DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

FATIGUE LIFE OF TUNGSTEN COBALT CARBIDE USED AS A CORE MATERIAL IN COLD FORGING DIES

by
Barış TANRIKULU

September, 2016
İZMİR

FATIGUE LIFE OF TUNGSTEN COBALT CARBIDE USED AS A CORE MATERIAL IN COLD FORGING DIES

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"FATIGUE LIFE OF TUNGSTEN COBALT CARBIDE USED AS A CORE MATERIAL IN COLD FORGING DIES"** completed by **BARIŞ TANRIKULU** under supervision of **PROF.DR. RAMAZAN KARAKUZU** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

Fatigue life behavior and prediction of materials used in die cores have always been a research target for many studies. Lack of fatigue testing standards and reliable test methods for Tungsten-Carbide's, have induced researchers to focus on comparative fatigue tests with bringing different approaches.

Experimental study focusses on fatigue life comparison with three point bending fatigue testing approach. Surface condition and grain size effect on fatigue life time of WC-Co have been investigated and comparative test result are given. Moreover, fatigue life maps of fine and coarse grain sized materials which are experimentally tested, were generated based on Goodman relations. Last part of the study contains simulation of cold forging process for estimating life cycle of a cold forging punch used in manufacturing process.

Keywords: Cold forging, WC-Co, fatigue, life prediction

SOĞUK DÖVME KALIPLARINDA ÇEKİRDEK OLARAK KULLANILAN TUNGSTEN KOBALT KARBÜR MALZEMESİNİN YORULMA ÖMRÜ

ÖZ

Soğuk dövme kalıplarında kullanılan malzemelerin yorulma ömür davranışları ve ömür tahmin konuları birçok çalışma için amaç olmuştur. Yorulma test standardının ve dolayısıyla güvenilir bir test metodunun olmaması, araştırmacıları farklı yaklaşımlar kullanarak karşılaştırmalı yorulma testleri yapmaya itmiştir.

Deneysel çalışma, üç nokta eğme bazlı yorulma metoduna yoğunlaşarak karşılaştırmalı yorulma testlerini kapsamaktadır. WC-Co malzemesinin yüzey koşulları ve tane yapısı etkileri yorulma ömrü açısından incelenmiş ve karşılaştırmalı sonuçlar paylaşılmıştır. Ayrıca, deneysel olarak test edilen ince ve kalın tane yapısına sahip kalıp malzemenin yorulma ömür haritaları Goodman bağıntısı referans alınarak oluşturulmuştur. Çalışmanın son bölümü ise üretim aşamasında kullanılan soğuk dövme zımbasının sayısal simülasyon çalışmaları ve yorulma haritaları yardımı ile ömür tahminini içermektedir.

Anahtar Kelimeler: Soğuk dövme, WC-Co, yorulma, ömür tahmini

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CHAPTER ONE
INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Fatigue life prediction has been always a critical research area for design processes. Estimating endurance limit at the design stage could lead engineers to make safer and durable products. Unpredictable fatigue cracks can cause severe and fatal accidents. Estimating fatigue life of components in design stage could prevent unpredictable accidents.

Forging is considered as mass production method among other manufacturing processes. Cost effective, rapid production abilities and near shape product capability separate forming from other manufacturing methods. Forging is also preferable for its strength hardening abilities during manufacturing processes, which is based on re-orientation of grain distribution caused by forging operation.

The study focusses on fatigue life investigation of WC-Co materials mostly used in cold forging dies. As it is known, most cold forging die materials have different fatigue behaviors from conventional steels. Needs of high stress durability, minimum thermal expansion and long service life capabilities were essential for cold forging die materials.

The most commonly used die material WC-Co %40 in fastener production has been chosen for investigation of fatigue lifes. As known, WC-Co materials are powder metallurgicaly manufactured products. Fatigue life prediction of such kind materials has not a precise methodology. Thus situation lead researchers to focus on different prediction methods for a precise life estimation.

Experimental studies were based on comparison of surface condition and grain size effect on fatigue lives of WC-Co material. Experimental test was conducted in resonating fatigue testing machine with three point bending test procedure according

to ISO 3327:2009. Fatigue tests were carried with different amplitude and mean stresses at a constant stress ratio. Wöhler diagrams and generalized fatigue life maps of fine grain sized and coarse grain sized materials were obtained.

Cold forging simulation was conducted on a bushing produced in Norm Fastener using Simufact 12.0. Station designs and formability analysis was performed based on the manufacturing parameters. Stress analysis of cold forging punch used in forming was investigated and critical stresses were determined.

Based on the life maps, which were obtained from experimental results, fatigue life prediction of the punch was done and compared from the life cycle data of the factory.

1.2 Literature Review

In this section, literature reviews based on mechanical behavior of Tungsten Carbides and simulation analysis of forging tools are given.

Klünsner made researches on the mechanical properties of WC-Co cemented carbide with different grain sizes. Three point bending fracture and compressive tests were carried on specimens. Stress-Strain diagrams and rupture force comparison among different grain sized specimens were investigated (Klünsner, 2010).

Kawahara worked on different surface finishing methods and their effects on fatigue life of carbide tools with 22 mass%Co. Different sized wheels for grinding operation was used and different EDM processes were compared based on three point bending fatigue lives. Each specimens were polished before the experimental test and results obtained were compared with a stress-life curves. From the experimental studies it is stated that residual stresses caused by different surface finishing process has a key role on fatigue lives of WC-CO materials (Kawahara, 2013).

Anhai L. researches were based on three-point bending fatigue behavior of WC-Co materials. Different grain size and Co binder materials in notched condition were tested under static and dynamic loading with three point bending test. From the experimental study it is claimed that fracture in dynamically loading condition begin from materials defects near notches. It is also find out that the fatigue life of Cemented Carbides are in relation with both transvers rupture strength and fracture toughness (Anhai, 2013).

Torres worked on the fatigue mechanics of cemented carbides with %10 cobalt content. Fracture toughness, transvers rupture strength and fatigue crack growth behavior were investigated under monotonic and dynamic loading conditions. Based on the study, fatigue life limits could be considered with mean stress effects using Goodman diagrams (Torres, 2001).

"*Fatigue properties of high-strength materials used in cold forging tools*" namely research by Povl Bronsted was focused on the fatigue behavior of high-strength materials which are used in cold forging tools. Research was based on static stress-strain curves, dynamic low cycle fatigue and fatigue crack growth behavior of high strength materials. Experimental tests were carried on Calmax, ASP 23 and G7-HIP materials and results are given in the study (Bronsted, 1998).

In a view of mechanical behavior of WC-Co hard metals which were mainly used in machining tools was examined by J.A.M Ferreira. Two materials were experimentedfor determining young modulus, bending strength and fracture toughness (Ferreira, 2009).

M. Geigar worked on a methodology for predicting service life and failure probability of forging tools with a combination of Fe analysis (Geiger & Falk, 2001).

Peder Skov Hansen investigated tool lifes of cold forging dies with a combination of low cycle fatigue, fatigue crack growth tests and finite element methods. Low cycle fatigue test are made and hysteresis loops were given in the study. An

assumption of tool life in the cold forging process was taken as the same to the life which was experimentally obtained (Peder, 1999).

Ryuichiro researches named "*fatigue crack initiation and propagation behavior of forging die steels*" were based on fracture mechanics approaches with a combination of experimental results (Ryuichiro, 2010).

H.C.Lee work was based on predicting tool life in bolt forming process in consideration high-cycle fatigue and wear effects. Archard wear model is used for prediction of forging tools with a combination of finite element methods. The study shows that fatigue lifes decrease with the increase of strength. Contrary wear life increase parallel to mechanical strength of tools materials.

CHAPTER TWO
FORGING, EXTRUSION AND DRAWING PROCESSES

2.1 Forging

Forging can be defined as manufacturing process based on plastic deformation of workpiece materials using external forces.In this context Forging can be considered the oldest manufacturing technology among other manufacturing processes. Besides that forging, could be operated in room temperature or in different temperatures with specific tool parts. Application in room temperature is classified as cold forging on the other hand operations in elevated temperatures are classified as warm and hot forging as seen in Figure 2.1 (Tekkaya, 2001).

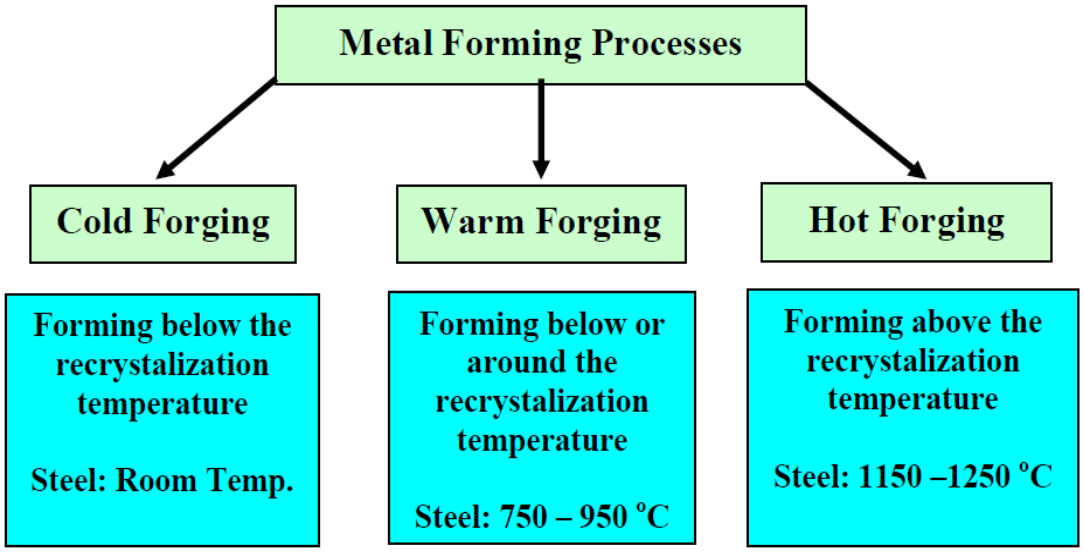


Figure 2.1 Metal forming processes (Tekkaya, 2001)

Forging is also preferable for mass production because of its narrow tolerances capabilities and rapid production abilities. Due to mass production, costs are also reduced comparing to machining process. As a result of compressive force and plastic deformation of the material, grain distribution is re-oriented by the shape of the product during forming process. Benefits of the oriented grain distribution cause an improvement on the mechanical properties of the product compared to other

production techniques. Figure 2.2 shows different grain distribution of different manufacturing methods (Kalpakjian, 2014).

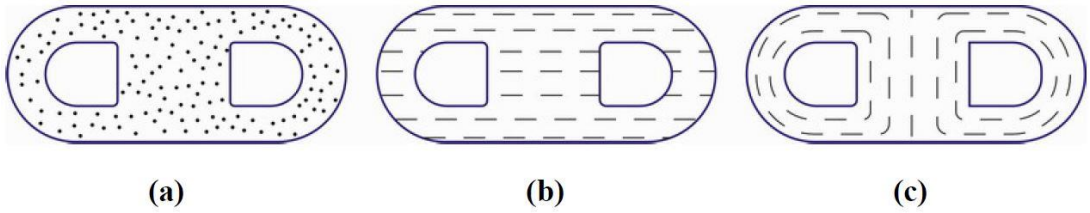


Figure 2.2 Grain distribution of casting, machining and forging respectively (Kalpakjian, 2014).

2.1.1 Open-Die Forging

Open-die forging can be described as shaping workpieces by external forces between two dies without enclosing the workpiece material. Compression testing which is given in Figure 2.3 (Kalpakjian, 2014), could be an example in open-die operation. It can also be called as "flat-die forging". Open die forging often needs secondary manufacturing processes for obtaining final shape and close tolerances. It is mainly used in shaping simple geometric parts. The process increase strength of the workpiece by orienting grain distribution by the shape of the die.

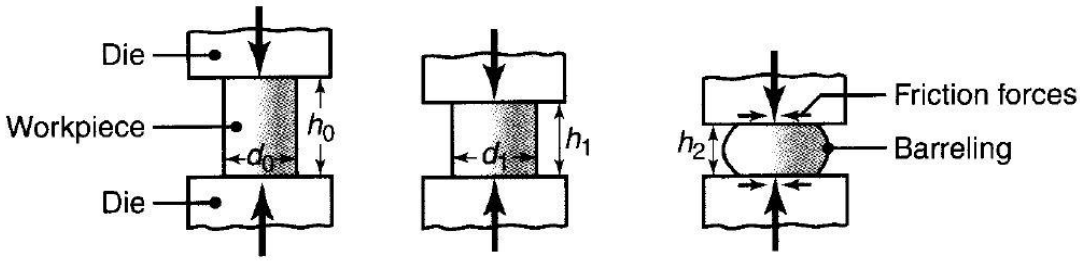


Figure 2.3 Compression test (Kalpakjian, 2014).

