# Effect of fretting on fatigue strength of steel

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Fretting fatigue is one of the most important phenomena for inducing a reduction of fatigue strength and consequently, unexpected failure accidents. In this study, plain and fretting fatigue tests with zero mean stress were carried out on two different types of steel (low-carbon and stainless steels) by means of a reversed bending fatigue testing machine. Fretting fatigue strengths of the tested steel were investigated through two cases. case (1), fretting fatigue that occurs between two identical specimens and case (2), at vice clamp-specimen interface. A special kind of transducers has been made for measuring the relative slip motions that occurs in both cases. The current investigations show that the reduction in fatigue strength in case (2) is larger than that in case (1), and the stainless steel has a higher resistance to the fretting fatigue compared with the low-carbon steel.

تعتبر عملية الاحتكاك البسيط بين المعادن من الظواهر المهمة والتي ينتج عنها النقصان في مقاومة الكلل مما يؤدى إلى حدوث الفشل غير المتوقع. في هذه الدراسة تم اختبار تأثير ظاهر الكلل الاعتيادي والكلل الناتج عن الاحتكاك لغرض المقارنة على نوعين من الفولاذ.(فولاذ قليل الكربون، وفولاذ مقاوم للصدأ) وذلك بواسطة ماكنة اختبار الكلل ذات الحناية العكسية. وقد تم التحري عن نتائج الاختبار على حالتين: الحالة الأولى كانت حول تأثير الكلل الناتج عن الاحتكاك بين نموذجين متماثلين من الفولاذ. الحالة الثانية حول تأثير الكلل في منطقة التداخل بين النموذج وبين المعدن القابض للنموذج. وقد تم قياس واحتساب الحركة الانزلاقية النسبية بين النماذج المتلامسة وكذلك بين النموذج والقابض ولكلا الحالتين. ومن نتائج الاختبار لوحظ إن هنالك نقص في مقاومة الكلل في الحالة الثانية اكبر عما هو علية فى الحالة الأولى كما وان معدن الفولاذ المقاوم للصدأ له مقاومة كلل نتيجة الاحتكاك أعلى من الفولاذ قليل الكربون.

**Keywords**: Fretting fatigue, Plain fatigue, Fretting diagnosis, Low-carbon steel, Martensitic stainless steel

## 1. Introduction

The nature of fretting- induced fatigue failures is not well understood and the terms used to describe the phenomena are not universal. Fretting, the harmful combination of wear, corrosion and fatigue phenomena driving by partial slip of tribosurfaces, has been attributed to severe reductions in service life-time of a myrial coating components, including bearings, turbine blades and mechanically- fastened joints- both structure and biological [1]. It is effected by various parameters but most important of them are friction force, relative slip, and clamping pressure which appear in the area of contacting surfaces [2].

Fretting fatigue lives decreased with increase of contact pressure [3]. The contact of two mating surfaces occurs at local high asperities and oscillatory rubbing action produces tangential cyclic shear stresses causing local plastic deformation in these asperities which is usually an important feature [4]. Micro welding and fracture of these asperities can occur and be repeated under small oscillatory relative motion causing transfer of metal from one surface to another (cracks to be developed) [5].

The process of fretting fatigue may conveniently be divided into three distinct regimes. First the initiation (or nucleation) phases in which damage accumulate at the fretting interface. Secondly a phase of short crack growth to which crack grows in a manner which is influenced by the micro-structure of the material and microscopic conditions at the contact; thirdly is a phase of long crack propagation which is the easiest to analyze [6].

Fretting damage is a reel preoccupation for various industrial situations. The most damageable phenomenon linked to this contact loading is a great decrease in component life. This decrease is the consequence of the early initiation and propagation of fatigue cracks under cumulative effects of contact and fatigue loadings [7].

The numbers of independent research studies have shown that fretting fatigue cracks can be initiated at a very early stage (<5-10%) of fretting fatigue life. It is well established that as well as accelerating crack initiation, fretting can also cause an increase in the rate of crack growth. Additionally, a crack that might be dormant under pure fatigue loading might resume propagation under fretting fatigue conditions. In fracture mechanics models, the stress intensity factor at the tip of a crack growing beneath a fretting contact will arise not only from the body stresses but also from contributions arising from the tangential and vertical forces due to the fretting contact [8].

