EFFECT OF SURFACE ROUGHNESS ON FATIGUE LIFE

AHMAD KAMIL BIN MISKAM

BACHELOR OF ENGINEERING

UNIVERSITI MALAYSIA PAHANG

2010

UNIVERSITI MALAYSIA PAHANG

BORANG PENGESAHAN STATUS TESIS

JUDUL: **EFFECT OF SURFACE ROUGHNESS ON FATIGUE LIFE**

SESI PENGAJIAN: 2010/2011

Saya **AHMAD KAMIL BIN MISKAM (880830-05-5341)**
(HURUF BESAR)

mengaku membenarkan tesis (Sarjana Muda/~~Sarjana~~ /~~Doktor Falsafah~~)* ini disimpan di Perpustakaan dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hakmilik Universiti Malaysia Pahang (UMP).
2. Perpustakaan dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (√)

[ ] **SULIT** (Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)

[ ] **TERHAD** (Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)

[√] **TIDAK TERHAD**

Disahkan oleh:

(TANDATANGAN PENULIS) | (TANDATANGAN PENYELIA)

Alamat Tetap:

NO7, JLN KUINI,
KG. BKT BANGKONG, SG PELEK,
43950, SEPANG,
SELANGOR DARUL EHSAN.

Tarikh: 6/12/2010

Nama Penyelia:

NASRUL AZUAN BIN ALANG

Tarikh: 6/12/2010

CATATAN: * Potong yang tidak berkenaan.

** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali tempoh tesis ini perlu dikelaskan sebagai atau TERHAD.

Tesis dimaksudkan sebagai tesis bagi Ijazah doktor Falsafah dan Sarjana secara Penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (PSM).

EFFECT OF SURFACE ROUGHNESS ON FATIGUE LIFE

AHMAD KAMIL BIN MISKAM

Report submitted in fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

DECEMBER 2010

UNIVERSITI MALAYSIA PAHANG

FACULTY OF MECHANICAL ENGINEERING

We certify that the project entitled *"Effect of Surface Roughness on Fatigue Life"* is written by *Ahmad Kamil Bin Miskam*. We have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering.

Mr. Lee Giok Chui
Examiner

Signature

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature:

Name of Supervisor: NASRUL AZUAN BIN ALANG

Position: LECTURER

Date: 6/12/2010

STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurently submitted for award of other degree.

Signature:

Name: AHMAD KAMIL BIN MISKAM

ID Number: MA08011

Date: 6/12/2010

Dedicated to God whose guidance, help and grace was instrumental in making this humble work a reality. To my beloved father, mother, friends, without they and his/her lifetime efforts, my pursuit of higher education would not have been possible and I would not have had the chance to study for a mechanical course. Also to my supervisor, Mr. Nasrul Azuan for their guide and help especially in finishing this project report.

ACKNOWLEDGEMENTS

This project was conducted under the supervision of Mr Nasrul Azuan Bin Alang in Universiti Malaysia Pahang (UMP). I am very grateful to him for his patience and his constructive comments that enriched this research project. His time and efforts have been a great contribution during the preparation of this thesis that cannot be forgotten forever.

I would also like to acknowledge with much appreciation the crucial role of the staff of Mechanical Laboratory, who gave the permission to use all required machinery and the necessary material to complete the rotating bending fatigue testing and for their comments and sharing their time and knowledge on this research project during the project was carried out.

I also gratefully acknowledge the assistance of everybody who helped in the execution of this project in UMP. I also thank to all Mechanical students for their friendship and help when thinking through problems and for sharing their knowledge of machining equipment and experimental apparatus. Finally, I thank my family for their continuous support and confidence in my efforts.

Last but not least, many thanks go to the supervisor of the project, Mr. Nasrul Azuan Bin Alang, whose have given his full effort in guiding in achieving the goal as well as his encouragement to maintain a progress in track. I would to appreciate the guidance given by other supervisor and panels especially in project presentation that has improved my presentation skills by their comment and tips.

Thank you.

ABSTRACT

The main purpose of this project is to determine the effect of surface roughness on fatigue life for Mild steel specimen. The study of fatigue life and effect of surface roughness is very important in order to minimize the cost of machining and time of machining and also to study the durability of materials. The influence of machined surface roughness on the fatigue life of Mild steel has been investigated. Fifth teen bending fatigue specimens have been machined according to various machining roughness conditions and tested in fatigue test. In order to explain the effect of surface roughness, S-N curves has been plotted to express the test results. After the fatigue test has been completed, the surface fractures are analyzed to ensure that the specimens are failed due to fatigue. Based on the examination, the Mild steel specimen was failed due to transgranular manners and the failure surfaces consist of two region which is crack propagation region and rapid fracture region.

ABSTRAK

Tujuan utama projek ini ialah untuk menentukan kesan kekasaran permukaan besi rendah karbon terhadap hayat lesu. Kajian terhadap hayat lesu dan kesan kekasaran permukaan adalah sangat penting dalam untuk mengurangkan kos dan masa permesinan dan juga untuk mengkaji ketahanan sesuatu bahan. Kesan daripada kekasaran permukaan terhadap hayat lesu telah pun dikaji. Sebanyak lima belas bahan kaji besi rendah karbon telah dimesin mengikut pelbagai keadaan kekasaran dan telah diuji pada ujian lesu. Untuk menerangkan kesan kekasaran permukaan, lengkung S-N telah diplotkan untuk menunjukkan keputusan ujian. Setelah ujian lesu telah selesai, permukaan bahan yang patah di analisis bagi memastikan bahan telah gagal atau patah disebabkan oleh ujian lesu. Berdasarkan dari pemeriksaan, bahan uji kaji besi rendah karbon telah gagal disebabakan struktur ‘transgranular’ dan permukaan yang patah terdiri dari dua kawasan iaitu kawasan perambatan retak lesu dan kawasan cepat patah.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a_0	Crack magnitude
$s(t)$	Stress-related variable
s_{max}	Maximum stress
s_{min}	Minimum stress
s_m	Average stresst
s_a	Amplitude stress
Δs	Stress range
R	Stress ratio
N	Cycle number
t	Time
l	Crack length
R_a	Average roughness parameter
cs	Cutting speed
d	Worpiece diameter
v_f	Feed rate
f	Feed
R_{max}	Maximum Roughness Depth
R_z	Average Maximum Height of the Profile
σ	Stress amplitude

LIST OF ABBREVIATIONS

Al	Aluminium
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CNC	Computer Numerical Control
DC	Direct Current
EP	Electrical Potential
FKM	Faculty of Mechanical Engineering
NDI	Non-destructive inspection
OM	Optical Microscope
PSB	Persistent Slip Band
RPM	Revolution per Minute
RST	Reset
SEM	Scanning Electron Microscope
SN	Stress Number

CHAPTER 1

INTRODUCTION

1.1 PROJECT SYNOPSIS

This project concerned on experiment that is to investigate the effect of surface roughness on the fatigue life which are conducted in a rotating bending fatigue test with constant amplitude until the specimen are failed. The fatigue limit is recognized as a threshold for the growth of small crack, fatigue crack initiation is a surface phenomenon, but thousand of grains are found at the material surface of unnotched specimens. Nucleation depends on the occurrence of cyclic slip. If crack nucleation occurs at small inclusion near the free surface of the material, the size, the shape and orientation of the inclusions is another source for differences between grains. Surface roughness can also contribute to some preferred location for crack initiation. Nucleation of fatigue cracks in an unnotched specimen will therefore occur at a location where all combined conditions are most favorable for cyclic slip and crack nucleation. It seems to be reasonable that in a fatigue test only one dominant fatigue crack nucleus is detected on the fracture surface. This is particularly true if the cyclic stress level is close to the fatigue limit. The location of crack nucleation site may then be called the “weakest link” of the specimen.

1.1.1 Specific Project Synopsis

My project title is to investigate effect of surface roughness on the fatigue life. The purpose of this study is to reveal general aspects related to the fatigue life. As consequence, various kind of surface effect can be of great importance for the fatigue life. Surface effects include all conditions which can reduce or enhance the crack initiation period. In other word, they cover the phenomena which have an influence on the crack initiation mechanism. Surface roughness and surface damage imply that the free surface is no longer perfectly flat. As a consequence, small sized stress concentrations along the material surface occur. Although the stress concentration will rapidly fade away from the surface, it is still significant for promoting cyclic slip and crack nucleation at the material surface.

1.2 PROJECT PROBLEM STATEMENT

Fatigue failures are causes from a many factor such as material type, residual stresses, notch geometry, surface quality and etc. In a fatigue failure, an incident of a stress can exceed the material's fatigue strength and initiate a crack to make that material to be failed that also have caused from the effect of some parameter to the material such as the surface roughness effect. In the machining process, the finishing process to the material are required the higher cost to be produced. As the surface finishing affected the fatigue life of a material, the machining process must be considered this parameter in order to minimize the cost and time in producing a product.

1.3 OBJECTIVES OF PROJECT

(i) To investigate the effect of surface roughness on fatigue life.
(ii) To identify different regions on fracture surface due to cyclic loading.

1.4 SCOPE OF WORK

Scope of work is an about the limitation of the project, which is all about the project must be done accordingly to this project scopes only. Special scope of works has to be determined so that the main objective and goal can be achieved. These scopes helped to be focused and knew about a concentration job. These scopes of this project are:

(i) Different surface roughness of specimens will be prepared.
(ii) Rotating bending fatigue tests will be conducted in order to investigate the effect of surface roughness on fatigue life.

(iii) The experiment is conducted at room temperature with constant frequency.

(iv) The fracture surface is analyzed by using SEM (Scanning Electron Microscope)

(v) The experiment is conducted with constant stress amplitude and stress ratio.

1.5 PROJECT PLANNING

The project progress start with gather the information by research and literature review via internet, journal, reference books, supervisor and other relevant academic material that related to this project. To understand more about the project, need to study more about material related to the project topic and spend more than three week to make a literature review.

All the literature review that related to the project need to be collected. The literature review must have a review of definition of fatigue crack, material type for fatigue, crack growth prediction, Characteristics of fatigue, fatigue test, detecting and measuring cracks, factors that affect fatigue-life, the review of using Scanning Electron Microscope (SEM), and the method for specimen preparation. In this project, the specimens are need to be machined with different surface roughness machining by using a turning machine either conventional or Computer Numerical Control (CNC). Before this step, the specimen dimensions are needed to be measure according to the rotating fatigue specimen example that has in the FKM material lab. After that the type of material are need to be determine before starting the machining process. This machining process will take a few weeks to complete. After that, task is preparation of progress presentation and report writing chapter one until chapter three. These tasks take three week to be finish. On that particular week, preparation needed to make a Final Year project one presentation.

The next task will be continuing on second semester with Final Year Project two. The first task on second semester is discussed with supervisor about current progress and continuing the project progress. After that, project progress will be continuing with Experiment on effect of surface roughness on rate of fatigue crack growth by using a rotating bending fatigue machine. The experiment process begins with setup for the experiment apparatus by using a standard procedure. The analysis should be repeated by different level of surface roughness of specimens. This process will take a few weeks to done it. Then the fracture surface is needed to be analyzed using a SEM (Scanning Electron Microscope) to identify different region on fracture surface due to cyclic loading. Then, the project will continue with collect the data such as the crack initiation life and crack propagation life and others. The data will be collect to obtain the S-N curve as a result.

Lastly, the final report writing and prepare the final presentation. A report is guided by FKM thesis format and also guidance from supervisor. All task scheduled is take around two semesters to complete.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Fatigue is one of the primary damage mechanisms of structural components. Fatigue results from cyclic stresses that are below the ultimate tensile stress, or even the yield stress of the material. The name “fatigue” is based on the concept that a material becomes “tired” and fails at a stress level below the nominal strength of the material.

The facts that the original bulk design strengths are not exceeded and the only warning sign of an impending fracture is an often hard to see crack, makes fatigue damage especially dangerous. The fatigue life of a component can be expressed as the number of loading cycles required to initiate a fatigue crack and to propagate the crack to critical size (Beer et al., 2006). Therefore, it can be said that fatigue failure occurs in three stages–crack initiation; crack propagation; and rapid fracture.

2.2 FATIGUE OF MATERIAL AND RELATED PHENOMENA

In a narrow sense, the term fatigue of materials and structural components means damage and fracture due to cyclic, repeatedly applied stresses. In a wide sense, it includes a large number of phenomena of delayed damage and fracture under loads and environmental conditions. The systematic study of fatigue was initiated by Wohler, who in the period 1858-1860 performed the first systematic experimentation on damage of material under cyclic loading. In particular, Wohler introduced the concept of fatigue curve, i.e., the diagram where a characteristic magnitude of cyclic stress is plotted against the cycle number until fatigue failure. Up to now the Wohler curve has been used widely in the applied structural analysis. At the same time, fatigue and related phenomena are considered as a subject of mechanics of solids, material science, as well as that of basic engineering.

It is expedient to distinguish between high cycle (classic) and low cycle fatigue. If plastic deformations are small and localized in the vicinity of the crack tip while the main part of the body is deformed elastically, then one has one cycle fatigue. If the cyclic loading is accompanied by elasto-plastic deformation in the bilk of the body, then one has low cycle fatigue. Usually we say low cycle fatigue if the cycle number up to initiation of a visible crack or until final fracture is below 10^4 or 5. 10^4 cycles.The mode of damage and final fracture depend on environmental conditions. At elevated temperature plasticity of most materials increase, metals display creep, and polymers thermo-plastic behavior. At lower temperatures plasticity of metal decrease and brittle fracture become more probable. If a structural component is subjected both to cyclic loading and variable thermal actions, mixed phenomena takes place, such as creep fatigue, creep accelerated by vibration, and thermo-fatigue (Wagner et al., 1986). The combination of fatigue and corrosion is called corrosion fatigue. It is a type of damage typical for metal interacting with active media, humid air, etc. The delayed fracture occurs not only under cyclic, but also under constant or slowly varying loading. Typical examples are the delayed fracture of polymers and crack initiation and propagation in metals under the combination of active environment and non-cyclic loads.

Fatigue is a gradual process of damages accumulation that proceeds on various levels beginning from the scale of the crystal lattice, dislocation and other objects of solid state physics up to the scales of structural components, three or four stages of fatigue damages are usually distinguishable, In the first stage, the damage accumulation occurs on the level of microstructure. Where a polycrystalline alloy is concerned, it is the level of grains and intergranular layers. The damage is dispersed over the volume of a specimen or structural component or at least, over the most stressed part. At the end of this stage, nuclei of macroscopic cracks originate, such as aggregates of microcracks that are strong stress concentrators and under the following loading, have a tendency to grow. Surface nuclei usually can be observed visually (at least with proper magnification). The second stage is the growth of cracks whose depth is small compared with the size of the cross section. At the same time, the sizes of these cracks are equal to a few characteristic scales of microstructure, say, to several grain sizes. Such crack are called small crack. The number of small cracks in a body may be large. The pattern of their propagation is different from that of completely developed macroscopic cracks. Small crack find find their way through the nonhomogeneous material. Most of them stop growing upon meeting some obstacles, but one or several cracks transform into macroscopic, "long" fatigue cracks that propagate in a direct way as strong stress concentrators. This process forms the third stage of fatigue damage. The fourth stage is rapid final fracture due to the sharp stress concentration at the crack front and the expenditure of the material's resistance to fracture (Beer et al., 2006).

The initiation and following growth of a macroscopic crack are schematically shown in Figure 2.1 for the case of a polycrystalline material under uniaxial cyclic tension. Nuclei appear near the surface of the specimen, in particular, in the local stress concentration domains as we, as near the damaged or weakest grains. The initial slip planes and microcracks in grain are oriented mostly along the planes with maximal shear stresses. Small crack are inclined, at least approximately, in the same directions. These crack go through the grains, intergranular boundaries or in a mixed way. When one of the small cracks becomes sufficiently long, the direction of its growth changes: the crack propagates into the cross section of the specimen, in the so-called opening mode. Such a "long" macroscopic crack intersects in its growth a large number of grains. Therefore, this growth is determined mainly with averaged properties. The border between small and "long" cracks is rather conditional. In particular, it depends on the ratio of the current crack size a and the characteristic size of grains. If the grain size is of the order of 0.1mm, a crack may be considered as "long" when it reaches the magnitude a_0= 0.5mm or 1mm (Bolotin, 1999).

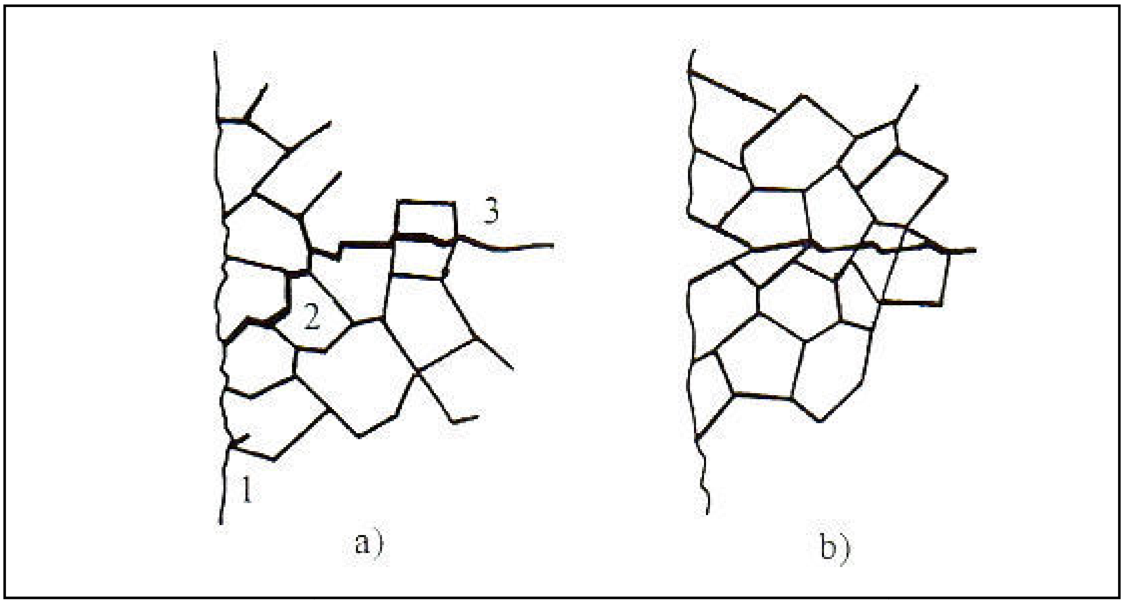

Figure 2.1: Fatigue crack initiation in polycrystalline material: (a) near the regular surfaces; (b) near a strong stress concentrator.

Source: Bolotin (1999)

The ratio of durations of these stages varies to a large extent depending on material properties, type of loading and environmental conditions. The first two stages are absent if a crack propagates from an initial macroscopic crack, sharp crack-like defect or another strong stress concentrator as shown in figure 2.1. In this case the position of the macroscopic cracks is conditioned beforehand, and the crack begins to propagate after a comparatively small number of cycles. On the other hand, for very brittle materials the final fracture may occur suddenly, without the formation of any stable macroscopic cracks. For example, it may be a result that microcrack density attains a certain critical level.

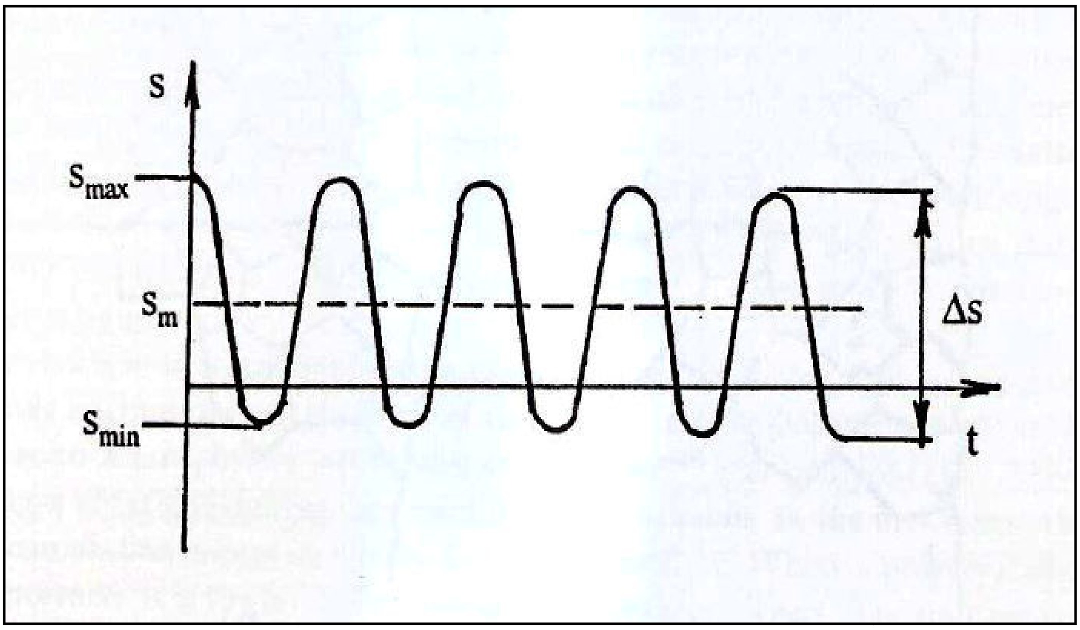

Figure 2.2: Cyclic loading and its characteristic stresses

Source: Bolotin (1999)

A typical cyclic loading process is presents in Figure 2.2. The notation *s(t)* is used here for any stress-related variable characterizing the loading process. It may be interpreted, for example. As a remotely applied normal stress relating to the whole cross section of a specimen subjected to cyclic tension/compression. If *s(t)* is varying as a sinusoidal function, the duration of cycle coincides with the period of the function *s(t).* Each cycle contain maximal s_{max} and minimal s_{min} magnitudes of the applied stresses. A cycle is usually considered as a segment of the loading process limited with two neighboring up-crossing of the average stress $s_m = (s_{max} + s_{min})/2$. The cyclic loading is usually described by the amplitude stress $s_a = (s_{max} - s_{min})/2$ or the stress range $\Delta s = s_{max} - s_{min}$. Stress ratio $R = s_{min} / s_{max}$ is also a significant characteristic of the cyclic loading. For symmetrical cycle $R = -1$; when a cycle contains non-negative stresses only the, $R > 0$. The cycle number *N* is an integer number, although it is usually treated as a continuous variable **(**Bolotin, 1999). Actually, the cycle number corresponding to significant damage, or moreover to final value, as a rule is very large compared with unity. Time *t* is useful as independent damage phenomena are considered**.**

2.3 DIFFERENT PHASES OF THE FATIGUE LIFE

After more microscopic information on the growth of small cracks became available, it turned out that nucleation of microcracks generally occurs very early in the fatigue life. In spite of early crack nucleation, microcracks remain invisible for a considerable part of the total fatigue life (Krupp, 2007). Once crack become visible, the remaining fatigue life of a laboratory specimen is usually small percentage of the total life.