2.1.2 Closed-Die Forging

Closed-die forging or impression-die forging is a process based on forming workpiece through multiple enclosed dies by external forces as seen in Figure 2.4 (Kalpakjian, 2014). Aim of the process is to fill enclosed die with workpiece material and take the shape of the dies. Closed die forging operation is more precise process

compared to open die forging for net shape results and close tolerances. Closed die forging operation need some special die design because of high forces caused by forming operations. Elevated temperature can reduce force required for forming workpiece for desired shapes (Kalpakjian, 2014).

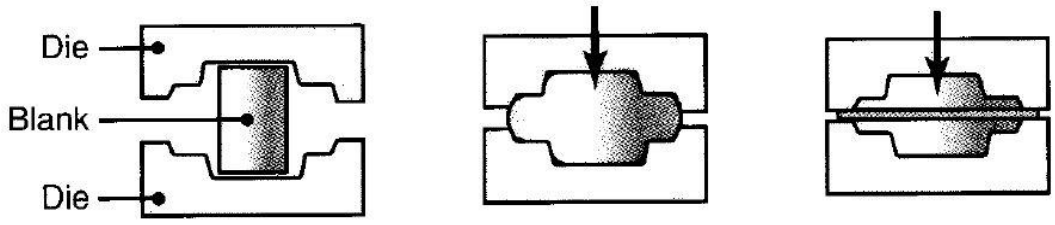


Figure 2.4 Closed die forging (Kalpakjian, 2014).

2.1.3 Heading

Heading can be described as an upsetting operation for increasing cross-section area of the workpiece material at the end of the wire/rod. An example of the heading operation is given in Figure 2.5. 1:3 ratio of length to diameter must be considered before the heading operation. Exceeding 1:3 ratio can cause buckling situation.

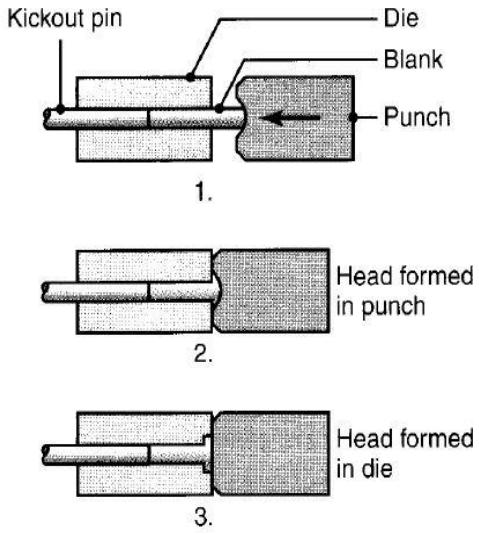


Figure 2.5 Heading operation

2.2 Extrusion

Extrusion process can be described as pushing workpiece through a shaped die by the help of external forces. The process is continuous till the workpiece finishes. Material is forced to be shaped by compressive and shear forces without fracture. Close tolerances and complex shapes could be manufactured without stopping the process. Extrusion force is described as forces needed to start extrusion process. There are several variables effecting extrusion forces. Strength of the workpiece material, extrusion ratio, frictions between extrusion die and workpiece, die shapes and temperature of the extrusion process. Extrusion ratio could be described as cross sectional area of the workpiece divided to extruded part cross sectional area. An example of the extrusion process is given in Figure 2.6.

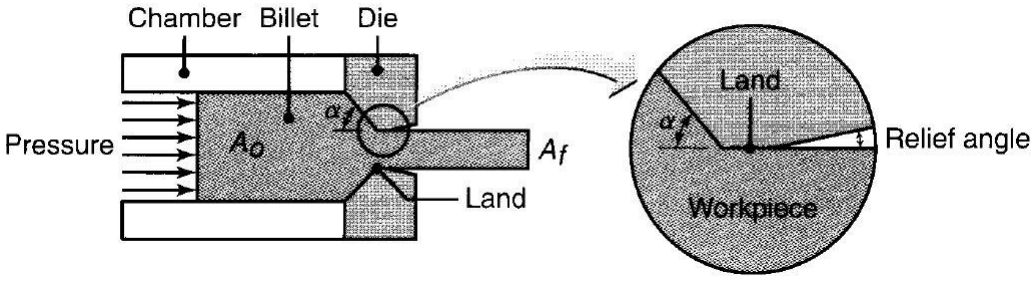


Figure 2.6 Extrusion process (Kalpakjian,2014)

Forces needed for starting extrusion process in frictionless and ideal conditions could be described as the formulation situated in Equation 2.1 (Kalpakjian, 2014).

Where A_0 is the cross-sectional area of the applied force

$$F = A_0 k \ln\left(\frac{A_0}{A_f}\right) \tag{2.1}$$

2.2.1 Forward Extrusion

Forward or direct extrusion could be described as extrusion process with forcing material in a closed chamber to flow through extrusion die shape. Die forms could be

round shaped or complex shaped. An example of direct extrusion is given below in Figure 2.7

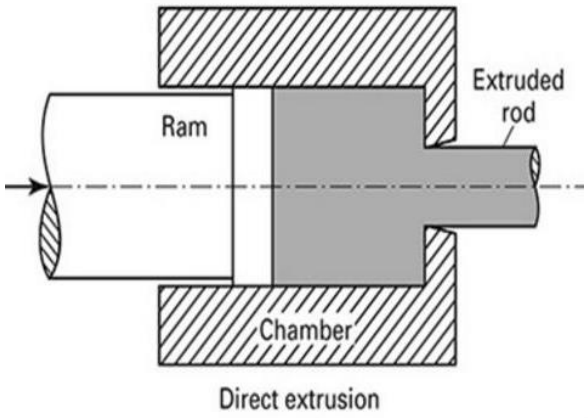


Figure 2.7 Example of direct extrusion

2.2.2 Backward Extrusion

Backward extrusion was also called as indirect extrusion. Die moves through the workpiece material and cause material flow through the die shape. Generaly, workpiece material is forced to flow in reverse direction of the die motion. An example of indirect extrusion is given in Figure 3.8.

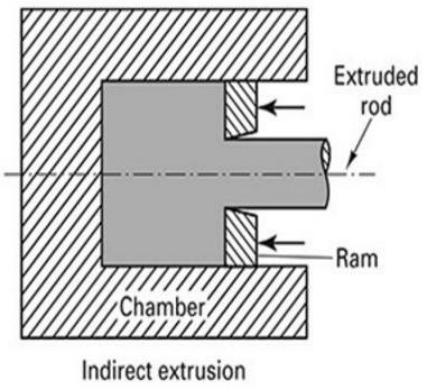


Figure 2.8 Example of indirect extrusion

2.3 Drawing

Drawing process could be described as a manufacturing operation based on pulling the workpiece material through a shaped drawing die and decrease the cross

sectional area of the workpiece material. There was a close differences with extrusion process. In drawing applications forces are applied directly to the workpieces instead of dies as shown in Figure 2.9.

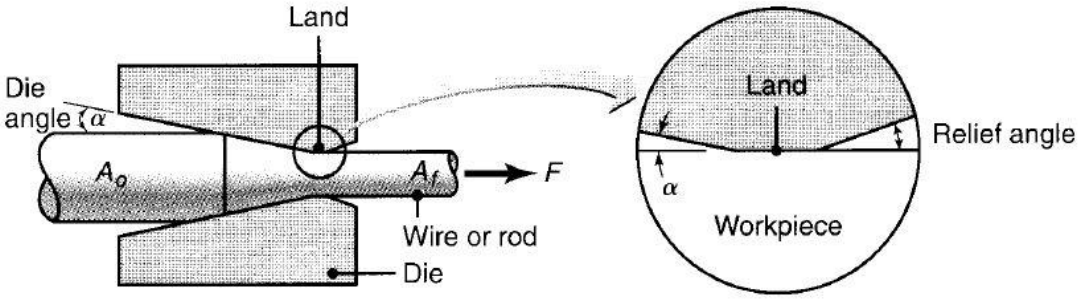


Figure 2.9 Drawing operation (Kalpakjian, 2014)

Drawing force can be found with the formulation given in equation 2.2 for frictionless and perfect condition, where the Y_{avg} is the true stress of the material. Drawing force can also be defined as the forces needed to start the drawing operation.

$$F = Y_{avg}\, A_f \ln\left(\frac{A_0}{A_f}\right) \tag{2.2}$$

2.4 Cold Forging Dies and Punches

Forging dies are tools for shaping metallic materials based on its surface geometry with a help of external forces. Forging dies are subjected to high loads and high temperature caused by friction between die and metallic material. High load and friction forces mostly cause die failures based on fatigue and wear as seen in Figure 2.10. Thereby materials are specifically chosen by considering external forces and working conditions. Commonly, Carbide materials are used in tool systems because of its numerous advantages compared to conventional steels. Some forging dies which are used in fastener production has a pre-stressing ring which implies a compression stress on the core of the die. Pre-stressed die can withstand to high

tensile loads during forging operation. Pre-stressing ratio, surface conditions, binder ratio and grain size are some key parameter affecting fatigue life of forging dies.

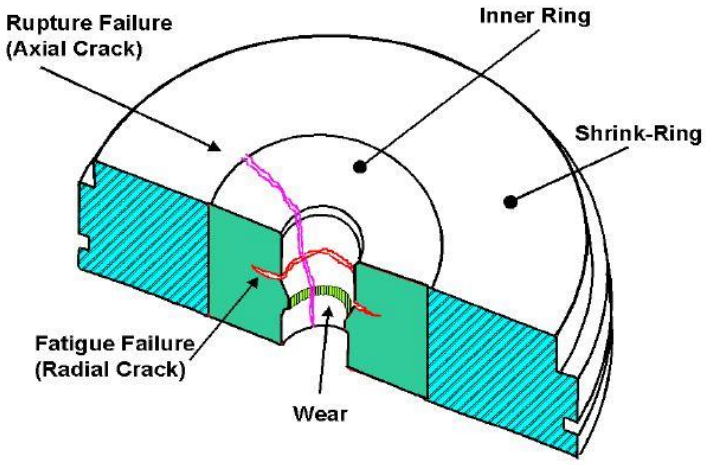


Figure 2.10 Cold forging die failure modes (Aygen, 2006)

Certain forging processes needs also some special punch design for forming the workpiece shapes. Those parts, are often subjected to high loads during forming operation. Axial misalignment often causes fatigue and wear based failures in these tools, which are given in Figure 2.11



Figure 3.11 Punch and die failures due to fatigue

2.4.1 Cold Forging Die Materials

Due to extreme loading conditions in forging operation, die design needs some special interest to maintain its working ability under extreme loading conditions. Material for forging dies requires high strength endurance, high toughness, high hardness capabilities and high wear resistance. Those necessity and extreme values are coverable generally by sintered materials. Based on the forging operation type, best option for preventing failure mechanism could be chosen for long service life. Generally high strength steels manufactured with powder metallurgy were chosen like carbides.

2.4.2 Parameters Affecting Fatigue Life of Cold Forging Dies

Fatigue phenomena depends on variable parameter such as surface integrity, material toughness, environmental effects and many more external and internal parameters. With a narrow perspective, it could be said that cold forging dies fatigue is a complex phenomenon because of the variable parameters which are stated in Figure 2.12

Due to complexity of the forging operation, dies often fails by fatigue fractures. Studies in this area have been concentrated mostly on surface conditions and die materials from the view of the material conditions.

