# Surface Roughness Effect on Fatigue Life Preditions under Cumulative Damage

**Khairallah S. Jabur ***
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**Abstract**

The influence of surface roughness parameter on the fatigue life is studied using rotory bending loading under room temperature and zero mean stress (R=-1).

Three levels of average surface roughness (Ra), namely smooth, medium and rough, are considered. For the above three levels, three equations which describe the S-N curve are established. The application of these equations to specimens tested under cumulative fatigue damage shows that the roughness parameter must not be ignored. Hence a new model considering this parameter is formulated which may take the form

$$N_f = \left[ \frac{476624(Ra)^{-0.436}}{\sigma_f} \right]^{2.087}$$

From the applications of the proposed model, it is concluded that fatigue life predictions are in good agreement with the experimental results.

## تاثير خشونة السطح على التنبؤ بعمر الكلل في ظروف الضرر المتراكم

**الخلاصة**

تمت دراسة خشونة السطح وتأثيرها على اعمار العينات المسلط عليها احمال كلل ترددي من نوع الانحناء الدوار تحت درجة حرارة الغرفة وقيمة متوسط الاجهاد مساويا الى صفر.
اخذت ثلاثة مستويات لقيم الخشونة – ناعم – ومتوسط الخشونة وخشونة عالية واستخرجت ثلاثة معادلات لمنحني ويلر S-N ( منحني الاجهاد – العمر ) وتم تطبيق هذه المعادلات على عينات سلطت عليها احمال من نوع الضرر المتراكم والتي تمثل الحالة العملية وتبين ان للخشونة تأثير بالغ وعليه تم اخذ هذا العامل بنظر الاعتبار واستخراج نموذج رياضي تجريبي اخذ الصيغة التالية:

$$N_f = \left[ \frac{476624(Ra)^{-0.436}}{\sigma_f} \right]^{2.087}$$

وعند تطبيق النموذج أعلاه اعطى نتائج جيدة جدا مقارنة مع النتائج العملية

Where:
$N_f$: Number of cycles to failure
$\sigma_f$: Stress at failure
Ra: Average surface roughness

## 1-Introduction

It is noted that little of the general body of data on the effect of surface finish on fatigue has separated or, in many cases recognized the additional effects of residual stresses introduced by the machining process which would interfere with the

*Institute of Technology / Baghdad .

Evaluation of surface irregularities. Suhr [1] has tested unnotched and notched specimens of low alloy steel under cyclic axial loading conditions . The results of the study indicated that the fatigue limit decreased with increasing depth of defect at the crack initiation site and surface grooves or inclusions about (0.05 mm ) in depth reduced the fatigue limit of a fine ground surface by (50) percent . A reduction in fatigue limit varying between (10) to (25) percent has been reported for carbon steel when the method of preparation of the specimens changed from fine grinding to rough turning [2]. Siehel and Gaier [3]compared fatigue strength with maximum depth of surface roughness and found a critical depth below which there was no change in fatigue strength . This work is concerned with the effect of surface roughness on fatigue life under cumulative damage .

## 2- Experimental Work

### 2-1 Material

A medium carbon steel was used for all the tests in this study.

The chemical composition of the material is given in table (1).

While the mechanical properties are shown in table (2)

This material is widely used in applications where higher strength than that for mild steel is required.

### 2-2 Test Machine

Arotary bending machine of type (PUNN) is used which has a load capacity of ±27. N. m (maximum working stress of +900 Mpa).

This machine is able to provide a sinusoidal wave at a speed of (6000) or (12000) rpm.

More details about the machine are given in reference [4].

### 2-3 Test Programme

The test programme is divided into the following four groups:

**Group (1)** of mean average roughness (Ra=1.17 µm)

Seven specimens are tested at high cycle fatigue (Stresses slightly above the fatigue limit) to obtain fatigue lifetime date at constant amplitude loading and zero mean stress.

