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Investigation of Titanium Alloy Material by Mixing of Plain and Fretting Fatigues

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Abstract

The material failure occurred is categorized into different types such as the fatigue. Fatigue itself can be categorized also into fretting and plain. Several studies have been placed to investigate the material performance under only one condition of these mentioned types. No testing methods were considered in the literature to investigate the required material by mixing of plain and fretting fatigues. Such mixing environment is where most of the parts and system components are subject to in many applications. The aim of this paper is to examine the behavior of the material under the condition of combined plain and fretting fatigues. Experimental study was carried out on Titanium alloy to understand its behavior under combination between plain and fretting fatigue. Five tests were carried out under different cycles load ratio between plain and fretting fatigues. If initially 50% of the cyclic life of fretting fatigue life was applied and then followed by the cycles of plain fatigue till failure occurred, it is found that the plain fatigue has no impact on the life of the material as compared to fretting fatigue. Such observation displays that utmost of the material fretting fatigue life is consumed in the initiation of the crack. Additionally, the cycle ratio between the plain fatigue and the fretting fatigue has a huge effect on the material fatigue life. For example, when the ratio decreases, the impact of the fretting fatigue increases which in turn results in the reduction of the fatigue life. This work was conducted considering only a constant contact applied load, hence it is imperative to consider variable contact load to inspect the life of the material with mixing of both plain and fretting fatigues.

Keywords: Combination, Plain fatigue, Fretting fatigue, Titanium alloy, Crack initiation.

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سلوك المادة في ظل الجمع بين الاعياء العادي والاعياء الناتج عن الحنق

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ملخص

يمكن تصنيف عطل المواد إلى عدة أنواع، أحدهما هو الأعياء الذي يصنف كذلك إلى إجهاد عادي وإجهاد ناتج عن الحنق أو مزعج. تم إجراء العديد من الدراسات لفهم سلوك المادة تحت الظروف الخاصة بأحد هذين النوعين لوحده فقط. لم تفكر أي من الدراسات السابقة في اختبار المواد في ظل مزيج بين الأعياء العادي والأعياء الناتج عن الحنق والذي يعتبر الحالة التي تتعرض لها المادة في معظم المكونات في التطبيقات الهندسية والصناعية. هذه الدراسة موجهة لهذه الغاية. أجريت دراسة تجريبية على سبيكة التيتانيوم لفهم سلوكها في ظل الجمع بين التعب البسيط والتعب الناتج عن الحنق. تم إجراء خمسة اختبارات بنسب مختلفة بين دورات التعب العادي ودورات التعب المزعج. عندما تم تطبيق نصف عمر إجهاد الحنق بالكامل في البداية ثم تلاه دورات التعب العادي حتى الفشل، وجد أن التعب العادي ليس له أي تأثير على العمر المادي مقارنة بالتعب الناتج عن الحنق. هذا يدل على أن معظم عمر التعب الناتج عن الحنق يقضي في بدء الشرخ في المادة. إن النسبة بين التعب البسيط والتعب الناتج عن الحنق لها تأثير كبير على عمر المادة. إذا قللت هذه النسبة، فإن تأثير التعب يزيد مما يؤدي إلى تقليل العمر. تم إجراء هذه الدراسة تحت حمل التلامس المستمر، لذلك يوصى بفحص المادة تحت التركيبة بين التعب العادي والإجهاد مع حمل التلامس المتغير.

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1. Introduction

1.1 Background

Material selection is an essential step in designing the components for any engineering project. This selection depends on the environmental condition that the product will experience, such as the type and magnitude of the applied loads. The goal of material selection is to lessen the hazards related to the worst situations. The engineering design requires a comprehensive understanding of the product condition such as the load and the environmental service. The failure of the material starts when the product becomes unable to function as planned. For the high technology application such as aerospace arena and engines, the failure is considered to be very costly and catastrophic. However, if the environmental condition of the operation service is known, the reasons for failure can be determined and the failure can be corrected to avoid such a disaster. There are many types of material failure such as fatigue, wear, corrosion, creep, …etc. This study focused on the fatigue failure. Fatigue is the situation when the material is subjected to a cyclic load. There are two type of fatigues; plain fatigue and fretting fatigue. Plain fatigue is well recognized and occurs when the material is subjected to only axial load in cyclic mode. Fretting fatigue is the case where the material is subjected to both axial and normal loads. This is the situation where two materials are in contact with each other. Most of the industrial and engineering applications experience the fretting fatigue phenomenon.