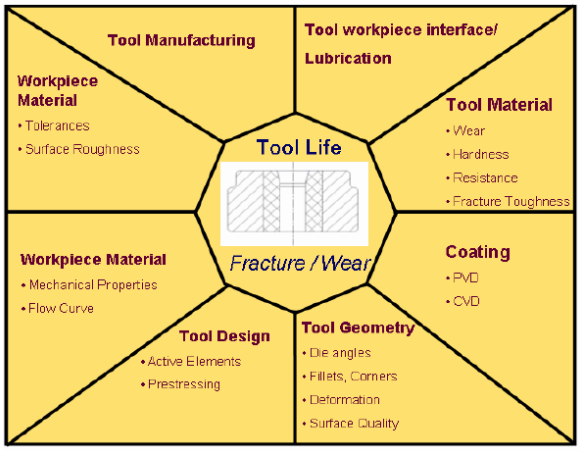


Figure 2.12 Tool life parameters

2.5 Tungsten Carbides

Tungsten Carbide is a common name of Tungsten and Carbon based sintered materials in a same volumetric ratio. Cobalt added Tungsten Carbides are named as WC-Co (Volfram carbide cobalt). Cobalt binder ratio and grain size determine the mechanical behavior of the material. Increase in Cobalt ratio make the material more tough and thus raise the fatigue life of the material. Grain size is also a key parameter effecting the mechanical behavior of sintered materials. As seen in Figure 2.13, there are two key parameter effecting the mechanical behavior of WC-Co. A critical balance between mechanical properties could be chosen for the needed operations by changing grain size and Cobalt content of the material.

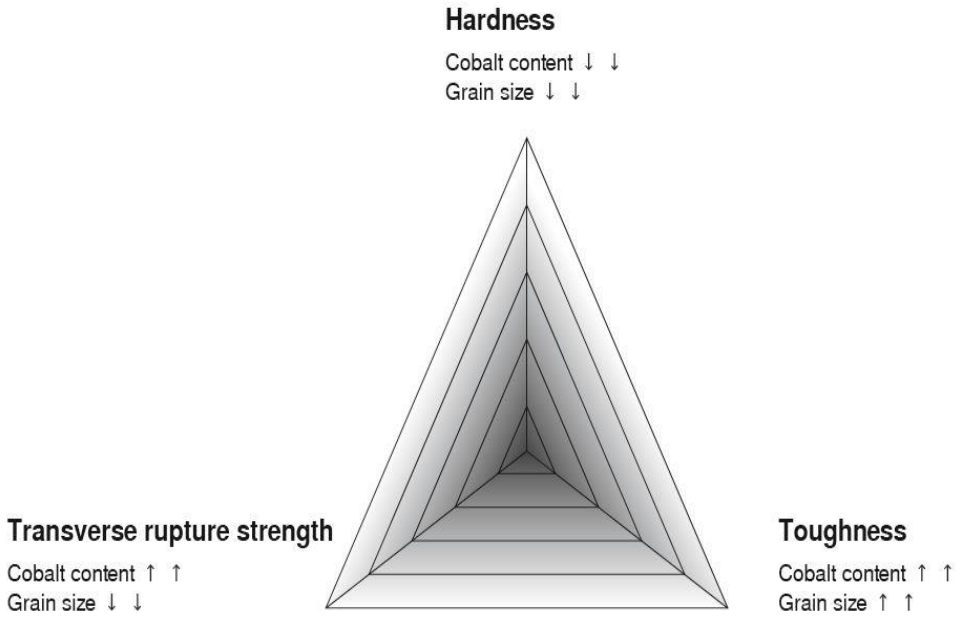


Figure 2.13 Effects of Cobalt content and grain size on mechanical properties (Ceratizit, 2016)

CHAPTER THREE
FATIGUE LIFE

3.1 Fatigue Evaluation

Fatigue, is a failure phenomenon caused by repeated fluctuating stresses under monotonic endurance limit. Fatigue situation occurs in repeated loading conditions and cause failures under the ultimate strength of the material. Fatigue failure propagation could be described in three different stages as named; crack initiation, crack propagation and final failure as seen in Figure 3.1 (Schijve, 2009).

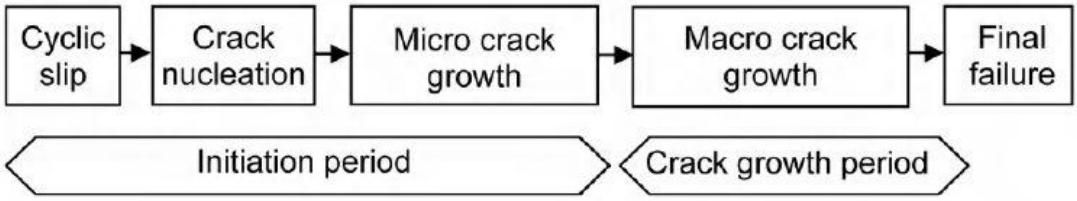


Figure 3.1 Fatigue crack evaluation (Schijve, 2009)

Failure caused by fatigue phenomena differs from monotonic failures. Crack surface integrity shows differences compared to brittle or ductile fracture. With a macro inspection it is possible to see crack initiation phase, crack growth bands and final failure as seen in Figure 3.2 (Schijve, 2009). Finale failure surface condition can differ with the ductility or brittleness of the material.

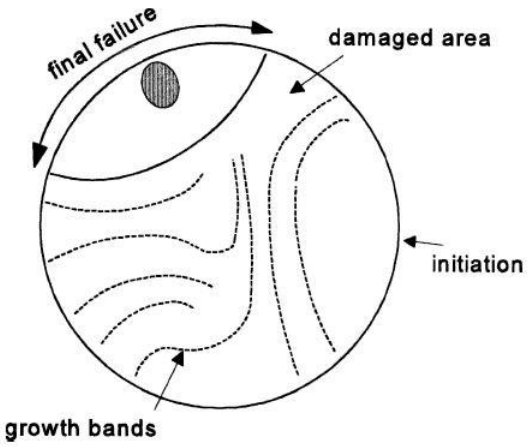


Figure 3.2 Fatigue crack surface (Schijve, 2009)

3.1.1 Crack Initiation

First stage of the fatigue generation could be called as crack initiation period. Fatigue originates from free surfaces of the material. Forces under plastic deformation limits are only effective on few number of grains. Each cycle of stress causes a cycle plastic deformation in free surfaces of the grain by slipping as seen in Figure 3.3. Repeated loading condition cause new free surfaces and fatigue crack initiation continue by. Crack initiation period is depended to surfaces conditions of the material (Schijve, 2009).

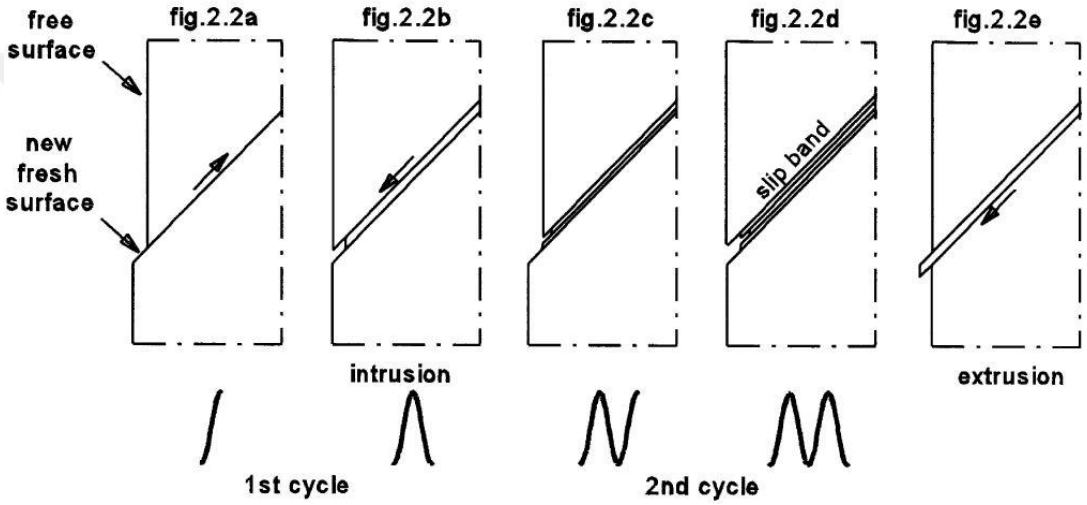


Figure 3.3 Crack initiation by cyclic slip (Schijve, 2009).

3.1.2 Crack Propagation

Crack propagation could be classified in two steps as Stage I and Stage II. Fatigue cracks initiated in grain slip bands free surfaces in microstructure scale, play a role like stress intensity raiser and thus phenomena cause the crack growth through the slip planes direction under loading conditions. Crack propagation through the slip band direction was called stage one propagation and Stage 2 could be described as propagated cracks through the slip bands which starts to propagate in a normal to the maximum stress direction. Demonstration of the fatigue crack propagation is given in Figure 3.4.

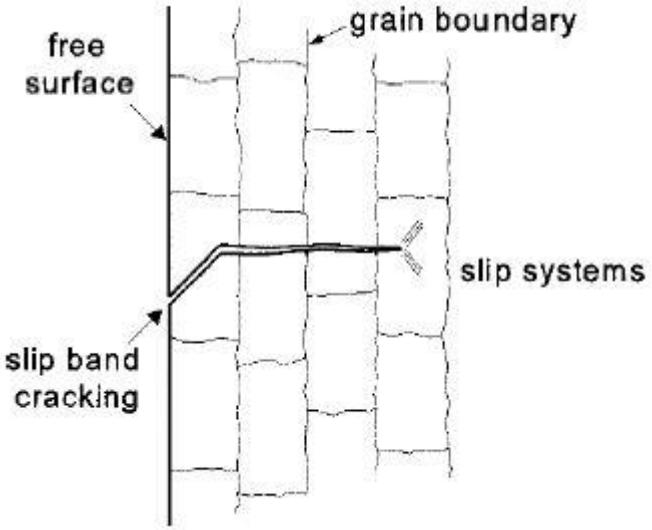


Figure 3.4 Crack propagation in microscale (Schijve, 2009).

3.1.3 Finale Rupture

At a point of propagated cracks through the material decrease the cross sectional area, force applied in cyclic loading passes the stress limits and ductile or brittle fracture occurs. Figure 3.5 shows a fracture surface of a fastener subjected to fatigue loading.



Figure 3.5 Crack surface of dynamically failed fastener

3.2 Fatigue Stresses in Different Loading Conditions

Fatigue testing could be described in different stress and strain conditions. Fatigue stresses in load condition can be classified based on mean stress and stress ratio values.

3.2.1 Fully Reversed Loading

The state of σ_m=0 and R= -1 situation could be described as fully reversed loading condition. Mostly rotating bending test procedure is used for experimental investigation. G_a and G_{mean} are stress amplitude and mean stress value in loading conditions.

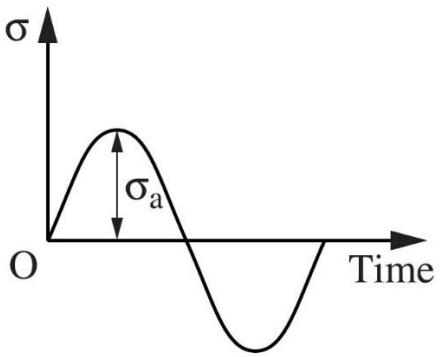


Figure 3.6 Fully reversed loading (Bathias, 2010)

3.2.1 Tension-Compression Loading

Tension compression loading can be described as amplitude stresses above the mean stress. Mean stress value corresponds to a positive value during loading

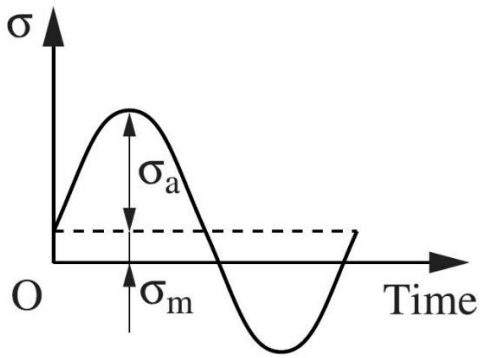


Figure 3.7 Tension-compression loading (Bathias, 2010)

3.2.3 Repeated Tension

Repeated tension could be described as where G_{min} =0 and G_{mean} value is in a positive range.

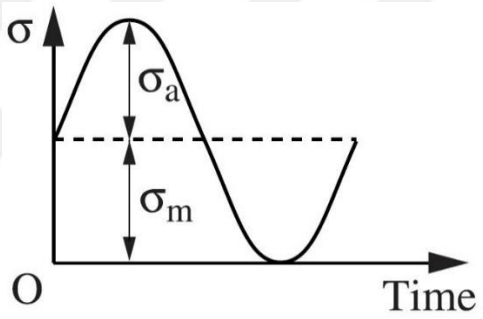


Figure 3.8 Repeated tension (Bathias, 2010)

3.2.4 Alternating Tension

Loading where, G_{min} and G_{mean} are in positive region.

