.0322)</td>
<td>(1.0894)</td>
<td>(1.0234)</td>
</tr>
<tr>
<td>$M_3$</td>
<td>3.073</td>
<td>2.682</td>
<td>2.672</td>
<td>2.682</td>
<td>3.186</td>
<td>2.802</td>
</tr>
<tr>
<td></td>
<td>(2.841)</td>
<td>(2.686)</td>
<td>(2.686)</td>
<td>(2.775)</td>
<td>(3.062)</td>
<td>(2.731)</td>
</tr>
<tr>
<td>$M_5$</td>
<td>29.92</td>
<td>16.55</td>
<td>21.83</td>
<td>14.81</td>
<td>23.26</td>
<td>19.57</td>
</tr>
<tr>
<td></td>
<td>(13.80)</td>
<td>(12.89)</td>
<td>(12.89)</td>
<td>(13.41)</td>
<td>(15.10)</td>
<td>(13.15)</td>
</tr>
<tr>
<td>$M_7$</td>
<td>209.61</td>
<td>163.40</td>
<td>315.94</td>
<td>127.49</td>
<td>252.46</td>
<td>275.38</td>
</tr>
<tr>
<td></td>
<td>(95.47)</td>
<td>(88.61)</td>
<td>(88.61)</td>
<td>(92.53)</td>
<td>(105.27)</td>
<td>(90.57)</td>
</tr>
<tr>
<td>$M_9$</td>
<td>2655.3</td>
<td>2118.1</td>
<td>5996.9</td>
<td>1454.6</td>
<td>3506.6</td>
<td>5958.6</td>
</tr>
<tr>
<td></td>
<td>(854.4)</td>
<td>(790.2)</td>
<td>(790.2)</td>
<td>(826.9)</td>
<td>(946.0)</td>
<td>(808.6)</td>
</tr>
<tr>
<td>SPECIMEN DESIGNATION</td>
<td>STRESS RANGE (KSI)</td>
<td>MEASURED $V_s$ (in)</td>
<td>PREDICTED $V_s(V_s)$ (in)</td>
<td>PREDICTED $V_s(V_s)$ (in)</td>
<td>PREDICTED $V_s(V_s)$ (in)</td>
<td>PREDICTED $V_s(V_s)$ (in)</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------</td>
<td>---------------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>SN1</td>
<td>66.03</td>
<td>2516</td>
<td>2516</td>
<td>2800</td>
<td>2955</td>
<td>0.000885</td>
</tr>
<tr>
<td>SN2</td>
<td>63.62</td>
<td>2788</td>
<td>2788</td>
<td>3085</td>
<td>3296</td>
<td>0.000860</td>
</tr>
<tr>
<td>SN3</td>
<td>68.15</td>
<td>1694</td>
<td>2317</td>
<td>2527</td>
<td>2720</td>
<td>0.001124</td>
</tr>
<tr>
<td>SN4</td>
<td>46.64</td>
<td>3177</td>
<td>3617</td>
<td>3970</td>
<td>4250</td>
<td>0.000828</td>
</tr>
<tr>
<td>SN5</td>
<td>47.92</td>
<td>3126</td>
<td>3517</td>
<td>3877</td>
<td>4160</td>
<td>0.000935</td>
</tr>
<tr>
<td>SN6</td>
<td>46.47</td>
<td>3228</td>
<td>3532</td>
<td>3833</td>
<td>4154</td>
<td>0.001049</td>
</tr>
<tr>
<td>SN61</td>
<td>35.96</td>
<td>4238</td>
<td>4531</td>
<td>5002</td>
<td>5358</td>
<td>0.000608</td>
</tr>
<tr>
<td>SN62</td>
<td>36.46</td>
<td>3886</td>
<td>4639</td>
<td>5111</td>
<td>5503</td>
<td>0.000607</td>
</tr>
<tr>
<td>SN63</td>
<td>43.90</td>
<td>3700</td>
<td>3407</td>
<td>3516</td>
<td>4092</td>
<td>0.000773</td>
</tr>
<tr>
<td>G26</td>
<td>73.76</td>
<td>605</td>
<td>690</td>
<td>940</td>
<td>1026</td>
<td>0.001279</td>
</tr>
<tr>
<td>G21</td>
<td>64.70</td>
<td>787</td>
<td>773</td>
<td>1046</td>
<td>1141</td>
<td>0.001245</td>
</tr>
<tr>
<td>G27</td>
<td>64.70</td>
<td>685</td>
<td>605</td>
<td>819</td>
<td>893</td>
<td>0.001118</td>
</tr>
<tr>
<td>G23</td>
<td>82.34</td>
<td>575</td>
<td>622</td>
<td>842</td>
<td>918</td>
<td>0.001266</td>
</tr>
</tbody>
</table>

$SN$ - Hannemann Pipe Specimens

$G$ - Ground (24 Grit) Specimens

Predicted life is from single scratch spectra, using First Passage criteria to predict the deepest scratch and assuming measured surfaces to be Gaussian.
FATIGUE LIFE, N (CYCLES)  
Ground With 24 Grit

\[ N = 6.91 \times 10^{20} \times 20^{8.45} \]

Stress Range σ (ksi)

Figure 5-2: Denotes Predicted Life From Single Scratch Spectra And Using First Passage Criteria To Predict The Deepest Scratch Assuming A Gaussian Process With 99.99% Confidence, λ=2 Inches
FATIGUE LIFE, N (CYCLES)
Mannesmann Riser Pipe

\[ N = 1.87 \times 10^{11} \times \sigma_r^{-3.46} \]

Figure 5-3: Denotes Predicted Life From Single Scratch Spectra
And Using First Passage Criteria To Predict The Deepest Scratch
Assuming A Gaussian Process, And 99.99% Confidence, L_s=2 inches
FIGURE 5-4  FATIGUE LIFE, N (CYCLES)
Mannesmann Riser Pipe

\[ N = 1.87 \times 10^{11} S_r^{-3.46} \]

* Denotes Predicted Life From Single Scratch Spectra
And Using First Passage Criteria To Predict The Deepest Scratch
Assuming A Gaussian Process, Chebyshev’s Inequality, L_e=40 ft
Figure 5-5  Fatigue Life, N (Cycles)  
Ground With 24 Grit

\[ N = 5.79 \times 10^{19} \cdot S_r^{-7.77} \]

Predicted life from single scratch spectra and using first passage criteria to predict the deepest scratch assuming a Gaussian process, Chebyshev's inequality, \( L_s = 48 \text{ ft} \)
FIGURE 5-6  FATIGUE LIFE, N (CYCLES)
Mannesmann Riser Pipe

$N = 1.87 \times 10^{11} \text{ Sr}^{-3.46}$

* Denotes Predicted Life From Single Scratch Spectra
And Using First Passage Criteria To Predict The Deepest Scratch
Assuming A Gaussian Process, Chebyshov's Inequality, $L_s=1800 \text{ ft}$
FIGURE 5-7  FATIGUE LIFE, N (CYCLES)
Ground With 24 Grit

N = 5.79 \times 10^{19} S_r^{-7.77}

* Denotes Predicted Life From Single Scratch Spectra
And Using First Passage Criteria To Predict The Deepest Scratch
Assuming A Gaussian Process, Chebychev's Inequality, L_x = 1000 ft
<table>
<thead>
<tr>
<th></th>
<th>MANNESMANN PIPE SPECIMENS</th>
<th></th>
<th>GROUND (24 GRIT) SPECIMENS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( L_s = 2' )</td>
<td>( L_s = 40' )</td>
<td>( L_s = 1000' )</td>
</tr>
<tr>
<td>( \tilde{V}_D(\mu') )</td>
<td>3162</td>
<td>3786</td>
<td>4059</td>
</tr>
<tr>
<td>( \sigma_{VD}(\mu') )</td>
<td>712</td>
<td>839</td>
<td>903</td>
</tr>
<tr>
<td>( s )</td>
<td>0.225</td>
<td>0.222</td>
<td>0.222</td>
</tr>
<tr>
<td>( \sigma_1 )</td>
<td>0.2407</td>
<td>0.2407</td>
<td>0.2407</td>
</tr>
<tr>
<td>( \sigma_2(1/\mu') )</td>
<td>0.0008632</td>
<td>0.0008632</td>
<td>0.0008632</td>
</tr>
</tbody>
</table>
### TABLE (5-7)