To understand this phenomena, many studies were conducted on different materials and different situations under plain fatigue and fretting fatigue conditions. Several researches were conducted considering only the plain fatigue failure by investigating with applied cyclic axial load on many types of material such as Aluminum, titanium or even concrete (Sterlinga, 2015; Wang et al., 2014; Iliopoulos et al., 2018; Chen et al., 2020; Arora & Singh, 2017). Recently, (Majzoobi and Minaii, 2014) introduced a method for estimation of fretting fatigue life of Al7075-T6 from plain fatigue experiments under rotary bending loading by using the Fatemi-Socie parameter (FSP) as a multiaxial criterion to account for the stress multi-axiality on focus path. Another study (Ounpanich et al., 2009) was conducted for plain fatigue and fretting fatigue tests of specimens sectioned from actual fabricated wheels after cold spinning to understand the influence of surface condition after plastic forming on fretting fatigue behavior. It was revealed that the cold spinning increased surface roughness and induced surface defects, which significantly degraded plain fatigue strength.

(Movaghghar & Lvov, 2012) developed an energy-based model for predicting fatigue life and evaluation of progressive damage in composite materials based on the concepts of continuum damage mechanics. His results show that the theoretical fatigue strength curves are in good agreement with experimental data.

Regarding fretting fatigue behavior, many studies were also implemented experimentally, analytically and numerically (Zehsaz and Shahiriary, 2013; Swalla and Richard, 2001; Namjoshi et al., 2002; Huang, 2019). Most of these studies carried out to figure out the effect of the main parameters affecting material behavior under fretting fatigue condition. Those parameters include coefficient of friction, applied axial and contact loads, phase angle between the axial and contact load, material geometry, elevated temperature environmental condition…etc. (Hintikka, 2016), inspected the influence of contact mechanics of fretting fatigue with induced frictional behavior. He observed that the frictional behavior was controlled by non-Coulomb friction and the behavior of the material wear was changed as the interface started to block with the debris of the wear that decreased further wear. (Lee, 2004), on the other hand, revealed that when the contact load increased, the fatigue life decreased. (Lee et al., 2003) also studied the effect of variable contact load on the fatigue life and he noticed that the axial stress was the main parameter in determining the material life.

(Almajali et al., 2019) conducted an experimental study on the effect of phase difference between the axial and contact load on the fatigue life of titanium alloy. He found that if the axial and the contact loads have a phase lag in between, the fatigue life of the material is increased. In general, the fatigue life of the material subjected to unlike fatigue situations can be descended from high to low as follow: High Cyclic Fatigue (HCF), Low Cyclic Fatigue (LCF) with low temperature, high temperature LCF and finally thermal shock (Xin, 2013). (Chan and Lee, 1998) wrote program using Fortran language to determine the numerical solutions for related variables in terms of stresses, strains, peak pressure, and so on. He named this program “Ruiz Program”. (Kadiric et al., 2003), in his numerical study, revealed that the magnitude of the local shear stress increases with increasing ratio between the root mean square roughness to the correlation length. Recently, (Chen et al., 2019) also investigated the fretting fatigue in dovetail assembly experiments and finite element method. He concluded that based on a total fatigue life prediction model, the total life was obtained by summing up the crack initiation life and the crack growth life using a fixed initial crack length, and the predicted results agreed well with experiments.

The majority of the previous studies were carried out under only plain fatigue or fretting fatigue. Most of the literature didn’t consider investigating the behavior of the material with mixing both plain and fretting fatigues at the same time. The main goal of this study is to consider this condition of both mentioned fatigue to inspect how the material behaves. An experimental set up has been carried out for the sake of determining the behavior of the material under the condition considered above. The configuration model used in previous studies (Almajali et al., 2019) was adopted in this study. This configuration is modeled by a flat body in contact with cylindrical end body. The flat body has a cylinder with infinite radius.