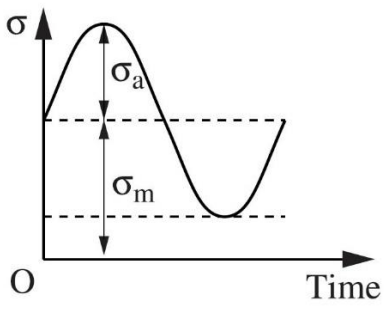


Figure 4.9 Alternating tension (Bathias, 2010)

3.2 Fatigue life Prediction

3.1.1 Stress-Life Method

Stress-life methods are also used mostly in high cycle fatigue region where the cyclic stresses are elastic and lifes are above 10^3 cycles. Fatigue life under different stress amplitude loadings are counted till the final fracture occurs. It is also the most commonly used fatigue life approaches because of the easy implementation to design processes. Cycle number at a different stress levels are counted till the fracture occurs and the data's gathered were placed in a stress-cycle graphic as seen in Figure 3.10. S-N curves which is also named as Wöhler curve could be used as a life prediction methods in design process for different stress amplitude conditions.

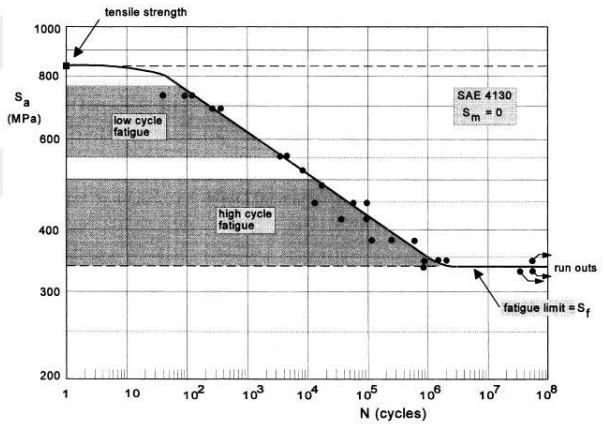


Figure 3.10 Wöhler diagram (Schijve, 2014)

3.1.1.1 Effect of Mean Stress on Stress-Life Prediction

Materials subjected to dynamic loading often fails due to fatigue damages however mean stress play a critical role on the life cycle of the component. Thus situation has been studied and many empirical estimations have been established. Mathematical models based on predicting fatigue life in a view of mean stress effects have been developed by Goodman, Gerber and Soderberg as seen in Figure 3.11 (Çoban, 2015).

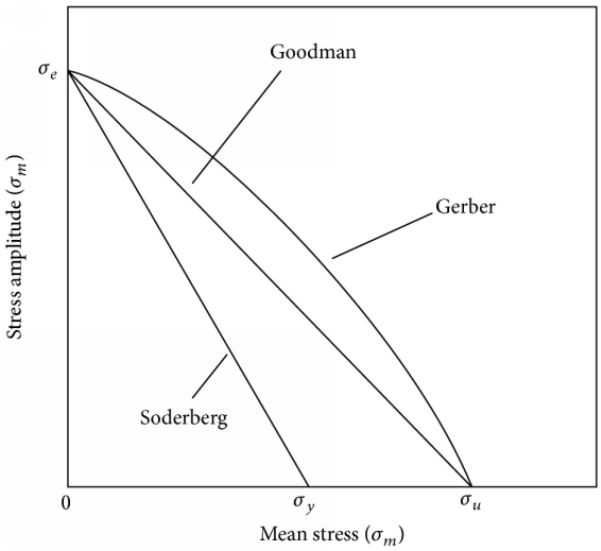


Figure 3.11 Goodman, Gerber and Soderberg diagrams (Scientific, 2016)

Goodman Equation $$\sigma_a = \sigma_f \left[1 - \left(\frac{\sigma_m}{\sigma_u}\right)\right] \quad (3.1)$$

Gerber Equation $$\sigma_a = \sigma_f \left[1 - \left(\frac{\sigma_m}{\sigma_y}\right)\right] \quad (3.2)$$

Soderberg Equation $$\sigma_a = \sigma_f \left[1 - \left(\frac{\sigma_m}{\sigma_u}\right)^2\right] \quad (3.3)$$

3.3.2 Strain-Life Method

Strain life approach focusses on plastic strain caused by cyclic loading conditions at a zones where the stress intensity or notch defect are effective. It is stated that strain-life approaches are in good agreement with low cycle fatigue zone where the life cycles are under 10^3. With a strain changes during loading and stress values of the loading condition it is possible to determine the fatigue life of the part. Hysterisis loop of true stress-true strain situation has been given in Figure 3.12, where $\Delta\sigma$ is the stress range, $\Delta\varepsilon p$ is the plastic strain range and $\Delta\varepsilon e$ in elastic region (Richard, 2010).

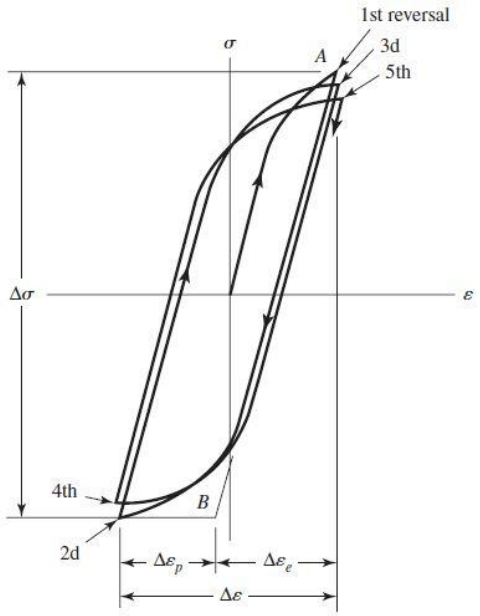


Figure 3.12 Hysterisis loop of true stress-true strain condition (Richard, 2010)

3.3.3 Linear-Elastic Fracture Mechanic Method

One of the frequently used theory in fracture mechanics for determining the life cycle of the material is Paris-Erdogan Law which is given in equation 3.6. Where a is the crack length, N is the cyclic life of the component, da/dN crack propagation speed, C and m material constant taken from experimental results. Where, Δk is the stress intensity ranges per cycle can be described as equation 3.7 (Richard, 2010).

$$\frac{da}{dN} = C\,(\Delta K)^m \tag{3.6}$$

$$\Delta k = \frac{fa}{w}\sigma\sqrt{\pi a} \tag{3.7}$$

Paris-Erdogan law describes the fatigue cycle of a crack propagation period only for Stage II as seen in Figure 3.13. Situation which are not taken into consideration like environmental conditions make the relation less reliable is some cases.

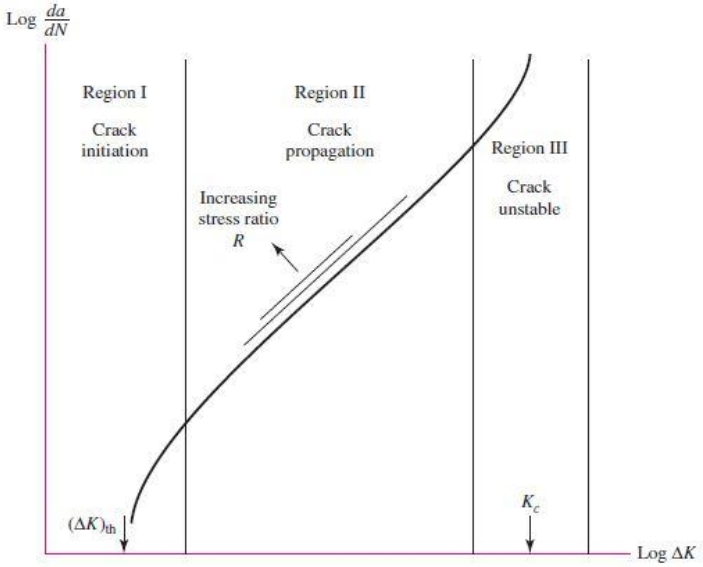


Figure 3.13 Fatigue crack regions (Richard, 2010)

CHAPTER FOUR
FATIGUE LIFE INVESTIGATION OF TUNGSTEN COBALT CARBIDE

4.1 Fatigue Test Setup and Specimen Geometry

There has been a lack of standard for determining the fatigue behavior of Tungsten Carbides. Thus situation forces researches to focus on different type of experimental procedure for determining the fatigue behavior of hard metals. In the study, fatigue experiments were done by a scope of transvers rupture strength.

Fatigue test were carried on three point bending test system based on ISO 3327:2009 "*determination of the transverse rupture strength of hard metals*." Specimen's size were chosen as 5.25x6.5x20 for three point bending tests. The three point bending system and equation of the transvers rupture force is given in Figure 4.1 and Equation 4.1.

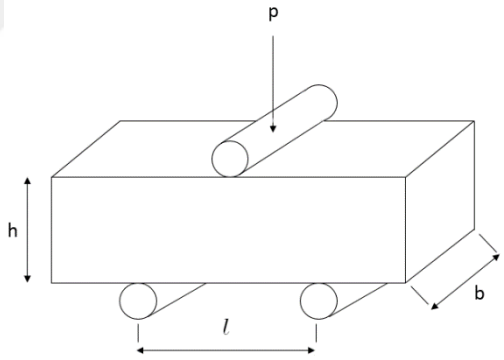


Figure 4.1 Three point bending

$$\mathrm{TRS} = \frac{3.\mathrm{P.l}}{2.\mathrm{b.h}^2} \qquad (4.1)$$

Two different specimen were studied, those are fine grain sized and coarse grain sized Carbides with a Cobalt ratio of %20 which were tested experimentally and comparative results are given in the study. During the study, CTE 40 and CTF 40 names are used for determining coarse and fine grain sized materials respectively. Mechanical properties taken from catalogue values of Ceratizit Gmbh are given in Table 4.1.

Table 4.1 Mechanical properties of CTF 40 and CTE 40

Material	Co Binder (m %)	Grain type	Average Grain Size (µm)	Hardness (HV10)	Transvers Rupture Strength (MPa)
WC-Co 40 (CTF 40)	20	Fine	0.8-< 1.3	1070	3400
WC-Co 40 (CTE 40)	20	Coarse	2.5-<6.0	850	2900

Loading in alternating stress will be subjected to the specimen in dynamical loading condition. An example of the loading stress changes was given in Figure 4.2, where σ_a, σ_{max}, σ_{min} and σ_{mean} corresponds to stress amplitude, maximum stress, minimum stress and mean stress respectively.

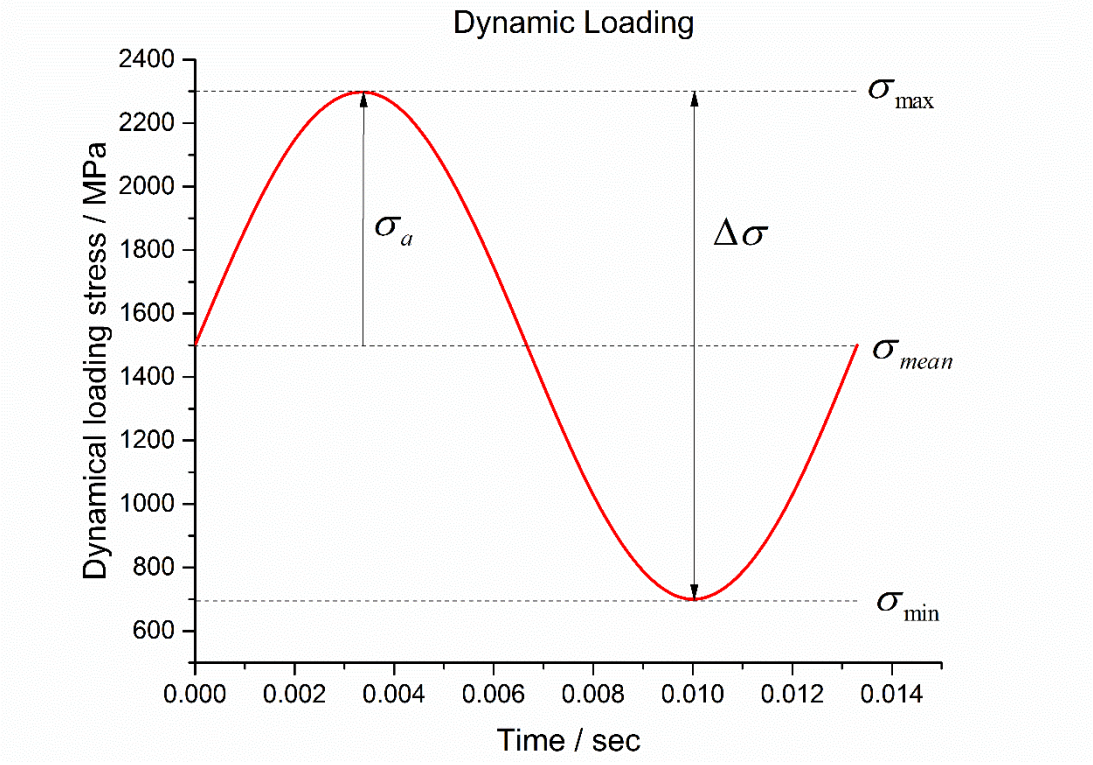


Figure 4.2 Dynamic Loading in alternating 3 point bending test

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (4.2)$$

$$\sigma_{min} = \frac{2.R.\sigma_a}{1-R} \quad (4.3)$$

$$\sigma_{mean} = \frac{\sigma_{min}+\sigma_{min}}{2} \quad (4.4)$$

$$\sigma_{max} = \frac{\sigma_{min}}{R} \quad (4.5)$$



Figure 4.3 Three point bending fixture

Test plan has been scheduled based on three experiments for each stress levels at a total of 15 tests in 5 different stress level. Tests were planned based on R=0.1 stress condition and stress amplitude starts from 850 MPa to 650 MPa with an interval of 50 MPa. σ_{max}, σ_{min} and σ_{mean} values were calculated with the reference of equations 4.2, 4.3, 4.4 and 4.5. Three point bending fixture before the test can be seen in Table 4.3.