After a microcrack has been nucleated, crack growth can still be a slow and erratic process, due to effects of the micro structure,e.g. grain boundaries. However, after some microcrack growth has occurred away from the nucleation site, a more regular growth is observed (Schijve, 2001). This is the beginning of the real crack growth period. Various steps in the fatigue life are indicated in Figure 2.3. The important point is that the fatigue life until failure consists of two period: the crack initiation period and the crack growth period.

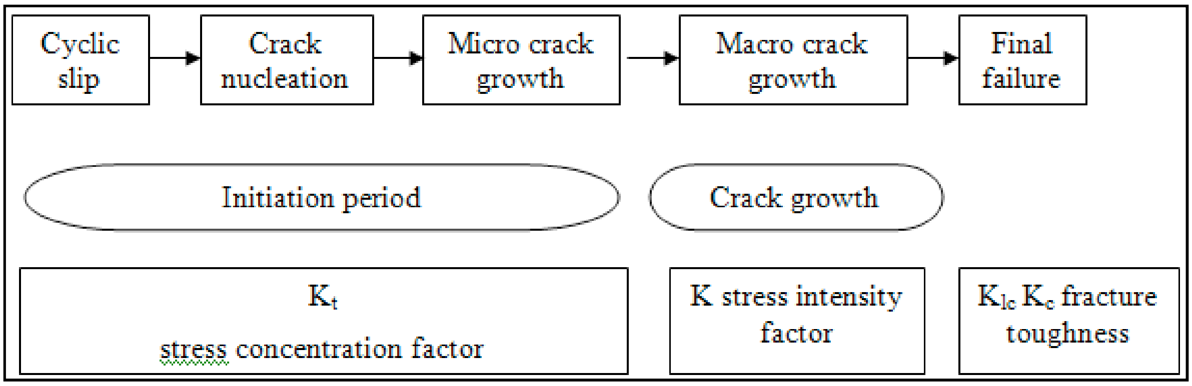

Figure 2.3: Different phases of the fatigue life and relevant factors

Source: Schijve (2001)

2.4 FATIGUE FAILURE STAGES

In the first stage, dislocations accumulate near surface stress concentrations and form structures called persistent slip bands (PSB) after a large number of loading cycles.

PSBs are areas that rise above (extrusion) or fall below (intrusion) the surface of the component due to movement of material along slip planes. This leaves tiny steps in the surface that serve as stress risers where tiny cracks can initiate. These tiny crack (called microcracks) nucleate along planes of high shear stress which is often 45^{o} to the loading direction (http://www.ndt-ed.org).

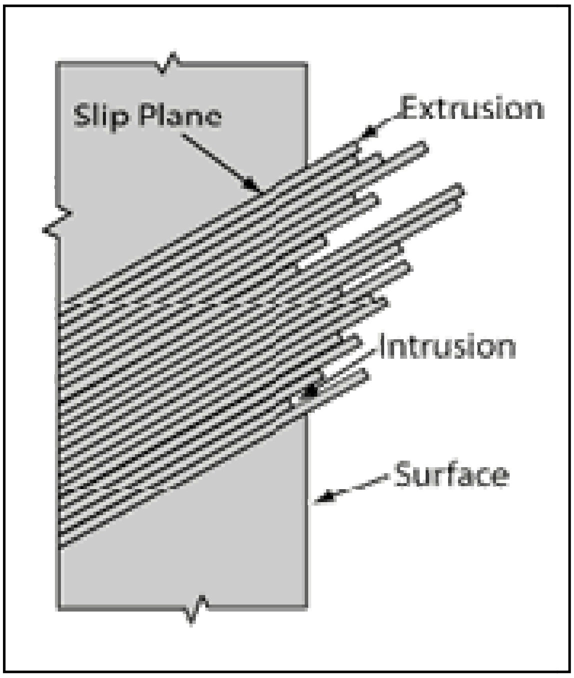

Figure 2.4: Fatigue crack initiation

Source: Krupp (2007)

The most common reasons for crack initiation in a component include:

- Notches, corners, or other geometric inconsistencies in the component
- Material inclusions, impurities, defects, or material loss due to wear or corrosion
- Mechanical or thermal fatigue

Once a crack has been initiated, repeated loadings can cause the crack to lengthen. Depending on the stress level and the number of load cycles applied, crack growth can be stable, with a predictable rate; unstable, with imminent failure; or occasionally a decrease or cessation of growth altogether.

In the second stage of fatigue, some of the tiny microcracks join together and begin to propagate through the material in a direction that is perpendicular to the maximum tensile stress. Eventually, the growth of one or a few crack of the larger cracks will dominate over the rest of the cracks (Kristoff, 2009).

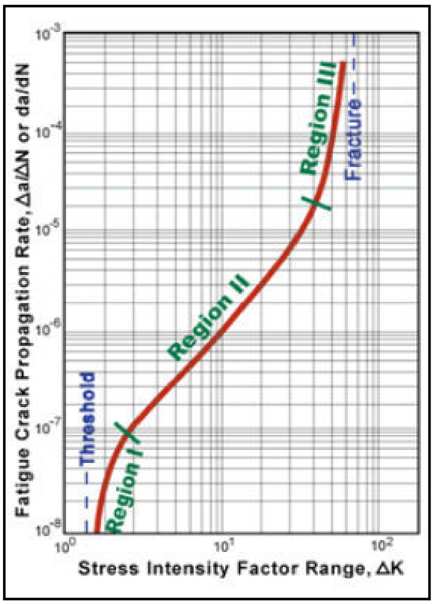

Figure 2.5: Fatigue crack propagation rate

Source: Krupp (2007)

The fatigue crack propagation behavior of many materials can be divided into three regions as shown in the image (http://www.ndt.ed.org). Region I is the fatigue threshold region where the Dk is too low to propagate a crack. Region II encompasses data where the rate of crack growth changes roughly linearly with a change in stress intensity fluctuation. In region III, small increases in the stress intensity amplitude, produce relatively large increases in crack growth rate since the material is nearing the point of unstable fracture.

With continued cyclic loading, the growth of the dominate crack or cracks will continue until the remaining uncracked section of the component can no longer support the load. At this point, the fracture toughness is exceeded and the remaining cross-section of the material experiences rapid fracture. This rapid overload fracture is the third stage of fatigue failure.

Figure 2.6: Crack growth due to fatigue

Source: Bolotin (1999)

Crack growth can be encouraged by factors other than applied load. Environmental effects, such as corrosion due to exposure to water or other solvents, as well as component wear can result in an overall loss of material in the component cross section, increasing the stress carried by the remaining material (De vries et al., 1998). This increased stress can accelerate crack growth and ultimate failure.

2.5 IMPORTANT OF FATIGUE

Fatigue failure generally consists of three stages: crack initiating and crack propagation and until total fracture. For machine components containing no pre-existing cracks, the majority of fatigue life is spent in initiating or starting fatigue cracks and the fatigue process is described as initiation-controlled (Stephens, 2000). Examples of these include crank shafts, gear teeth, and rotating shafts or axles. On the other hand, large structures or welded parts almost always contain pre-existing cracks such as in bridges, ships, aircraft fuselage, and pressure vessels. In such structures, the majority of fatigue life is spent in growing a pre-existing crack to a critical size and then to final fracture. The fatigue process in this case is described propagation-controlled (Gasem, 2004). This session will be concerned only with fatigue testing of un-cracked specimens where most of fatigue life is spent in the initiation stage.

Engineering structures and components often contain stress concentrations such as notches. Fatigue cracks almost always start at regions of high stress concentrations. For example, Figure 2.7 shows a fatigue crack starting from a keyhole in a rotating shaft. Fracture surfaces of components failed by fatigue are usually flat and perpendicular to the applied stress and often show features called beachmark ridges as shown in Figure 2.7. These marks are positive indication for fatigue failure and they represent the crack fronts during loading. Furthermore, fatigue failure is brittle in nature and does not involve gross plastic deformation even in metals that behave in a ductile manner under static loading (Gasem, 2004). Hence, fatigue failure occurs suddenly and can cause catastrophic consequences.

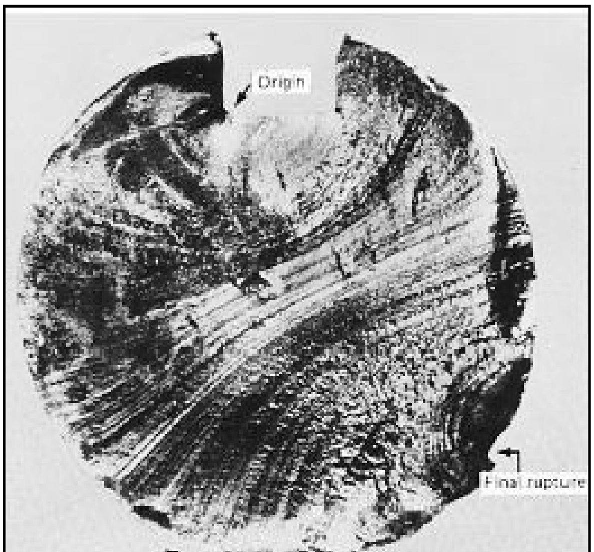

Figure 2.7: A shaft containing a keyhole failed due to fatigue

Source: Gasem (2004)

2.6 MATERIAL TYPE AND CRACK GROWTH PREDICTION

Homogeneous materials such as steel or aluminum have relatively predictable crack growth rates that have been verified through extensive material coupon tests. Based on the current crack size and the stress per load cycle, the remaining life of the part can be estimated using reference graphs generated through coupon testing.

However, crack growth in composite materials, such as fiberglass, are far more difficult to predict. Crack growth can depend on the materials in the composite, orientation of the materials in the matrix, orientation of multiple layers in the matrix, etc. (Kristoff, 2009). Crack growth in composite materials can also be influenced by other damage mechanisms, such as delamination, that generally do not occur in homogeneous materials.

2.7 FATIGUE TEST

Initial information for the design of engineering systems against fatigue is based on standard fatigue tests. Among them are test in cyclic tension, tension compression, rotating, bending, etc. Shape and sizes of specimen, requirements for their manufacturing and finishing, test techniques and methods of treatment of results are specified by national and international codes. As examples, the documentation of the American Society of Testing Material (ASTM), American Society of Mechanical Engineers (ASME), DIN, and GOST (the former USSR Committee of Standardization) can be mentioned.

Both load-controlled and displacement-controlled types of loading are used in fatigue test. In load-controlled test, the characteristic magnitudes of loads or of applied stresses are maintained constant throughout the duration of testing. In displacement-controlled test, the displacement, e.g., the maximal and minimal deflections of a rotating cantilever specimen are kept constant. In high-cycle fatigue, the type of loading affects the first stage of damage accumulation insignificantly (Bolotin 1999). Its influence becomes more substantial during the stage of growth of macroscopic crack when the specimen stiffness begins to decrease rather rapidly. The role of the type of loading in low-cycle fatigue test may be essential.

Results of standard fatigue test are presented in the form of fatigue curves that show the relationship between one of the characteristic cycle stresses *s* (the amplitude, the maximal stress, the stress range) and the limit cycle number *N*. Other characteristic cycle stresses, as well as parameters of the environmental conditions, including temperature, are maintained constant. The number *N* is counted either until the complete fracture of a specimen or until the observation of the first macroscopic crack of a given size. In particular, it can be just a visible surface crack.

Fatigue curves are plotted in the log-log or log-uniform scales. In figure 2.8 typical fatigue curves are shown for symmetrical ($s_{max} = - s_{min}$) and pulsating (at $s_{min} = 0$) tensile cycle loading s(t). Stress ratio R = -1 and R=0, respectively**.** Figure 2.8 represents the standard test procedure.

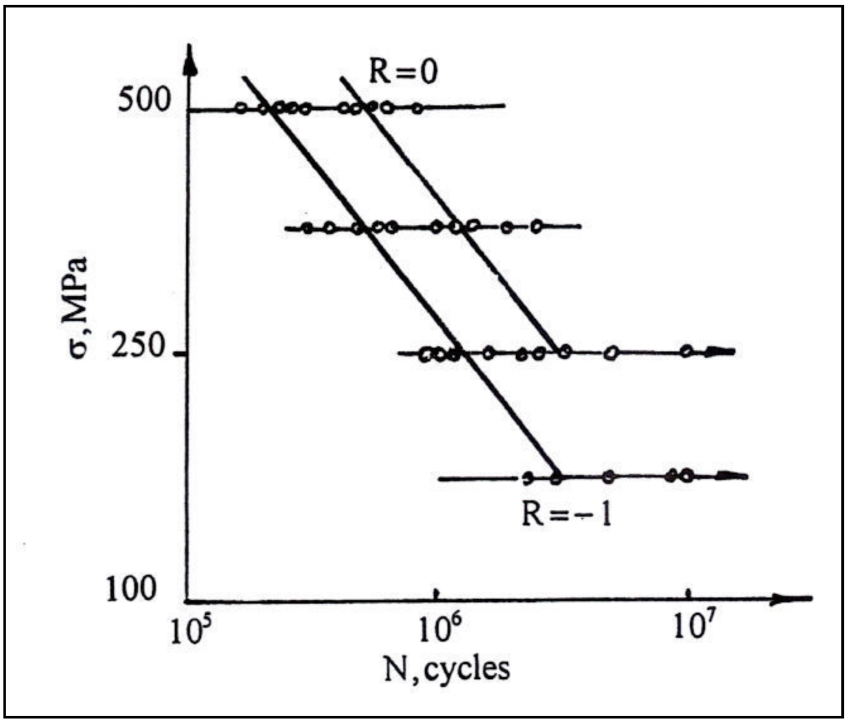

Figure 2.8: Fatigue curves in log-log scale for two stress ratios

Source: Bolotin (1999)

At each stress level s_{max} a group of specimen is tested, and for each group the limit cycle N is estimated. This number is subjected to significant scatter, over a half of decimal order and even more. Therefore, the fatigue curves in fact are either regression curves or fractile curves corresponding to a certain confidence level.

Fatigue test are terminated, as a rule, when beforehand stated cycle number N_b is achieved. In high-cycle fatigue test, it is usually taken as $N_b = 10^6$ …..10^7. If a fatigue curve in the log-log scale is close to a straight line, the analytical presentation is used.

$$N = N_b\left(\frac{s_b}{s}\right)^m \tag{2.1}$$

Here m is the fatigue curve power exponent, and s_b is a constant with the dimension of stress. These parameters, in general, depend on the mean stress (or on thestress ratio R), the loading frequency, test temperature, etc. Typical magnitudes of power exponents in high-cycle fatigue of ferrous and aluminum alloys are m = 6…..12.

There is evidence that, for some structural materials such as common low-carbon steels, and for polished specimens, macrocrack initiation does not take place if stress amplitudes are sufficiently small. One says in these cases that an endurance limit exists, e.g., a magnitude of stress amplitude (at a given mean stress of the cycle) such that fatigue fracture does not occur even at an arbitrary large cycle.The influence of the mean stress on the magnitude is significant. Test results are usually plotted either on the s_m ,s_a plane or on the s_{ma} , s_{max} plane (Bolotin, 1999). The cycle number N is treated as a parameter.

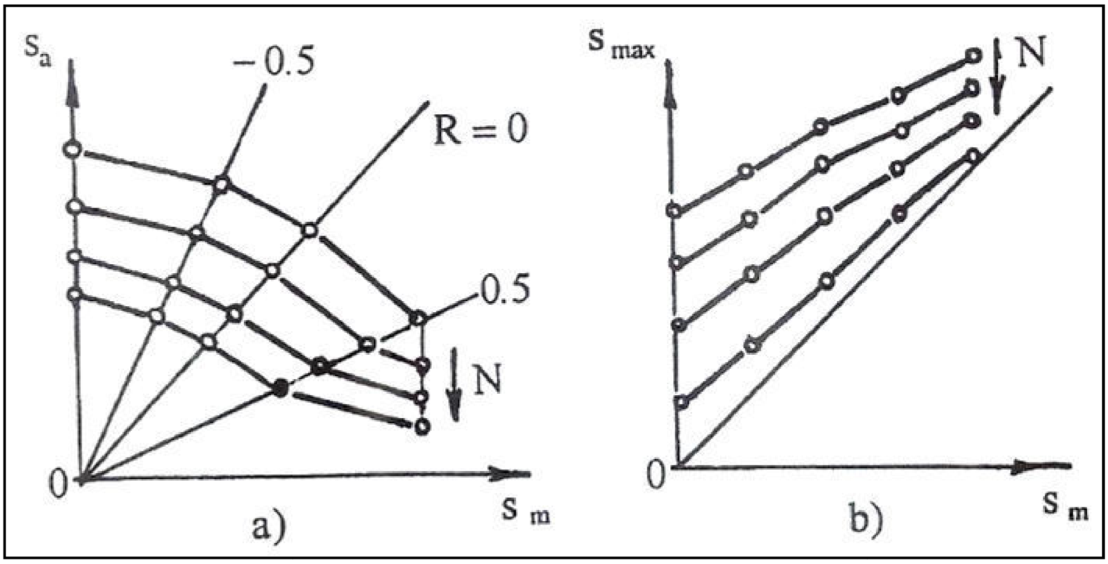

Figure 2.9: Schematic presentation of fatigue data

Source: Bolotin (1999)

2.7.1 Detecting and Measuring Cracks

The most common methods used to determine the size of small fatigue crack are optical or scanning electron microscopy of the crack or its replicated surface. Normally, information is provided only about the intersection of the crack with the surface. In some cases, crack depth has been measured by progressively removing surface layers. In other instances, electrical potential (EP) techniques have been used to study the formation and growth of small cracks, DC electrical potential measurement can be use to monitored crack depth, with the calibration model accounting for the shape as well as for variations in depth of the elliptical surfaces cracks (Farahani, 2005). Others method are an electro-chemical method for detecting small fatigue cracks in both steel and aluminum alloys through the identification of locations where cracks ruptured the oxide film on the surface. These rupture sites were imaged using photoelectron microscopy and fatigue crack as short as 10 μm in length were frequently detected.

Cracks are difficult to defect when they initiate because cracks begin at the microscopic level. There are a variety of non-destructive inspection (NDI) methods that can be used to detect and measure cracks. The most successful NDI method for a specific application will depend on the material to be examined, crack dimensions, orientation, and location in the part; and overall part geometry. Some of the NDI methods used for crack detection and measurement include dye penetrants, x-ray, acoustic methods, magnetic-based systems, or microwaves. Cracks can cause catastrophic damage to engineered systems if not detected and monitored before they grow to a critical length (Kristoff, 2009). By understanding the properties of the material involved, engineers can predict crack initiation and repair cracked components before failures occur.

2.7.2 Characteristics of fatigue failures

The process starts with dislocation movements, eventually forming persistent slip bands that nucleate short cracks. Fatigue is a stochastic process, often showing considerable scatter even in controlled environments, a stochastic process is one whose behavior is non-deterministic, in that a system's subsequent state is determined both by the process's predictable actions and by a random element. The greater the applied stress range, the shorter the life, Fatigue life scatter tends to increase for longer fatigue lives. Fatigue life is influenced by a variety of factors, such as temperature, surface finish, microstructure, presence of oxidizing or inert chemicals, residual stresses, contact (fretting), etc. Some materials (e.g., some steel and titanium alloys) exhibit a theoretical fatigue limit below which continued loading does not lead to failure. An ultrasonic resonance technique is used in these experiments with frequencies around 10–20 kHz (Farahani, 2005). Low cycle fatigue (typically less than 10^3 cycles) is associated with widespread plasticity; thus, a strain-based parameter should be used for fatigue life prediction. Testing is conducted with constant strain amplitudes typically at 0.01–5 Hz.

The characteristic features are significant in failure analysis in order to distinguish between fatigue failures, static failures, including brittle failures, stress corrosion failures and creep failures. Moreover, if a fracture surface indicates that a failure is due to fatigue, it may well be possible to arrive at more details about the service fatigue load history. Examination of fatigue failure of laboratory specimens can also give worthwhile information to validate fatigue prediction models (Schijve, 2001).