**PREDICTED LIFE FOR ESTIMATORS OF TABLE (5-6) USING SINGLE SCRATCH SPECTRA**

<table>
<thead>
<tr>
<th>SPECIMEN DESIGNATION</th>
<th>STRESS RANGE (KSI)</th>
<th>ESTIMATED $V_D(\mu^*)$</th>
<th>ESTIMATED $V_B(\mu^*)$</th>
<th>ESTIMATED $V_B(\mu^*)$</th>
<th>PREDICTED $N_f(L_s = 2^{&quot;}$) (CYCLES)</th>
<th>PREDICTED $N_f(L_s = 40^{`}$) (CYCLES)</th>
<th>PREDICTED $N_f(L_s = 1000^{`}$) (CYCLES)</th>
<th>MEASURED $N_f$ (CYCLES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN1</td>
<td>68.03</td>
<td>3162</td>
<td>3786</td>
<td>4059</td>
<td>0.0008632</td>
<td>58,319</td>
<td>46,435</td>
<td>42,449</td>
</tr>
<tr>
<td>SN2</td>
<td>63.62</td>
<td>3162</td>
<td>3786</td>
<td>4059</td>
<td>0.0008632</td>
<td>80,973</td>
<td>62,866</td>
<td>56,531</td>
</tr>
<tr>
<td>SN3</td>
<td>68.15</td>
<td>3162</td>
<td>3786</td>
<td>4059</td>
<td>0.0008632</td>
<td>57,818</td>
<td>46,072</td>
<td>42,131</td>
</tr>
<tr>
<td>SN4</td>
<td>46.64</td>
<td>3162</td>
<td>3786</td>
<td>4059</td>
<td>0.0008632</td>
<td>370,334</td>
<td>249,438</td>
<td>213,132</td>
</tr>
<tr>
<td>SN5</td>
<td>47.92</td>
<td>3162</td>
<td>3786</td>
<td>4059</td>
<td>0.0008632</td>
<td>324,351</td>
<td>221,104</td>
<td>189,840</td>
</tr>
<tr>
<td>SN6</td>
<td>46.47</td>
<td>3162</td>
<td>3786</td>
<td>4059</td>
<td>0.0008632</td>
<td>377,015</td>
<td>253,528</td>
<td>216,485</td>
</tr>
<tr>
<td>SN61</td>
<td>35.96</td>
<td>3162</td>
<td>3786</td>
<td>4059</td>
<td>0.0008632</td>
<td>1,323,205</td>
<td>794,210</td>
<td>647,754</td>
</tr>
<tr>
<td>SN62</td>
<td>36.46</td>
<td>3162</td>
<td>3786</td>
<td>4059</td>
<td>0.0008632</td>
<td>1,236,691</td>
<td>746,840</td>
<td>610,627</td>
</tr>
<tr>
<td>SN63</td>
<td>43.90</td>
<td>3162</td>
<td>3786</td>
<td>4059</td>
<td>0.0008632</td>
<td>498,137</td>
<td>326,635</td>
<td>276,085</td>
</tr>
<tr>
<td>G26</td>
<td>73.76</td>
<td>635</td>
<td>912</td>
<td>995</td>
<td>0.001220</td>
<td>112,938</td>
<td>82,278</td>
<td>79,073</td>
</tr>
<tr>
<td>G21</td>
<td>64.70</td>
<td>635</td>
<td>912</td>
<td>995</td>
<td>0.001220</td>
<td>288,957</td>
<td>193,026</td>
<td>180,252</td>
</tr>
<tr>
<td>G27</td>
<td>64.70</td>
<td>635</td>
<td>912</td>
<td>995</td>
<td>0.001220</td>
<td>288,957</td>
<td>193,026</td>
<td>180,252</td>
</tr>
<tr>
<td>G23</td>
<td>82.34</td>
<td>635</td>
<td>912</td>
<td>995</td>
<td>0.001220</td>
<td>51,318</td>
<td>40,210</td>
<td>38,589</td>
</tr>
</tbody>
</table>

SN - Mannesmann Pipe Specimens  
G - Ground (24 Grit) Specimens
$N = 1.87 \times 10^{11} S_r^{-3.46}$

* Denotes Predicted Life from Single Scratch Spectra
And Using First Passage Criteria To Predict The Deepest Scratch
Assuming A Gaussian Process, Chebyshev's Inequality, $L_s=2$ inches
And Using The Method Of Moments To Calculate The Estimators For The Vd, Rms Slope, And Rms Curvature.
Figure 5-9  
FATIGUE LIFE, N (CYCLES)  
Ground With 24 Grit

\[ N = 6.91 \times 10^{20} \, Sr^{-8.45} \]

* Denotes Predicted Life From Single Scratch Spectra  
And Using First Passage Criteria To Predict The Deepest Scratch  
Assuming A Gaussian Process, Chebyshov's Inequality, L=2 inches  
And Using The Method Of Moments To Calculate The Estimators For The Vd, Rms Slope, And Rms Curvature.
FIGURE 5-10  FATIGUE LIFE, N (CYCLES)
Mannesmann Riser Pipe

\[ N = 1.07 \times 10^{11} \frac{S_r^{-3.46}}{ } \]

* Denotes Predicted Life From Single Scratch Spectra
And Using First Passage Criteria To Predict The Deepest Scratch
Assuming A Gaussian Process, Chebyshev's Inequality, L=48 ft
And Using The Method Of Moments To Calculate The Estimators For The Vd, Rms Slope, And Rms Curvature.
\[ N = 5.79 \times 10^{19} \quad S_r ^{-7.77} \]

* Denotes Predicted Life From Single Scratch Spectra  
And Using First Passage Criteria To Predict The Deepest Scratch  
Assuming A Gaussian Process, Chebyshev's Inequality, \( L_s = 40 \) ft  
And Using The Method Of Moments To Calculate The Estimators For The \( V_d, R_m, \) Slope, And \( R_m \) Curvature.
\[ N = 1.87 \times 10^{11} \cdot Sr^{-3.46} \]

- Denotes Predicted Life From Single Scratch Spectra
- And Using First Passage Criteria To Predict The Deepest Scratch
- Assuming A Gaussian Process, Chebyshev's Inequality, Lz=1000 ft
- And Using The Method Of Moments To Calculate The Estimators For The Vd, Rms Slope, And Rms Curvature.
Figure 5-13: Fatigue Life, N (cycles)
Ground With 24 Grit

N = 5.79 x 10^{19} \text{ Sr}^{-7.77}

* Denotes Predicted Life From Single Scratch Spectra
And Using First Passage Criteria To Predict The Deepest Scratch
Assuming A Gaussian Process, Chebyshev's Inequality, L_s=1000 \text{ ft}
And Using The Method Of Moments To Calculate The Estimators For The V_d, Rms Slope, And Rms Curvature.
CHAPTER IV

CONCLUSIONS

The objectives of this study were to establish a correlation between surface roughness parameters and fatigue crack initiation and to arrive at the functional relationships that would be used to predict fatigue failure.

Two surface roughness parameters were considered; namely the deepest scratch of a measured surface and the product of the deepest scratch with the rms valley curvature of that measured surface. The parameter that exhibited a high correlation coefficient with fatigue initiation was the product of the deepest scratch with the rms valley curvature \( V_D^* \times \sigma_3^* \). Using the regression relationships obtained for the S-N curves of single scratches that varied in depth from 0.004" to 0.020", a relationship was derived between cycles to failure, the stress range and the product \( (V_D^* \times \sigma_3^*) \). This relationship was utilized to predict failure given a stress range and the product \( (V_D^* \times \sigma_3^*) \) for a measured surface. The predicted cycles to failure, of two groups of specimens with different surface roughness characteristics, fell within the 95% confidence band of the measured cycles to failure. Moreover, the predicted cycles to failure were generally lower than the measured cycles and hence, tend to be more conservative for design purposes.

The next task was to predict the deepest scratch for samples that had much longer sampling lengths on the order of \( L_S = 40' \) and \( L_S = 1000' \) utilizing the measured surface characteristics of the specimens with a two inch sampling length. The First-passage criteria
were used to make those predictions. After predicting the deepest
scratch in the sampling lengths \( L_s = 40' \) and \( L_s = 1000' \), the product
\( (V_0^* \times \sigma_1^*) \) was calculated and predictions of cycles to failure were
made using the relationship established from the regression lines
of the single scratches. The results were encouraging and the predicted
cycles to failure fell within the 95% confidence band of the measured
cycles. Again, the predicted cycles were lower than the measured
cycles.