1.2 Problem Statement

Material life is one of the main topics should be investigated to use such material in the design and manufacturing systems. Most of the experiments conducted on the material, for the case of understating its fatigue life, considered only the condition of plain fatigue or fretting fatigue. However, the material in all engineering and industrial applications subjected to combination of both plain fatigue and fretting fatigue. It is imperative to realize the performance of the material under both fatigues. This study is directed to that end.

1.3 Aim and objectives

The aim of this study is to understand the behavior of the material under combination of plain fatigue and fretting fatigue. In addition to that, the following objectives are intended to achieve:

a. Collecting data on material fatigue properties for material selection.
b. Conducting an experiment on specific material namely the titanium alloy.
c. Choosing several fatigue configurations within the conducted experiments.

d. Inspections on the impact of different surface finishes and production techniques.

e. Investigations on crack nucleation and crack propagation for the tested material.

f. Verifying the predicted of the proposed of fatigue model.

g. Comparing the results of this study with the previous studies.

2. Experimental set up methodology

2.1 Contact mechanics configuration

If one body is in contact with other body, there will be two loads applied on both bodies namely; normal or contact load and axial load. As a result, there will be a shearing force perpendicular to the direction of the normal force. The configuration of fretting fatigue was modified from previous studies to simplify the problem, give better understanding, and be easier to solve. This configuration can be shown in figure (1) where the specimen represents the flat body with infinite radius and the pad represents a cylindrical end body. Those two components are in contact with each other in case of fretting fatigue while in the case of plain fatigue there will be no contact between them. During the test, the flat body (specimen) should be gripped at one of its end while the second end is subjected to axial stress (σaxial). When fretting fatigue is investigated, the cylindrical end body (pads) are pushed perpendicularly against the other body by applying the contact load (P). The test was conducted using servo hydraulic machine. This machine is used to control the axial load and contact load in term of their magnitude, frequency, and so on to be able to have the desired conditions. Partial slip will be generated as the tangential load (Q) is formulated due to the contact mechanics. The magnitude of the tangential force is defined as the half of the difference between the measured axial force and the force at the gripped end. Figure 1 also shows both the trailing and leading edges of the contact region during the contact mechanics. Fretting fatigue in general reduces the material fatigue life comparing to plain fatigue as revealed by several studies. Additionally, an analytical model was developed to give a solution for the fretting fatigue phenomenon.

2.2 Test Set-up

The material used to be investigated under combination of plain and fretting fatigues is titanium alloy (Ti-6A1-4VA). The machine used is a bi axial servo hydraulic test machine. This machine has two main actuators and the system is capable to allow varying the associated parameters such as the load magnitude, frequency, phase angle…etc. The axial applied force is controlled by 100 kN servo actuator while the lower servo is used to measure the load variation. The normal load is applied and controlled by the hydraulic servo at left side and the left servo load cell is used to measure the load variation. To make sure that both loads are perpendicular to each other, it is imperative to align the specified pad. A dog bone specimen was used with length of 228 mm, 3.8 mm thickness, 6.3 mm width and the cross section area is 24.19 mm^2as taken from (Almajali, 2006). The pad is one cylindrical end with radius of 50.8 mm and its thickness is equal to its width of 9.53 mm. The properties of the material used are: 930 MPa yield strength, 0.33 Poisson’s ratio and 126 GPa elastic modulus.

Five tests were carried out. The frequency for both the axial and contact loads was kept a constant value of 10 Hz and the phase angle was zero. For all tests the maximum and minimum axial stresses were 564 MPa and 56.4 MPa respectively. Regarding the contact load, it was chosen to be constant of 3336 N for four tests. For test # 1, the contact load was varying between 2224 N to 4448 N (Table-1). The application of the axial force was in the condition of tension- tension while the variation of axial mean stress was at 0.1 constant stress ratio. Tests # 1 and test # 2 were conducted under fretting fatigue condition only. The contact load was varying in test # 1 and constant in test # 2. Test # 3 was conducted initially under 21,000 cycles of fretting fatigue and then under plain fatigue until failed. Test # 4 was carried out under sequence of 5,000 and 10,000 of fretting fatigue and plain fatigue respectively. This sequence is repeated until the failure happened. Finally, test # 5 was conducted under repeatable 1,000 cycles of fretting fatigue followed by 200,000 cycles of plain fatigues.