2.8 DIFFERENT APPROACHES TO FATIGUE

There are different stages of fatigue damage in an engineering component where defect may nucleate in an initially undamaged section and propagate in a stable manner until catastrophic fracture ensues. For this most general situation, the progression of fatigue damage can broadly classify into the following stages.

1) Substructural and microstructural changes which cause nucleation of permanent damage.
2) The creation of microscopic cracks.
3) The growth and coalescence of microscopic flow to form ‘ dominant’ cracks, which may eventually lead to catastrophic failure
4) Stable propagation of the dominant microcrack.
5) Structural instability or complete fracture.

The conditions for the nucleation of microdefects and the rate of advance of the dominant fatigue crack are strongly influenced by a wide range of mechanical, microstructural and environmental factors (Schijve, 2001). The principal differences among different design often rest on how the crack initiation and the crack propagation stages of fatigue are quantitatively treated.

It is important to note here that a major obstacle to the development of life prediction model for fatigue lies in the choice of a definition for crack initiation. Material scientists concerned with the microscopic mechanism of fatigue are likely to regard the nucleation of micrometer size flaws along slip bands and grain boundaries, and the roughening of fatigued surfaces as the crack inception stage of fatigue failure. A practicing engineer, on the other hand, tends to relate (Schijve 2001).

2.9 CYCLIC TENSION AND CYCLIC TORSION

As stated before, cyclic slip is essential for micro-crack nucleation and early micro-crack growth. Crack nucleation in an unnotched specimen will now be considered for two loading cases: (1) cyclic tension, and (2) cyclic torsion, see Figure 2.10. Under cyclic tension the maximum shear stress occurs on planes at an angle of 45^0 with respect to the longitudinal axis. Under cyclic torsion, planes with a maximum shear stress are perpendicular and parallel to the longitudinal axis. An important different between the two loading systems is that the plane of maximum shear stress in the tension case also carries a normal stress component ($\sigma = \tau$). For cyclic torsion,however, this normal stress component on the slip plane is zero. As long as the initiation is still a matter of cyclic slip in a single grain, the two cases are essentially different. In the cyclic tension case the normal stress tries to open the microcrack and that will enhance the efficiency of the transition from cyclic slip along microcrack growth along the slip band. However, under cyclic torsion this crack opening effect is absent (Schijve, 2001). Microscopic investigations have shown that nucleation in a slip band under cyclic torsion is problematic if the load amplitude is low, i.e. close to the fatigue limit.

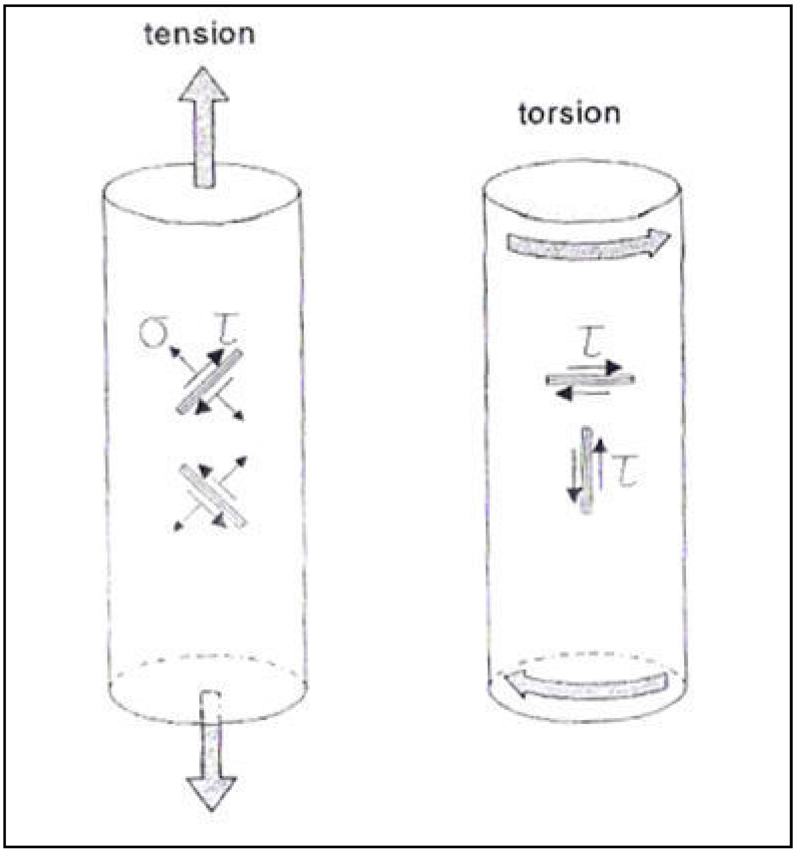

Figure 2.10: Slip plane with maximum shear stress

Source: Schijve (2001)

For higher amplitudes above the fatigue limit, microcracks under cyclic torsion are generated which then grow further in a direction perpendicular to the main principal stress. In the cylindrical bar of Figure 2.10 this direction occurs at an angle 45^0 with the axis of the bar. As a consequence, crack in a round axle under cyclic torsion grow as a spiral around the surface of the axis (Schijve, 2001). An example is shown in the Figure 2.11, a driveshaft of a scooter broken by a torsional fatigue. The fatigue failure started at a surface damaging pit.

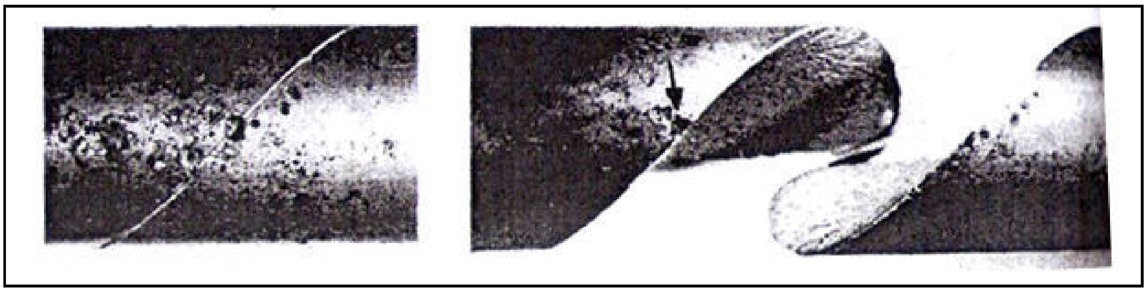

Figure 2.11: Fatigue failure of drive shaft

Source: Schijve (2001)

2.10 FACTORS THAT AFFECT FATIGUE-LIFE

1. Cyclic stress state: Depending on the complexity of the geometry and the loading, one or more properties of the stress state need to be considered, such as stress amplitude, mean stress, biaxiality, in-phase or out-of-phase shear stress, and load sequence,
2. Geometry: Notches and variation in cross section throughout a part lead to stress concentrations where fatigue cracks initiate.
3. Surface quality. Surface roughness cause microscopic stress concentrations that lower the fatigue strength. Compressive residual stresses can be introduced in the surface by e.g. shot peening to increase fatigue life. Such techniques for producing surface stress are often referred to as peening, whatever the mechanism used to produce the stress. Laser peening and ultrasonic impact treatment can also produce this surface compressive stress and can increase the

fatigue life of the component. This improvement is normally observed only for high-cycle fatigue.

4. Material Type: Fatigue life, as well as the behavior during cyclic loading, varies widely for different materials, e.g. composites and polymers differ markedly from metals.
5. Residual stresses: Welding, cutting, casting, and other manufacturing processes involving heat or deformation can produce high levels of tensile residual stress, which decreases the fatigue strength.
6. Size and distribution of internal defects: Casting defects such as gas porosity, non-metallic inclusions and shrinkage voids can significantly reduce fatigue strength.
7. Direction of loading: For non-isotropic materials, fatigue strength depends on the direction of the principal stress.
8. Grain size: For most metals, smaller grains yield longer fatigue lives, however, the presence of surface defects or scratches will have a greater influence than in a coarse grained alloy.
9. Environment: Environmental conditions can cause erosion, corrosion, or gas-phase embrittlement, which all affect fatigue life. Corrosion fatigue is a problem encountered in many aggressive environments.
10. Temperature: Higher temperatures generally decrease fatigue strength.

The resistance against fatigue depends essentially on a number of factors. Among them are; stress concentration, surface roughness, frequency of loading, loading history, residual stress strain fields, temperature, environmental conditions, etc. Manufacturing process feature such as heat treatment and cold deformation also affect fatigue life. Each group of factors requires special study, and hundreds of papers are published every year dedicated to their experimental analysis. The survey of these result and practical recommendation can be found in many manuals for engineers.

Much attention has been paid by experimenters to the influence of loading history. Now most experiments are performed with the modern fatigue testing equipment that provides arbitrary loading programs, and are not limited to one-directional stress-strain conditions. Already, in the earlier stage of experiment studies of fatigue, a paradoxal effect of short overloading was observed, for example, the crack growth retardation after s single overloading. During unloading the faces of crack may close before the cyclic stresses reach the minimum (Bolotin, 1999). In this case only a part of the range of tensile stresses is active during the next cycle of loading.

Another factor is loading frequency. At sufficiently high frequencies, thermal effects due to cyclic deformation become significant, and the resulting change of mechanical properties must be taken into account. This phenomenon is important for polymers as well as for metallic materials at elevated temperatures when fatigue and creep enter in combination. However, to observe a significant cyclic heating effect, sufficiently high loading frequencies are needed.

One of the most specific features of fatigue is the statistical scatter of experimental results. Generally, the scatter is present in all experiments, in particular, due to the random microstructure of real materials. In terms of ultimate stresses, the variance coefficient usually has the order of 0.05. The fatigue life, being measured in cycle numbers until failure, is much more sensitive to material nonhomogeneities. That is directly obvious, e.g., from equation 2.1, since the power exponent m is essentially larger than unity. In addition, the fatigue ultimate stress and, moreover, the fatigue life are under the influence of many factors that interact in a complex way and are difficult to control, even in laboratory conditions. The statistical scatter of fatigue data is accompanied by a related phenomenon, a distinct size effect, i.e., by the influence of absolute sizes of geometrically similar and similarly loaded specimens on fatigue life (Bolotin, 1999). The presence of the size effect indicates, generally, that additional parameters of the dimension of length must be taken into account to describe the phenomenon adequately. The nuclei of fatigue cracks are usually situated near the surface of a body, and that makes the surface roughness an important factor in fatigue.

2.11 SURFACE EFFECTS ON FATIGUE

Fatigue in the crack initiation period is a surface phenomenon. It was also pointed out that the initiation period may cover the major part of the fatigue life until failure. As a consequence, various kind of surface effect can be of great importance for the fatigue life. Surface effect includes all conditions which can reduce or enhance the crack initiation period. In other words, they cover the phenomena which have an influence on the crack initiation mechanism. Several effects are mentioned in Figure 2.12. The list is not necessarily complete, but various well-known affects are listed. They are briefly discussed below while most effects are covered more extensively in later chapters (Schijve, 2001). The purpose of the discussion here is to reveal general aspects related to the fatigue process in terms of the crack initiation period and crack growth period.

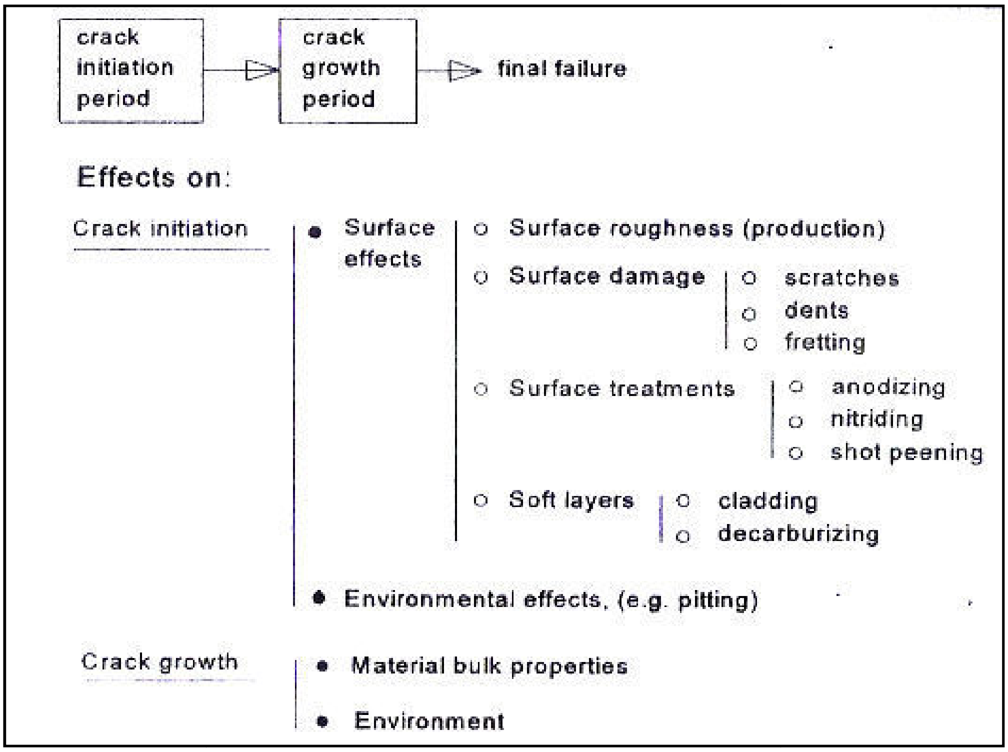

Figure 2.12: Effect on the crack initiation and crack growth period

Source: Schijve (2001)

Surface roughness and surface damage imply that the free surface is no longer perfectly flat. As a consequence, small sized stress concentrations along the material surface occur. Although the stress concentration will rapidly fade away from the surface, it is still significant for promoting cyclic slip and crack nucleation at the material surface. As an example, result of the de Forest shown in figure 2.14 are carried out the rotating bending fatigue tests on specimen with two different surface roughnesses, coarse machining and fine machining. Rough machining cause deeper circumferential grooves that fine machining. De forest periodically interrupted his test to observe possible crack growth. He then defined the crack initiation period as the fatigue life until a circumference crack length *l*= 2.5mm (0.1 inch) was reached as shown in figure 2.13, while the crack growth period covered the life from *l*= 2.5mm until it failure.

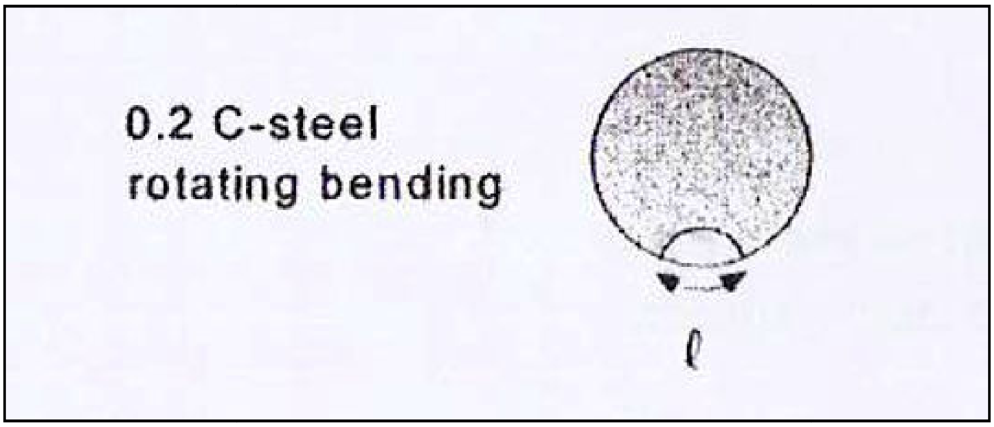

Figure 2.13: Circumference crack length

Source: Schijve (2001)

As shown by the test results at three different stress amplitudes, the crack initiation life is significantly shorter for rough machining as compared to fine machining, see the left graph in Figure 2.14(note the log-scale of the fatigue life). However, according to the right graph of Figure 2.15 the crack growth period is hardly affected by the surface roughness. A comparison of the two graphs in 2.14 and 2.15 also reveals that the crack growth period is much shorter than the crack initiation period.

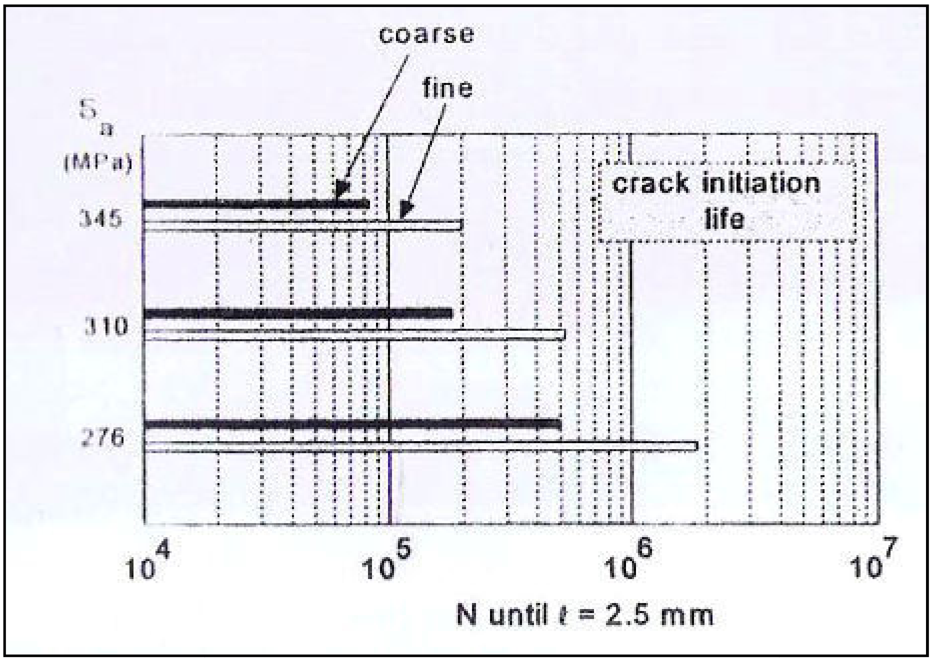

Figure 2.14: Effect of surface roughness on the crack initiation

Source: Schijve (2001)

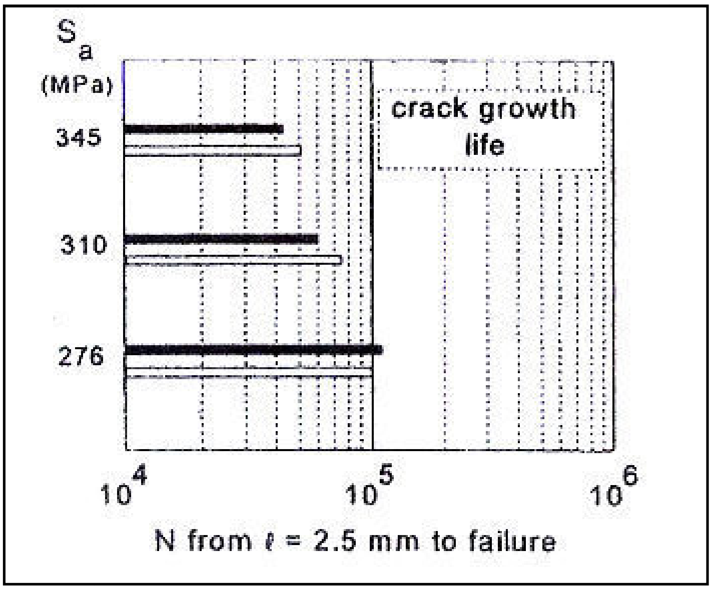

Figure 2.15: Effect of surface roughness on the crack growth period

Source: Schijve (2001)

There is still another message in Figure 2.14. The crack initiation period significantly increase for a lower stress level, as should be expected. If the stress amplitude is reduced further to the fatigue limit, the crack initiation life becomes very large, confirming the threshold idea about the fatigue limit. The crack growth period in Figure 2.14 also increases for lower stress amplitude, but the effect is much smaller. This trend is generally observed for surface effects. The amplitude-dependent sensitivity is illustrated in Figure 2.15. The most detrimental consequence of an unfavorable surface effect is the large reduction of the fatigue limit. This is especially important for structural component designed for an infinite life, i.e. with all amplitudes in service below the fatigue limit. Unintentional surface damage, such as nicks and dents, can then be very harmful. The large reduction of the fatigue limit indicates that there is a range of stress amplitudes between the original s_f and the reduced s_f which can be harmful if surface damage is present. Without surface damage such fatigue cracks are not initiated, but with the assistance of surface damage cracks can be started and cause failure (Schijve, 2001). Due to the relatively low stress amplitude, the crack growth life will be large. As a consequence, the inflection point of the S-N curve to the horizontal part (the so-called knee of the S-N curve) occurs at a higher fatigue life as for the original S-N curve; see the shift of the knee in Figure 2.15.