Localized high temperature can also be occurred which can accelerate oxidation. The temperature field around the micro-contact asperity affects significantly the material properties, its micro-structure, the oxidation process and thermo-elastic stresses in the contact zone [9, 10].

In the ultra high cycle fatigue regime (>$10^7$ cycles), fretting fatigue cracks initiated under stresses lower than the conventional fretting fatigue limit , which was determined at $10^7$cycles.They could propagate without arresting at the lower stress level [11].

It was found that fretting fatigue occurs even if the slip amplitude is very small, the slope of slip amplitude in S-N curve was remarkably reduced to 2-3μm. However the reduction ratio of fatigue limits was negligible. Fretting fatigue limits under various testing conditions were successfully estimated by modified Goodman diagram method used tangential and mean stress on fretting surface calculated by FEM analysis as compared with the fatigue limit of smooth specimen obtained by plain fatigue test [12].

The effects of fretting can be minimized by a suitable choice of materials. Researchers have been noticed that in the case of the same types of steel in contact (specimen and clamp), it is apparent that the harder, and hence stronger steels suffer the greatest relative reduction in fatigue strength due to fretting. In the case of fretting when the clamp material was made from a material of hardness lower than that of the specimen, the lowest reduction in fatigue strength due to fretting is obtained. Shot-peening, nitriding, carbonizing and surface rolling can increase fretting fatigue strength to almost the value of the non fretted material [13, 14].

Table 1
Weight loss results due to fretting with grease lubrication

| Type of grease | Weight loss (mg) |
|---|---|
| Na-Soap grease | 19.7 |
| Ca-Soap grease | 23.0 |
| Li—Soap grease | 11.5 |
| Without lubrication | 44.6 |

Reducing the coefficient of friction as much as possible can minimize the fretting damage. This can be done by introducing a sort of good lubricant between the surfaces in contact. The influence of several types of lubricant on the fretting damage of carbon steel has been studied [15], and the results obtained for the duration of $5\times10^5$ cycles are shown in table 1. Using the Na-Soap grease, the weight loss due to fretting was dropped to about half the amount compared with the loss during test with unlubricated surfaces, Ca-Soap grease shows least effective, and Li-Soap grease was the most effective.

Improvement of fretting fatigue strength by titanium nitride (TiN) coating resulted mainly from the retardation of fretting fatigue crack initiation due to existence of hard (TiN) film on the contact surface of the specimens [16]

Fretting fatigue behavior of plasma nitride En19 steel was examined and found that a 10h plasma nitriding treatment improved the fatigue strength of the steel by 24.5% and the plane fatigue strength by 70% [17].

The major objective of this research is to investigate and determine the effect of fretting on fatigue life of steel by means of plane bending fatigue testing machine, using two different types of steels (low-carbon steel and martensitic stainless steel).

## 2. Experimental work

### 2.1. Fatigue testing machine

A constant deflection cantilever bending testing machine has been used. It consists mainly of four-bar mechanism. One of the links is used to hold the specimen and hinged at the lower end to the machine main frame. With the upper end of the frame subjected to an oscillating motion by means of coupler. The coupler is then driven by rotating wheel as a crank link with variable eccentric pin. Power supplied by electric motor used to drive crank through a two-stage of speed reduction as shown in fig. 1.

### 2.2. Material and specimens

Two types of steel were used in this study. Low-Carbon and Martensitic Stainless Steel, both are cold rolled sheets 1mm thickness with chemical compositions and static mechanical properties are shown on tables 2 and 3 with surface roughness of Ra= 1.6µm for low carbon steel and Ra= 0.35µm for martensitic stainless steel.