**Group (2)** of mean average roughness (Ra= 10.9 µm)

Seven specimens are tested as in group (1)

**Group (3)** of mean average roughness (Ra= 23.92 µm)

As in group (1) and (2)

**Group (4)** This group is tested under cumulative fatigue damage.

Four specimens of average roughness of (18, 1.27, 7 and 12 µm). Are tested under cumulative fatigue damage. The sequence of loading is either low to high or high to low.

**3-**Experimental results and analysis

3-1 Experimental results (constant amplitude tests)

Table (3), (4) and (5) represents the results of group (1), (2) and (3) respectively.

Fig(1) illustrates the S-N curve for data tabulated in table 3 , 4 and 5

The S-N curve equation for the above data may be formulated as (using the least square method)

$$\sigma = 583869\ N_f^{-0.535} \qquad \text{---- (1)}$$

(Low roughness or smooth surface)

The S-N curve equation which describes the results in the above table is:

$$\sigma_f = 59340\ N_f^{-0.378} \qquad \text{---- (2)}$$

(medium roughness)

The S-N curve equation of the above results can be written as:

$$\sigma_f = 259049\ N_f^{-0.516} \qquad \text{---- (3)}$$

(high roughness, rough surface)

### 3-2 Cumulative fatigue tests

Table (6) shows the results of four specimens of average roughness tested under cumulative fatigue damage, and

table (7) gives the life prediction of specimens according to equations (1, 2 and 3).
Knowing that the stress value used in these equations is the average value of the variable applied stresses.

**Surface roughness factor (Ks)**
Ks can be defined by the following equation:

$$K_s = \frac{N_f\ (f\ \ a\ \ s}{N_f\ (for\ \ rough\ \ polished\ \ s} \quad ---- (4)$$

It is clear from the above table that the value of Ks (smooth surface) equals unity while Ks (medium surface) equals to (0.78) and Ks (rough surface) equals to (0.345).

**Correction factor (Kc)**
This factor may be calculated from the comparison between the experimental and predicted life of each specimen.

$$Kc = \frac{N_f \exp rimental}{N_f \ predicted} \quad ---- (5)$$

**4- Discussion**

Generally an increase in surface roughness is accompanied by a decrease in fatigue strength and in fatigue life [5]. Also it is clear that, from table (I), for high surface roughness (rough surface) Kc is about (0.8) based on equation (3) while this value becomes (0.2719) based on equ. (1) and (0.2667) based on equ. (2).
This difference in Ks values is due the difference in surface roughness value (Ra). [6].In order to avoid the large error in life prediction and to make Kc about unity, It is necessary to take into account the roughness (Ra) especially when the difference in (Ra value is big. [7]. A new model is proposed which takes into account the difference in (Ra) values.
This model can be written as:

$$\sigma_f = 476624 (Ra)^{-0.436} \quad N_f^{-0.476} \quad --(6)$$

OR

$$N_f = \left( \frac{476624 (Ra)^{-0.436}}{\sigma_f} \right)^{2.087}$$

The above equation is formulated based on experimental data of the groups A.B and C.
A comparison between the life prediction of specimens using equ. (6) and the experimental lives is given in table (10) .
The values of Kc based on equation (6) is tabulated in table (11)
It is clear that when using equ. (6) the values of Kc are close to unity and the life prediction is in good agreement with the experimental life .

**5- Conclusions**

1- Roughness of the surface is important factor and must be taken into consideration for prediction of fatigue life.
2- A new life prediction model is derived from this study which includes the effect of difference roughness values. This model is formulated as

$$N_f = \left( \frac{476624\ (Ra)^{-0.436}}{\sigma_f} \right)^{2.087}$$

3- The application of the new model to cumulative fatigue specimens gives good life prediction compared to the experimental life.