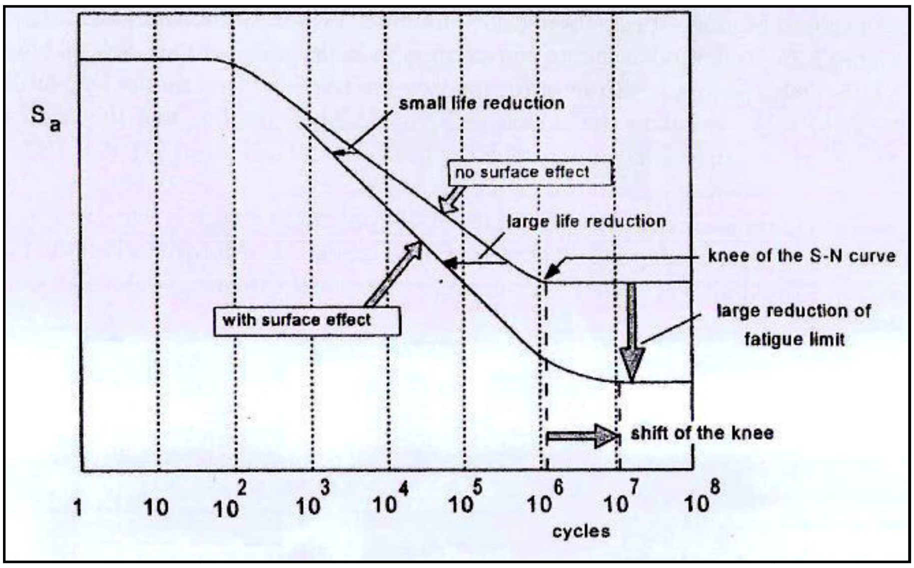

Figure 2.16: Surface effects on the S-N curve

Source: Schijve (2001)

If a design is made for a finite life, detrimental surface effects may be less important, specifically if the design life is short. Although surface damage can accelerate crack initiation, the high stress amplitude cycles can anyway generate crack nuclei early in the fatigue life. The assistance of surface damage is less important for the initiation process. However, if the design life is large in number cycles, the significance of adverse surface effect should be recognized. The high sensitivity for surface effect at low stress amplitudes and the relatively low sensitivity for surface effects at high amplitudes. This trend is generally observed in fatigue experiments. The trend was already mentioned in the previous section for similar reasons (Schijve 2001).

The other example was the (Suraratchai et al., 2008) result, they carried out the experiment of the influence of machined surface roughness on the fatigue life of aluminium alloy by using four-point bending specimen that have been machined according to various machining conditions. Four-point bending tests have been conducted at room temperature in order to explore fatigue lives around 10^5 cycles. Tests were performed with a load ratio R = 0.1 and a frequency of 10 Hz. Two types of specimens were considered: on one hand, specimens provided by an industrial partner and made by high speed machining and, on the other hand, laboratory specimens. The surfaces under tensile loading of the laboratory specimens have been machined using a shaper. Machining parameters have been chosen in order to generate various groove direction (UL specimens: perpendicular to the loading direction; UT specimens: parallel to the loading direction), various roughness (11 and 12 specimens: low roughness; 21 and 22 specimens: high roughness) using various cutting speed. Table 2.1 presents the various surface preparations of laboratory specimens. For the surfaces measurement residual stresses have been measured using X-ray diffraction technique with ASTX2001 device. The so-obtained values of residual stresses are given within ±30 MPa. Concerning the geometrical characterization of the surfaces, a Mahr (Perthometer PKG-120) contour and roughness measuring system has been used (Suraratchai et al., 2008). It is a diamond stylus instrument that can give conventional roughness parameters (Ra,Rt,Rq) and surface topography thanks to an automatically moving table.

Table 2.1: Summary of the surface preparation of the laboratory specimens

Specimen reference	Ra T-direction(µm)	Ra L-direction(µm)	Cutting speed(m/mm)	Residual stress T-direction(MPa)
UL11	0.5	n.a	12	-137
UL12	0.5	n.a	50	-45
UL21	7	n.a	12	-54
UL22	7	n.a	50	-21
UT11	0.25	n.a	12	-172
UT21	0.35	n.a	12	-152
UT22	0.3	n.a	50	-29

Source: Suraratchai et al. (2008)

S-N curves of all laboratory specimens are presented in Figure 2.17. The influence of surface condition on the fatigue life is more important for high cycle fatigue ($Nf > 3.10^5$ cycles). Roughness has a predominant influence on the fatigue life. For UL specimens, for instance, low roughness specimens (UL12) have better fatigue strength than high roughness specimens (UL21) for approximately the same residual stresses.

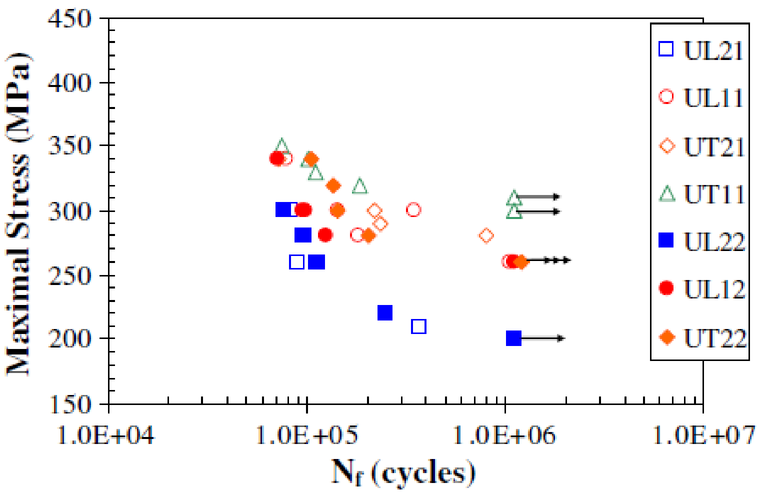

Figure 2.17: S-N curves for the various surface conditions

Source: Suraratchai et al. (2008)

In addition, for a given roughness, residual stresses only seem to have a slight influence on the fatigue life: UL11 and UL12 exhibit the same fatigue behaviour. The same remark applies to the couples UT11/UT21 and UT21/UT22, respectively. However, the geometric roughness parameter Ra is not able to fully describe the difference in fatigue strength between all the samples (Suraratchai et al., 2008). For such highly textured surfaces, it highly depends on the direction of the assessment length, as seen in Table 2.1 for UT specimens.

Fracture surfaces observations in Figure 2.18 show that whatever the specimen and the load level, fatigue cracks initiated on microstructural defects (essentially intermetallic inclusions and sometimes porosity) located on the flat loaded surface (within 20 lm under the surface) and at the bottom of the machining grooves (when grooves are perpendicular to the loading). These defects were included in small re-crystallized grains.

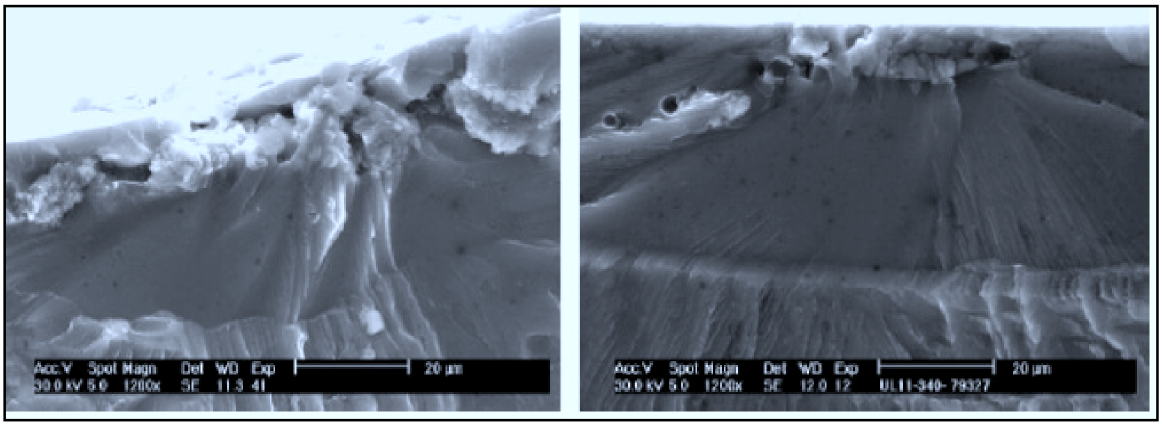

Figure 2.18: Fracture surfaces of UT specimen (left) and UL specimen (right).

Source: Suraratchai et al. (2008)

2.12 CHARACTERISTIC FEATURES OF FATIGUE FAILURE

The characteristic features are significant in failure analysis in order to distinguish between fatigue failures, static failures, including brittle failures, stress corrosion failures and creep failures. Moreover, if a fracture surfaces indicates that a failure is due to fatigue, it may well be possible to arrive at more details about the service fatigue load history (Schijve 2001). Examinations of fatigue failures of laboratory specimens can also give worthwhile information to validate fatigue prediction models. The characteristics of a fatigue fracture are divide into two groups, microscopic features and macroscopic features, see figure 2.19.

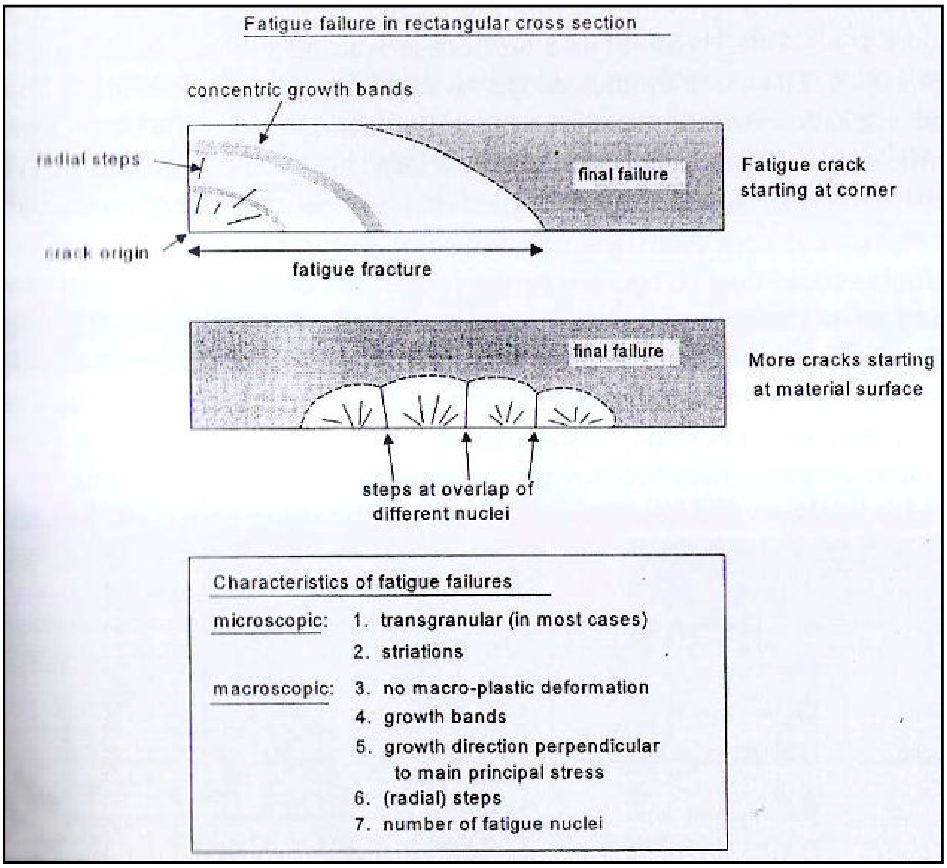

Figure 2.19: Survey of characteristic features of fatigue fracture surfaces

Source: Schijve (2001)

2.12.1 Microscopic characteristics

(1) Transgranular crack growth

Fatigue cracks in almost all materials are growing along the transgranular path, i.e. through the grains. They do not follow the grain boundary, contrary to stress corrosion cracks and creep failures. Because fatigue crack growth is a consequence of cyclic slip, it is not surprising that fatigue crack prefers to grow through the grains. Restraint on slip exerted by the grain boundaries is minimal inside the grains (Lee et al., 2005). The transgranular character can easily be observed on microscopical samples in the optical microscope. Figure 2.20 and 2.21 are shown the different of intergranular fracture and transgranular fracture.

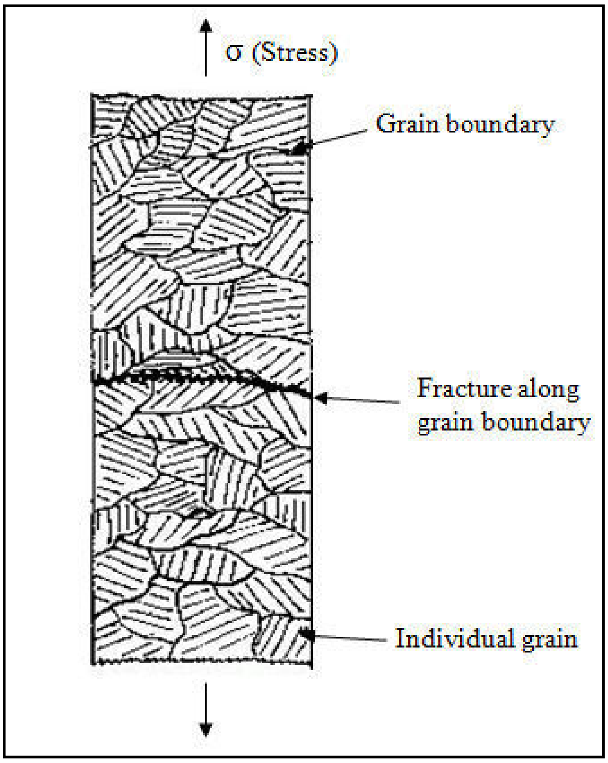

Figure 2.20: Intergranular fracture

Source: Lee et al. (2005)

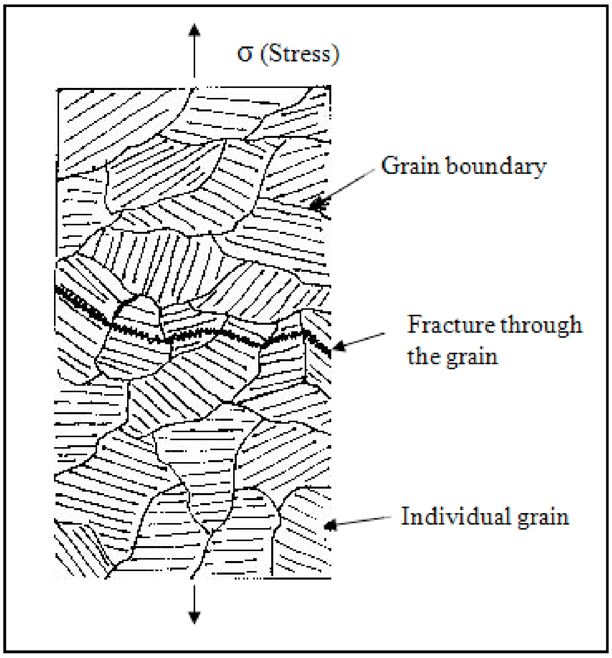

Figure 2.21: Transgranular fracture

Source: Lee et al. (2005)

(2) Striations

Striations are remnants of microplastic deformations of individual load cycle. The striations indicate the cyclic nature of the load history.The visibility of striations depends on the type of material and the load history as well. If striations cannot be observed, it does not necessarily mean that the failure is not due to fatigue **(**Schijve, 2001). An example of striations on the fracture surface of a failure occurring in service is given in figure 2.22. A flap beam of an aircraft failed during landing due to fatigue at bolt hole. The electron microscope revealed that striations occurred in a pairs with a larger and smaller striation spacing respectively shown in figure 2.23. The flap beam was loaded significantly twice in each flight. This example of striations also confirm that crack propagation occurs cycle-by-cycle

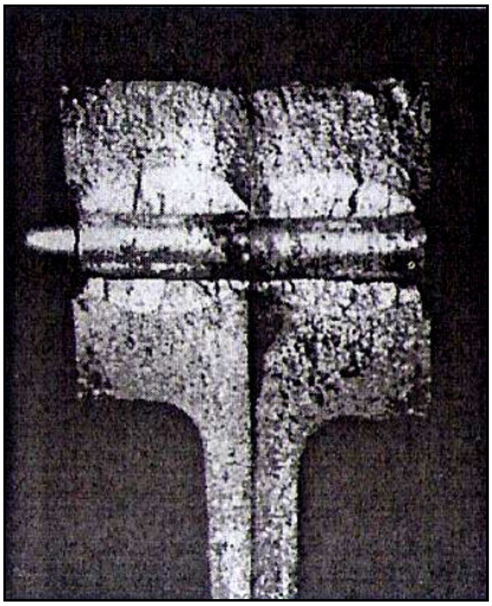

Figure 2.22: Fatigue crack at bolt hole

Source: Schijve (2001)

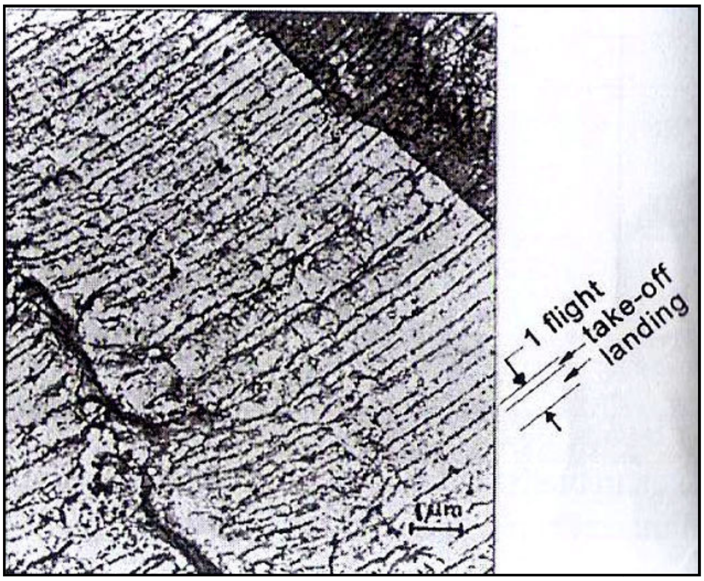

Figure 2.23: Striations occur in pair

Source: Schijve (2001)

2.12.2 Macroscopic characteristics

Macroscopic characteristic of a fatigue failure can be observed with the naked eye. However, it always is advisable to look also with a small magnifying glass with a magnification of 6x to 8x. It is often surprising how many details can then be observed, e.g. small crack nuclei, sites of crack nuclei, surface damage causing a crack nucleus, etc., details which escape visual observations by eye but which may be significant for the evaluation of the fatigue problem (De vries et al., 1998). Furthermore, some details are sometimes overlooked at latger magnification in the electron microscope.

(1) No macroplastic deformation and a flat fatigue fracture surface

The fracture surface of a fatigue failure usually show two different parts:

(i) The real fatigue failure caused by fatigue crack growth is characterized by practically no macro plasticity. Because fatigue is a result of microplastic deformations, which are partly reversed on each cycle, it is not surprising that microscopic deformations appear to be absent. For the major part of the fatigue life, the crack is a fine line on the material surface. In many cases, fatigue crack hardly be seen and crack detection during service inspections can be problematic. Various NDI technique have been developed for that purpose.

(ii) The second part of the fracture surface is caused by the final failure in the last load cycle. It occurs if the remaining uncracked cross section of the material can no longer carry the maximum load of the cycle. In general, the final failure can be considered to be a quasistatic failure. It will exhibit macroplastic deformation, depending on the ductility of the material. The different between the fatigue failure without visible plastic deformation and a static failure with visible plastic deformation is illustrated by two picture of a failure in a light alloy helicopter blade in figure 2.24.

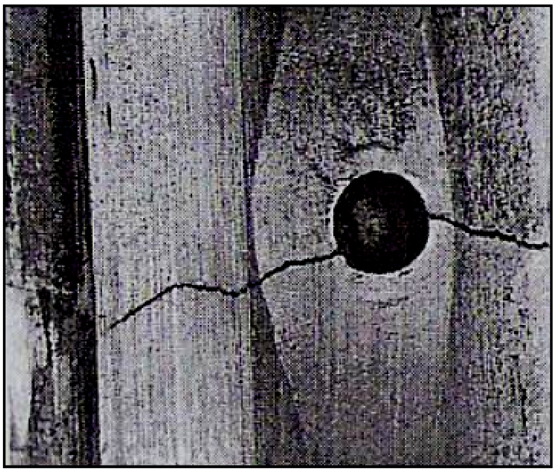

Figure 2.24: View of fatigue failure of a helicopter blade

Source: Schijve (2001)

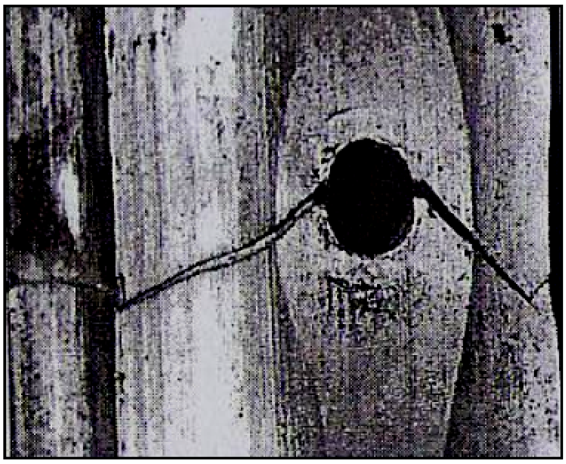

Figure 2.25: View of static failure of a helicopter blade

Source: Schijve (2001)

(2) Growth bands

Fatigue failures obtained in service often show growth bands which are visible with the naked eye, see figure 2.26. The bands are also referred to as oyster-shell markings or beach markings. The bands indicate how the crack has been growing. Different degrees of corrosive attack can also cause bands, especially if crack are domant for certain periods.