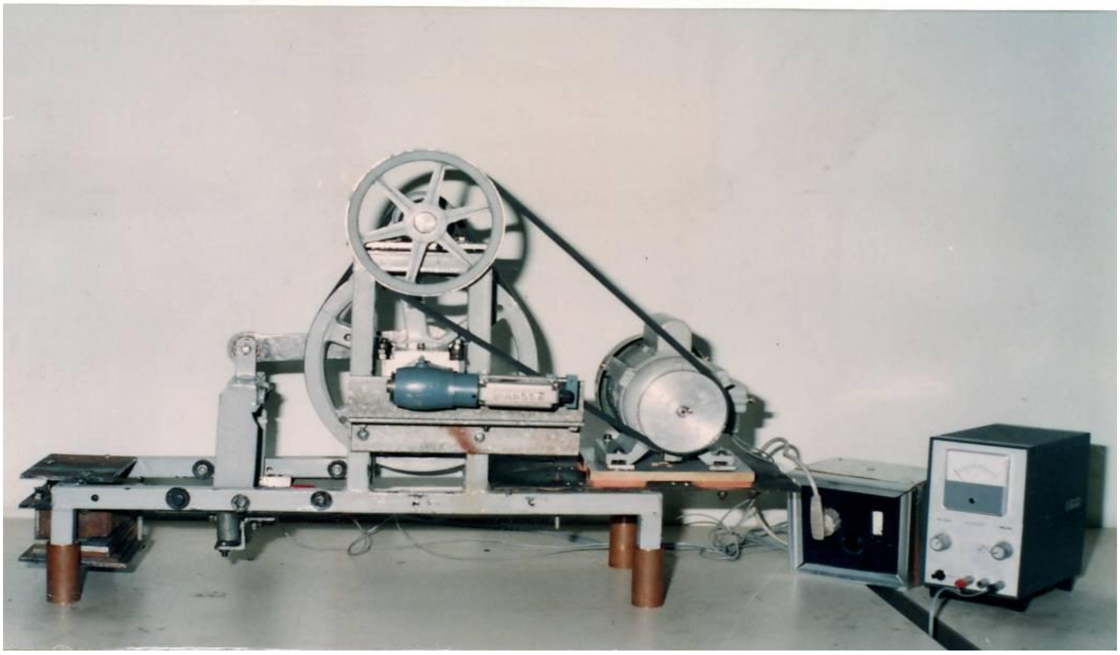

Fig. 1. View of the plane bending fatigue testing machine.

Table 2
Chemical compositions of steel specimens

| Material | % C | %Si | % Mn | %P | %S | %Cr | %Mo | %Fe |
|---|---|---|---|---|---|---|---|---|
| Low-carbon steel | 0.17 | 0.05 | 0.29 | 0.05 | --- | --- | --- | Rem. |
| Martensitic Stainless steel | 0.1-0.15 | 1.0 | 1.5 | 0.06 | 0.15-0.35 | 15.5 | 0.2 | Rem. |

Table 3
Static mechanical properties of steel specimens

| Material | E (GPa) | Sy (MPa) | Su (MPa) | % Elongation | HRB |
|---|---|---|---|---|---|
| Low-carbon steel | 206 | 199 | 384 | 29 | 36 |
| Martensitic stainless steel | 186 | 397 | 648 | 38.6 | 76 |

The clamping device used in fatigue testing machine for gripping the tested specimens were made from two pieces of steel plate, each of which has dimension of 60mm length, 30mm width and 10mm thickness. The chemical composition and static mechanical properties are shown on tables 4 and 5 with average surface roughness of Ra= 2.1µm

Table 4
Chemical composition of the clamping device material

| % C | % Si | % Mn | % P | % | % F |
|---|---|---|---|---|---|
| 0.31 | 0.22 | 0.55 | 0.023 | 0.04 | Rem. |

Table 5
Static mechanical properties of the clamping device material

| E(GPa) | Sy(MPa) | Su(MPa) | %Elongation | HRC |
|---|---|---|---|---|
| 209 | 296 | 580 | 34 | 31 |

For both tested steels, two groups of specimen were prepared. Group (I) was used to determine the plain fatigue behavior and to clarify the influence of the fretting damage between two identical specimens. Group (Π) was used to study the influence of the fretting damage occurs at the vice clamp-specimen interface on the fatigue strengths. The size and shapes of specimens (I) and (Π) are shown in figs. 2-a and 2-b.

The principal stress developed in the test specimen under repeated bending is either tensile or compressive or both. The method used for determining the alternating stress distribution within the specimen is the application of electrical resistance strain gauges technique. This measuring method depending on the application of elastic formula $\sigma = \frac{MC}{I}$, was taking in consideration. A Kyowa gauge of kind foil phester (KFC) with 5mm gauge length has been bonded to the test specimen. The alternating strains detected by the gauge were amplified and recorded and the corresponding alternating stress for each load condition and for both types of steel has been determined.