From the achieved results, one can conclude that by knowing the
surface characteristics \( (V_0^*, \sigma_1, \sigma_2, \sigma_3^*) \) of specimens having a small
sampling length, one can predict conservatively the cycles to failure
for much longer sampling lengths. Moreover, this method of prediction
can be used to compare the fatigue life of two different samples and
would give a good relative comparison.
REFERENCES


APPENDIX A

PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 613 microinches
STANDARD DEVIATION (rms) = 765 microinches
SKEWNESS = -.603
KURTOSIS = 2.824
NUMBER OF ZERO CROSSINGS = 244
TOTAL NUMBER OF PEAKS & VALLEYS = 2371
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1288
BAND WIDTH PARAMETER (ALPHA) = .102
THE FREQUENCY OF POSITIVE PEAKS = .845
THE RMS SLOPE = .1188
THE AVERAGE WAVE LENGTH = .0258 inches
THE RMS WAVE LENGTH = .0222 inches
THE RMS CURVATURE = .000146 1/inch.
THE RMS VALLEY CURVATURE = .000105 1/inch.
THE MINIMUM VALLEY CURVATURE = -.000584 1/inches w .007 inches
THE CURVATURE OF DEEPEST SCRATCH = .001166 1/inches w .160 inches
THE RANGE- 3931 microinches
THE DEEPEST VALLEY= -2501 microinches
THE MAXIMUM PEAK = 1430 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 9.319 w .167 inches

AVERAGE OF PEAK MOMENTS USING POSITIVE PEAK EXTREM
FIRST MOMENT M1 = .811
THIRD MOMENT M3 = 1.894
FIFTH MOMENT M5 = 6.427
SEVENTH MOMENT M7 = 49.273
NINTH MOMENT M9 = 336.001
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 243 microinches
STANDARD DEVIATION (rms) = 363 microinches
SKEWNESS = -.223
KURTOSIS = 8.52
NUMBER OF ZERO CROSSINGS = 660
TOTAL NUMBER OF PEAKS & VALLEYS = 2688
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1669
BAND WIDTH PARAMETER (ALPHA) = .227
THE FREQUENCY OF POSITIVE PEAKS = .575
THE RMS SLOPE = .2178
THE AVERAGE WAVE LENGTH = .0102 inches
THE RMS WAVE LENGTH = .0105 inches
THE RMS CURVATURE = .043 1/inches
THE RMS VALLEY CURVATURE = .085 1/inches
THE MINIMUM VALLEY CURVATURE = -7645 1/inches @ 0.000 inches
THE CURVATURE OF DEEPEST SPOUT = 1683 1/inches @ 1.508 inches
THE RANGE = 3553 microinches
THE DEEPEST VALLEY = -1565 microinches
THE MAXIMUM PEAK = 1648 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 2.348 1/inches

MEAN VALUE OF PEAK MOMENTS USING POSITIVE PEAK EXTREMUM
FIRST MOMENT M1 = .756
THIRD MOMENT M3 = 2.887
FIFTH MOMENT M5 = 29.973
SEVENTH MOMENT M7 = 449.81
NINTH MOMENT M9 = 6110.197
PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 626 microinches
STANDARD DEVIATION (rms) = 763 microinches
SKEWNESS = -.781
KURTOSIS = 3.139
NUMBER OF ZERO CROSSINGS = 158
TOTAL NUMBER OF PEAKS & VALLEYS = 2015
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1109
BAND WIDTH PARAMETER (ALPHA) = .079

THE FREQUENCY OF POSITIVE PEAKS = .55
THE RMS SLOPE = .2366
THE AVERAGE WAVE LENGTH = .0254 inches
THE RMS WAVE LENGTH = .0203 inches
THE RMS CURVATURE = .0000781/1/inches
THE RMS VALLEY CURVATURE = .0000761/1/inches
THE MINIMUM VALLEY CURVATURE = -.0090771/1/inches u .311 inches
THE CURVATURE OF DEEPEST SCRATCH = .0009531/1/inches u .083 inches
THE ANGLE = 41.11 microinches
THE DEEPEST VALLEY = -2598 microinches
THE MAXIMUM PEAK = 1173 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 15.439 u .534 inches

AVERAGE OF PEAK MOMENTS USING POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = .0894
THIRD MOMENT M3 = 2.181
FIFTH MOMENT M5 = 11.318
SEVENTH MOMENT M7 = 98.417
NINTH MOMENT M9 = 1013.799
PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 372 microinches
STANDARD DEVIATION (rms) = 351 microinches
SKEWNESS = -.701
KURTOSIS = 4.919
NUMBER OF ZERO CROSSINGS = 557
TOTAL NUMBER OF PEAKS & VALLEYS = 2407
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1417
BAND WIDTH PARAMETER (ALPHA) = .231
THE FREQUENCY OF POSITIVE PEAKS = .596
THE RMS SLOPE = .2349
THE AVERAGE WAVE LENGTH = .0111 inches
THE RMS WAVE LENGTH = .0195 inches
THE RMS CURVATURE = 978 1/inches
THE RMS VALLEY CURVATURE = 990 1/inches
THE MINIMUM VALLEY CURVATURE = -9870 1/inches & .511 inches
THE CURVATURE OF DEEPEST SCRATCH = 1989 1/inches & 1.672 inches
THE RANGE 3245 microinches
THE DEEPEST VALLEY = -1921 microinches
THE MAXIMUM PEAK = 1333 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 4.049 & .353 inches
AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .615
THIRD MOMENT M3 = 2.605
FIFTH MOMENT M5 = 22.902
SEVENTH MOMENT M7 = 284.584
NINTH MOMENT M9 = 4398.181
PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO

MEAN DEVIATION (CLA) = 552 microinches

STANDARD DEVIATION (rms) = 638 microinches

SKEWNESS = -.832

KURTOSIS = 3.172

NUMBER OF ZERO CROSSINGS = 435

TOTAL NUMBER OF PEAKS & VALLEYS = 2508

NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1399

BAND WIDTH PARAMETER (ALPHA) = .173

THE FREQUENCY OF POSITIVE PEAKS = .557

THE RMS SLOPE = .2534

THE AVERAGE WAVE LENGTH = .0194 inches

THE RMS WAVE LENGTH = .0173 inches

THE RMS CURVATURE = .000794 1/inches

THE RMS VALLEY CURVATURE = .000835 1/inches

THE MINIMUM VALLEY CURVATURE = -.004307 1/inches = .054 inches

THE CURVATURE OF DEEPEST SCRATCH = .000219 1/inches = 1.186 inches

THE RANGE = 3811 microinches

THE DEEPEST VALLEY = 2597 microinches

THE MAXIMUM PEAK = 1214 microinches

MAXIMUM VALUE OF VALLEY TANGENCY CURVATURE = .191 = .454 inches

AVERAGE OF PEAK MOMENTS USING

POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = .805
THIRD MOMENT M3 = 1.941
FIFTH MOMENT M5 = 9.005
SEVENTH MOMENT M7 = 58.057
NINTH MOMENT M9 = 446.718
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLM) = 392 microinches
STANDARD DEVIATION (rms) = 510 microinches
SKEWNESS = -.909
KURTOSIS = 3.846
NUMBER OF ZERO CROSSINGS = 463
TOTAL NUMBER OF PEAKS & VALLEYS = 2434
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1400
BAND WIDTH PARAMETER (ALPHA) = .182
THE FREQUENCY OF POSITIVE PEAKS = .555
THE RMS SLOPE = .2532
THE AVERAGE WAVE LENGTH = .0134 inches
THE RMS WAVE LENGTH = .0127 inches
THE RMS CURVATURE = .000794 1/inches
THE RMS VALLEY CURVATURE = .000629 1/inches
THE MINIMUM VALLEY CURVATURE = -.004507 1/inches
THE CURVATURE OF DEEPEST SCRATCH = .000219 1/inches
THE RANGE = 3245 microinches
THE DEEPEST VALLEY = -2055 microinches
THE MAXIMUM PEAK = 1190 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 6.044 vs .424 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .851
THIRD MOMENT M3 = 2.207
FIFTH MOMENT M5 = 12.145
SEVENTH MOMENT M7 = 96.014
NINTH MOMENT M9 = 991.636
PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 779 microinches
STANDARD DEVIATION (rms) = 975 microinches
SKEWNESS = -.6
KURTOSIS = 2.987
NUMBER OF ZERO CROSSINGS = 198
TOTAL NUMBER OF PEAKS & VALLEYS = 2256
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1225
BAND WIDTH PARAMETER (ALPHA) = .657
THE FREQUENCY OF POSITIVE PEAKS = .542
THE RMS SLOPE = .2124
THE AVERAGE WAVc LENGTH = .0334 inches
THE RMS WAVE LENGTH = .0236 inches
THE RMS CURVATURE = .000017 1/inches
THE RMS VALLEY CURVATURE = .000027 1/inches
THE MINIMUM VALLEY CURVATURE = -.000213 1/inches or 1.079 inches
THE CURVATURE OF DEEPEST SINK = .000003 1/inches or .481 inches
THE RANGE = 4270 microinches
THE DEEPEST VALLEY = -2767 microinches
THE MAXIMUM PEAK = 1482 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 8.337 x .447 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMES
FIRST MOMENT M1 = .707
THIRD MOMENT M3 = 1.375
FIFTH MOMENT M5 = 5.162
SEVENTH MOMENT M7 = 24.464
NINTH MOMENT M9 = 131.117
PROFILE STATISTICAL PROPERTIES