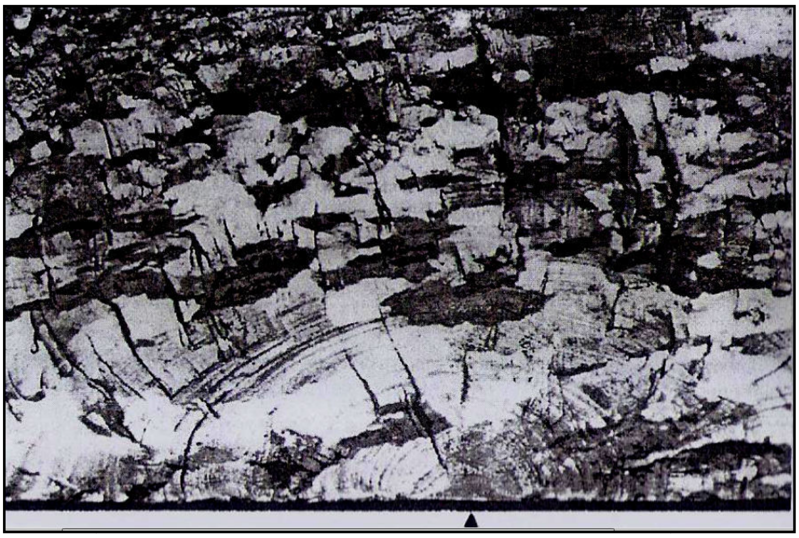

Figure 2.26: Fracture surface of a light metal compressor blade. The fatigue failure started at the lower surface (arrow).

Source: Schijve (2001)

(3) The growing direction, perpendicular to the main principal stress.

Fatigue cracks are growing in a direction perpendicular to the main principle stress (provided the crack growth rate is not very high). Depending on the geometry of the component, it implies for a cyclic tension load that crack growth will be perpendicular to the loading direction. For cyclic torsion the crack in a circular bar will occur at 45^0 with the longitudinal axis.

(4) Radial steps and the number of fatigue crack nuclei.

The radial steps as schematically indicated in Figure 2.25, are also visible in Figure 2.26 where the deformation texture of the forged alloy promotes crack growth on planes in slightly different directions. This is also confirmed by the dark and light areas, which are reflections of crack surfaces in different grains.

CHAPTER 3

METHODOLOGY

3.1. PROCESS FLOW CHART

In preparations of the project, there is need a planning of the overall progress to assure the project can be finish on schedule and to make sure the project are going with the flow that has been planned. The projects planning for this project are point out in the process flow chart in Figure 3.1.

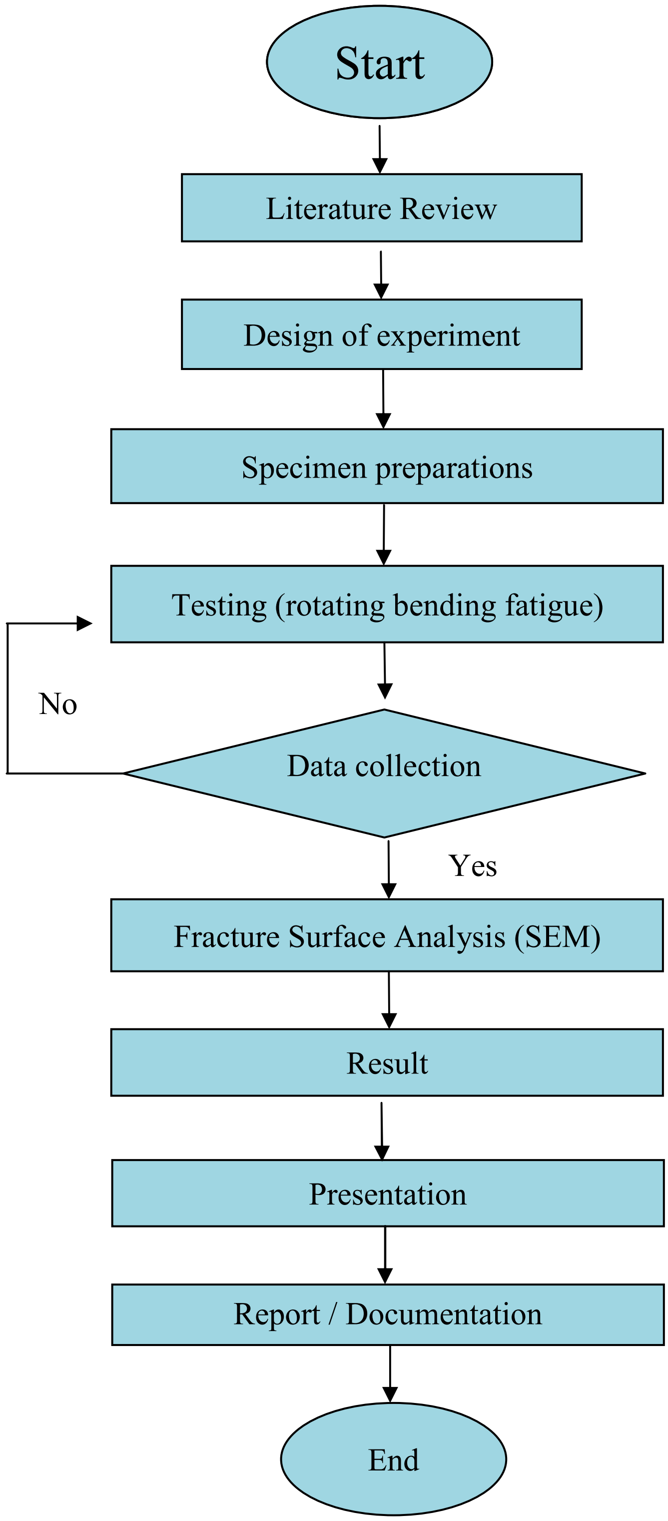

Figure 3.1: Project flow chart

3.2 FLOW CHART DESCRIPTION

3.2.1 Literature Review

As mention in the flow chart diagram as shown as above, the project starts with literature review and research about the title. This consist a review of definition of fatigue crack, material type for fatigue, crack growth prediction, Characteristics of fatigue, fatigue test, detecting and measuring cracks, factors that affect fatigue-life, the review of using Scanning Electron Microscope (SEM), and the method for specimen preparation. These tasks have been done through research on the internet, books, journals and others resources.

3.2.2 Design of Experiment

Brain storming session will be held, to gather some ideas for the preliminary design of experiment. The design of experiment is need to be determining by following the objective of the project need. The experiment design consist of determining the type of machine to use in the experiment, the type of material to be use, the experiment requirement, and also determining the way to indicate and interpret the results of the experiment.

3.2.3 Specimens Preparation

.

After the design of experiment stage, the specimen preparation process will begin. Before specimens start to do a machining process, the material type is needed to be selected. Then, the raw material are need to be cutting into 15 pieces by using bandsaw machine approximately length 150mm. Then, the specimen materials are need to be machining as many as 15 pieces by using a lathe machine either by conventional or computer numerical control (CNC) machine. The specimens geometry is shown in figure 3.2.

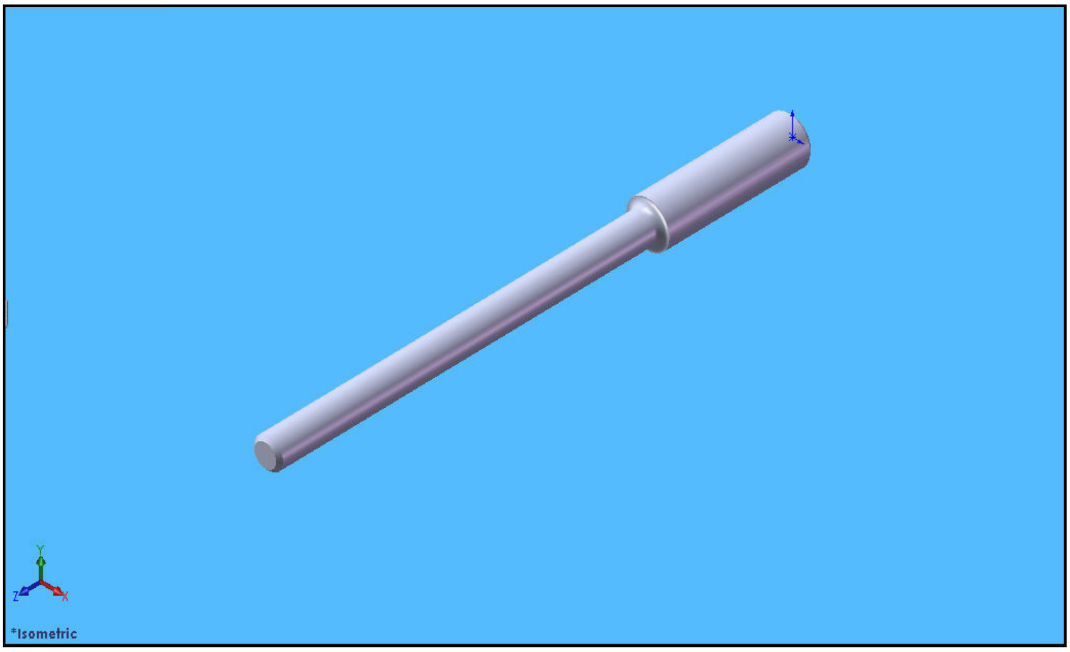

Figure 3.2: Fatigue test specimen

3.2.3.1 Material

The material investigated in this project is Mild steel. The example type of Mild steel is 1018 Mild steel whose composition is presented in Table 3.1. It was provided in the form of a round rod of 20 mm diameter. It is generally available in round rod, square bar, and rectangle bar. It has a good combination of all of the typical traits of steel - strength, some ductility, and comparative ease of machining. Chemically, it is very similar to A36 Hot Rolled steel, but the cold rolling process creates a better surface finish and better properties.

Table 3.1: Composition of 1018 Mild steel

1018 Mild steel		
Minimum properties	Ultimate Tensile Strength, Mpa	440
	Yield Strength, Mpa	370
	Elongation	15.0%
	Rockwell Hardness	B71
Chemistry	Iron (Fe)	98.81 - 99.26%
	Carbon (C)	0.18 - 0.23%
	Manganese (Mn)	0.6 - 0.9%
	Phosphorus (P)	0.04% max
	Sulfur (S)	0.05% max

Source: www.eaglesteel.com/download/techdocs/Carbon_Steel_Grades

3.2.3.2 Machining Process

The machining process are required to make this specimens are turning process. The specimens need to be machining with a 3 different surfaces roughness level, each surface roughness level are for each 5 pieces specimens. To make this, the parameters there are needed to be control in the turning process are the spindle speed, the feed rate and also the depth of cut. This type of parameter is affecting the surface roughness of machining material and can also be chosen either to use any of that parameter as a controlled parameter to get a different surface roughness. The smaller feed the better surface roughness and the higher spindle speed will get the finer surface roughness. The spindle speeds are needed to be calculated by using the equation below

$$\mathrm{RPM} = \frac{\mathrm{CS} \times 1000}{\pi \times \mathrm{d}} \tag{3.1}$$

Where:

cs = cutting speed

d = workpiece diameter

The feed rate calculation equation is like below

The feed rate v_f (mm/min),

$$v_f = f \times N \tag{3.2}$$

Where:

f = feed

N = spindle speed

Sample calculation for spindle speed:

Recommendation cutting speed = 60-135 m/min

Diameter of workpiece = 20 mm

$$\text{RPM} = \frac{60 \times 1000}{\pi \times 20}$$

$$= 955 \text{ rpm}$$

Sample calculation for feed rate:

Recommendation feed = 0.15-1.1mm/rev

Spindle speed = 1600-990 rpm

From eq. 3.2:

$$v_f = f \times N$$

$$= 0.15\text{x}1600 = 240 \text{ mm/min}$$

Refer to Appendix B for General recommendation for Turning Operation.

Calculated machining parameters for turning operation are shown in Table 3.2:

Table 3.2: Machining parameters

Machining parameters	**Level of Roughness**		
	Low	**Medium**	**High**
Spindle speed(rpm)	1600	1305	990
Feed(mm/rev)	0.22	0.22	0.22
Feed rate(mm/min)	352	287	217
Depth of cut(mm)	0.2	0.2	0.2

The step or procedure to use a Lathe Machine is listed below:

1. Set up the lathe machine to be ready to perform the process.
2. Switch on the lathe machine to make sure the power supply is on.
3. Set up the cutting tool. To make sure the cutting tool is centralized, use dead center.
4. Attach the mild steel bar to the spindle and clamped to the chucks. Make sure the mild steel bar is being hold tightly.
5. Set up the spindle speed to the highest speed first which is 1600rpm. Set 0,0 point for x and z axis of cutting tool.
6. Do the facing processes first in x axis to make sure the cutting tool is truly centralize. If there any nipples, repeat the procedure number 4. Then, set the x axis to zero.
7. Set the z axis to zero when the cutting tool slightly touch the work piece in z direction.
8. The work piece then being machined following geometry shape in drawing. Refer appendix.
9. The feed is to be set up with value that has been calculated. Refer to table 3.2.
10. During the machining process, the depth of cut is being cut slowly with the value of 0.2mm.
11. After finished the machining process, measure the work piece by using vernier caliper.
12. Repeat the process for spindle speed 1300rpm and 900rpm to get the different surface roughness level.

Figure 3.3: Conventional lathe machine

Figure 3.4: Raw material

Figure 3.5: Turning process

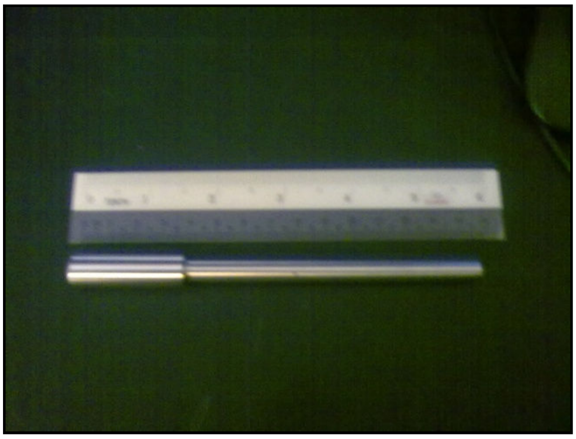

Figure 3.6: Finished specimen

3.2.3.3 Check the Surface Roughness

The details of the surface roughness must be taken by using a Mahr perthometer. As shown in table 3.2, there are three level of surfaces roughness different.

Step to check the surface roughness level:

1. After the machining process, the surface roughness is needed to be measured.
2. The surface roughness machine must be calibrated to make sure it is precise.
3. Put the material specimen on the material vee block stand.
4. Switch on the Perthometer power.
5. Take the drive unit and touch it closely to the surface to be measure.
6. Press the start button on the perthometer, the surface roughness is measured.
7. Data is recorded.

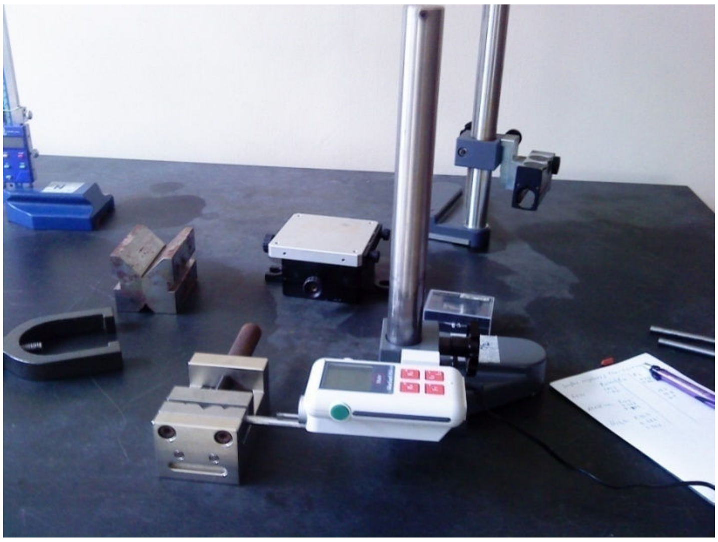

Figure 3.7: Perthometer drive unit

Table 3.3: Specification of Mahr perthometer

Measuring range	: 350 µm/180 µm/90 µm (changes automatically)
Pick-up	: Inductive skidded pick-up, 2 µm (80 µin)stylus tip, measuring force approx. 0.7 mN
Unit of measurement	: Metric, inch
Standards	: DIN/ISO/JIS/ASME
Traversing length, Lt	: 1.75 mm, 5.6 mm, 17.5 mm; automatic (0.069 in, 0.22 in, 0.69 in)
Traversing length (acc. to MOTIF)	: 1 mm, 2 mm, 4 mm, 8 mm, 12 mm, 16mm
Cutoff lc*	: 0.25 mm, 0.8 mm, 2.5 mm; automatic (0.010 in, 0.030 in, 0.100 in)
Short cutoff*	: Selectable
Parameters 24 (with tolerance limits)	: Ra, Rq, Rz equiv. to Ry (JIS), Rz (JIS), Rmax, Rp, Rp (ASME), Rpm (ASME), Rpk, Rk, Rvk, Mr1, Mr2, A1, A2, Vo, Rt, R3z, RPc, Rmr equiv. to tp (JIS, ASME), RSm, R, Ar, Rx
Memory capacity	: Max. 15 profiles, max. 20,000 results
Calibration function	: Dynamic
Other functions	: Blocking of settings (code-protected)

3.2.4 Experiment

The experiment process will be beginning after the material preparation process. After finished all the machining process of the specimens, the experiment session will be start to analyze the effect of surface roughness on fatigue life, which is the experiment and analysis session will beginning. The experiment will be done using a rotating bending fatigue machine. The data need to be collected are the life cycle for each three level of surface roughness of the specimens. If there is not enough or wrong data collected, the experiment needs to be repeated to collect that data be completed. The data then are use to obtain the S-N curve, from the S-N curve, the effect of surface roughness to fatigue life can be analyze and discussed.

3.2.4.1 Experiment apparatus

The experiment apparatus that are involve in this experiment is Gunt Hamburg WP 140 rotating bending fatigue machine. This machine is needed to be setup according to the standard procedure that has been fixed from the manufacturer and following the design of the experiment that has been define.

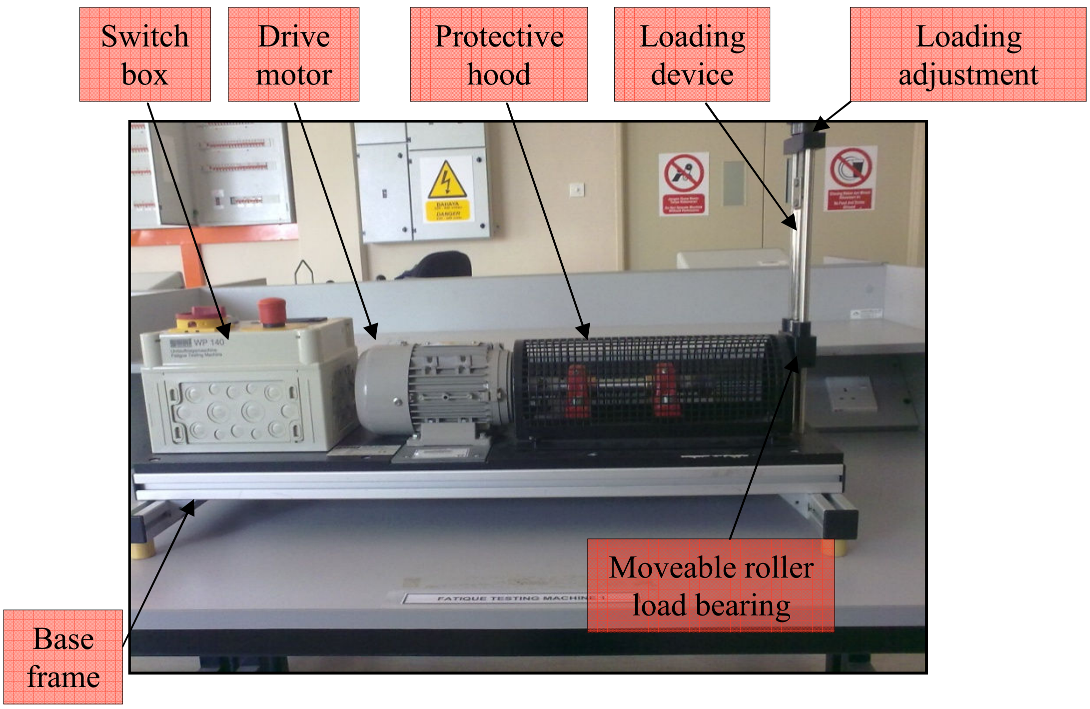

Figure 3.8: Fatigue testing machine

The experiment setup for rotating bending fatigue machine is like below:

- Before start, check the following :
  - (i) EMERGENCY OFF switch is released(pulled out)
  - (ii) Switch on the machine is functioning
  - (iii)Reset the cycle counter using the RST button and counter must display zero.
  - (iv)Start the motor using the motor control switch.
  - (v) Check the spindle rotates smoothly and truly.
  - (vi) Check the cycle counter.
  - (vii) Check the automatic stop device.
- Properly insert the specimen to the collet chuck and check its concentricity by rotating the spindle.