Slip measurement and strain gauge transducer which is similar to that used by Nishioka [18] has been designed and constructed (by the author) from 0.38mm thickness spring steel sheet with compact size of about $1.1 cm^3$ for measuring the minute relative slip.

When the two identical specimens are clamped together by the clamp of the testing machine and then subjected to a cyclic bending moment, a cyclic relative slip is observed between them and it was varied along the specimen length. A measurement of cyclic slip by the transducer mentioned above has been conducted and the results of the calibration wear recorded. The clamping load condition that applied by tightening the

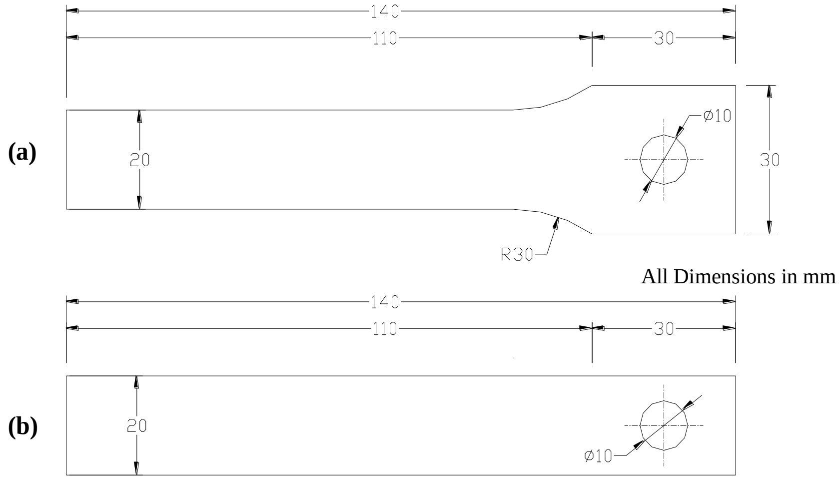

Fig. 2. Dimensions and shapes of specimens. (a) specimen I, (b) specimen Π.

clamping nut over the clamping plates to grip the specimen. Full bridge measuring circuits consisting of four identical active strain gauges were mounted upon the clamping plates. The calibrated results were recorded.

## 3. Experimental procedures

### 3.1. Test conditions

According to the specimen preparation previously mentioned, the plain, fretting (two cases) and improved fretting fatigue tests were carried out under the following conditions:-

1. The initial mean stress in the test specimen is kept constant (Sm = 0).
2. The frequency of the alternating stress is kept constant of 4Hz.
3. For each case of study, at least seven alternating stress levels were chosen with three replications.
4. Tests where curried out in laboratory air, and no special considerations have been given to temperature and humidity.

### 3.2. Test method to determine the plain fatigue behaviors

A constant stress-specimen (I) was used with constant clamping pressure of 10.5 MPa. This value of clamping pressure has been selected in order to prevent any relative slip at the vice clamp-specimen interface, to prevent any fretting damage that affects the fatigue strengths.

### 3.3. Investigation of the fretting fatigue behavior

Two cases have been investigated. Firstly, the fretting fatigue that occurred between two identical specimens. These tests are achieved by clamping two identical specimens (I) with a constant pressure of 10.5MPa controlled by the method of clamping the specimen that has been used for all stress levels. Secondly, the fretting fatigue that occurred at the vice clamp-specimen interface. Tests are achieved by utilizing a specimen (Π) with a constant clamping pressure of 8.5MPa for all stress levels.

## 4. Results and discussions

### 4.1 Diagnosis of fretting

The surface damage which appeared after $10^5$ cycles of fretting has been shown on fig. 3, where the alternating stress and the amplitude of fretting slip are 183MPa and 27μm respectively. After a few hundred of cycles, visible fretting corrosion begins to appear near the vice clamp-specimen interface. The general debris is much redder than the normal rust is observed on the surface damage and significant cold welds and large pits are found near the outside of the contact surface in the direction of the slip (in which the larger contact pressure acts). The same surface damage is observed on the stainless steel specimen with less damaging area than that on the carbon steel specimen.