Table 4.2 Test plan

TEST PLAN (5.25x6.5x20 mm)						
R	**σ_a**	**σ_{min} (MPa)**	**σ_{max} (MPa)**	**σ_{mean} (MPa)**	**static (kN)**	**dynamic (kN)**
0,1	850	188.9	1888.9	1038.9	7.8	6.3
0,1	800	177.8	1777.8	977.8	7.3	6.0
0,1	750	166.7	1666.7	916.7	6.8	5.6
0,1	700	155.6	1555.6	855.6	6.4	5.2
0,1	650	144.4	1444.4	794.4	5.9	4.9

4.2 Sample Preparation by Polishing

Each specimens were first polished at both sides. Polishing operation was conducted by using 4 different polishing paste at a rate of 50-30-15-3. Firstly the roughest paste are used for the operation afterword's polishing operation continued step by step through the finest paste. Each diamonds has been used for 3 minutes and a total polishing time was resulted as 12 min for each sides. Polished and unpolished specimens of CTF 40 and CTE 40 are given in Figure 4.4.

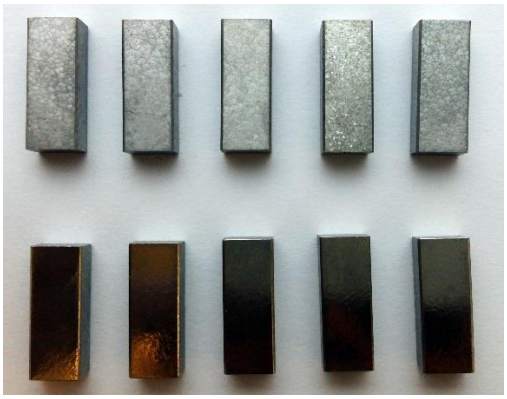


Figure 4.4 Unpolished and polished specimens

4.3 Surface Roughness, Hardness Tests and Microstructural Inspection

Polished and unpolished specimens were subjected to surface roughness tests. From the experimental results, it is clarified that polished specimens surface value based on R_a was measured around 0.06. On the other hand unpolished specimens surface roughness are measured around 0.75. Thus values are the average of 3 different measurements taken from different specimens. Comparative results of surface roughness values are given in Figure 4.5.

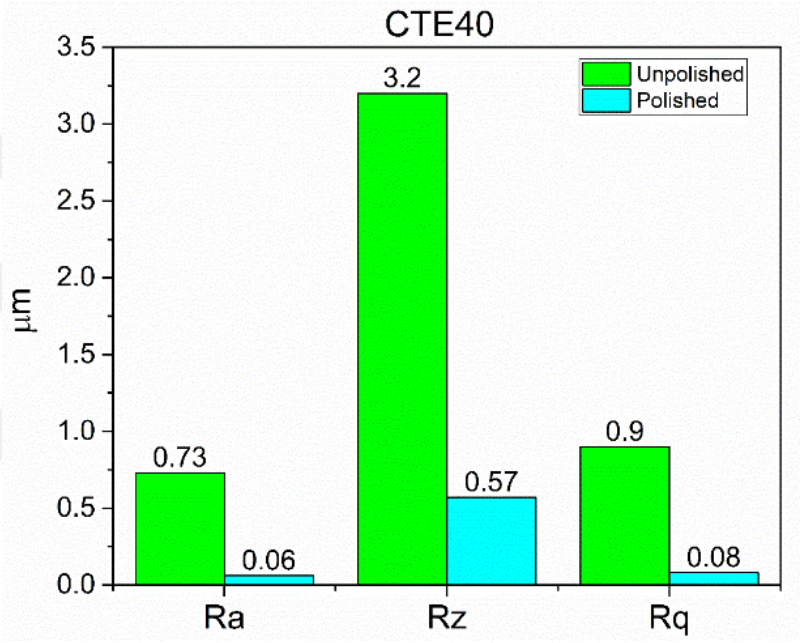


Figure 4.5 Surface roughness value of polished and unpolished CTE 40 specimens

For obtaining more accurate hardness measurement results, specimens were taken in bakelite as seen in Figure 4.6 and hardness measurement were carried. Hardness test of CTF 40 and CTE 40 specimens are carried out with Vickers Hardness measurement method at a value of HV10 and comparative results are given in Figure 4.7. From the result it is seen that finer grain sized WC-Co has a much more hardness value compared to coarse grain sized WC-Co. The hardness test results are in good agreement with the catalogue value of the material which was taken from the supplier firm.

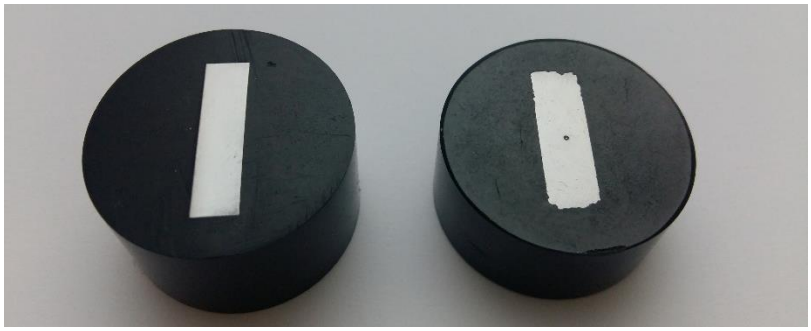


Figure 4.6 Hardness measurement specimens taken in bakelite (CTF 40 on the left, CTE 40 on the right)

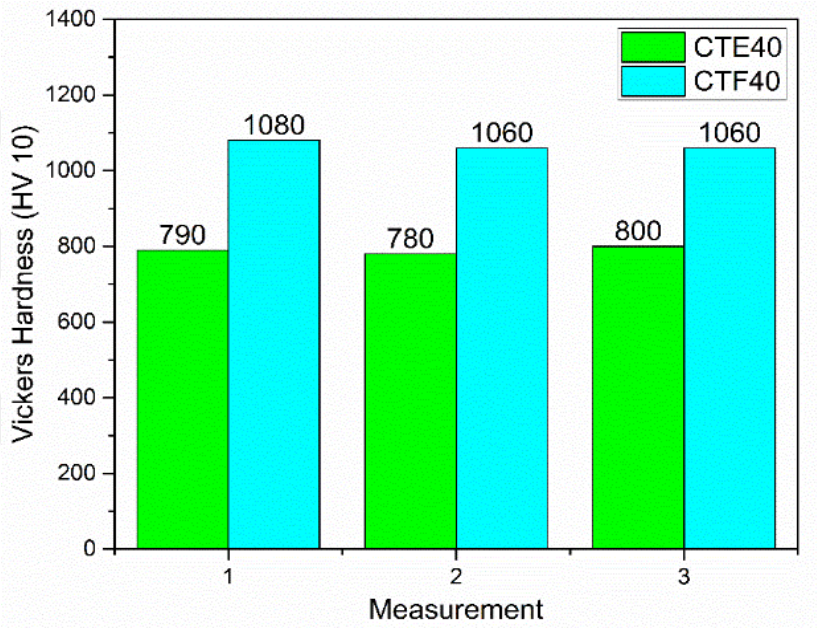


Figure 4.7 Hardness results comparison of fine and coarse grained specimens

Microstructural inspection has been done based on the standard of ASTM B657 '*Metallographic determination of microstructure in cemented carbides'* for determining grain sizes of fine and coarse grained specimens. Etching solution was prepared as equivalent on the solution from the standard. 10 ml Hydrochloric acid and 10 ml Hydrogen Peroxide (%30) were used as an etching solution. Etching operation had continued approximately three minutes at a room temperature for each specimens. Microstructural inspection were carried on with an optical microscope at 1500x magnitude and Picture taken from the inspection was given in Figure 4.8. From the inspection result Alpha phase is clearly visible for Tungsten grains.

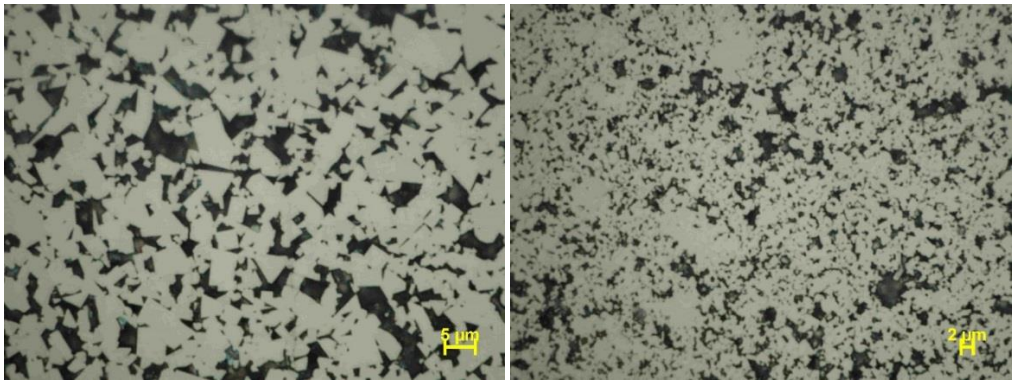


Figure 4.8 Microstructural investigation of CTE40 and CTF40 respectively

Results given in Figure 2 clearly shows that fine grain sized specimen grain sizes are around 0.7-0.1 µm and coarse grains are approximately 3-5 µm. Metallic binder phase and hard material binder phase can be seen in both situation. These results are also in good agreement with the information previously given by the supplier firm in Table 4.1.

4.4 Fatigue Tests and Results

3 point bending fatigue tests were carried on Zwick Roell Amsler 250 HFP 5100 resonating fatigue testing machine in Norm Fasteners R&D center. Tests were conducted in a constant stress ratio of 0.1. For determining the effect of the surface condition, polished and unpolished specimens fatigue tests were experimentally studied. Based on the result gathered from experimental studies it is obvious that fatigue life differs crucially with surface conditions. S-N Curves at R=0.1 stress ratio was generated using fatigue data and stress amplitude ratio. Results in S-N plot and Log-scale plot for unpolished and polished surface conditions of CTE 40 specimens was given in Figure 4.9 and Figure 4.10 respectively. Comparative result of both situation is given in Figure 4.11.