The anticipated process for any of the requested tests is planned in multipurpose test. Initially, several steps have to be carried out before such process starts. The first step is to install the pads into the holding blocks which are attached to the frame. Then to make sura that contact surface of the pad is perpendicular to the contact surface of the specimen, the pads have to be aligned correctly. This is to ensure that both axial force and contact force are orthogonal. This is followed by a warm up process after removing the specimen by programming in the multipurpose. The duration of the warm up procedure is preferable to be around half an hour. This is also to make sure that the machine has no malfunction. After that, the specimen is reinstalled and the required procedure is ready to function.

It is recommended initially to apply the normal load gradually until reaching the maximum magnitude of the applied normal load. Similarly, the axial load is applied gradually until reaching the highest value. Then, the application of the axial load will be cyclic load such as sinusoidal function between the lowest and highest magnitudes of the axial load. However, the normal load is applied as constant load in this study. The frequency of the axial load was selected to be 10 Hz. The test was run until the failure happened. During the running process, the required parameters have to be monitored and recorded. Those parameters include running time, lower and upper axial loads, applied contact load, life cycles and the displacement. Once the failure occurred, the material life was considered as the number of the cycles for fretting fatigue.

Table (1) The input load conditions for the test of plain and fretting fatigue

Test No.	σ_{ma} MPa	σ_{mi} MPa	P_{ma} N	P_{mi} N	Notes
1	546	56	4448	2224	Variable contact load
2	546	56	3336	3336	Constant contact load
3	546	56	3336	3336	21,000 fretting cycles followed by plain fatigue
4	546	56	3336	3336	Repeatable 5,000 fretting cycles and 10,000 plain cycles
5	546	56	3336	3336	Repeatable 1,000 fretting cycles and 200,000 plain cycles