MEAN VALUE: Adjusted to Zero
MEAN DEVIATION (CLA) = 384 microinches
STANDARD DEVIATION (rms) = 513 microinches
SKEWNESS = -1.897
KURTOSIS = 4.302
NUMBER OF ZERO CROSSINGS = 429
TOTAL NUMBER OF PEAKS & VALLEYS = 2324
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1290
BAND WIDTH PARAMETER (ALPHA) = 0.184
THE FREQUENCY OF POSITIVE PEAKS = 0.595
THE RMS SLOPE = 0.2122
THE AVERAGE WAVE LENGTH = 0.0165 inches
THE AVERAGE WAVE LENGTH = 0.0192 inches
THE RMS CURVATURE = 0.003471 inches
THE RMS VALLEY CURVATURE = 0.001835 inches
THE MINIMUM VALLEY CURVATURE = 0.002113 inches = 0.0103 inches
THE CURVATURE OF DEEPEST SCRATCH = 0.001835 inches = 0.0103 inches
THE RANGE = 3.466 microinches
THE DEEPEST VALLEY = -2100 microinches
THE MAXIMUM PEAK = 1327 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 5.056 x 1.003 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = 0.005
THIRD MOMENT M3 = 2.023
FIFTH MOMENT M5 = 10.725
SEVENTH MOMENT M7 = 63.494
NINTH MOMENT M9 = 890.629
PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) - 652 microinches
STANDARD DEVIATION (RMS) - 1038 microinches
SKNOWNESS - -.553
KURTOSIS - 2.895
NUMBER OF ZERO CROSSINGS - 219
TOTAL NUMBER OF PEAKS & VALLEYS - 2031
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS - 1129
BAND WIDTH PARAMETER (ALPHA) = .163
THE FREQUENCY OF POSITIVE PEAKS - .553
THE RMS SLOPE = .2792
THE AVERAGE WAVE LENGTH = .0262 inches
THE RMS WAVE LENGTH = .0234 inches
THE RMS CURVATURE = .000029 1/inches
THE RMS VALLEY CURVATURE = .0001064 1/inches
THE MINIMUM VALLEY CURVATURE = -.010083 1/inches @ 1.124 inches
THE CURVATURE OF DEEPEST SCRATCH = .0000555 1/inches @ 1.045 inches
THE RANGE = 4215 microinches
THE DEEPEST VALLEY = -2760 microinches
THE MAXIMUM PEAK = 1435 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 9.764 @ .821 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = .738
THIRD MOMENT M3 = 1.283
FIFTH MOMENT M5 = 4.167
SEVENTH MOMENT M7 = 17.601
NINTH MOMENT M9 = .97.404
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 372 microinches
STANDARD DEVIATION (rms) = 498 microinches
SKEWNESS = -.443
KURTOSIS = 4.22
NUMBER OF ZERO CROSSINGS = 412
TOTAL NUMBER OF PEAKS & VALLEYS = 2407
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1340
BANDWIDTH PARAMETER (ALPHA) = .171
THE FREQUENCY OF POSITIVE PEAKS = .556
THE RMS SLOPE = .2787
THE AVERAGE WAVE LENGTH = .0124 inches
THE RMS WAVE LENGTH = .0113 inches
THE RMS CURVATURE = 381 1/inches
THE RMS VALLEY CURVATURE = 1049 1/inches
THE MINIMUM VALLEY CURVATURE = -10094 1/inches & 1.124 inches
THE CURVATURE OF DEEPEST SCRATCH = 9310 1/inches & .002 inches
THE RANGE = 4095 microinches
THE DEEPEST VALLEY = -2137 microinches
THE MAXIMUM PEAK = 1548 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 3.697 & 1.096 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = .076
THIRD MOMENT M3 = 2.443
FIFTH MOMENT M5 = 16.239
SEVENTH MOMENT M7 = 164.659
NINTH MOMENT M9 = 2063.579
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 1423 microinches
STANDARD DEVIATION (rms) = 1790 microinches
SKEWNESS = -.271
KURTOSIS = 2.646
NUMBER OF ZERO CROSSINGS = 99
TOTAL NUMBER OF PEAKS & VALLEYS = 1013
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 631
BANDWIDTH PARAMETER (ALPHA) = .087
THE FREQUENCY OF POSITIVE PEAKS = .532
THE RMS SLOPE = .2334
THE AVERAGE WAVE LENGTH = .0575 inches
THE RMS WAVE LENGTH = .0492 inches
THE RMS CURVATURE = .0000981/inches
THE RMS VALLEY CURVATURE = .0000401/inches
THE MINIMUM VALLEY CURVATURE = -.0000713/inches = .209 inches
THE CURVATURE OF DEEPEST SCRATCH = .0001101/inches = 1.345 inches
THE RANGE = 8126 microinches
THE DEEPEST VALLEY = -4546 microinches
THE MAXIMUM PEAK = 3861 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 17.247 @ .209 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .644
THIRD MOMENT M3 = 1.5
FIFTH MOMENT M5 = 4.485
SEVENTH MOMENT M7 = 16.64
NINTH MOMENT M9 = 71.532
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 476 microinches
STANDARD DEVIATION (rms) = 645 microinches
SKEWNESS = -0.557
KURTOSIS = 4.137
NUMBER OF ZERO CROSSINGS = 243
TOTAL NUMBER OF PEAKS & VALLEYS = 1133
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 681
DIP AND WIDTH PARAMETER (ALPHA) = .214
THE FREQUENCY OF POSITIVE PEAKS = .601
THE RMS SLOPE = .2308
THE AVERAGE WAVE LENGTH = .0195 inches
THE RMS WAVE LENGTH = .0176 inches
THE RMS CURVATURE = .0000568 1/inches
THE RMS VALLEY CURVATURE = .0000568 1/inches
THE MINIMUM VALLEY CURVATURE = -.0006714 1/inches & .209 inches
THE CURVATURE OF DEEPEST SCRATCH = .001077 1/inches & .327 inches
THE RANGE = 4770 microinches
THE DEEPEST VALLEY: -2019 microinches
THE MAXIMUM PEAK = 1951 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 6.103 & .073 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = 0.25
THIRD MOMENT M3 = 2.532
FIFTH MOMENT M5 = 17.699
SEVENTH MOMENT M7 = 189.625
NINTH MOMENT M9 = 2589.351
PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLR) = 1213 microinches
STANDARD DEVIATION (rms) = 1579 microinches
SKEWNESS = -0.526
KURTOSIS = 3.193
NUMBER OF ZERO CROSSINGS = 113
TOTAL NUMBER OF PEAKS & VALLEYS = 551
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 621
BAND WIDTH PARAMETER (mLPM) = .121
THE FREQUENCY OF POSITIVE PEAKS = .667
THE RMS SLOPE = .232
THE AVERAGE WAVE LENGTH = .048 inches
THE RMS WAVE LENGTH = .0439 inches
THE RMS CURVATURE = .000557 1/inches
THE RMS VALLEY CURVATURE = .000646 1/inches
THE MINIMUM VALLEY CURVATURE = -.000036 1/inches & .562 inches
THE CURVATURE OF DEEPEST SCRATCH = .000103 1/inches & 1.246 inches
THE RANGE = 7.438 microinches
THE DEEPEST VALLEY = -1.511 microinches
THE MAXIMUM PEAK = 4.880 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 12.005 x .976 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEEK EXTREMUM