### 4.2. Processes of the crack initiation and propagation to the final fracture

The fracture surface appears to have two distinct regions. The coarse area at the time of the fracture and the fatigue cracks region. At first the crack propagates at about 45° for few millimeters (first stage) before turning at right angles to the specimen longitudinal axis (second stage) which is the plane of maximum tensile stress fig. 4-a. However, failures similar to that mentioned above are often called typical fatigue failures because they exhibit the following common aspects: (a) Distinct crack initiation site, (b) beach marks indicative of crack growth and (c) distinct final fracture region. The microscopic examination of a surface which has undergone fretting fatigue shows the loose debris, pitting and frequently a fatigue crack is found passing through the damaged area.

From the observations of longitudinal cross-sections of fretted specimens, the point of crack initiation was at the edge region of the contact surface and near the outside fig. 3. The crack induced by fretting propagates at an oblique angle to the specimen longitudinal axis (first stage crack). The direction of crack growth then becomes normal, as the crack grows away from the contact surface and the effects of fretting are reduced (second stage crack), as illustrated in fig. 4-b.

In the plain fatigue, the crack will yield initially in shear stress at inclined plane of about 45° to the specimen longitudinal axis. In the fretting fatigue the yielding occurred initially in shear stress at the oblique plane about 31° due to the influence of the frictional force between the contact surfaces.

### 4.3. Plain fatigue behaviors

The S-N curves obtained from the plain reversed bending fatigue tests for both types of tested steels are shown in fig. 5. A great deal of similarity will be noticed. Because fatigue failures originated at local points of relative weakness, the results obtained in this study have considerably large scatter. Statistical analysis and curve fitting equations were carried out on the fatigue data. This analysis

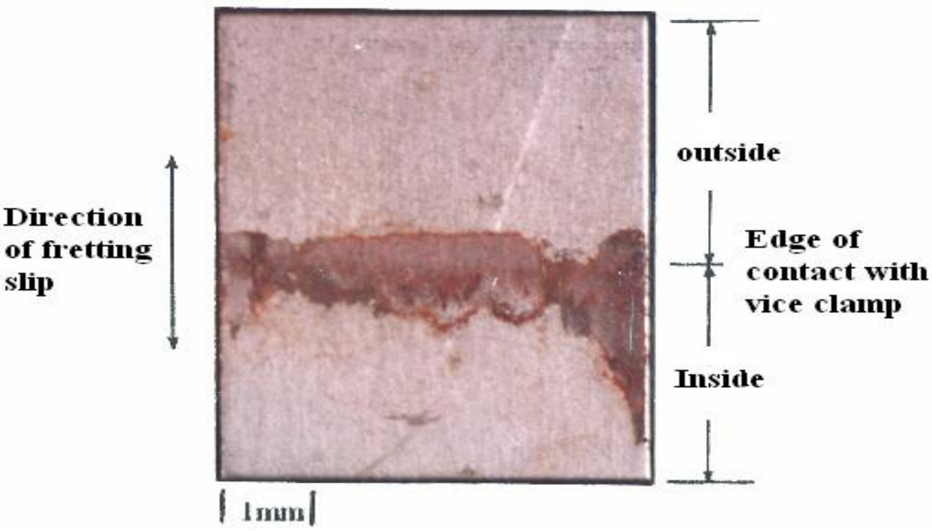

Fig. 3. Appearance of fritted area for carbon steel, specimen (II).