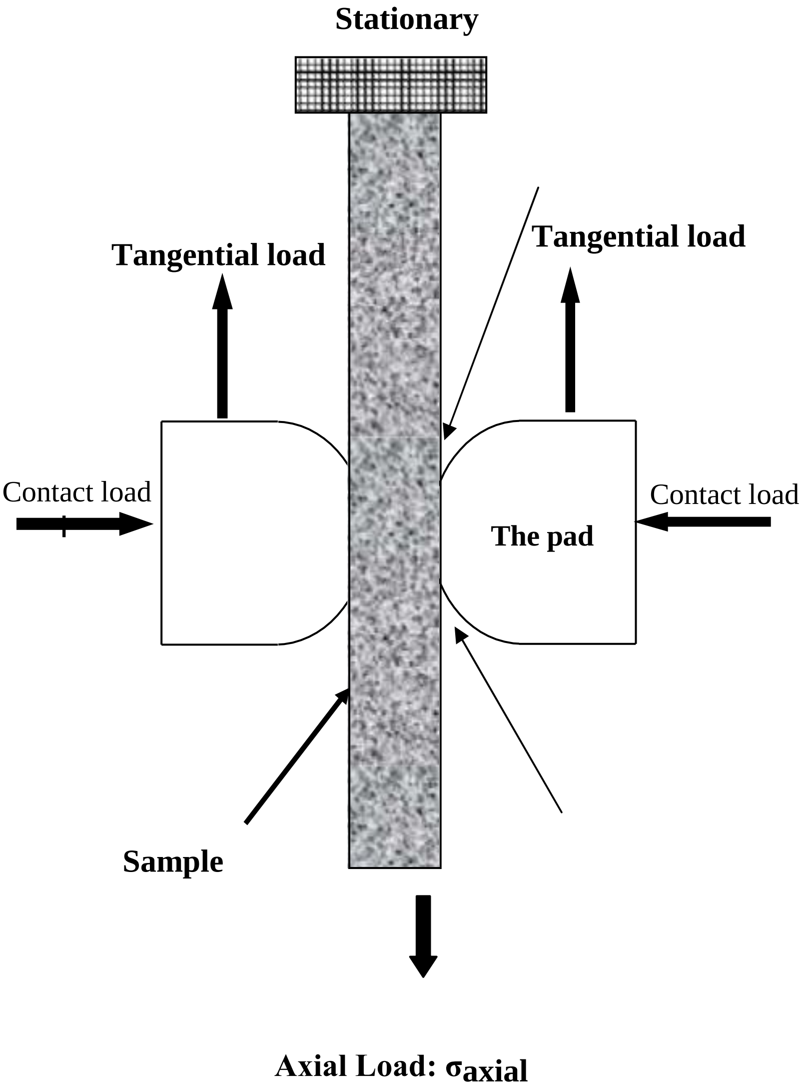


Figure (1) Configuration of the adopted fretting fatigue in this study.

3. Results and Discussion

In this study five experiments have been conducted where four of them were carried out at dissimilar combinations of fretting and plain fatigues. The applied contact/normal load was kept constant while the axial load was varying as a cyclic load. The load ratio between the contact load and the axial load was also varied. Since the load condition is varied between the fretting fatigue to plain fatigue and vice versa, the condition of the steady state is changed. The results out of this study are discussed below:

a. For the tests conducted under the combination between plain and fretting fatigues, the condition of steady state varies since the applied force is changing from plain fatigue to fretting fatigue. While for the test done under constant contact load as in test # 2, the condition of the steady state has been encountered after first hundreds of cycles as shown in figure 2. This figure shows also that the maximum magnitude of the tangential load reaches around 800 MPa.

b. Figure 3 shows the tangential load against the life cycle for test # 3 which has been carried out initially under fretting fatigue for 21,000 cycle then under plain fatigue until failure. The 21,000 cycle was chosen as it is the half of the life of test # 2. It is clear how the tangential load disappeared and decreased immediately from around 800 MPa to zero after releasing the fretting fatigue condition since there is no contact load. It behaves like a discontinuity and the maximum tangential load condition. On the other hand; the behavior of tangential load for test # 4 which was conducted under combination of 5,000 cycles of fretting fatigue and 10,000 cycles of plain fatigue is shown in figure 4. It is clear that when the contact load disappeared, the fretting condition disappeared and the tangential load down to zero. Once the fretting fatigue appears the tangential load goes up to almost 800 MPa.

c. Regarding the fatigue life, table 2 shows the fatigue life for all experiments done and the assessment of the material life of the conducted experiments is shown in figure 5.

1) Test # 1 and test # 2 were done completely under fretting fatigue condition where test # 1was done under variable contact load and test # 2 under constant contact load of 3336N. The fatigue life of test # 2 was around 42,000 cycles which is less than around 13 % than test # 1. This means that the constant contact load has more impact on reducing the life of the material as verified by previous works. This was also verified and reported from in previous study (Lee, 2004).

2) Test # 3 was carried out initially under fretting fatigue with half cycles resulted from test # 2 then continued under plain fatigue until failure. As seen, once the constant contact load is compared to 21,000 fretting cycles followed by plain fatigue, the fatigue life impressively increases from 42,000 to 10,000,000 cycles! This also approves the significant effect of the fretting fatigue regime. The fatigue life of this test was around 10 million cycles. This life is almost as the same of the fatigue life of this material. This means that the fretting fatigue has no effect if it is applied only at initial. This might come from the fact that around 50 % of the material life from fretting fatigue didn’t initiate the crack and it is considered only for the crack initiation.

3) Test # 4 was carried out with combination of 5,000 and 10,000 cycles of fretting fatigue and plain fatigue respectively. The life of this test was around 80 thousand cycles which including 30,000 cycles of fretting fatigue and 50,000cycles of plain fatigue. The crack seems to be initiated at around 25,000- 30,000 cycles of fretting fatigue life. This means that the low load ratio between the cycles of both plain fatigue to fretting fatigue (2 in this case) doesn’t enhance the material life. Hence test # 5 was carried out under higher load ratio of 200. In this test the cycles of fretting fatigue were only one thousand (1,000) and the cycles of plain fatigue were 200 thousand (200,000). It was observed that the life increased to more than 3 million (3,300,000) with only 16,000 of them under fretting fatigue. The difference in the numbers of the fatigue life have be shown to be noteworthy This means that as the ratio increases the material life will increase,