FIRST MOMENT M1 = .793
THIRD MOMENT M3 = 1.808
FIFTH MOMENT M5 = 7.727
SEVENTH MOMENT M7 = 43.150
NINTH MOMENT M9 = 271.954
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 537 microinches
STANDARD DEVIATION (rms) = 762 microinches
SKEWNESS = -.407
KURTOSIS = 3.529
NUMBER OF ZERO CROSSINGS = 196
TOTAL NUMBER OF PEAKS & VALLEYS = 1004
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 593
BAND WIDTH PARAMETER (ALPHA) = .195
THE FREQUENCY OF POSITIVE PEAKS = .59
THE RMS SLOPE = .2388
THE AVERAGE WAVE LENGTH = .0213 inches
THE RMS WAVE LENGTH = .0191 inches
THE RMS CURVATURE = .000557 1/inches
THE RMS VALLEY CURVATURE = .000697 1/inches
THE MINIMUM VALLEY CURVATURE = -.000936 1/inches \& .982 inches
THE CURVATURE OF DEEPEST SCRATCH = .001757 1/inches \& .506 inches
THE RANGE = 4710 microinches
THE DEEPEST VALLEY = -2622 microinches
THE MAXIMUM PEAK = 2040 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 3.161 \& 1.319 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .875
THIRD MOMENT M3 = 2.303
FIFTH MOMENT M5 = 13.416
SEVENTH MOMENT M7 = 111.299
NINTH MOMENT M9 = 1151.638
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (DLA) = 1195 microinches
STANDARD DEVIATION (rms) = 1554 microinches
SKEWNESS = -.703
KURTOSIS = 3.254
NUMBER OF ZERO CROSSINGS = 56
TOTAL NUMBER OF PEAKS & VALLEYS = 1634
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 850
BANDWIDTH PARAMETER (ALPHA) = .997
THE FREQUENCY OF POSITIVE PEAKS = .63
THE RMS SLOPE = .2401
THE AVERAGE WAVE LENGTH = .9472 inches
THE RMS WAVE LENGTH = .0407 inches
THE RMS CURVATURE = .000082 1/inches
THE RMS VALLEY CURVATURE = .000074 1/inches
THE MINIMUM VALLEY CURVATURE = -.000052 1/inches = .074 inches
THE CURVATURE OF DEEPEST SCRATCH = .000091 1/inches = .176 inches
THE RANGE = 7546 microinches
THE DEEPEST VALLEY = -4836 microinches
THE MAXIMUM PEAK = 2720 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 36.728 = .074 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .786
THIRD MOMENT M3 = 1.833
FIFTH MOMENT M5 = 6.54
SEVENTH MOMENT M7 = 53.934
NINTH MOMENT M9 = 883.798
PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO

MEAN DEVIATION (CLA) = 373 microinches

STANDARD DEVIATION (rms) = 510 microinches

SKEWNESS = -.744

KURTOSIS = 5.184

NUMBER OF ZERO CROSSINGS = 316

TOTAL NUMBER OF PEAKS & VALLEYS = 1188

NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 749

BAND WIDTH PARAMETER (ALPHA) = .765

THE FREQUENCY OF POSITIVE PEAKS = .63

THE RMS SLOPE = .2387

THE AVERAGE WAVE LENGTH = .0143 inches

THE RMS WAVE LENGTH = .0134 inches

THE RMS CURVATURE = .000002 1/inches

THE RMS VALLEY CURVATURE = .000073 1/inches

THE MINIMUM VALLEY CURVATURE = -.016454 1/inches & .674 inches

THE CURVATURE OF DEEPEST SCRATCH = .009071 1/inches & .672 inches

THE RANGE = 4271 microinches

THE DEEPEST VALLEY = -2792 microinches

THE MAXIMUM PEAK = 1489 microinches

MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 4.508 & .561 inches

AVERAGE OF PEAK MOMENTS USING

POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = .802
THIRD MOMENT M3 = 2.717
FIFTH MOMENT M5 = 28.941
SEVENTH MOMENT M7 = 532.663
NINTH MOMENT M9 = 12274.941
**Profile Statistical Properties**

Mean Value Adjusted to Zero
Mean Deviation (CLA) - 452 microinches
Standard Deviation (rms) - 550 microinches
Skewness = -0.26
Kurtosis = 2.43

*Number of Zero Crossings* = 365
*Total Number of Peaks & Valleys* = 2451
*Number of Positive Peaks & Negative Valleys* = 1432

Band Width Parameter ($\alpha$) = 0.144
The Frequency of Positive Peaks = 0.584
The RMS Slope = 0.335
The Average Wave Length = 0.014 inches
The RMS Wave Length = 0.013 inches
The RMS Curvature = 0.0013 in/inches
The RMS Valley Curvature = 0.0019 in/inches
The Minimum Valley Curvature = 0.0050 in/inches $\times$ 0.673 inches
The Curvature of Deepest Scratch = 0.0015 in/inches $\times$ 1.107 inches
The Range = 3156 microinches
The Deepest Valley = -1547 microinches
The Maximum Peak = 1610 microinches
Maximum Value of Valley Times Curvature = 0.810 $\times$ 1.546 inches

**Average of Peak Moments Using Positive Peak Extrema**

First Moment $M_1 = 1.377$
Third Moment $M_3 = 1.723$
Fifth Moment $M_5 = 5.613$
Seventh Moment $M_7 = 23.455$
Ninth Moment $M_9 = 115.301$
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CMn) = 189 microinches
STANDARD DEVIATION (rms) = 163 microinches
SKEWNESS = 0.193
KURTOSIS = 4.856
NUMBER OF ZERO CROSSINGS = 1395
TOTAL NUMBER OF PEAKS & VALLEYS = 2764
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 2015
BAND WIDTH PARAMETER (ALPHA) = .467
THE FREQUENCY OF POSITIVE PEAKS = .722
THE RMS SLOPE = .3355
THE AVERAGE WAVE LENGTH = .00351 inches
THE RMS WAVE LENGTH = .00374 inches
THE RMS CURVATURE = 1318 1/inches
THE RMS VALLEY CURVATURE = 1207 1/inches
THE MINIMUM VALLEY CURVATURE = -664 1/inches = 1.673 inches
THE CURVATURE OF DEEPEST SCRATCH = 547 1/inches = 1.154 inches
THE RANGE OF CURVATURE = 1811 microinches
THE DEEPEST VALLEY = -664 microinches
THE MAXIMUM PEAK = 525 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 1.231 x .605 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .9
THIRD MOMENT M3 = 2.672
FIFTH MOMENT M5 = 21.631
SEVENTH MOMENT M7 = 315.941
NINTH MOMENT M9 = 5996.597
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 333 microinches
STANDARD DEVIATION (rms) = 455 microinches
SKEWNESS = .42
KURTOSIS = 3.564
NUMBER OF ZERO CROSSINGS = 635
TOTAL NUMBER OF PEAKS & VALLEYS = 2392
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1531
BAND WIDTH PARAMETER (ALPHA) = .255
THE FREQUENCY OF POSITIVE PEAKS = .64
THE RMS SLOPE = .2934
THE AVERAGE WAVE LENGTH = .00932 inches
THE RMS WAVE LENGTH = .00976 inches
THE RMS CURVATURE = .001204 1/inches
THE RMS VALLEY CURVATURE = .001157 1/inches
THE MINIMUM VALLEY CURVATURE = -.00566 1/inches @ 1.50d inches
THE CURVATURE OF DEEPEST SCRATCH = .00468 1/inches @ 1.097 inches
THE RANGE = 2731 microinches
THE DEEPEST VALLEY = -1265 microinches
THE MAXIMUM PEAK = 1445 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 4.500 x 1.045 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .772
THIRD MOMENT M3 = 1.974
FIFTH MOMENT M5 = 9.433
SEVENTH MOMENT M7 = 55.649
NINTH MOMENT M9 = 308.659
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 199 microinches
STANDARD DEVIATION (rms) = 190 microinches
SKEWNESS = -.495
KURTOSIS = 5.787
NUMBER OF ZERO CROSSINGS = 1452
TOTAL NUMBER OF PEAKS & VALLEYS = 2794
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 2023
Band Width Parameter (Alm) = .527
The Frequency of Positive Peaks = .734
The RMS Slope = .2978
The Average Wave Length = .0032 inches
The RMS Wave Length = .00294 inches
The RMS Curvature = 1209 1/inches
The RMS Valley Curvature = 1118 1/inches
The Minimum Valley Curvature = -13163 1/inches vs 0.000 inches
The Curvature of Deepest Scratch = 1551 1/inches & .574 inches
The Range = 1180 microinches
The Deepest Valley = 582 microinches
The Maximum Peak = 399 microinches
Maximum Value of Valley Times Curvature = .521 vs 1.867 inches