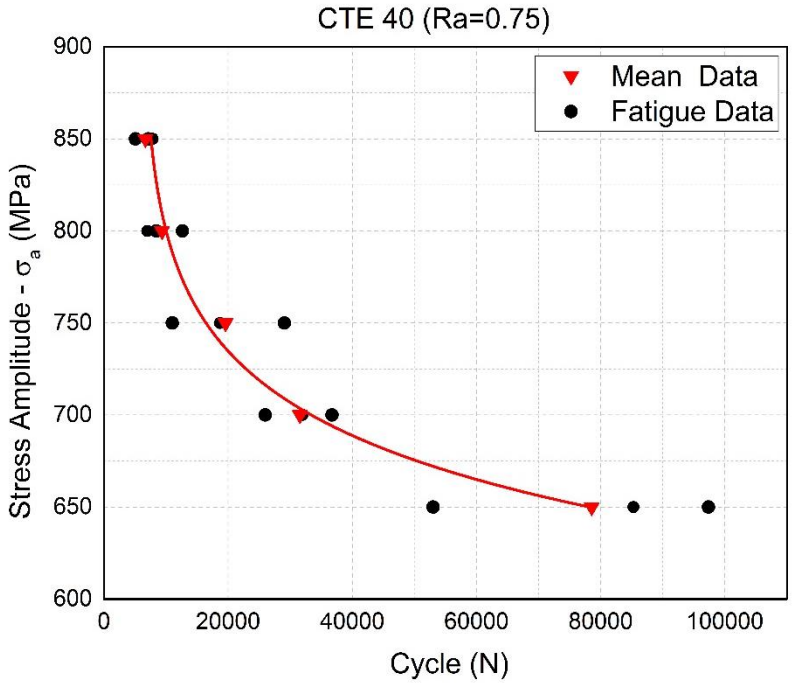


Figure 4.9 S-N diagram of CTE 40 unpolished specimens

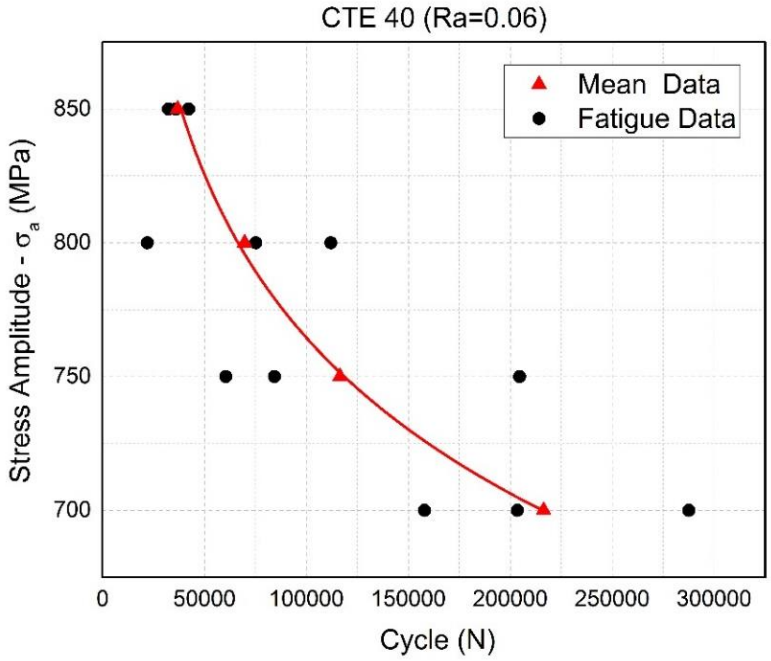


Figure 4.10 S-N diagram of CTE 40 polished specimens

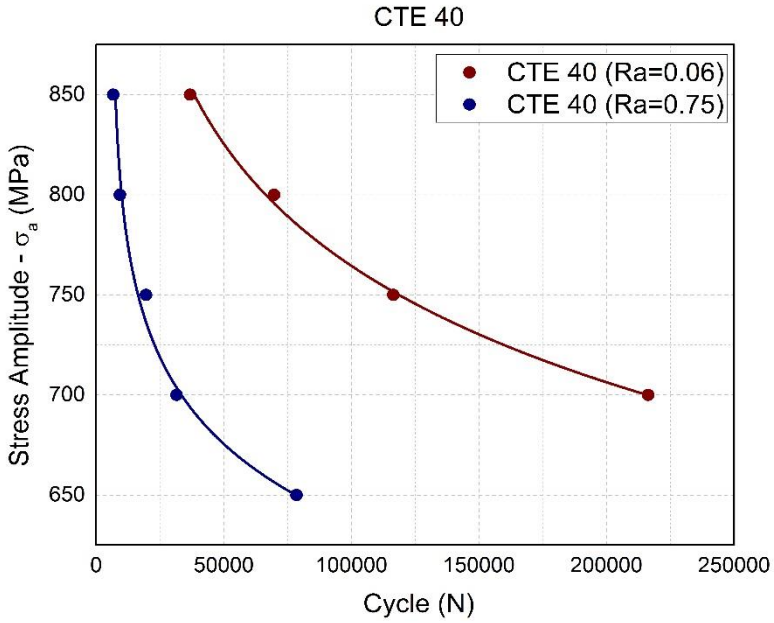


Figure 4.11 Comparative results of CTE 40 specimens

Comparative test results shows that surface conditions play a key role on lifetime of the material. Another significant result can be said from the results obtained is that polishing processes in forging dies has an important role for determining the life of the forging dies.

After the effect of surface condition has been discovered, fatigue tests of fine and coarse grain sized carbides were done only for polished conditions. Same amplitude stress and stress ratio was used from the previous experiments. Test results obtained from experimental tests were plotted in S-N diagram and given in Figure 4.12, Figure 4.13 and Figure 4.14.

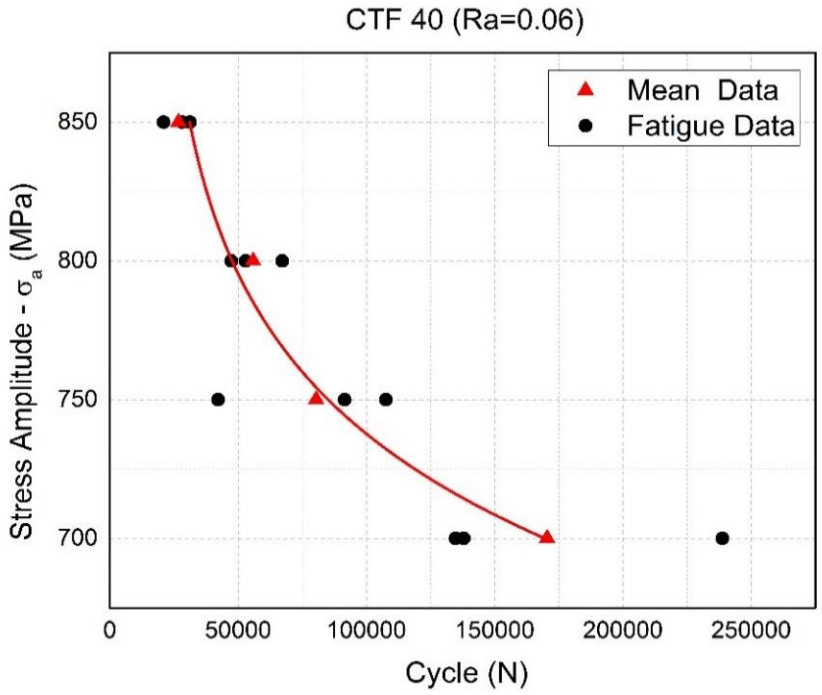


Figure 4.12 S-N diagram of polished CTF 40 specimens

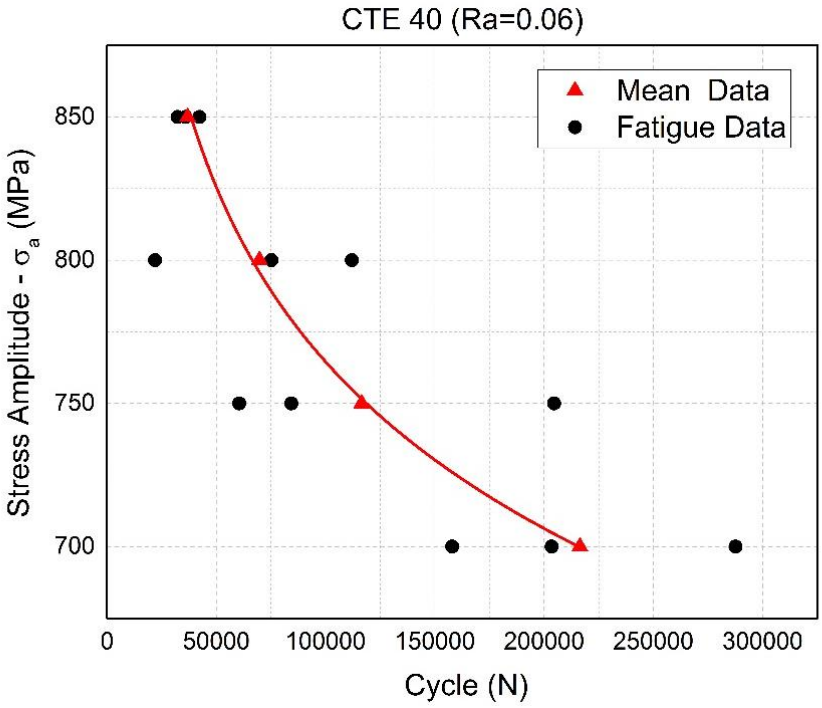


Figure 4.13 S-N diagram of polished CTE 40 specimens

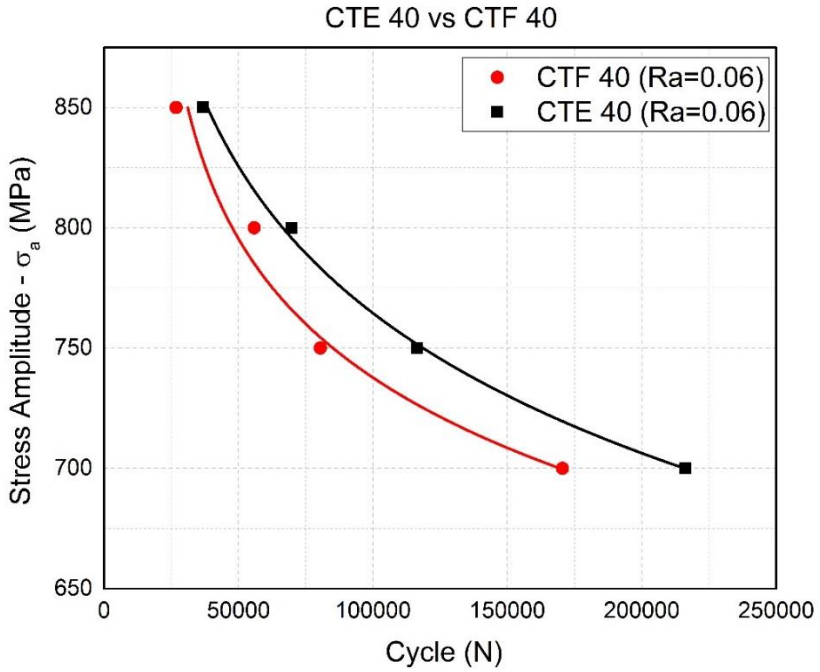


Figure 4.14 Comparative S-N diagrams of polished fine and coarse grain sized specimens

Results obtained from the study shows that finer grain sized carbides are more likely to originate fatigue fracture compared to coarse sized carbides. At same loading condition coarse grain sized carbides resist more to failure compared to fine grain sized specimens.



Figure 4.15 Fracture surface of 3 point bending specimen

In a conclusion, it can be said that grain size must be specifically chosen for forging processes. Hardness and wear durability needed application must considered with a finer grain sized carbides. Coarse grain sized carbides could be considered for long life and impact loading applications. Cross section of a tested specimen was given in Figure 4.15. For life prediction using Basquin equations log-log scales of the results are also drawn and given in Figure 4.16, Figure 4.17 and Figure 4.18. One benefits of log-log scale is that linear fit can be used for data averages.