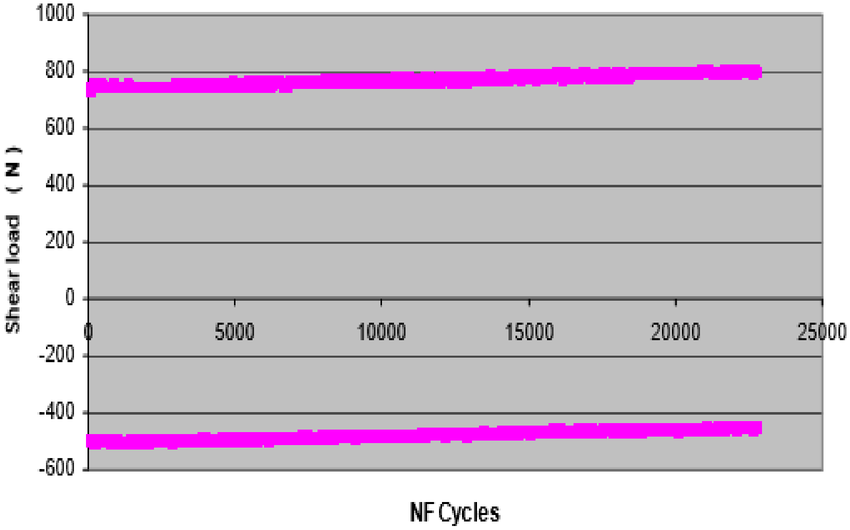
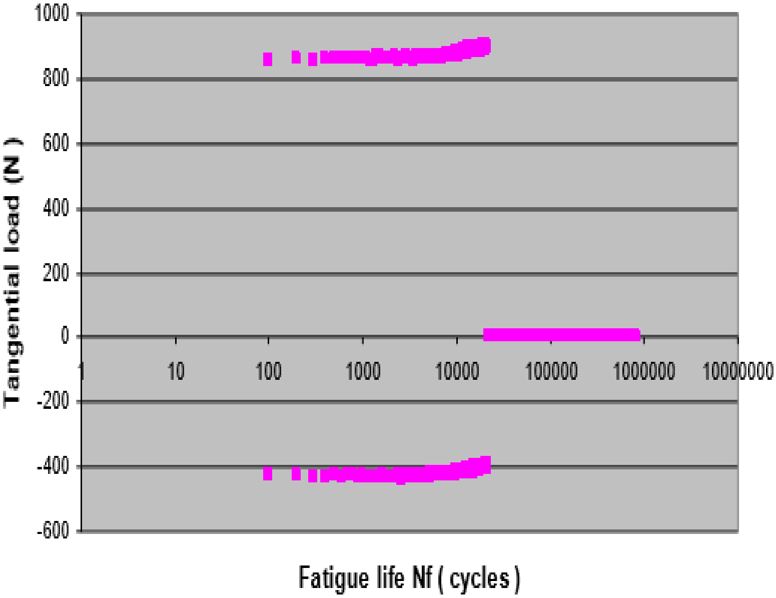


Figure. 2 Shear load (N) vs the material life cycle (NF) for test # 2 (constant contact load)