Average of Peak Moments Using Positive Peak Extrema
FIRST MOMENT M1 = .365
THIRD MOMENT M3 = 2.682
FIFTH MOMENT M5 = 14.886
SEVENTH MOMENT M7 = 127.491
NINTH MOMENT M9 = 1454.649
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 508 microinches
STANDARD DEVIATION (rms) = 630 microinches
SKEWNESS = .045
KURTOSIS = 2.67
NUMBER OF ZERO CROSSINGS = 306
TOTAL NUMBER OF PEAKS & VALLEYS = 2341
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1353
BAND WIDTH PARAMETER (ALPHA) = .13
THE FREQUENCY OF POSITIVE PEAKS = .577
THE RMS SLOPE = .2972
THE AVERAGE WAVE LENGTH = .0147 inches
THE RMS WAVE LENGTH = .0133 inches
THE RMS CURVATURE = .001216 1/ inches
THE RMS VALLEY CURVATURE = .001225 1/ inches
THE NINIMUM VALLEY CURVATURE = -.006310 1/ inches @ .086 inches
THE CURVATURE OF DEEPEST SCRATCH = .001755 1/ inches @ 1.193 inches
THE RANGE= 3525 microinches
THE DEEPEST VALLEY = -1565 microinches
THE MAXIMUM PEAK = 1568 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 6.585 @ .024 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .861
THIRD MOMENT M3 = 1.768
FIFTH MOMENT M5 = 6.25
SEVENTH MOMENT M7 = 28.867
NINTH MOMENT M9 = 158.177
PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 108 microinches
STANDARD DEVIATION (rms) = 144 microinches
SKEWNESS = -0.242
KURTOSIS = 4.111
NUMBER OF ZERO CROSINGS = 1056
TOTAL NUMBER OF PEAKS & VALLEYS = 2499
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1983
BAND WIDTH PARAMETER (ALPHA) = 0.562
THE FREQUENCY OF POSITIVE PEAKS = 0.795
THE RMS SLOPE = 0.3362
THE AVERAGE WAVE LENGTH = 0.00266 inches
THE RMS WAVE LENGTH = 0.00276 inches
THE RMS CURVATURE = 1273 1/inches
THE RMS VALLEY CURVATURE = 1266 1/inches
THE MINIMUM VALLEY CURVATURE = -0.672 1/inches θ 1.628 inches
THE CURVATURE OF DEEPEST SCRATCH = 28u0 1/inches θ 1.784 inches
THE RANGE = 1283 microinches
THE DEEPEST VALLEY = -575 microinches
THE MAXIMUM PEAK = 683 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = 0.482 θ 1.474 inches

AVERAGE OF PEAK MOMENTS USING
POSITIVE PEAK EXTREMA

FIRST MOMENT M1 = 0.955
THIRD MOMENT M3 = 3.186
FIFTH MOMENT M5 = 23.356
SEVENTH MOMENT M7 = 252.459
NINTH MOMENT M9 = 3505.642
PROFILE STATISTICAL PROPERTIES

MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 440 microinches
STANDARD DEVIATION (rms) = 553 microinches
SKEWNESS = -.257
KURTOSIS = 2.744
NUMBER OF ZERO CROSSINGS = 427
TOTAL NUMBER OF PEAKS & VALLEYS = 2763
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 1645
Band width parameter (ALPHA) = .154
The frequency of positive peaks = .595
The rms slope = .3136
The average wave length = .012 inches
The rms wave length = .0111 inches
The rms curvature = 1277 1/inch
The rms valley curvature = 1216 1/inch
The minimum valley curvature = -599 1/inch = 1.918 inches
The curvature of deepest scratch = 3587 1/inch = 1.805 inches
The range = 3245 microinches
The deepest valley = -1579 microinches
The maximum peak = 1675 microinches
Maximum value of valley times curvature = 5.774 w 1.662 inches

AVERAGE OF PEAK MOMENTS USING POSITIVE PEAK EXTREMA
First moment \( m_1 \) = .529
Third moment \( m_3 \) = 1.785
Fifth moment \( m_5 \) = 6.662
Seventh moment \( m_7 \) = 33.043
Ninth moment \( m_9 \) = 191.252
PROFILE STATISTICAL PROPERTIES
MEAN VALUE ADJUSTED TO ZERO
MEAN DEVIATION (CLA) = 118 microinches
STANDARD DEVIATION (rms) = 153 microinches
SKEWNESS = -.055
KURTOSIS = 4.098
NUMBER OF ZERO CROSSINGS = 1395
TOTAL NUMBER OF PEAKS & VALLEYS = 2743
NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = 2005
BAND WIDTH PARAMETER (ALPHA) = .508
THE FREQUENCY OF POSITIVE PEAKS = .73
THE RMS SLOPE = .3132
THE AVERAGE WAVE LENGTH = .00333 inches
THE RMS WAVE LENGTH = .00307 inches
THE RMS CURVATURE = 1277 1/inches
THE RMS VALLEY CURVATURE = 1211 1/inches
THE MINIMUM VALLEY CURVATURE = -5982 1/inches @ 1.516 inches
THE CURVATURE OF DEEPEST SCRATCH = 874 1/inches @ .574 inches
THE RANGE= 1433 microinches
THE DEEPEST VALLEY= -574 microinches
THE MAXIMUM PEAK = 859 microinches
MAXIMUM VALUE OF VALLEY TIMES CURVATURE = .661 @ .720 inches

AVERAGE OF PEAK MOMENTS USING POSITIVE PEAK EXTREMA
FIRST MOMENT M1 = .581
THIRD MOMENT M3 = 2.802
FIFTH MOMENT M5 = 19.565
SEVENTH MOMENT M7 = 275.375
NINTH MOMENT M9 = 5959.597
APPENDIX B

1000 REM PROGRAM FOR CONTROLLING FATIGUE TESTS AND FOR DATA ACQUISITION
1010 DIM V1(270), Range(4)
1020 PRINT 1, "PROGRAM FOR CONTROLLING FATIGUE TESTS AND FOR DATA ACQUISITION"
1030 INTEGER I,J,K,Min,N,NumberOfTests
1040 Maxdefl=0
1050 Cycles=0
1060 Page=0
1070 Lines=0
1080 Range(1)=1.5
1090 Range(2)=1.5
1100 Range(3)=0.6
1110 Range(4)=0.3
1120 ALLOCATE Rau(32), Volts(32)
1130 Junk=READ10(-10,6)
1140 Junk=READ10(-10,66)
1150 DIM Sk(30), A(100), B(130), C(130)
1160 INPUT "ENTER SPECIMEN ID","S"
1170 INPUT "ENTER MAXIMUM LOAD IN KIPS",M1
1180 INPUT "ENTER MINIMUM LOAD IN KIPS",M2
1190 INPUT "ENTER FREQUENCY",F
1200 IF F<1 THEN
1210 PRINT "FREQUENCY TOO LOW"
1220 GOTO 1190
1230 END IF
1240 IF F>10 THEN
1250 PRINT "FREQUENCY TOO HIGH"
1260 GOTO 1190
1270 END IF
1280 NumberOfTests=INT(270/F)
1290 FOR I=1 TO NumberOfTests
1300 A=SIN(2*3.14159/NumberOfTests)
1310 V(I)=INT(2500-400*A)
1320 NEXT I
1330 INPUT "ENTER WIDTH AND DEPTH OF SPECIMEN",W1,D1
1340 INPUT "NUMBER OF CYCLES BETWEEN READINGS",N
1350 INPUT "ENTER THE DEFORMATION RANGE (1,2,3, or 4)","R"
1360 A1=(M1+M2)/2
1370 As="MAXIMUM MINIMUM CYCLES TIME TOTAL"
1380 BS="LOAD DEFL LOAD DEFL"
1390 CS="KIPS IN KIPS IN"
1400 S=M1+W1/D1/2
1410 S=INT(S+100+.5)/100
1420 PRINT "MAX STRESS = ";S; " KSI"
1430 SI=S-(M1+M2)/4
1440 S2=(M1+M2)/1.6
1450 Setpoint=-(M1+M2)/2
1460 PRINT "APPROXIMATE SET POINT = ";Setpoint; " VOLTS"
1470 PRINT "APPROXIMATE SPAN = ";S2
1480 PRINT "BE SURE THAT THE LOAD RANGE IS 4 (10 KIPS)"
1490 PRINT "DEFLECTION RANGE IS "; A1; "(+ or -)(Range(R);" INCHES"
1500 PRINT "REORDER CHANNEL 2 IS STROKE."
1510 PRINT "REORDER CHANNEL 3 IS LOAD."
1520 INPUT "IS D TO A DEVICE TURNED ON? PRESS ENTER WHEN READY",R
1530 INPUT "BE SURE ALL PARAMETERS ARE SET ON MTS SYSTEM. ENTER WHEN READY",
RS
1540 Z=TIMEDATE
1550 INPUT "DO YOU WISH TO USE THE PRINTER? Y/N?",Y$;
1555 IF Y$="Y" THEN 1700
1570 INPUT "BE SURE PRINTER IS READY. PRESS ENTER.";J$
1580 GCLEAR
1590 GINIT
1600 GRAPHICS ON
1610 CSIZE 10
1620 MOVE 65,50
1630 LONG S
1640 LABEL "TEST IN PROGRESS"
1650 CSIZE 4
1660 MOVE 5,10
1670 LONG I
1680 LABEL "PRESS KEY 0 TO STOP TEST"
1690 PRINTER IS 701
1700 Page=Page+1
1710 IMAGE 0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,0000,0000
1720 PRINT "SPECIMEN ID: ";SS$;
1730 PRINT TAB(55);"PAGE NO. ";Page
1740 PRINT "MAXIMUM LOAD = ";M1$;" KIPS";TAB(55);DATE$(TIMEDATE)
1750 PRINT "MINIMUM LOAD = ";M2$;" KIPS";TAB(55);TIME$(TIMEDATE)
1760 PRINT "FREQUENCY = ";F1$;" HZ"
1770 PRINT "W11 INCHES AND DEPTH = ";D1$;" INCHES"
1780 PRINT "MAXIMUM STRESS = ";S1$;" KSI"
1790 PRINT
1800 PRINT
1810 PRINT A$
1820 PRINT B$
1830 PRINT C$
1840 PRINT
1850 FOR J=1 TO N
1860 FOR I=1 TO Number
1870 OUTPUT 706 USING ";.4D","V(I)
1880 NEXT I
1890 NEXT J
1900 PS=100
1910 FOR I=2500 TO 2500+PS STEP -S
1920 OUTPUT 706 USING ";.4D","I
1930 NEXT I
1940 K=0
1950 OUTPUT 706 USING ";.4D","2500+PS
1960 WAIT .1
1970 Junk=READ0(-18,64)
1980 Junk=READ0(-18,64)
1990 Pavg=0
2000 FOR I=1 TO 10
2010 P=READ0(-19,64)
2020 Raw=VAL(P,F.7)
2030 Volts=RPTS("Q",20)&Raw[21,32]
2040 V0=VAL(Volts,21)/409.5
2050 IF Raw[20,20]="J" THEN V0=V0
2060 Pavg=Pavg+V0/10
NEXT I