**References**

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**Table (1) The chemical composition of the material used -% wt-**

| C | Si | S | P | Mn | Fe |
|---|---|---|---|---|---|
| 0.44 | 0.12 | 0.0019 | 0.005 | 1.00 | Bal. |

**Table (2) mechanical properties of the material used**

| Yield strength $\sigma_y$ (Mpa) | Possion ratio $\upsilon$ | Tensile Strength $\sigma_u$ (Mpa) | Modules of elasticity E (Gpa) | Reduction in area RA % | Modules of rigidity G (Gpa) |
|---|---|---|---|---|---|
| 400 | 0.26 | 680 | 207 | 36 | 82 |
| 411 | 0.27 | 677 | 210 | 35 | 80 |

**Table (3) Represents the results of group (1) of mean average roughness (Ra =1.17 µm)**

| Specimen No. | Specimen Diameter (mm) | Ra (µm) | Stress ($\sigma_f$) N/mm$^2$ | $N_f$ exp (Cycles) |
|---|---|---|---|---|
| A1 | 7.07 | 0.7 | 250 | 1.44 $*10^6$ |
| A2 | 7.08 | 0.87 | 230 | 1.878 $*10^6$ |
| A3 | 7.11 | 1.2 | 200 | 3.71 $*10^6$ |
| A4 | 7.08 | 1.0 | 300 | 1.17 $*10^6$ |
| A5 | 7.2 | 1.7 | 350 | 1.077 $*10^6$ |
| A6 | 7.12 | 1.33 | 400 | 9.87 $*10^5$ |
| A7 | 7.15 | 1.41 | 430 | 9.08 $*10^5$ |

**Table (4) Represents the results of group (2) of mean average roughness (Ra =10.9 µm)**

| Specimen No. | Specimen Diameter (mm) | Ra (µm) | Stress ($\sigma_f$) N/mm$^2$ | $N_f$ exp(Cycles) |
|---|---|---|---|---|
| B1 | 7.0 | 8.2 | 250 | 1.077 $*10^6$ |
| B2 | 7.07 | 10.7 | 280 | 1.6 $*10^6$ |
| B3 | 7.1 | 10.0 | 290 | 1.03 $*10^6$ |
| B4 | 7.4 | 11.3 | 300 | 9.076 $*10^5$ |
| B5 | 7.31 | 10.8 | 350 | 8.2 $*10^5$ |
| B6 | 7.09 | 12.7 | 420 | 6.67 $*10^5$ |
| B7 | 7.17 | 12.8 | 470 | 1.2 $*10^6$ |

**Table (5) Represents the results of group (3) of mean average roughness (Ra =23.92** µm)

| Specimen No. | Specimen Diameter (mm) | Ra (µm) | Stress (N/mm$^2$) | $N_f$ exp (Cycles) |
|---|---|---|---|---|
| C1 | 7.1 | 2.07 | 200 | 1.32 $*10^6$ |
| C2 | 7.15 | 26 | 250 | 5.13 $*10^5$ |
| C3 | 7.09 | 24 | 280 | 4.7 $*10^5$ |
| C4 | 7.4 | 20.8 | 310 | 4.4 $*10^5$ |
| C5 | 7.2 | 21.7 | 370 | 3.5 $*10^5$ |
| C6 | 7.37 | 26.3 | 420 | 3.1 $*10^5$ |
| C7 | 7.25 | 28 | 480 | 2.22 $*10^6$ |

**Table (6) Represents the results of group (4) of average roughness tested under cumulative fatigue damage**

| Specimen No. | Sequence of loading | Applied Stress (N/mm$^2$) | Ra(av) (µm) | $N_f$ exp (Cycles) |
|---|---|---|---|---|
| E1 | (L-H) | 215-255 | 18 | 602767 |
| E2 | (H-L) | 305-275 | 1.27 | 2.9 $*10^6$ |
| E3 | (L-H) | 275-315 | 7 | 8.89 $*10^5$ |
| E4 | (H-L) | 300-250 | 12 | 6.07 $*10^5$ |

**Table (7) represents the life prediction of specimens according to equations (1,2 and 3)**

| Specimen No. | (A) $N_f$ predicted Cycles | (B) $N_f$ predicted Cycles | (C) $N_f$ predicted Cycles |
|---|---|---|---|
| E1(18 µm) | 2216754 | 2259590 | (787054) |
| E2(1.27µm) | (2496310) | 1295572 | 523608 |
| E3 (7 µm) | 1449259 | (1238297) | 506546 |
| E4(12 µm) | 1652459 | (1490971) | 580373 |