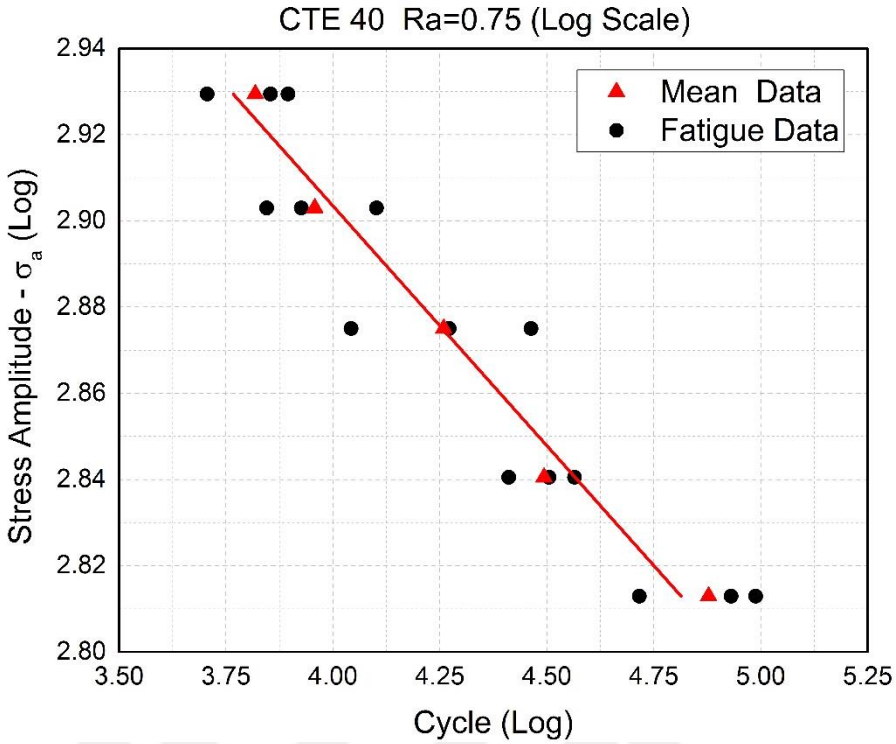


Figure 4.16 Log-log scale diagram based on unpolished CTE 40 results

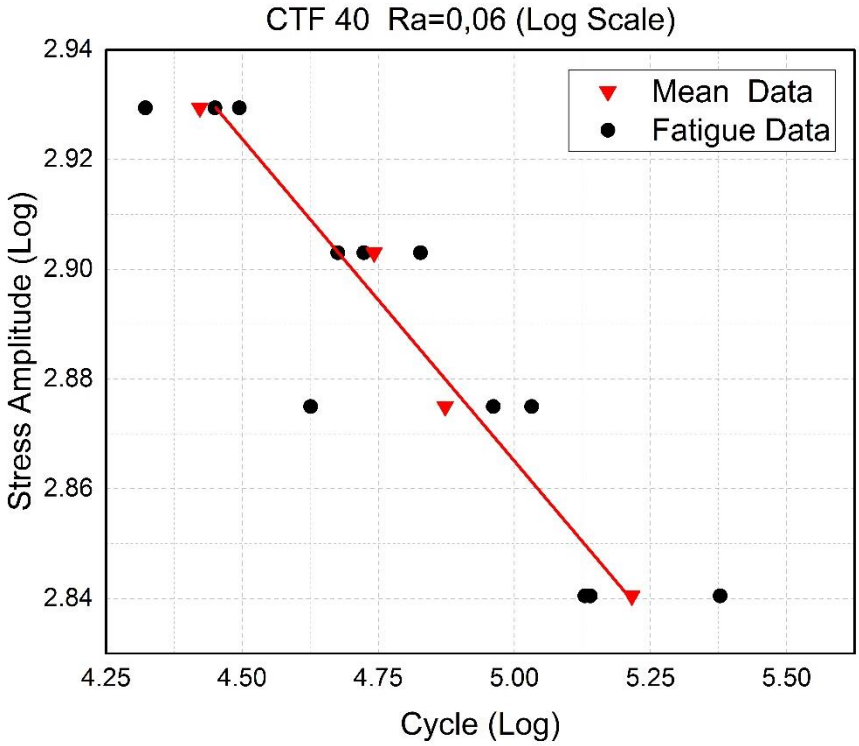


Figure 4.17 Log-log scale diagram based on polished CTF 40 results

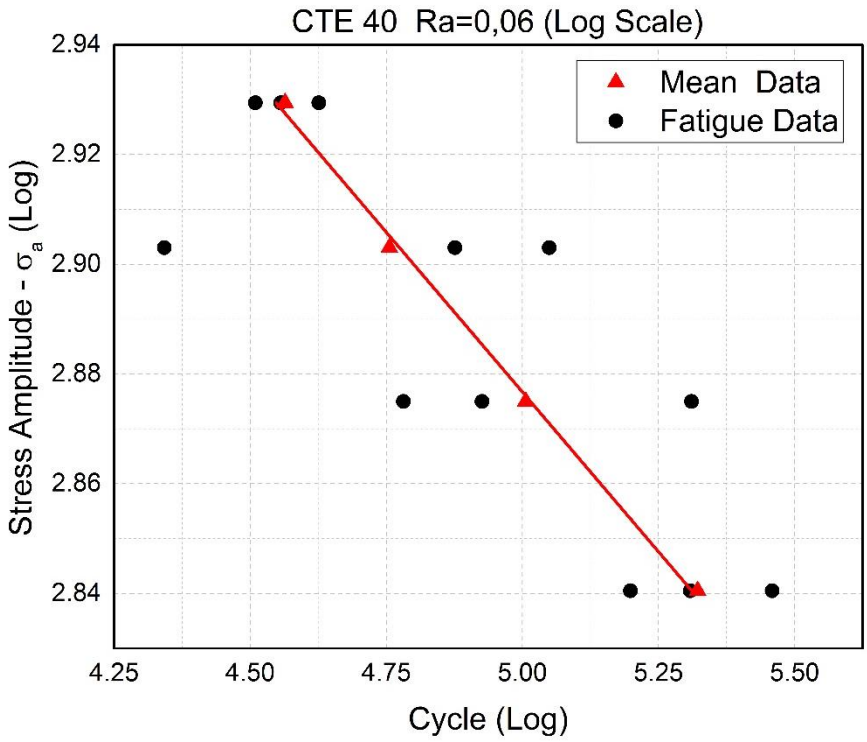


Figure 4.18 Log-log scale diagram based on polished CTE 40 results

Using Basquin equation stated in equation 4.6, it is capable of making life predictions for different stress amplitude values by using experimental results which are taken at the same stress ratio where b is the slope of the log-log plot. It should be not forgotten that Basquin relation is not an accurate method for different stress ratio value which are not experimentally obtained.

Basquin relation $$N_1 = N_2 \left(\frac{\sigma_{a1}}{\sigma_{a1}}\right)^{\frac{1}{b}} \quad (4.6)$$

4.5 Fatigue Life Maps

As known, life prediction using Basquin equation is limited for only tested conditions. At different G_{mean} and stress ratio value, result obtained from Basquin equation could misdirect the prediction value. Using Stress cycle value it is possible to determine generalized fatigue life map which is known as modified Goodman, Gerber, Soderberg lines. An example of the map formation where S_y is the yield point, S_{ut} is the ultimate strength, S_e infinite life is given in Figure 4.19.

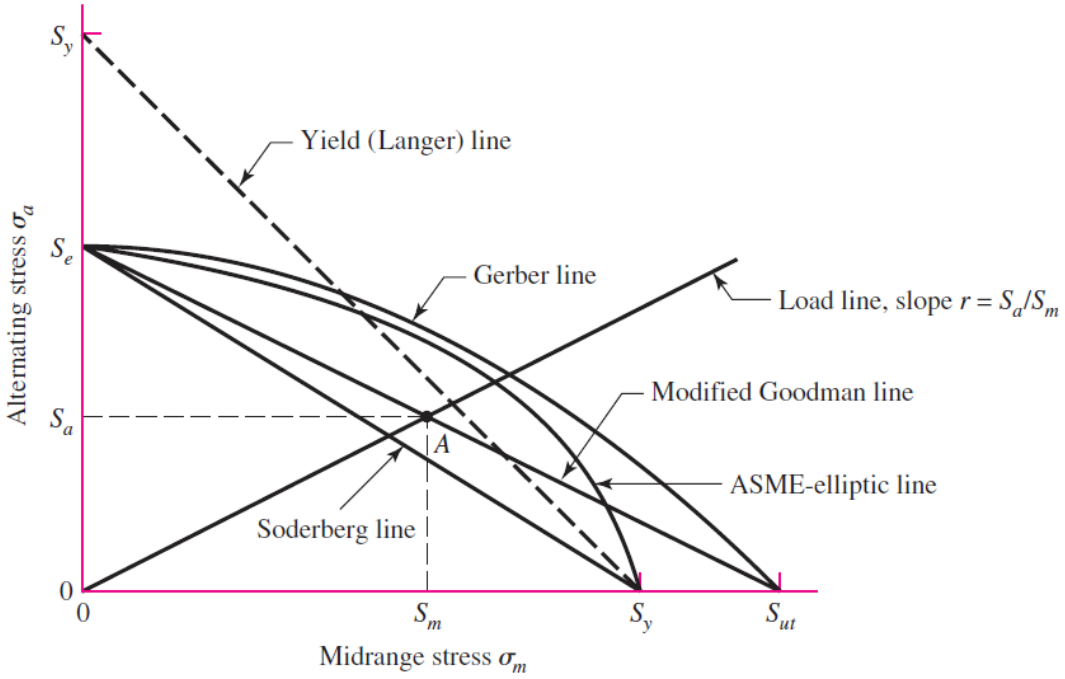


Figure 4.19 Fatigue life diagrams (Richard, 2010)

Based on Modified Goodman lines a life map for 3 point bending situation was created using transvers rupture strength as a replacement of ultimate strength. Due to impossibilities of doing fully reversed testing in three point bending specimens, values of tested in constant stress ratio are used for drawing the modified Goodman diagrams as seen in Figure 4.20.

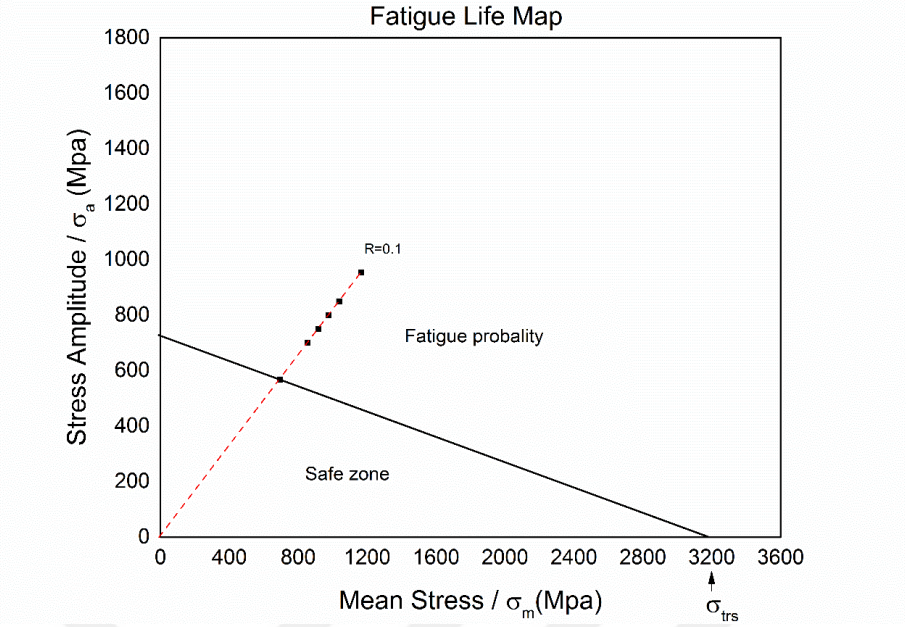


Figure 4.20 Fatigue life map generation for three point bending

Data earned from experimental test are implemented in a fatigue life map using transvers rupture strength value. Stress amplitude-mean stress graph has been created using result obtained at R=0.1 test condition. A line has been drawn from the transvers rupture strength value to the implemented test value in the map. Each colored lines shows cycle to fracture under cyclic loading in the experimental tests. Life map has been created only for polished CTF 40 and CTE 40 materials test result. Life diagram of fine grain sized CTF 40 material is given in Figure 4.21 and the map of coarse grain sized CTE 40 is given in Figure 4.22.