2070 IF ABS(Pavg-.9*M1)<.005 THEN 2170
2080 Pold=P9
2090 P9=P9+(.5*M1-A1)/(Pavg-A1)
2100 IF P9<550 THEN P9=550
2110 IF P9>1 THEN P9=1
2120 P9=(P9+Pold)/2
2130 K=K+1
2140 IF K>50 THEN 2900
2150 GOTO 1850
2160 Pmax=Pavg
2170 Davg=0
2180 Junk=READIO(-18,66)
2190 NEXT I
2200 FOR I=1 TO 10
2210 Def1=READIO(-18,66)
2220 Raw6=DVALS(Def1,2)
2230 Vq=DVAL(Voltz,2)/408.5
2240 IF Raw6(20,20)="1" THEN Vq=Vq
2250 Davg=Davg+Vq*Raw6(R)/100
2260 NEXT I
2270 Dmax=Davg
2280 FOR I=1 TO 10
2290 OUTPUT 706 USING "#,.4D";I
2300 NEXT I
2310 OUTPUT 706 USING "#,.4D";I
2320 Pavg=0
2330 Kmin=0
2340 OUTPUT 706 USING "#,.4D";I
2350 WAIT .1
2360 Junk=READIO(-18,64)
2370 Junk=READIO(-18,64)
2380 Pavg=0
2390 FOR I=1 TO 10
2400 P=READIO(-18,64)
2410 Raw6=DVALS(P,2)
2420 Vq=DVAL(Voltz,2)/408.5
2430 IF Raw6(20,20)="1" THEN Vq=Vq
2440 Pavg=Pavg+Vq/10
2450 NEXT I
2460 IF ABS(Pavg-M2)<.005 THEN 2570
2470 Pold=P9
2480 P9=P9+(M2-A1)/(Pavg-A1)
2490 IF P9>499 THEN P9=499
2500 IF P9<0 THEN P9=0
2510 P9=(P9+Pold)/2
2520 Kmin=Kmin+1
2530 IF Kmin>50 THEN 2900
2540 GOTO 2350
2550 Pmin=Pavg
2560 Davg=0
2570 Junk=READIO(-18,66)
2580 Junk=READIO(-18,66)
2610  FOR I=1 TO 10
2620    Def1=HEIQ(10,18,66)
2630    Raw=OVAL(Def1,2)
2640    Volts=RPT$("0",20)+Raw(21,32)
2650    VO=OVAL(Volts,21)/400.5
2660    IF Raw(20,20)="1" THEN VO=VO
2670    Duvg=Duvgr+VO*Range(1)/100
2680    NEXT I
2690    Dmin=Duvg
2700    FOR I=2500 TO 2500 STEP -10
2710      OUTPUT 706 USING "a,4D":I
2720    NEXT I
2730    Cycles=Cycles+N
2740    PRINT USING "171w;Pmax,Omeg,FMin,OMIN,Cycles,TIME(TIMEQATE-2),OMIN,OMax"
2750    Newmax=OMin-OMax
2760    IF Maxdef=0 THEN Maxdef=Newmax
2770    IF Newmax-Maxdef<0.03 THEN 2810
2780    Maxdef=Newmax
2790    N=INT(N/200)*100
2800    IF N<100 THEN N=100
2810    ON KEY 0 LABEL "STOP TEST" GOTO 2900
2820    CONTROL 1,121
2830    Lines=Lines+1
2840    IF Lines<42 THEN 1650
2850    FOR I=1 TO 12
2860      PRINT
2870    NEXT I
2880    Lines=0
2890    GOTO 1700
2900    OUTPUT 706 USING "a,4D":12500
2910    PRINTER IS 1
2920    GCLEAR
2930    GRAPHICS OFF
2940    END
REM PROGRAM TO FILTER MEASURED SURFACE PROFILES USING A FIVE POLE 
REM BUTTERWORTH DIGITAL FILTER