3.2.4.2 Experiment material

Three types of specimens Mild steel made of different surface roughness level are used in this experiment as follow:

1) 0.5mm curvature radius with finer surface roughness. (5 pieces)
2) 0.5mm curvature radius with medium surface roughness.(5 pieces)
3) 0.5mm curvature radius with rougher surface roughness.(5 pieces)

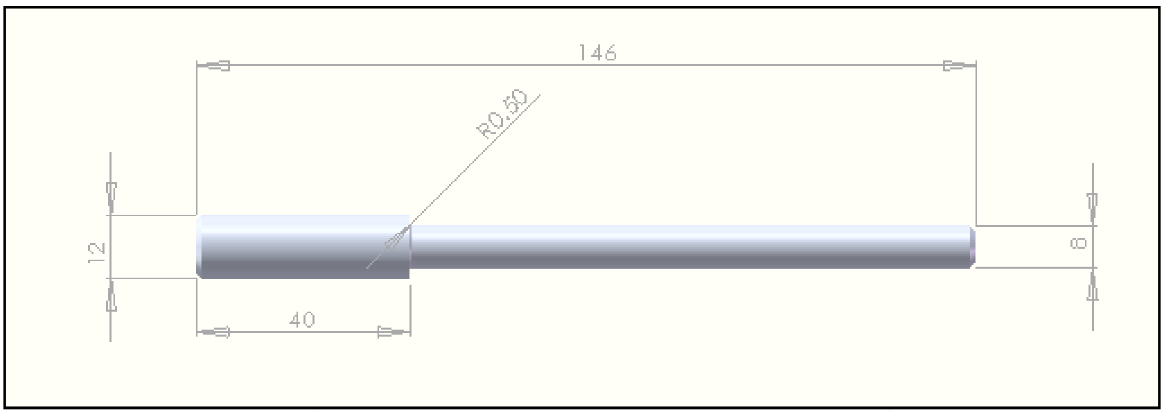

Figure 3.9: Specimen for fatigue test

3.2.4.3 Experiment procedure

The experiment is conducted to determine effect of surface roughness by using Stress- Number (S-N curve) diagram. The constant and variable parameters are needed to be deciding before start the experiment. The experiment parameter for this experiment is shown in table 3.4 below:

Table 3.4: Experiment parameters

Parameters	**Value**
Frequency (Hz)	50
Temperature (^{0}C)	20-25 (room temperature)
Load (N)	170-60
Stress ratio, R	-1

After all the experiment parameters have been set, the experiment then will be conducted by using the following procedure:

1) Start the experiment with the specimen roughness number 1.
2) Reduce the load generally from one experiment to the next from the maximum value 350 Mpa.
3) Determine the number of the load cycle until the specimen rupture.
4) Collect the load cycle data for each specimen.
5) Repeat the above procedure for the next different surface roughness specimens.

3.2.5 Data collection

Data collection is the process after the experiment process. The experiment parameter need to consider or record is load and the cycle to rupture value. Table 3.5 is the table of data collection for this experiment.

Table 3.5: Table of result for this experiment

Surface roughness	Specimen number	Load (Mpa)	Cycle to rupture (N)
Low	1		
	2		
	3		
	4		
	5		
Medium	1		
	2		
	3		
	4		
	5		
High	1		
	2		
	3		
	4		
	5		

3.2.6 Scanning Electron Microscope

Scanning Electron Microscope (SEM) is a powerful method for the investigation of surface structures of material. The scanning electron microscope generates an image with the help of secondary electrons that gives the viewer the impression of three dimensions. The use of Scanning Electron Microscope in this experiment is to get the image of fracture surface and to define the regions of fatigue failure to ensure that the specimens are failed due to the fatigue. The types of signals made by an SEM can include secondary electrons, back scattered electrons, characteristic x-rays and light (cathodoluminescence). These signals come from the beam of electrons striking the surface of the specimen and interacting with the sample at or near its surface. In its primary detection mode, secondary electron imaging, the SEM can produce very high-resolution images of a sample surface, revealing details about 1 to 5 nm in size. Due to the way these images are created, SEM micrographs have a very large depth of focus yielding a characteristic three-dimensional appearance useful for understanding the surface structure of a sample.

Figure 3.10: Scanning Electron Microscope Carl Zeiss

3.2.6.1 Step in Scanning Electron Microscope

The basic steps involved in SEM sample preparation include surface cleaning, stabilizing the sample with a fixative, rinsing, dehydrating, drying, mounting the specimen on a metal holder, and coating the sample with a layer of a material that is electrically conductive because each of these steps are crucial and will affect the outcome of the study, they will all be described individually in more detail below.

1) Cleaning the surface of the specimen
   The proper cleaning of the surface of the sample is important because the surface can contain a variety of unwanted deposits, such as dust, silt, and detritus, media components, or other contaminants.
2) Stabilizing the specimen
   There are various ways of stabilizing a biological specimen. Stabilization is typically done with fixatives
3) Rinsing the specimen
   After the fixation step, samples must be rinsed in order to remove the excess fixative. Perhaps the best protocol is to rinse the specimens in 0.1 M cacodylic

acid buffer (pH 7.3), starting with one time for 10 min, and then three times for 20 min at 4 ^{o}C

4) Dehydrating the specimen

   The dehydration process of a biological sample needs to be done very carefully. It is typically performed with either a graded series of acetone or ethanol. The protocol that proved most suitable for dehydrating mollicutes for SEM includes the immersion of the specimens in 50% acetone for 5 min, 70% acetone for 10 min, 80% acetone for 10 min, 90% acetone for 15 min, and 100% acetone (dried with CaCl2) twice for 20 min at 4 ^{o}C. This process allows the water in the samples to be slowly exchanged through liquids with lower surface tensions

5) Drying the specimen

   The scanning electron microscope operates with a vacuum. Thus, the specimens must be dry or the sample will be destroyed in the electron microscope chamber.

6) Mounting the specimen

   Specimens must be mounted on a holder that can be inserted into the scanning electron microscope. Samples are typically mounted on metallic (aluminums) stubs using a double-sticky tape.

7) Coating the specimen

   The idea of coating the specimen is to increase its conductivity in the scanning electron microscope and to prevent the build-up of high voltage charges on the specimen by conducting the charge to ground.

After all the steps described above have been performed, the investigator is ready to view the fractography in the scanning electron microscope. This is the moment when to find out whether or not the multi-step sample preparation for SEM was successful. It is important to remember that each step has to be performed to perfection in order to achieve SEM images that can be interpreted without the influence of artefacts caused by specimen handling.

3.2.7 Preliminary Result

After all the experiment has been done completely, and the data result has been completely collected, the result needs to be point out. The result are then need to be plotted in the stress-number (S-N curve) diagram.

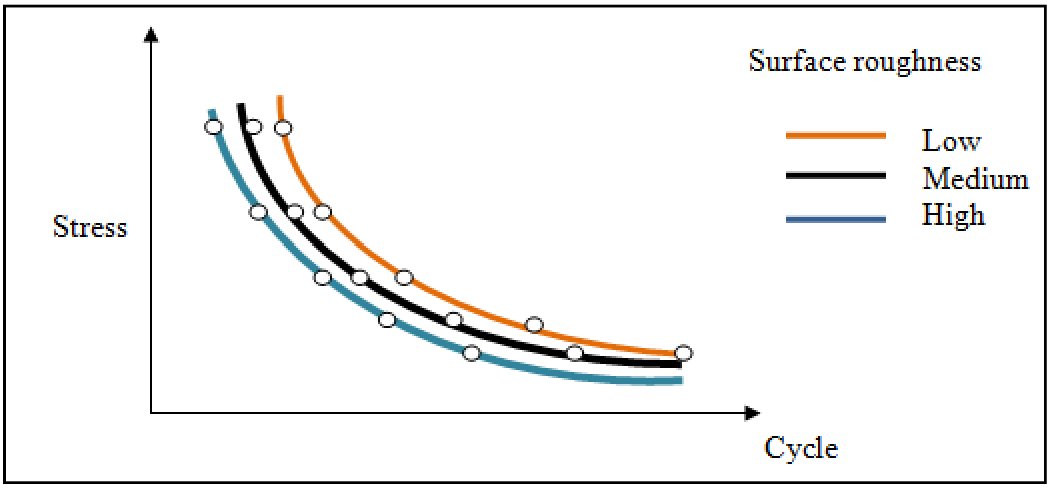

Figure 3.11: Expected S-N curve diagram

As shown in the expected result in Figure 3.11, the fatigue life is significantly shorter for the high level surface roughness compare to the medium and low surface roughness level that is the longer life cycle. Others expected is the fatigue life period is significantly increased for lower stress amplitude level which is for a finer machining it has longer fatigue life at the lower stress level.

3.2.8 Presentation and Documentation

Lastly, the final report writing and prepare the presentation. The presentation process will be held two times, at the last first semester and at the last second semester. First presentation should be present about project title, problem statement, objective, project scope, literature review and project methodology. Second presentation must be showing the result and the project outcome. The presentation session will be judge by three person of panel from Mechanical Engineering Faculty (FKM). For the report or documentation, the report draft chapter one until chapter three need to submit at the first semester. Second semester, the report must be complete and need to hard cover binding. All the report writing is guided by FKM thesis format and also guidance from supervisor. All task scheduled is take around fourteen weeks to complete for each semester.

3.3 Gantt Chart

Gantt Chart is a planning schedule for a project to ensure the project are following the planning schedule that have been decide by this Gantt chart. The detail of the Gantt chart for this project is shown in Appendix A1 and Appendix A2.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

The analysis is the process to gather the result from simulation, equation or experiment. The analysis method that used in this project is conducted an experiment for the rotating bending fatigue testing to get the number of cycles of the specimens until it failure. In this project, rotating bending testing has been conducted to define the cycle life of fatigue before failure in a certain range of applied stress for different surface roughness of material. The purpose of this experiment is to study the effect of surface roughness on fatigue life. Based on the studies, it was shown that the finer material will result the higher fatigue life compared to coarser surface roughness.

4.2 MATERIAL COMPOSITION

The material compositions for the specimens have been analyzed by using a Spectrometer machine. The main purpose for doing this analysis is to define the percent of carbon and iron to type of material used in presence study. The percentage of the chemical composition for this material is shown in Table 4.1 and for detail results refer in appendix C. As shows in Table 4.1, the composition of carbon in this material is about 0.2% and this was shows that this material is a low carbon steel.

Table 4.1: Chemical composition of the specimen

Chemical composition	Reading			
	1	**2**	**3**	**Average (%)**
Iron (Fe)	97.9	98.0	98.0	98.0
Carbon (C)	0.224	0.21	0.207	0.214
Manganese (Mn)	0.731	0.718	0.726	0.725
Sulfur (S)	0.0389	0.0422	0.0379	0.0379
Silicone (Si)	0.135	0.136	0.13	0.133
Chromium (Cr)	0.169	0.16	0.161	0.164
Molybdenum (Mo)	0.016	0.0178	0.0057	0.0132
Nickel (Ni)	0.122	0.0984	0.101	0.107
Stannum (Sn)	0.015	0.0145	0.0139	0.0145

4.3 SURFACE ROUGHNESS PARAMETER

In order to investigate the effect of surface roughness on fatigue life, surface roughness of all specimens were measured. This process has been done by using portable Perthometer machine as shown in Figure 4.1. The measurements were repeated with three times at different points for every specimen. The average value for each surface roughness value was calculated and has been summarize in table 4.2.

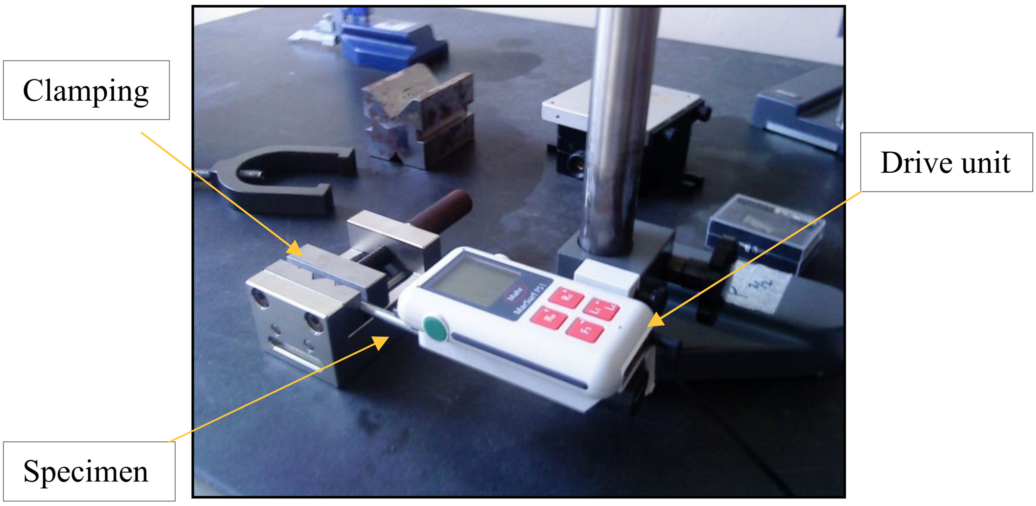

Figure 4.1: Mahr portable perthometer machine

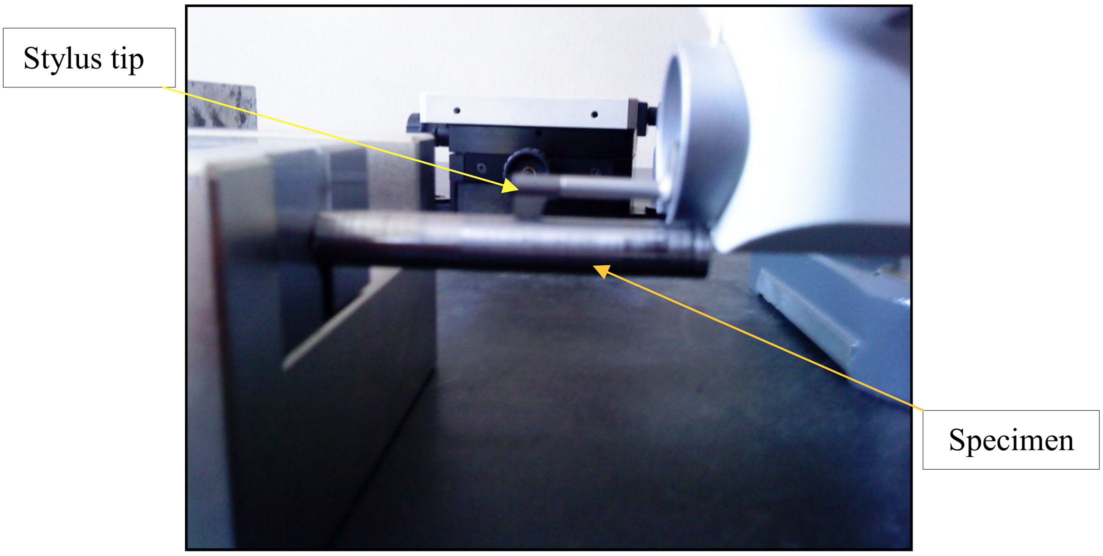

Figure 4.2: Stylus tip on specimen

Figure 4.2 shows stylus tip used to measure the surface profile on specimen to obtain the surface roughness parameter. Referring to table 4.2, it is shows the surface roughness parameter values for Roughness Average (R_a), Maximum Roughness Depth (R_{max}) and Average Maximum Height of the Profile (R_z) for each specimen.

Table 4.2: Surface roughness parameters value

	Ra(µm)	Average	Rmax(µm)	Average	Rz(µm)	Average
	1.813		15.200		9.770	
Low	1.741	1.778	12.700	13.067	9.700	9.567
	1.779		11.300		9.230	
	3.110		21.900		17.500	
Medium	2.655	2.885	22.000	22.267	16.700	16.900
	2.889		22.900		16.500	
	5.309		35.000		26.400	
High	5.582	5.484	42.800	38.267	29.300	27.333
	5.562		37.000		26.300	

4.4 ROTATING BENDING FATIGUE TEST

The rotating bending Fatigue test was conducted in order to study the number of cycle to failure for Mild steel specimen due to surface roughness effect and to make a comparison between the finer surface roughness, medium and coarser roughness effect to fatigue life. This analysis will show the life period for each surface roughness differences with different loading stress as shown in figure 4.3. The experiment was done using experiment apparatus as shown in figure 4.4.

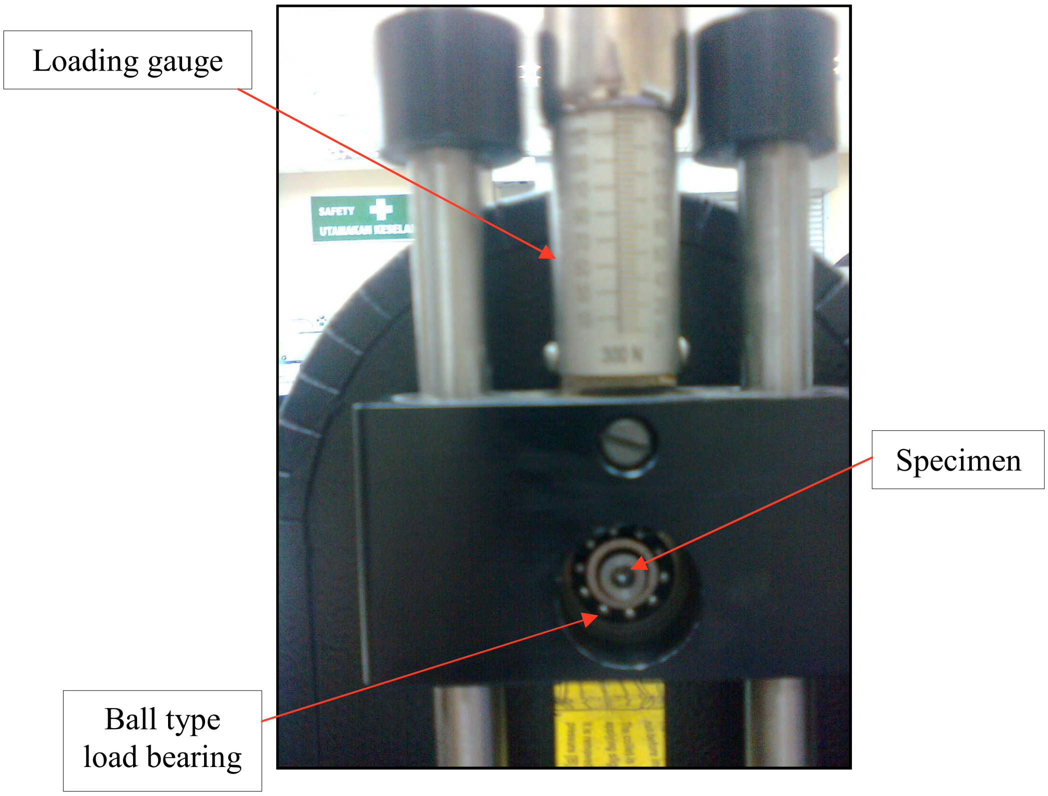

Figure 4.3: Applied load

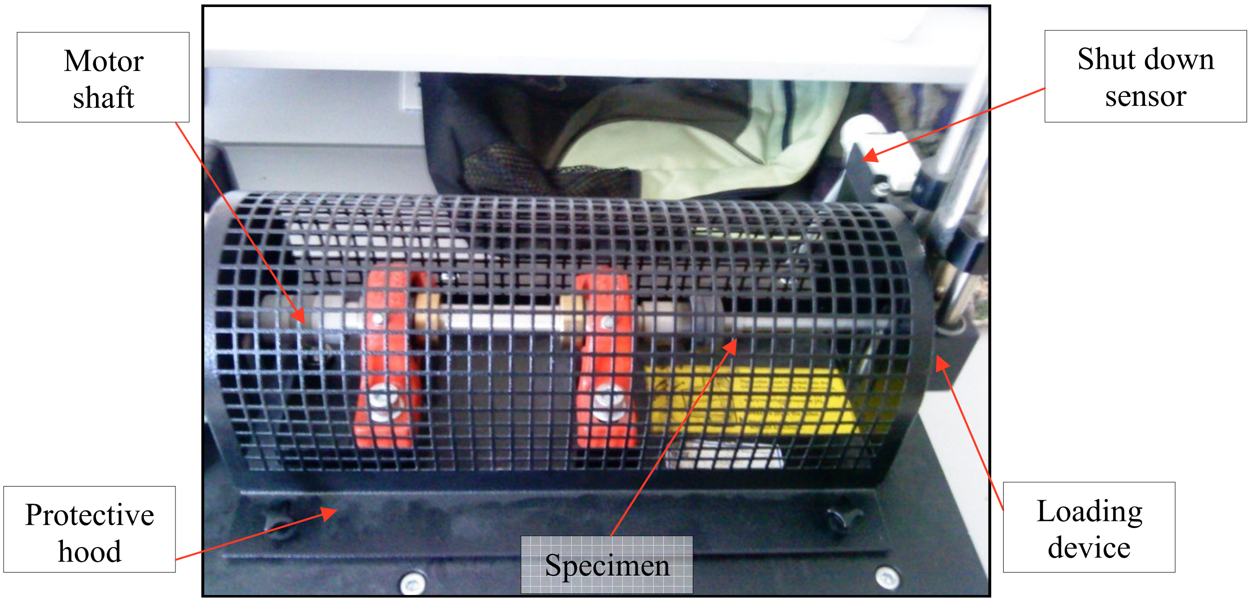

Figure 4.4: Experiment setup

4.5 EXPERIMENT RESULT

The experiment result is taken by repeating fifth teen experiment with three different surface roughnesses and five different stress value ranges between 130 MPa and 360 MPa for each surface roughness type. Table 4.3 shows the data collection from the experiments. The value for low surface roughness (finer) specimen is 1.778 µm, for medium is 2.885 µm and for higher surface roughness (coarser) is 5.484 µm. These values are taken from Ra parameter which is considering as average roughness.