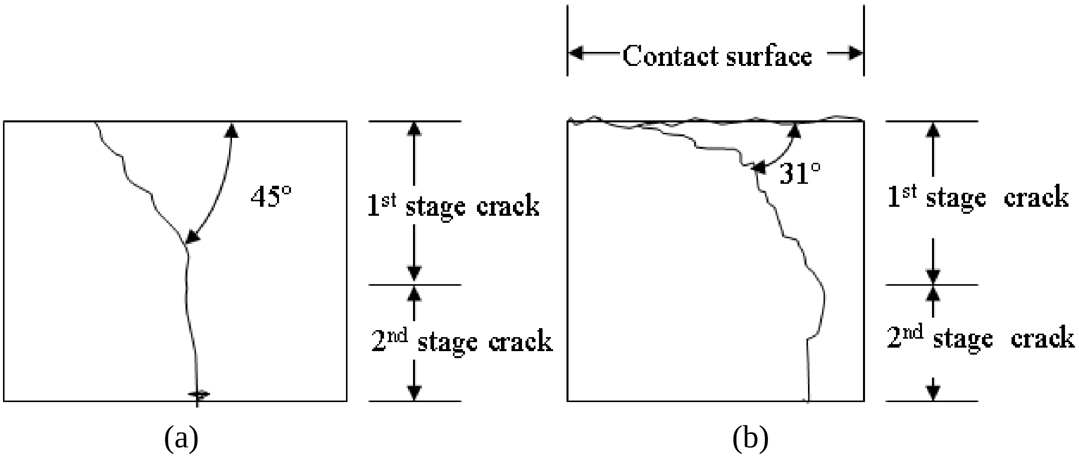

Fig. 4. Direction of crack growth, (a) Path of plane fatigue crack and (b) Path of fretting fatigue crack. Note that these figures were drawn as observed under the microscope.

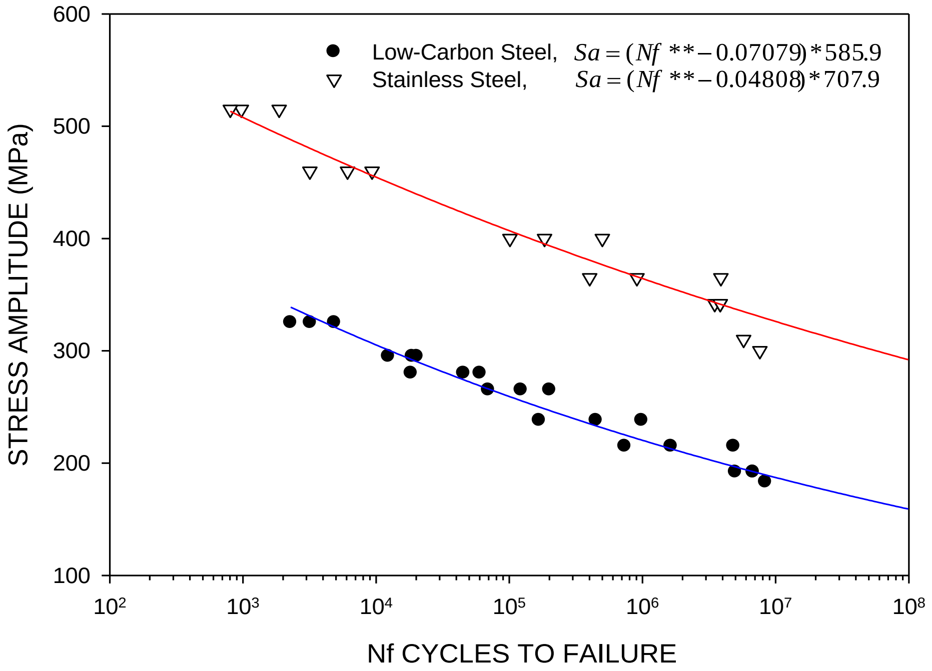

Fig. 5. S-N diagram for plain fatigue steel.

was shown that the scatter in fatigue strength corresponding to a given life is small, wile the scatter in fatigue life corresponding to a given stress level is large. The maximum scatter of these life values is 6:1 which is normally acceptable. Juvinall [19] has mentioned that even in a very carefully controlled tests these life values can vary over a range of five or ten to one.

### *4.4. Fretting fatigue behaviors*

The S-N relations were obtained for the low-carbon steel and martensitic stainless steel, which have suffered continuous fretting throughout the fatigue test and for both cases of fretting are shown in figs. 6 and 7.

In both cases of fretting, as the number of reversal cycles of fretting increases, the wear grows gradually on both mating surfaces and the iron oxide particles (debris) are observed to flow out from the fretted regions. So, the fatigue reduction strength is of the lowest value in the short-life region, and then the reduction gradually increases as the number of cycles increases

The fatigue life under fretting action is shorter than those under normal fatigue test. Above the knee of S-N diagram, the damage was occurred from the combination of fatigue and fretting actions, while below the knee the damage is solely fretting action. The fretting strength and the strength reduction factors (SRF is the ratio of plain fatigue strength to the fretting fatigue strength) are listed in table 6.