**Table (8) Represents surface roughness factor (Ks)**

| Stress ($N/mm^2$) | $N_f$ (based on eq.1) | $N_f$ (eq.2) | Ks | $N_f$ (eq.3) | Ks |
|---|---|---|---|---|---|
| 250 | $1.977 \quad *10^6$ | $1.9237 \quad *10^6$ | 0.973 | $6.98 \quad *10^5$ | 0.353 |
| 280 | $1.5997 \quad *10^6$ | $1.4254 \quad *10^6$ | 0.891 | $5.604 \quad *10^5$ | 0.35 |
| 350 | $1.054 \quad *10^6$ | $7.8989 \quad *10^5$ | 0.747 | $3.6365 \quad *10^5$ | 0.345 |
| 400 | $8.2129 \quad *10^5$ | $5.548 \quad *10^5$ | 9.6755 | $2.8074 \quad *10^5$ | 0.3418 |
| 450 | $6.59 \quad *10^5$ | $4.0628 \quad *10^5$ | 0.6165 | $2.234 \quad *10^5$ | 0.339 |

**Table (9) illustrates the values Kc of cumulative fatigue specimen tests.**
**(    ): represents the suitable Kc of the specimens**

| Specimen No. | Ra µm | Kc(based on Equ(1) | Kc (2) | Kc(3) |
|---|---|---|---|---|
| E1 | 18 | 0.2719 | 0.2667 | (0.7658) |
| E2 | 1.27 | (1.1617) | 2.238 | 5.538 |
| E3 | 7 | 0.6134 | (0.7179) | 1.755 |
| E4 | 12 | 0.673 | (0.407) | 1.045 |

**Table (10) illustrates a comparison between the theoretical and experimental tests**

| Specimen No. | Ra (µm) | $N_f$ Experimental | $N_f$ Predicted Equ.(6) | % error |
|---|---|---|---|---|
| E1 | 18 | 602767 | 575072 | -4.6 |
| E2 | 1.27 | $3.93 * 10^6$ | 4138797 | 5.3 |
| E3 | 7 | $8.89 * 10^5$ | 844992 | -4.95 |
| E4 | 12 | $6.07 * 10^5$ | 599079 | -1.3 |

**Table (11) illustrates correction factor (kc)**

| Specimen No. | Kc |
|---|---|
| E1 | 1.048 |
| E2 | 0.7 |
| E3 | 1.052 |
| E4 | 1.013 |

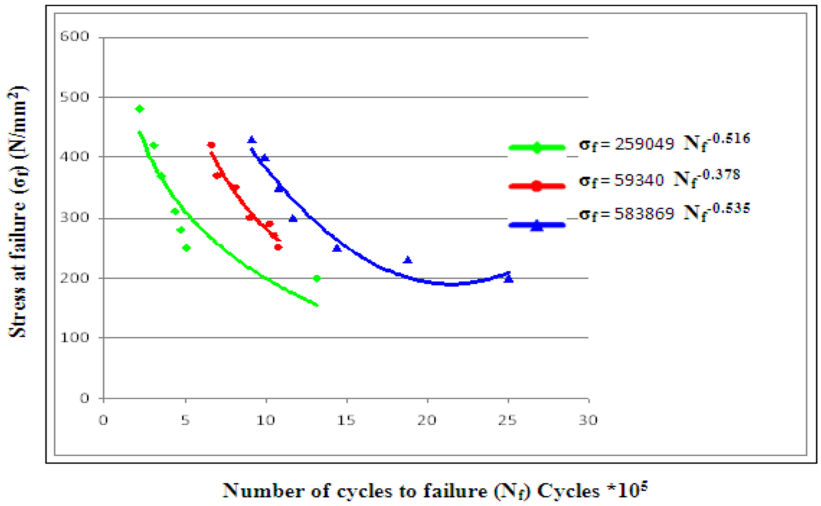


**Figure (1) shows the (S-N) curves for different Surface Roughness**