Table 4.3: Experiment result

Surface roughness, Ra (µm)	Specimen no	Applied stress, (MPa)	Cycles to failure (N)	Percent of difference (%)
1.778	1	360	7170	33.1
	2	295	77455	25.1
	3	190	460913	60.9
	4	150	766332	32.5
	5	130	1226892	35.9
2.885	1	360	6199	22.6
	2	295	70335	17.53
	3	190	408181	55.8
	4	150	654562	21.0
	5	130	1087372	28.0
5.484	1	360	4800	datum
	2	295	58002	datum
	3	190	180445	datum
	4	150	516972	datum
	5	130	786014	datum

From the data collection that have been collected in table 4.3, then S-N curve have been plotted by using Microsoft Excel to express the result in the logarithmic scale. Figure 4.5, Figure 4.6 and Figure 4.7 show the S-N curve that has been plotted for each surface roughness of specimen.

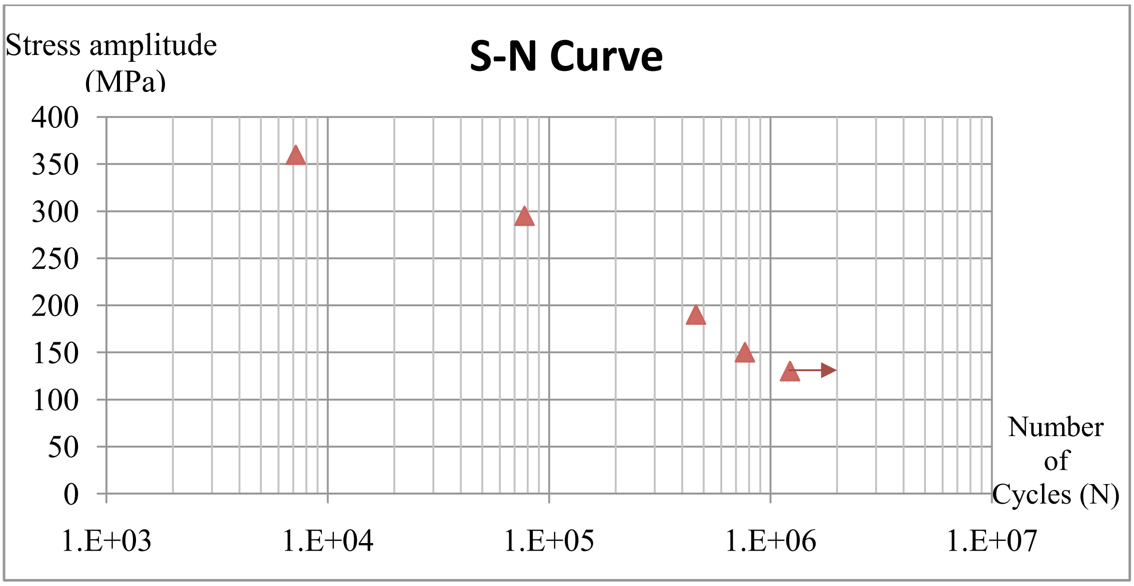

Figure 4.5 : S-N curve for R_a=1.778 µm

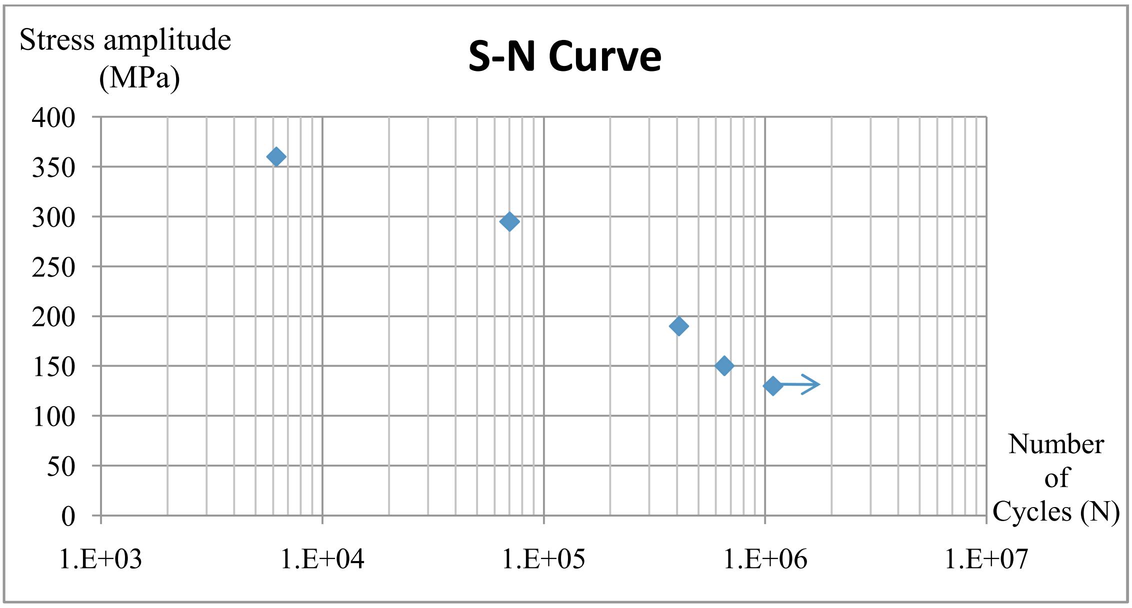

Figure 4.6 : S-N curve for R_a=2.885 µm

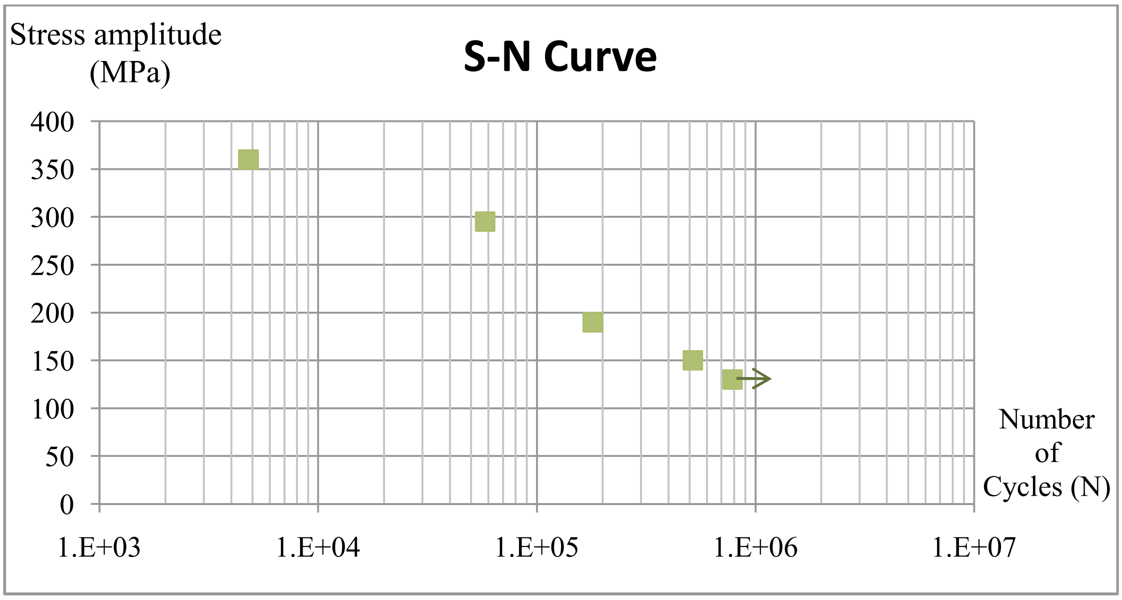

Figure 4.7 : S-N curve for R_a=5.484 µm

4.6 EXPERIMENT RESULT COMPARISON

Experiment results are obtained from collection data that has been done by conducting the rotating bending fatigue experiment. As shown in Figure 4.8. Vertical axis represents the stress amplitude applied during the fatigue test and the horizontal axis represents the number of cycles to failure. The maximum stress applied is 360 MPa for every surface roughness, at this stress level the specimens was failed at the cycles less than 1 x 10^4. The difference of cycle's life between 1.778 µm roughness specimens and 2.885 µm roughness specimens do not show much different to the surface roughness of 5.484 µm which show a much different. Then, at the stress level of 130 MPa, the specimens were failed at the cycle range of 1 x 10^6 which is considered as the fatigue limit for the tested material.

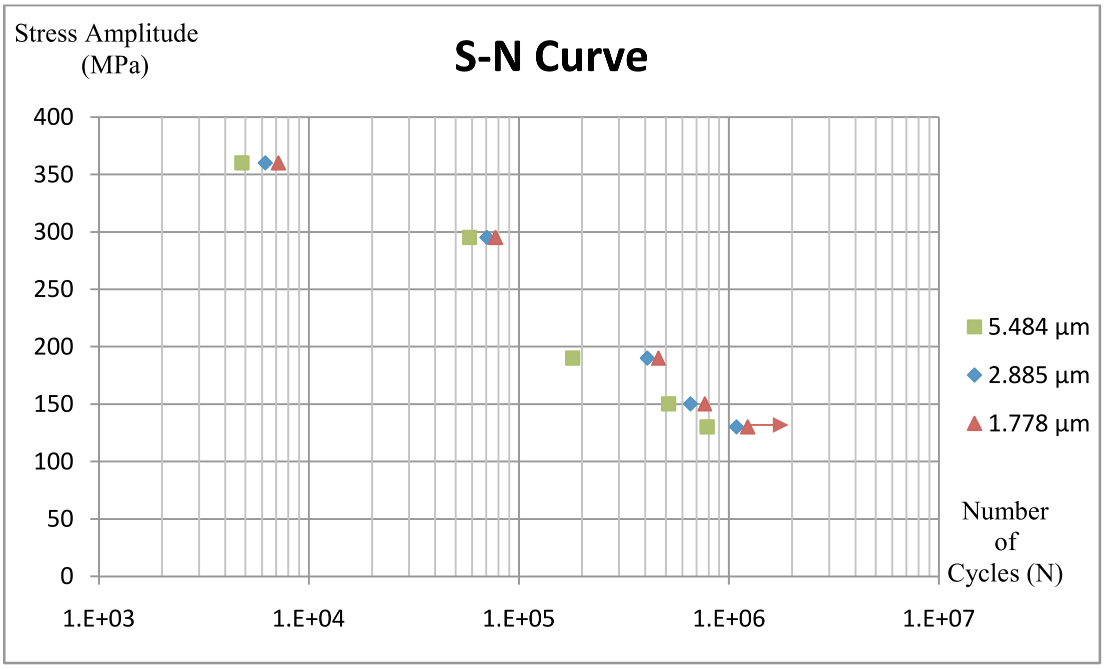

Figure 4.8: S-N curve for different surface roughness

Based on Figure 4.8, the fatigue life is significantly shorter for the high level surface roughness compare to the medium and low surface roughness level which is has the longer life cycle. In addition, the fatigue life period is significantly increased for lower stress amplitude level which is for a finer machining it has longer fatigue life at the lower stress level compare to the others roughness level

4.7 SAMPLE OF CALCULATION

This section will discuss about the calculation used to convert the load applied to stress value from Newton to MPa by using bending stress equation.

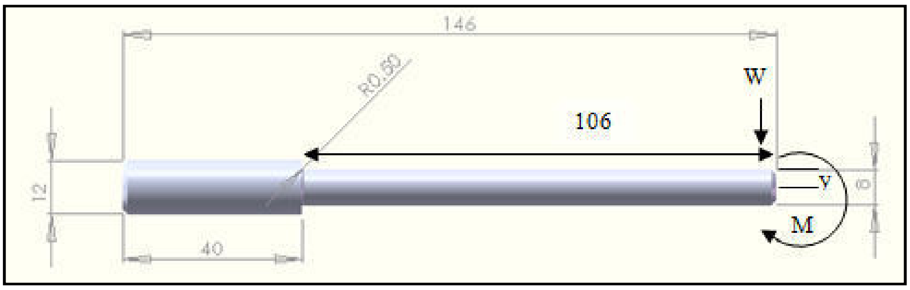

Figure 4.9 : Dimension of fatigue specimens (mm)

For the load applied of 90 N:

$$\sigma = \frac{My}{I}$$

$$I = \frac{\pi d^4}{64}$$

$$I = \frac{\pi (0.008)^4}{64}$$

$$= 2.0106 \text{ x } 10^{-10} \text{ m}^4$$

$$\sigma = \frac{My}{I}$$

$$= \frac{90\text{N } (0.106 \text{ m})(0.004 \text{ m})}{2.0106 \text{ x } 10^{-10} \text{ m}^4}$$

$$= 189{,}794{,}091.3 \text{ Pa}$$

Therefore,the stress value is,

$= 189.79$ MPa ≈ 190 MPa

4.8 FRACTURE SURFACE

The fracture surfaces on failed specimens have been analyzed by using Optical Microscope and Scanning Electron Microscope Zeiss EVO 50. The scanning electron microscope (SEM) is a type of electron microscope that images the sample surface by scanning it with a high-energy beam of electrons in a raster scan pattern. It was observed that the fracture surface for the rotating bending fatigue failures are different between the specimens with high nominal stress, medium nominal stress and low nominal stress. Figure 4.10 shows the failed specimens that were used in rotating bending fatigue test.

Figure 4.10: Failed specimen

4.8.1 Fracture Surface at High Stress Amplitude

Figure 4.11 shows an image taken by using Optical Microscope (OM) which show the fracture surface that are failed at high nominal stress. As shown in the Figure 4.11, the rapid fracture area which is in dark area showing more bigger than medium and low nominal stress rapid fractures, the crack initiation may be occur at any point which are normally discernible to being seen by naked eye.

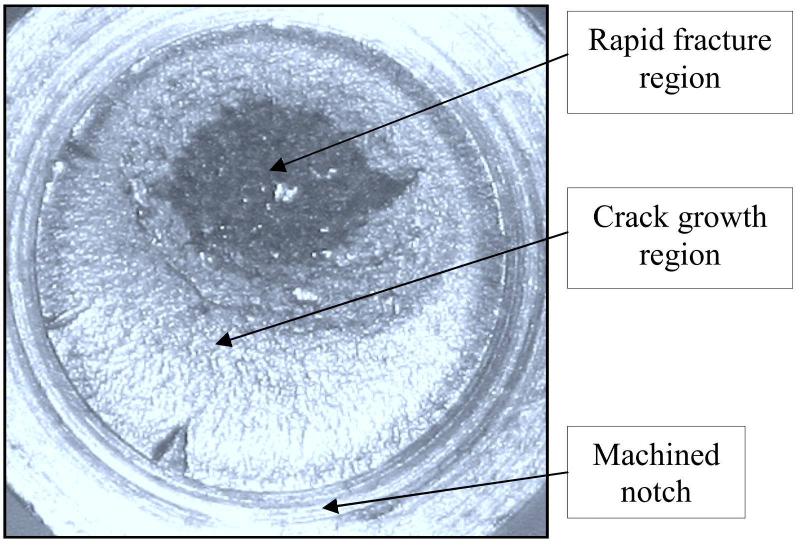

Figure 4.11: High stress amplitude

4.8.2 Fracture Surface at Medium Stress Amplitude

Figure 4.12 shown an image taken use Optical Microscope which show the surface fracture that are failed at medium nominal stress. As shown in the Figure 4.12, the rapid fracture area which is in dark area showing smaller area compare to high stress's rapid fractures, the crack initiation is same with high stress condition which may be occur at any points which are normally discernible to being seen by naked eye.

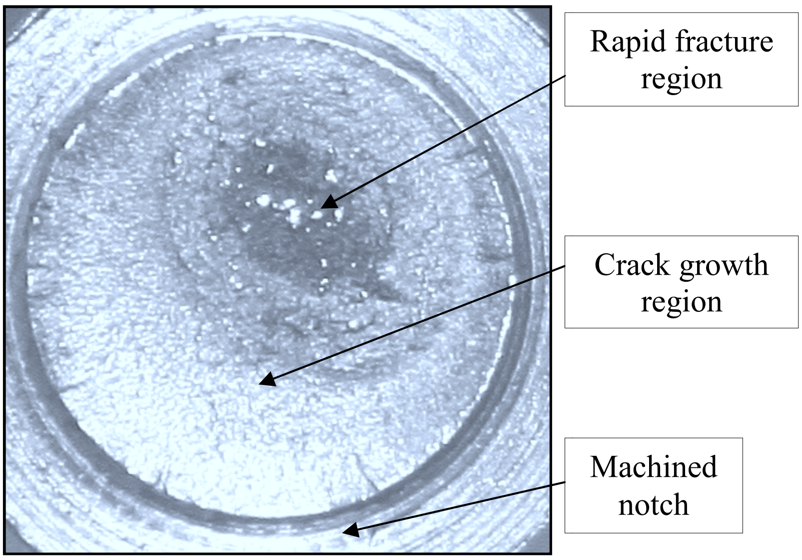

Figure 4.12: Medium nominal stress

4.8.3 Fracture Surface at Low Stress Amplitude

Finally, the fracture surface for low nominal stress as in figure 4.13 shows the pattern is more like arrows lines which is point toward the origins of initial cracks and similarly to torsion failure. This failure occurs when each part of the specimens is subjected to alternating compression and tension under load. A crack can start at any point on the surface where there is a stress raiser.

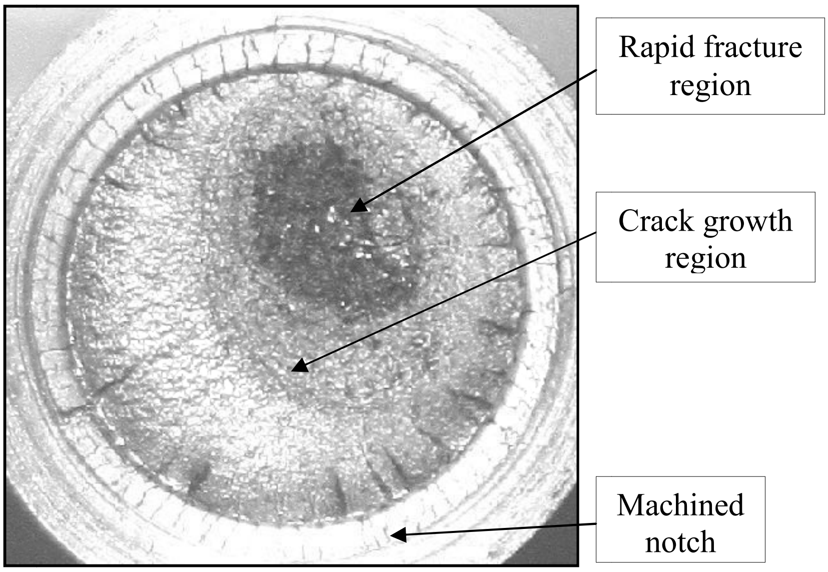

Figure 4.13: Low stress amplitude

4.8.4 Scanning Electron Microscope (SEM) Micrograph

Figure 4.14 shows the surface fracture micrograph been analyses by using SEM, the beach mark on the crack growth or crack propagation region are not much clearly seen because of the brittle material for mild steel used in this experiment. The observation on fracture surface on this specimen was indicates there are two distinct region generated when the specimen was subjected to fatigue stress as shown in Figure 4.14. At first region (point 2), it shows the stable crack propagation as the stress applied on the specimen. After certain length, the specimen cannot withstand with the applied stress anymore and it will causes the specimen to failed rapidly when entering second region (point 3) which is represented the rapid fracture region of the specimen.

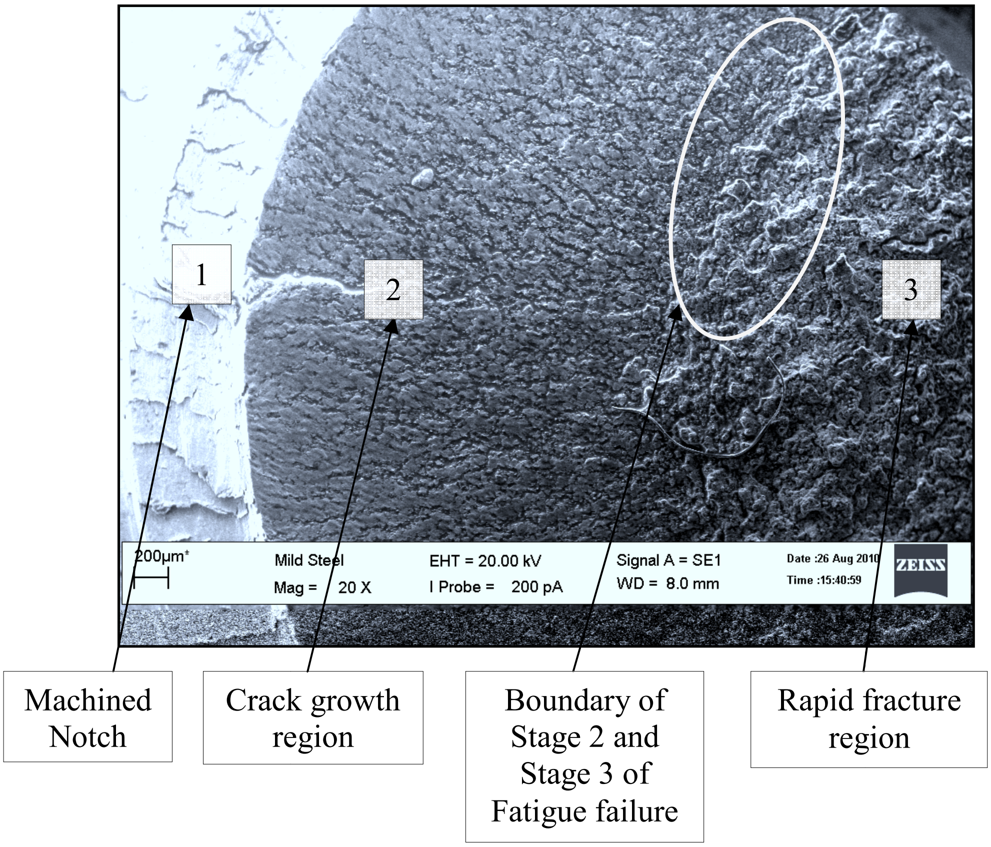

Figure 4.14: Difference surface fracture region

The micrograph of this fracture is shown in figure 4.15 and figure 4.16 for different magnification factor. From the figure, it was showed the transgranular fracture structure for this material at crack propagation region. As shown in figure 4.15 and figure 4.16, fatigue cracks traveling through the grain boundaries, and not along the actual grains which is showed the transgranular manner.