1000 OPTION BASE 1
1010 INPUT "ENTER FILE NAME", N$ 
1020 ASSIGN #Path1 TO N$ 
1030 ON END #Path1 GOTO 100 
1040 L=14000 ! Number of data points in 2 inch trace 
1050 ALLOCATE Q(L), W(L) 
1060 ENTER #Path1:Q(*) 
1070 PRINT "INPUT FILTER PERIOD IN INCHES"
1080 INPUT T 
1090 Q3=2/T 
1100 NS=0 
1110 N=5 
1120 K=2 
1130 S3=SIN(2*PI*Q3/T) 
1140 H1=-(S3^2) 
1150 DIM A3(S), B3(S), C3(S), D1(S), D2(S), E3(S) 
1160 FOR K1=1 TO K 
1170 A3(K1)=S3*SIN(PIN/2+(2*K1-1)) 
1180 B3(K1)=SQR(4*A3(K1)^2)-H1/2 
1190 C3(K1)=1/(SQR(B3(K1)+1)+SQR(B3(K1))) 
1200 D1(K1)=(2*A3(K1)*B3(K1)-1)*2*C3(K1)^2 
1210 D2(K1)=(-C3(K1)^4) 
1220 E3(K1)=1-D1(K1)-D2(K1) 
1230 NEXT K1 
1240 H2=2*S3^2+1-2*S3*SQR(S3^2+1) 
1250 G1=1-H2 
1260 NS=1 
1270 FOR K1=1 TO K 
1280 FOR K3=1 TO L 
1290 N4=K3+NS+(L+1-K3)*(1-NS) 
1300 K4=K3-1 
1310 IF K4>1 THEN 1350 
1320 K4=1 
1330 K5=K3-2 
1340 IF K5>1 THEN 1360 
1350 K5=1 
1360 IF K1+NS>1 THEN 1400 
1370 W(N4)=W(N4) 
1380 K6=K4+NS+(L+1-K4)+(1-NS) 
1390 K7=K5+NS+(L+1-K5)+(1-NS) 
1400 W(N4)=W(N4)-D1(K1)*(W(N4)-W(K6))-D2(K1)*(W(N4)-W(K7)) 
1410 NEXT K3 
1420 NS=0 
1430 NEXT K1 
1440 FOR K3=1 TO L 
1450 N4=K3+NS+(L+1-K3)*(1-NS) 
1460 K4=K3-1 
1470 IF K4>1 THEN 1510 
1480 K4=1 
1490 K5=K4+NS+(L+1-K4)*(1-NS) 
1500 W(N4)=G1+W(N4)+H2+W(K6)
1530 NEXT K3
1540 IF NS=1 THEN 1570
1550 NS=1
1560 GOTO 1590
1570 FOR I=1 TO 14000
1580 Q(I)-Q(I)-W(I)
1590 NEXT I
1600 PRINT CHR$(12)
1610 INPUT " Do you wish to save these data (Y/N)? (Default is 'Y').", Ans$
1620 IF Ans$="" THEN 1640
1630 IF Ans$="Y" THEN 1720
1640 INPUT " Enter the name of data file?", Names
1650 IF Names="" THEN 1640
1660 DISP "Saving data. Please do not disturb."
1670 Names=Names$(1,5)
1680 CREATE BCP Names$(1,8)
1690 ASSIGN WP2 TO Names
1700 ON END WP2 GOTO 1720
1710 OUTPUT WP2:Q(+)
1720 GINIT
1730 MOVE 0,50
1740 FOR I=1 TO 14000
1750 X=I/14000*130
1760 Y=Q(I)/70:50
1770 DRAW X,Y
1780 NEXT I
1790 END
REM A PROGRAM TO COMPUTE STATISTICAL PROPERTIES OF SURFACE PROFILES
1000 OPTION BASE 1
1010 INPUT "FILE NAME?", Name$
1020 IF Name$="" THEN 1020
1030 ASSIGN @Path! TO Name$
1040 ON END @Path! GOTO 1120
1050 REM DENOTE SURFACE VALUES BY SURF
1060 DIM Surf(14000)
1070 INTEGER I
1080 ENTER @Path!; Surf(*)
1090 REM CALCULATION OF THE PROFILE MEAN
1100 REM DENOTE MEAN VALUE MEAN
1120 S=0
1130 PLOTTER IS 3, "INTERNAL"
1140 GINIT
1150 GRAPHICS ON
1160 VIEWPORT 25.127.5.95
1170 WINDOW 0,14000,-5000,5000
1180 FRAME
1190 AXES 3500,1000
1200 LONG 5
1210 MOVE 7000,4500
1220 LABEL Name$
1230 LONG 8
1240 CSIZE 3
1250 CLIP OFF
1260 FOR I=5000 TO 5000.1 STEP 1000
1270 NS=VALS(I)+1
1280 MOVE 0,I
1290 LABEL NS
1300 NEXT I
1310 LONG 6
1320 X=0
1330 FOR I=1 TO 3
1340 X=X+.5
1350 NS=VALS(X)
1360 MOVE 3500+I,-150
1370 LABEL NS
1380 NEXT I
1390 CSIZE 4
1400 RAD
1410 LDIR PI/2
1420 MOVE -2500,0
1430 LABEL "SURFACE PROFILE - microinches"
1440 LDIR 0
1450 MOVE 7000,-4500
1460 LABEL "SAMPLING LENGTH - inches"
1470 MOVE 0,Surf(I)
1480 FOR I=1 TO 14000
1490 DRAW I,Surf(I)
1500 S=S+Surf(I)
1510 NEXT I
1520 Mean=S/14000
1530 REM CALCULATION OF CLA AND RMS, ETC.
1540 C=0
1550 E=0
1560 G=0
1570 L=0
1580 FOR I=1 TO 14000
1590 YI=Surf(I)-Mean
1500 C=C+ABS(Yt)
1510 E=E+Yt*Yt
1520 G=G+Yt*Yt+Yt
1530 L=L+Yt*Yt+Yt*Yt
1540 Surf(I)=Yt
1550 NEXT I
1560 C1a=C/14000
1570 Rm=SQR(E/14000)
1580 Skee=G(14000*Rm^2)
1590 Kurt=L/(14000*Rm^4)
1700 REM CALCULATION OF CURVATURE
1710 Inc=2*10^-6/14000
1720 C6=0
1730 LG=0
1740 D5=0
1750 F2=Surf(I)
1760 F3=Surf(I)
1770 Uj=0
1780 Uj=0
1790 L1=0
1800 L2=0
1810 T5=0
1820 G5=0
1830 G5=0
1850 T5=0
1850 V9=0
1870 Tol=20
1880 P=F3
1880 V=F3
1500 Pmax=-5000
1510 Pmin=5000
1520 Cur=0
1530 Curmin=0
1540 Vrho=0
1550 Ind=1
1560 FOR I=3 TO 13998
1570 F1=F2
1580 F2=F3
1590 F3=Surf(I)
2000 DS=(F3-F1)+.5/Inc
2010 O1=(2*(Surf(I)+Surf(I-2)+Surf(I-2))#F1-F3-2#F2)/T(IC^2)
2020 IF O1<Curmin THEN Curmin=O1
2030 IF Curmin=O1 THEN Imincur=I
2040 CS=C5*DS
2050 CS=CS+ABS(DS)
2060 LG=LG+DS+DS
2070 Uj=Uj+O1
2080 Wh=Wh+ABS(O1)
2090 Uj=Uj+O1+O1
2100 IF F2=F1 THEN 2470
2110 IF F3>F2 THEN T5=T5+1
2110 IF Ind=2 THEN 2230
2130 IF F2>P THEN
2140 P=F2
2150 IF P>Pmax THEN Pmax=P
2160 IF P>Pmax THEN Imax=I
2170 END IF
2180 IF F2>P-Tol THEN 2470
2190 L1=L1+1
Ind=2
P=-5000
GOTO 2390
IF Fz<=V THEN
V=Fz
IF Vrho<=Fz+01 THEN
Vrho=Fz+01
I=Vrho=1
END IF
IF V<=Vmin THEN Pmin=V
IF Pmin<=V THEN Imin=I
IF Imin=I THEN Cw=01
END IF
IF Fz<=V+11 THEN 2470
L=L+1
V=V+01
Vj=Vj+01
Ind=1
V=5000
IF (F3-Fz)+Fz>=0 THEN 2470
L2=L2+1
LS=ABS(Fz)
G=G+G+LS
G3=G3+LS
G5=G5+LS
G7=G7+LS
V8=V8+LS
V9=V9+LS
NEXT I
Abslope=CS/1398
Slope=CS/1398
Ris=ABS(SQR((LS/1398))
Avlen=2+PI+Clc/Abslope
Rms=Avlen+2+PI+Rms/Rislope
Rmcur=SQR((Uj/1398))
Rmscur=SQR(Vj/V0)
Range=Pmax-Pmin
T3=L2
J4=367/T3/Rms
J5=367/T3/Rms
J6=367/T3/Rms
J7=367/T3/Rms
J8=367/T3/Rms
J9=367/T3/Rms
J3=L1
J2=T5
T3=J2/J3
T4=J3/J3
PRINT "PROFILE STATISTICAL PROPERTIES"
PRINT "MEAN VALUE ADJUSTED TO ZERO";
PRINT "MEAN DEVIATION (CLA) = ";INT(Cla+.5);" microinches"
PRINT "STANDARD DEVIATION (rms) = ";INT(Rms+.5);" microinches"
PRINT "SKEWNESS = ";INT(Skw+1000)/1000
PRINT "KURTOSIS = ";INT(Kurt+1000)/1000
PRINT "NUMBER OF ZERO CROSSINGS = ";J2
PRINT "TOTAL NUMBER OF PEAKS & VALLEYS = ";J3
PRINT "NUMBER OF POSITIVE PEAKS & NEGATIVE VALLEYS = ";J2
PRINT "BAND WIDTH PARAMETER (ALPHA) = ";INT(T3+1000)/1000
PRINT "THE FREQUENCY OF POSITIVE PEAKS = ";INT(T4+1000)/1000
PRINT "THE RMS SLOPE = ";GROUND(Rmslope,4)
PRINT "THE AVERAGE WAVE LENGTH = ";GROUND(Avlen/1000000,3);" inches"
PRINT "THE RMS WAVE LENGTH = "; (ROUND(Renal/1000000,3))" inches"
PRINT USING "14A,MODDDDDDD,9A"; "THE RMS CURVATURE = ",Rnscur*1000000,1" inches"
PRINT USING "28A,MODDDDDDD,9A"; "THE RMS VALLEY CURVATURE = ",Rnscvur*1000000,1" inches"
PRINT USING "32A,MODDDDDDD,11A,MO.DDD,7A"; "THE MINIMUM VALLEY CURVATURE ",Curmin*1000000,1" inches "; (MIN/1000);" inches"
PRINT USING "34A,MODDDDDDD,11A,MO.DDD,7A"; "THE CURVATURE OF DEEPEST SCRATCH ",Cur*1000000,1" inches "; (MIN/1000);" inches"
PRINT "THE RANGE = "; (INT(Range+.5));" microinches"
PRINT "THE DEEPEST VALLEY = "; (INT(Prmax+.5));" microinches"
PRINT "THE MAXIMUM PEAK = "; (INT(Prmin+.5));" microinches"
PRINT USING "41A,MO.DDD,2A,MO.DDD,7A"; "MAXIMUM VALUE OF VALLEY TIMES CURVATURE ",Vrha,", \"; (Vrho/10000);" inches"
PRINT 
PRINT "AVERAGE OF PEAK MOMENTS USING ", PRINT "POSITIVE PEAK EXTREMA 
PRINT "FIRST MOMENT M1 = "; (INT(J4+1000)/1000
PRINT "THIRD MOMENT M3 = "; (INT(J5+1000)/1000
PRINT "FIFTH MOMENT M5 = "; (INT(J6+1000)/1000
PRINT "SEVENTH MOMENT M7 = "; (INT(J7+1000)/1000
PRINT "NINTH MOMENT M9 = "; (INT(J9+1000)/1000
PRINT IS I
PRINT "DO YOU WANT TO PRINT THESE DATA ? <Y/N>",AS
IF AS="Y" THEN 3020
3020 GOTO 2660
3020 END