Table 6
Plain, fretting fatigue limits and strength reduction factors of the tested steels

| Material | $S_{pf\ (MPa)}$ | $S_{pf}\ /S_u$ | $S_{ff1(MPa)}$ | SRF1 | $S_{ff2\ (MPa)}$ | SRF2 |
|---|---|---|---|---|---|---|
| Low- carbon steel | 191 | 0.51 | 152 | 1.26 | 138 | 1.39 |
| Martensitic stainless steel | 316.5 | 0.48 | 303 | 1.05 | 265 | 1.19 |

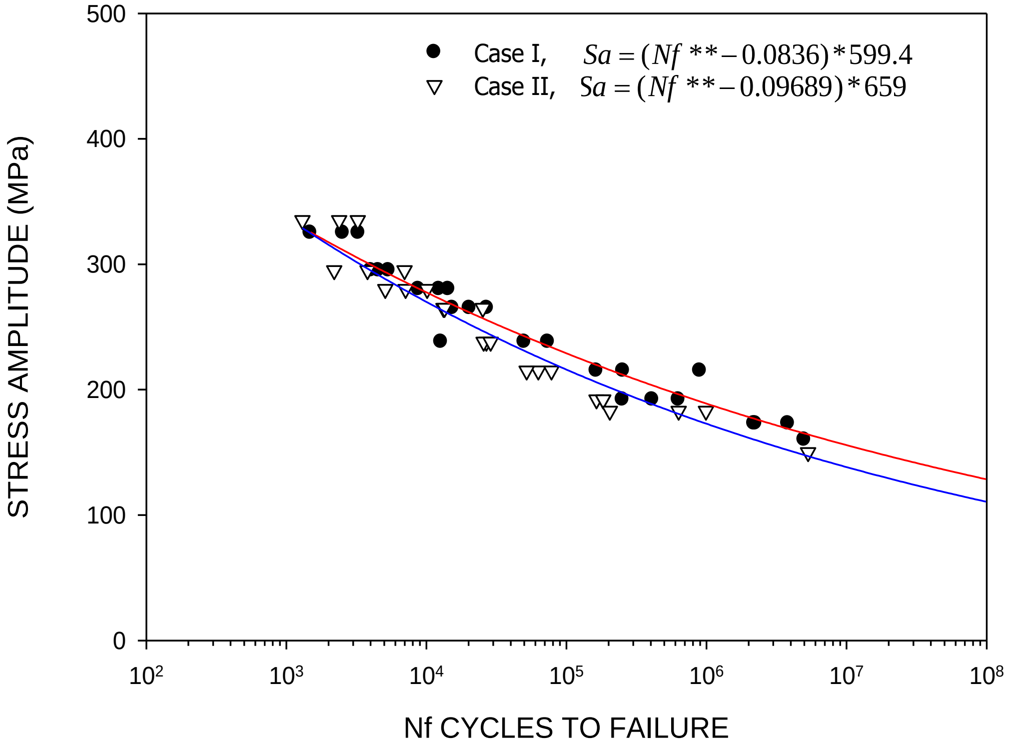

Fig. 6. S-N diagram for fretting fatigue of low- carbon steel.