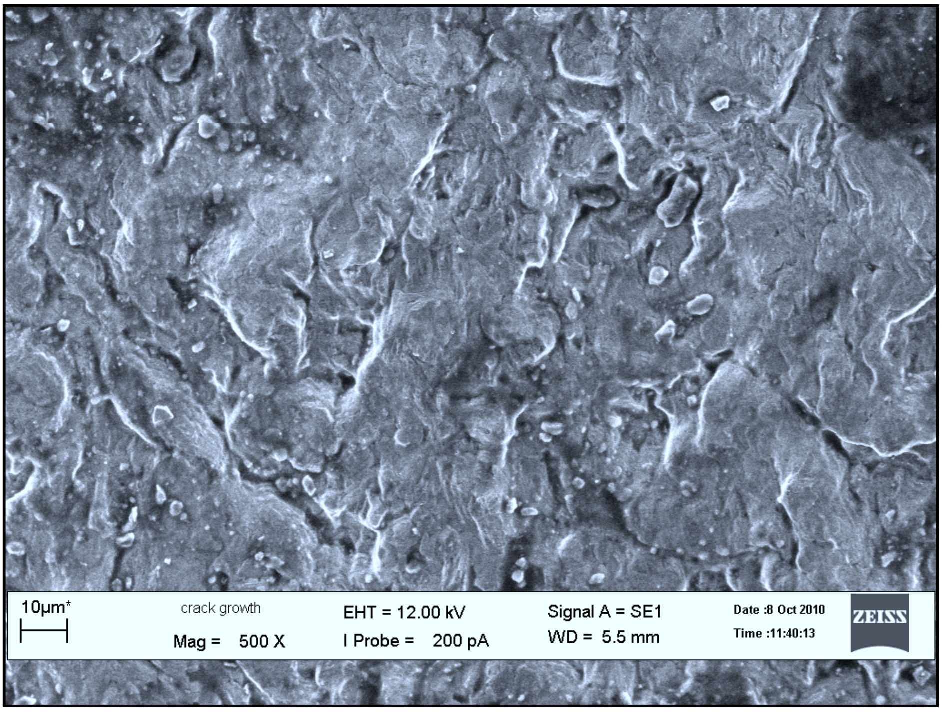

Figure 4.15: SEM micrograph of fatigue fracture for crack growth region at magnification of 500 x

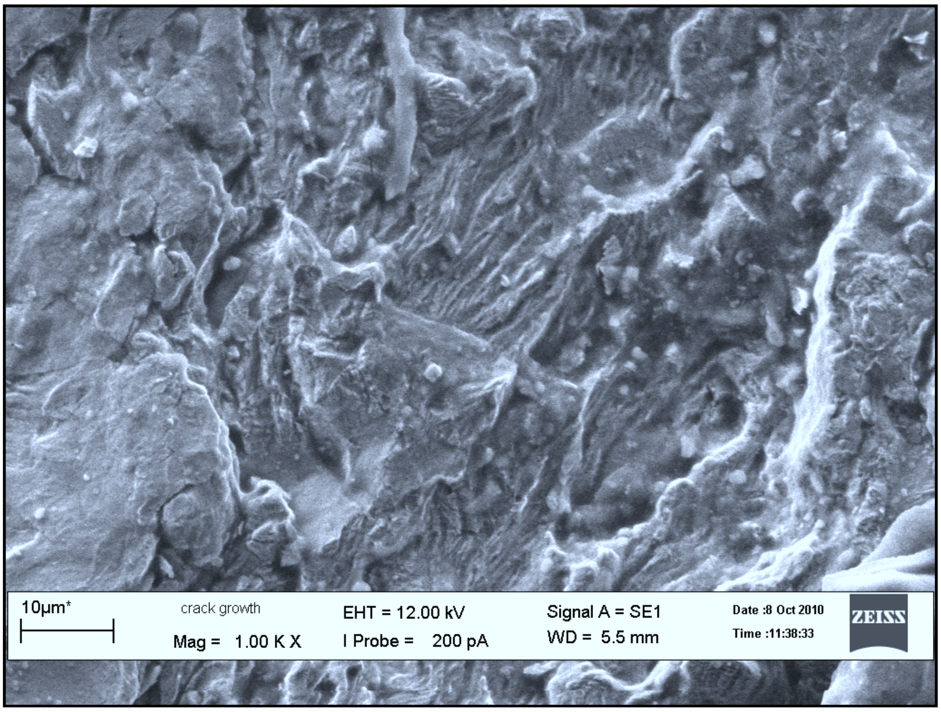

Figure 4.16: SEM micrograph of fatigue fracture for crack growth region at magnification of 1000 x

4.8.5 Fracture Surface Differences

Figure 4.17 and Figure 4.18 show the difference of fracture surfaces between crack propagation region which shows transgranular fracture and rapid fracture region which shows ductile fracture due to rapid failure. This difference was captured by Scanning Electron Microscope at the 1000 x magnification factor.

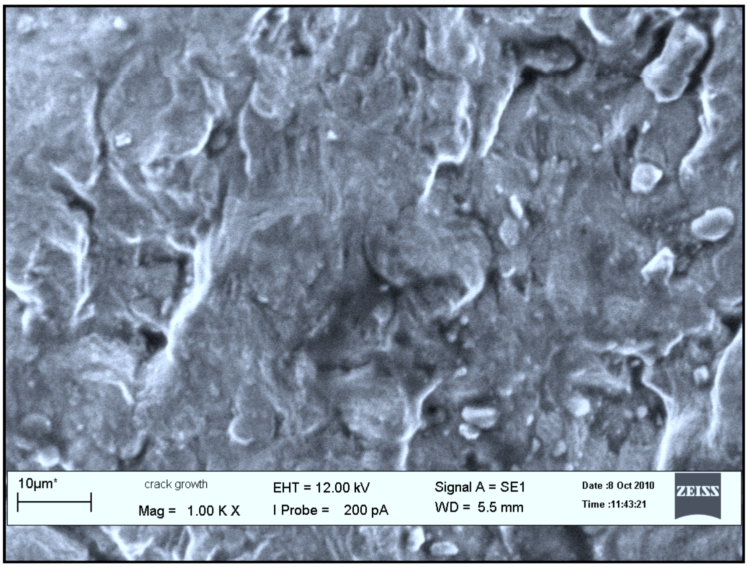

Figure 4.17: SEM micrograph for crack propagation region

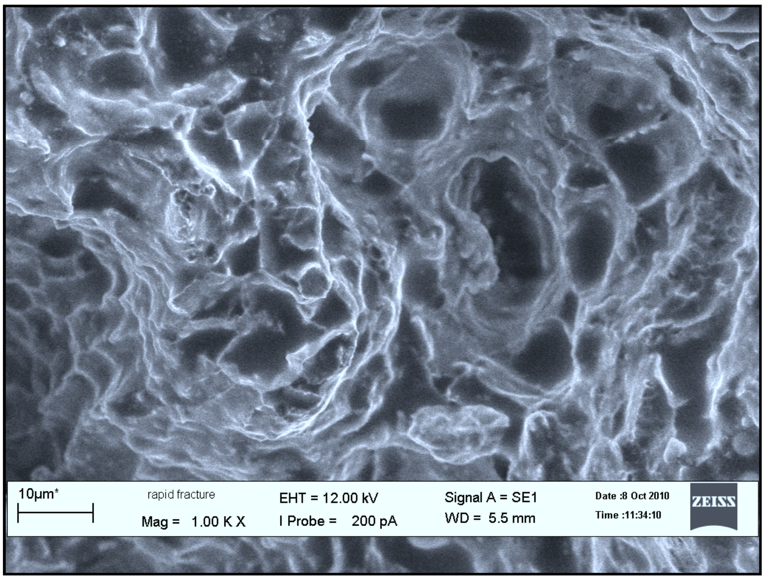

Figure 4.18: SEM micrograph for rapid fracture region

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSIONS

The effect of surface roughness of mild steel on fatigue life has been evaluated experimentally by rotating bending fatigue testing under constant amplitude stress. This project was done successfully with archiving the project objective. However, during the project stage, a few problems occurred such as machining process problem and experiment apparatus problem, the problems need to be solved in order to obtain the better result in the future work. Besides that, the project was running guidance by the scope of this project. It is because limitation of time and equipment to run the project. The project that has better result can be significant to the next researcher and as the references. Based on the rotating bending fatigue test conducted and the results obtained, there are some conclusion can be drawn from the current study:

1. Based on the result, the finer material (R_a=1.778 μm) will result longer life cycle (1226892 cycles) at 130 MPa stress amplitude compares to the coarser material (R_a=5.484 μm) which gives less cycles (786014 cycles) to fatigue life at the 130 MPa stress amplitude.

2. Based on the surface fracture observation, the micrograph of mild steel material result the large rapid fracture region size for high stress amplitude compare to the lower stress amplitude that was result smaller rapid fracture region.

3. It was observed from surface fracture observation that the fracture surface for this study is transgranular manner. It was shown in fatigue crack growth region the specimen was fractured in transgranular manner.

5.2 Recommendation

Some recommendations need to been discussed in order to improve the accuracy of the results, there are some different approach or methods can be followed while conducting the experiment. For this purpose, several recommendations will be discussed based on the study.

5.2.1 Specimens Machining

Since the specimens for this experiment are need to being machined with the different surfaces roughness, it is better for machined it by using the CNC machine instead of using the conventional lathe machine, this is because the machining process that are done by CNC are much more precise in terms of diameter, length, the roughness of surface finish and also the notch geometry making. For conventional lathe machine there are some limitation in machined the specimens since the machine are manually operates to turning the raw material becomes fatigue specimen geometry. The conventional machines also are not precisely perfect in dimensioning setting and tool insert setting.

5.2.2 Strain Gage for Alignment

Strain gage can be used to do an alignment for the specimen instead of using naked eye. The strain gage can be installed to the specimen surface and some analysis to determine whether the specimen is in good position or not is made. The correct alignment of the specimen in the testing machine is important to assure that the central axis of the specimen coincides with the loading axis of the machine.

5.2.3 Number of Specimens

The number of specimens required is one of the important aspect should be considered in any of testing methods. It is recommended to increase the number of specimen in this test in order to reduce the error of the result by taking the average value for all specimen used. In this test, there are only one specimen has been use for each applied stress. Due to time constraint and limited material, the test was perform by using fifth teen material which was divide for three different surface roughness. Even though only one specimen was used for each applied stress, the conditions of the test were always monitored to ensure the ASTM standard is followed. Moreover, two different types of specimens also can be used as comparison instead of similar type of specimens.

5.2.4 Future Work

The fatigue life of material are depends on many factor such as notched geometry, residual stresses and environment condition. On the other hand, the temperature surrounding also can has been an effect of fatigue life. Therefore, the further researches on all of these factors are recommended to be investigating how those factors affected the test results. There are many engineering structures in elevated temperature such as turbine blade, airplane body, and shaft itself for example increase the temperature as heat generated cause by friction between gear motor and the shaft. All these application are required or need much further studies on fatigue crack life at different temperature in order to investigate the material crack behavior and also at the same time improving the quality of some products or materials.

REFERENCES

This report is prepared based on the following references;

Baxter, W.J. 1983. Gel electrode imaging fatigue cracks in aluminum alloys. *International Journal of fatigue*. **16**(3): 37-42.

Beer, F., Johnston, E.R. and Dewolf, J.T. 2006. *Mechanics of Materials,* Fourth Edition. USA: McGraw-Hill.

Bolotin, V.V. 1999. *Mechanics of Fatigue*. Russian: CRC Press LLC

De forest, A.V. 1936. The rate of growth of fatigue cracks. *Journal of applied Mechanics*. **3**: 23-25.

De vries, M.I. and Mastenbroek. A. 1998. SEM Observations of Dislocation Substructures Around Fatigue Crack in AISI Type 304 Stainless Steel. Technical Report.

Farahani, A.V. 2005. *Advance in fatigue, Fracture and damage assessment of material.* Boston: WIT press.

Gangloff, R.P. 1981. Fatigue Crack Growth Measurement and Data Analysis. *American Society for Testing and Materials*, pp. 117-118.

Kalpakjian, S. and Schmid, S. 2006. *Manufacturing Engineering and Technology(5thed.)*. Singapore: Pearson Education South Asia Limited.

Kristoff, S. 2009. Introduction to Crack Growth (online). http://mechanical-engineering.suite101.com/article.cfm/introduction_to_crack_growth.html (7 January 2010)

Krupp, I.U. 2007. *Fatigue crack propagation in Metal and Alloys*. Weinheim: WILEY-VCH Verlag GmbH & Co. KGaA.

Lee, Y., Pan, J., Hathaway, R. and Barkey, M. 2005. *Fatigue testing and analysis: Theory and practice*. New York: Butterworth-Heinemann.

NDT Resource Center. (undated). Fatigue Properties (online). http://www.ndt-ed.org/EducationResources/CommunityCollege/Materials/ Mechanical/ Fatigue.html (13 January 2010)

Schijve, J. 2001. *Fatigue of Structures and materials*. Netherlands: Kluwer Academic Publisher.

Stephens, R.I., Fatemi, A., Stephens, R.R. and Fuchs, H.O. 2000. *Metal fatigue in engineering*. New York: John Wiley and Sons, Inc.

Suraratchai, M., Limido, J., Mabru, C. and Chieragatti, R. 2008. Modelling the influence of machined surface roughness on the fatigue life of aluminium alloy. *International Journal of Fatigue*. **30**: 2119–2126.

Wagner, L., Gregory, J.K., Gysler, A. and Lutjering, G. 1986. Propagation behavior of short cracks in Ti-8.6Al alloy. *Small fatigue cracks*, pp. 117-128.

APPENDIX A1

PROJECT ACTIVITIES		WEEK (S) FINAL YEAR PROJECT 1 (FYP 1)														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Knowing the project objective, project scope and Problem statement	Planning															
	Actual															
Do a literature review and collect all related information from various resources	Planning															
	Actual															
Do a review on previous research from book, journal and thesis	Planning															
	Actual															
Study of fatigue characteristic, effect of surfaces roughness specimen on fatigue life	Planning															
	Actual															
Define the rotating fatigue testing experiment method and experiment parameter	Planning															
	Actual															
Study the specimen machining process on surfaces roughness parameter	Planning															
	Actual															
Review on Rotating bending fatigue machine, Perthometer	Planning															
	Actual															
Specimen preparations	Planning															
	Actual															
Check the specimen's surface roughness parameter value	Planning															
	Actual															
Report writing	Planning															
	Actual															
Submit thesis draft	Planning															
	Actual															
Final year project 1 presentation	Planning															
	Actual															

APPENDIX A2

PROJECT ACTIVITIES		WEEK (S)														
		FINAL YEAR PROJECT 2 (FYP 2)														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Setup the rotating bending fatigue experiment apparatus	Planning															
	Actual															
Conduct the experiment for Low surface roughness specimen	Planning															
	Actual															
Conduct the experiment for Medium surface roughness specimen	Planning															
	Actual															
Conduct the experiment for High surface roughness specimen	Planning															
	Actual															
Collection data	Planning															
	Actual															
Fracture surfaces analysis using SEM	Planning															
	Actual															
Interpret the result and obtain the S-N curve	Planning															
	Actual															
Final report writing	Planning															
	Actual															
Submit project thesis	Planning															
	Actual															
Final year project 2 presentation	Planning															
	Actual															

APPENDIX B

General Recommendations for Turning Operations

Workpiece material	Cutting tool	General-purpose starting conditions: Depth of cut, mm (in.)	General-purpose starting conditions: Feed, mm/rev (in./rev)	General-purpose starting conditions: Cutting speed, m/min (ft/min)	Range for roughing and finishing: Depth of cut, mm (in.)	Range for roughing and finishing: Feed, mm/rev (in./rev)	Range for roughing and finishing: Cutting speed, m/min (ft/min)
Low-C and free machining steels	Uncoated carbide	1.5–6.3 (0.06–0.25)	0.35 (0.014)	90 (300)	0.5–7.6 (0.02–0.30)	0.15–1.1 (0.006–0.045)	60–135 (200–450)
	Ceramic-coated carbide	"	"	245–275 (800–900)	"	"	120–425 (400–1400)
	Triple-coated carbide	"	"	185–200 (600–650)	"	"	90–245 (300–800)
	TiN-coated carbide	"	"	105–150 (350–500)	"	"	60–230 (200–750)
	Al_2O_3 ceramic	"	0.25 (0.010)	395–440 (1300–1450)	"	"	365–550 (1200–1800)
	Cermet	"	0.30 (0.012)	215–290 (700–950)	"	"	105–455 (350–1500)
Medium and high-C steels	Uncoated carbide	1.2–4.0 (0.05–0.20)	0.30 (0.012)	75 (250)	2.5–7.6 (0.10–0.30)	0.15–0.75 (0.006–0.03)	45–120 (150–400)
	Ceramic-coated carbide	"	"	185–230 (600–750)	"	"	120–410 (400–1350)
	Triple-coated carbide	"	"	120–150 (400–500)	"	"	75–215 (250–700)
	TiN-coated carbide	"	"	90–200 (300–650)	"	"	45–215 (150–700)
	Al_2O_3 ceramic	"	0.25 (0.010)	335 (1100)	"	"	245–455 (800–1500)
	Cermet	"	0.25 (0.010)	170–245 (550–800)	"	"	105–305 (350–1000)
Cast iron, gray	Uncoated carbide	1.25–6.3 (0.05–0.25)	0.32 (0.013)	90 (300)	0.4–12.7 (0.015–0.5)	0.1–0.75 (0.004–0.03)	75–185 (250–600)
	Ceramic-coated carbide	"	"	200 (650)	"	"	120–365 (400–1200)
	TiN-coated carbide	"	"	90–135 (300–450)	"	"	60–215 (200–700)
	Al_2O_3 ceramic	"	0.25 (0.010)	455–490 (1500–1600)	"	"	365–855 (1200–2800)
	SiN ceramic	"	0.32 (0.013)	730 (2400)	"	"	200–990 (650–3250

APPENDIX C

WORLDWIDE ANALYTICAL SYSTEMS AG
WAS Sample Testing of different Qualities

Chemical Results

Probe Nr. / sample ID :115X 15261

Grundwerkstoff / material :Cu300

Kunde / customer :chandran laa

Abmessung / dimension :copper ingot

Kom.-Nr. / commision :10%

Zusatzwerkstoff / filler metals :no

Labor Nr. / lab-no. :foundry UMP

Wärmebehandlung / heat treatment :no

PTQ-Nr. / PTQ-no. :

Schmelze-Nr. / heat-no. :no

Spektralanalyse Foundry-MASTER   Werkstoff / grade :

	Fe	C	Si	Mn	P	S	Cr	Mo
1	97,9	0,224	0,135	0,731	> 0,100	0,0389	0,169	0,0160
2	98,0	0,210	0,136	0,718	> 0,100	0,0422	0,160	0,0178
3	98,0	0,207	0,130	0,726	> 0,100	0,0379	0,161	0,0057
Ave	98,0	0,214	0,133	0,725	> 0,100	0,0397	0,164	0,0132

	Ni	Al	Co	Cu	Nb	Ti	V	W
1	0,122	< 0,0010	0,0082	0,442	< 0,0020	< 0,0020	< 0,0020	< 0,0150
2	0,0984	< 0,0010	0,0073	0,431	< 0,0020	< 0,0020	< 0,0020	< 0,0150
3	0,101	< 0,0010	0,0073	0,420	< 0,0020	< 0,0020	< 0,0020	< 0,0150
Ave	0,107	< 0,0010	0,0076	0,431	< 0,0020	< 0,0020	< 0,0020	< 0,0150

	Pb	Sn	B	Ca	Zr	As	Bi
1	< 0,0250	0,0150	0,0012	0,0005	< 0,0020	0,0061	< 0,0300
2	< 0,0250	0,0145	0,0012	0,0008	< 0,0020	0,0076	< 0,0300
3	< 0,0250	0,0139	0,0012	0,0003	< 0,0020	< 0,0050	< 0,0300
Ave	< 0,0250	0,0145	0,0012	0,0005	< 0,0020	0,0060	< 0,0300

Ort / town   Datum / date 29/09/2010   Prüfer / tester   Sachverständiger / engineer

Worldwide Analytical Systems AG
Welleswег 31