Figure(3) Tangential load (N) vs material life cycles (NF) for test # 3

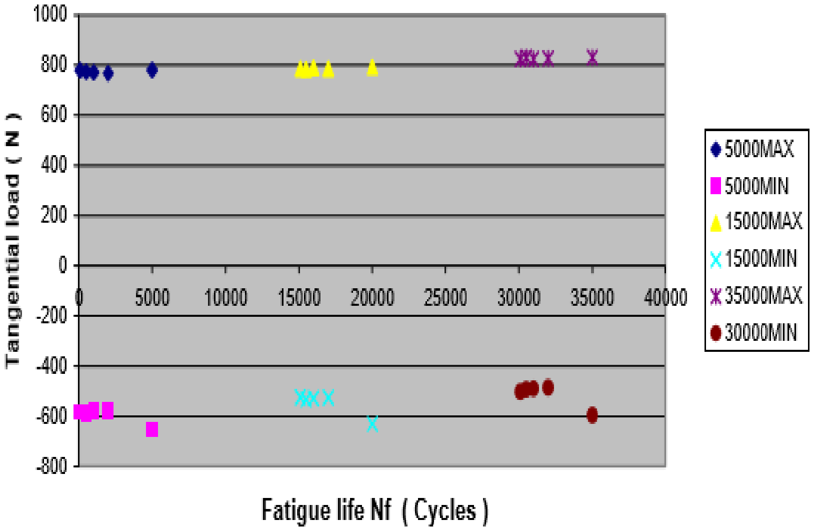
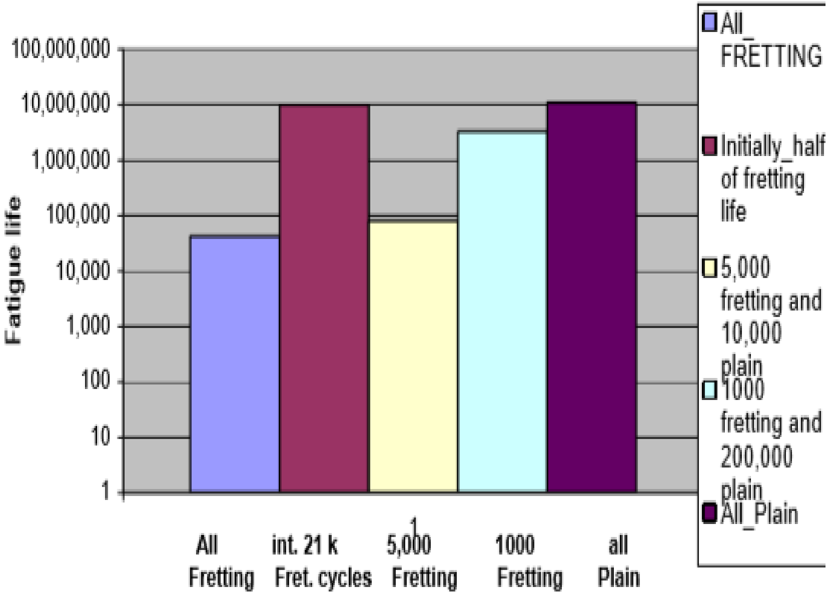


Figure. (4) Tangential load (N) against material life (NF) for test # 4



Figure(5) Fatigue life (NF) against load configuration for test # 4

Table(2) The fatigue life for all tests conducted with required input load conditions

Test No.	Conditions	Fatigue life NF (cycles)
1	Variable contact load	47,300
2	Constant contact load	42,000
3	21,000 fretting cycles followed by plain fatigue	10,000,000
4	Repeatable 5,000 fretting cycles and 10,000 plain cycles	80,000
5	Repeatable 1,000 fretting cycles and 200,000 plain cycles	3,300,000

4. Conclusion and Recommendation

Experimental study was conducted to understand the behavior of the material under combination of fretting fatigue and plain fatigue. Five tests were carried; two are fretting fatigue where the first one is under variable contact load and the second one under constant contact load. The rest three tests were conducted with the consideration of mixing of both fretting fatigue and plain fatigue regimes. The condition of the steady state for the fretting fatigue tests was at first few hundreds cycles while for the combination tests couldn’t reach the steady state. The tangential load was almost the same for all test when the contact load is applied. Regarding the fatigue life, the plain fatigue has no effect on the material life comparing to the fretting fatigue if 50% of the life of the fretting fatigue was applied initially and then followed by the remain cycles of the plain fatigue regime until the material failure. The results exhibit also that the majority of the life of fretting fatigue is consumed to initiate the crack. The load ratio of fretting fatigue and plain fatigue has a huge impact on the material fatigue. If the increase of the load ratio results in the reduction of the material fatigue life.

This is also verified in may previous studies which emphasizing that the fretting fatigue decreases the fatigue life compared to the plain fatigue.

To have a better idea about the material performance with mixing both plain fatigue and fretting fatigue, it is recommended to conduct different tests considering of such condition. The tests might be conducted with elevated temperature, varying contact load, specimen with shoot peening surface and environmental condition such as salty environment.

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