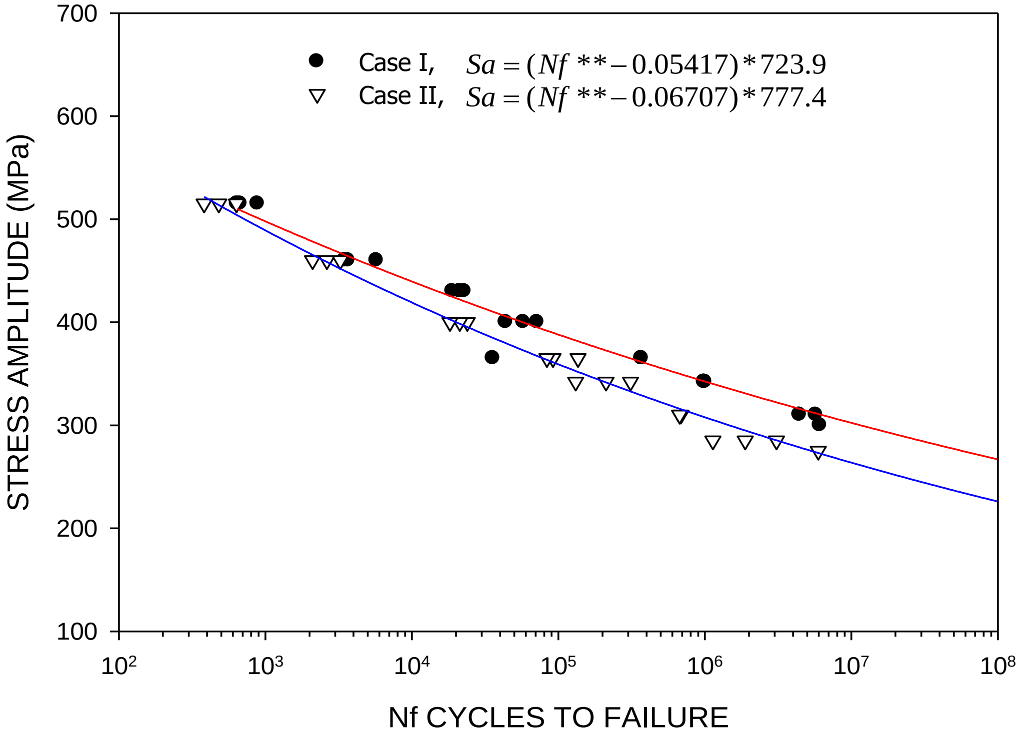

Fig.7. S-N diagram for fretting fatigue of the martensitic stainless steel.

The greater reduction in fatigue limit is obtained in the fretting case (2), where low-carbon steel specimens of hardness 36HRB are fretted with a medium carbon steel (vice clamp) of hardness 31 HRC. While, in the fretted case (1), where the two same specimens of hardness 36HRB are fretted with each other, the reduction in fatigue limit is lower than that in case (2). It is apparent that the fretting fatigue decreases with higher hardness material. Similar comparison where applied for martensitic stainless steel in both cases.

The composition between the results obtained for the tested steel show that the low-carbon steel suffers the greatest relative reduction in fatigue limit due to fretting action. On the other hand, the martensitic stainless steel has a high resistance to fretting fatigue.

## 5. Conclusions

The plain, fretting and improved fretting fatigue tests with zero mean stress where carried out using two different types of steels. The characteristic of fretting fatigue for both cases were discussed. The relative slip results were obtained and discussed as they vary with the alternating stress. The main conclusions are summarized as:

1- The fretting processes in low-carbon steel in both cases (1) and (2) showed a reduction in the fatigue strengths of 20.4% and 27.7% respectively mean while for martensitic stainless steel the reduction was 4.4% and 16.3% respectively. It means that less fretting strength in case of using the mating parts of similar materials, while the lower hardness material get more reduction in strength.

2- The two investigated cases of fretting fatigue were demonstrate the effect of fretting on fatigue strength in case (2) is higher than that in case(1) and the martensitic stainless steel has a high resistance to fretting fatigue compared with the low-carbon steel.

The fretting fatigue strength of the low-carbon steel was slightly improved by the application of grease lubricant, by the amount of about 3.3%.

## Nomenclature

| | |
|---|---|
| *E* | is the modulus of elasticity, N/m$^2$, |
| *HRB* | is the brinell hardness number, |
| *HRC* | is the rockwell hardness number, |
| *N* | is the number of stress cycles, cycle, |
| $N_f$ | is the number of stress to failure, cycle, |
| *Sa* | is the alternating stress mplitude, N/m$^2$, |
| *Sff1* | is the fretting fatigue limit for case (1), N/m$^2$, |
| *Sff2* | is the fretting fatigue limit for case (2), N/m$^2$, |
| *Sm* | is the mean stress, N/m$^2$, |
| *Spf* | is the plain fatigue limit, N/m$^2$, |
| *SRF1* | is the strength reduction factor, Case (1), |
| *SRF2* | is the strength reduction factor, Case (2), |
| *Su* | is the ultimate tensile strength, N/m$^2$, and |
| *Sy* | is the yield strength, N/m$^2$. |

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Received November 17, 2005
Accepted September 16, 2006