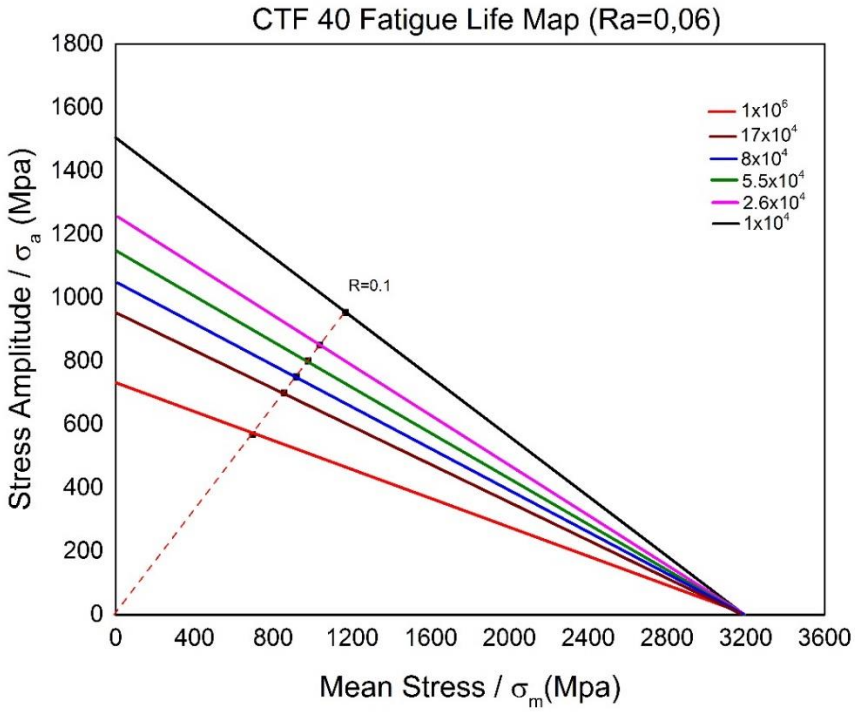


Figure 4.21 CTF 40 fatigue life map

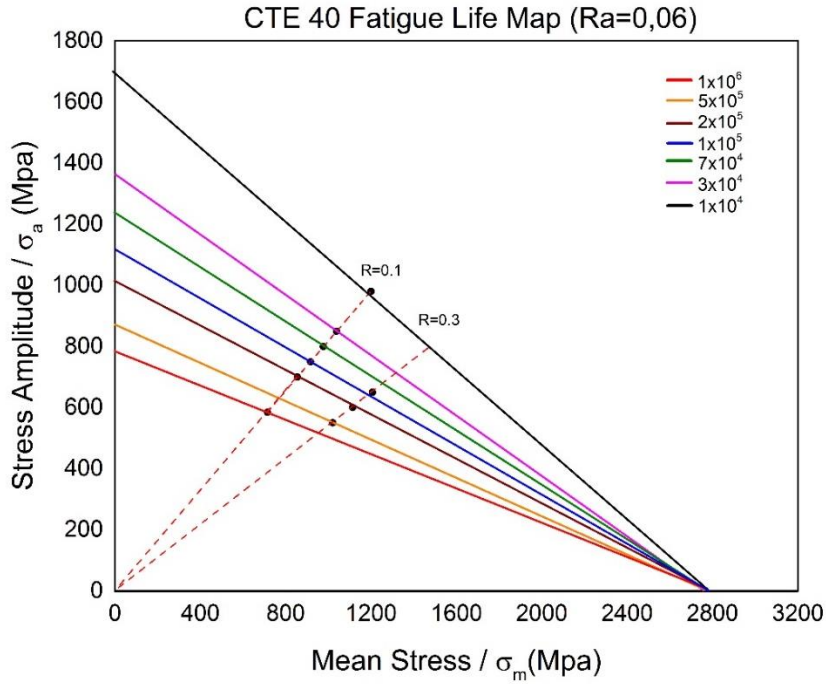


Figure 4.22 CTE 40 fatigue life map

As seen from the life maps of CTF 40 and CTE 40 material in polished conditions, each colored lines corresponds to a different life of the materials. If data of loading condition with a perspective of stress amplitude and mean stresses are known, fatigue life prediction could be possible.

CHAPTER FIVE
COLD FORGING PUNCH SIMULATION

5.1 Station Design

Forging simulation of a cold forging punches which is being used in Norm Fastener Co. for bushing production has been investigated. For an accurate simulation process materials properties and production conditions has been taken into consideration as same as the forging process.

Station design of the desired product has been done in a concept of 5 different stages and given in Figure 5.1. ST0 can be described as workpiece material with a precise volumetrik value. In ST1, ST2 and ST3 forging process were based on to re-form the surface shapes and make the workpiece surfaces more smooth for the last two operations.

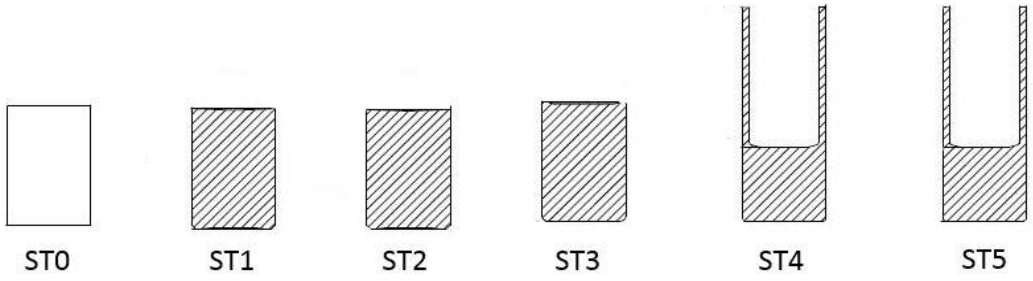


Figure 5.1 Station design

5.2 Forming Simulation

Forming simulations has been done with Simufact Forming 12.0 with elastic-plastic conditions. Workpiece material was defined with plastic conditions and other parts has been taken as a rigid body. The material of the workpiece has been chosed as Mnb4 from the firm simulation database. Every die has been designed as exact of the manufacturing conditions. In the 4 th station where the elastic analysis of the forging punch has been done, the simulation has been conducted elastically with a

deformable die model. ST4 Punch given in Figure 5.2 had been designed using the real dimensions of the process and meshing was done with tetrahedral elements.

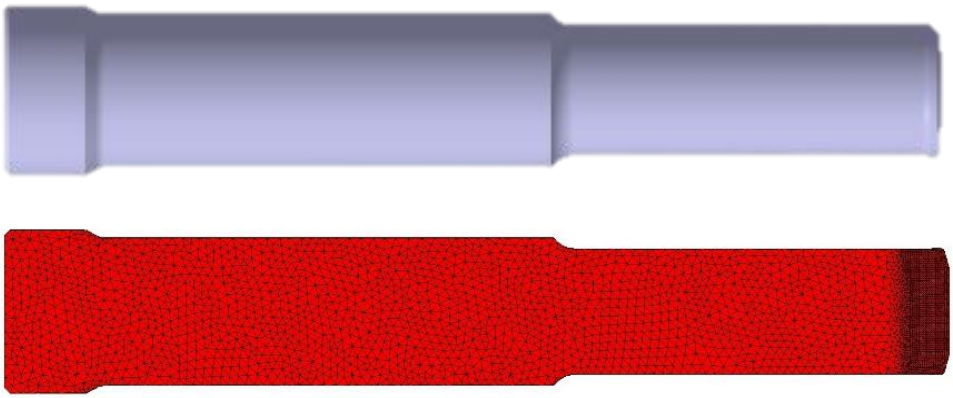


Figure 5.2 ST4 punch with tetrahedral mesh

Each forming station has been done one after another and formability of the material based on the process is shown in Figure 5.3.

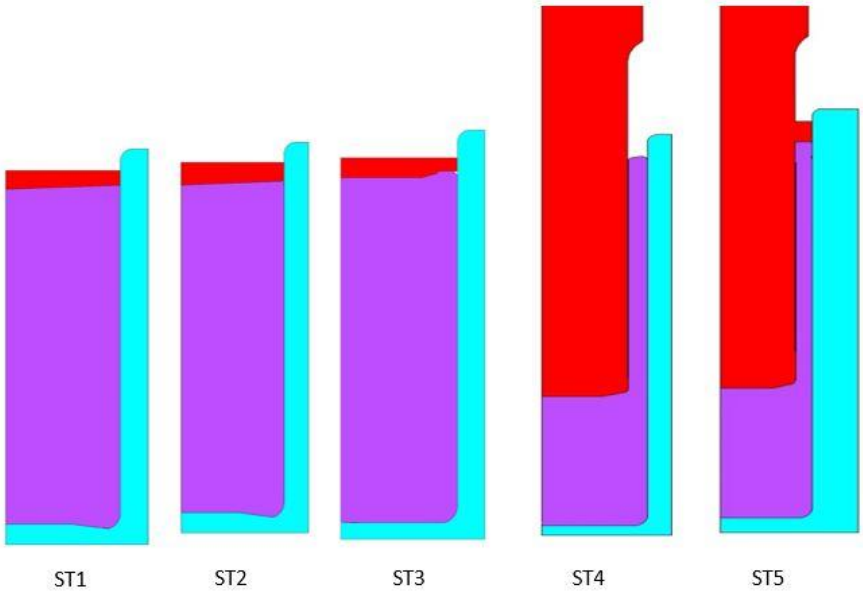


Figure 5.3 Forming simulation result of the bush

Effective stress value of the punches has been taken into consideration at the most critical point which is the corners or the punch as seen in Figure 5.4

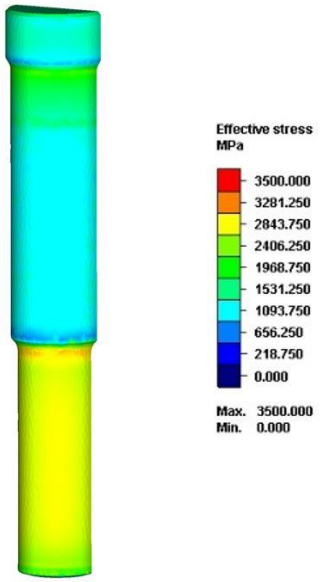


Figure 5.4 Effective stress distribution of ST4 punch

Values taken from the simulation has been graphically shown in Figure 5.5. Also, stress amplitude and mean stress values were calculated for one cycle.

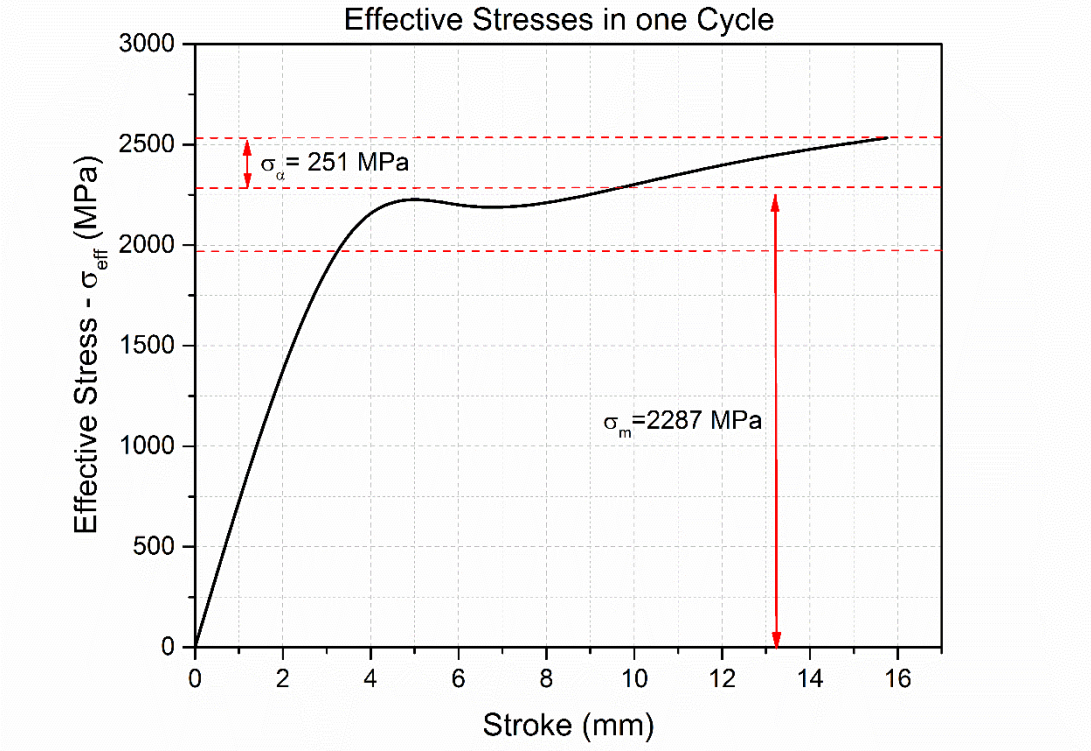


Figure 5.5 Effective stresses in one cycle

5.3 Life Prediction Using Simulation Values and Life Maps

Stress amplitude and mean stress values were implemented to the life cycle map of CTF 40 material and life prediction of the punch was basically done in Figure 5.6. Predicted life cycle of the punch was around 200.000 -250.000 cycle.

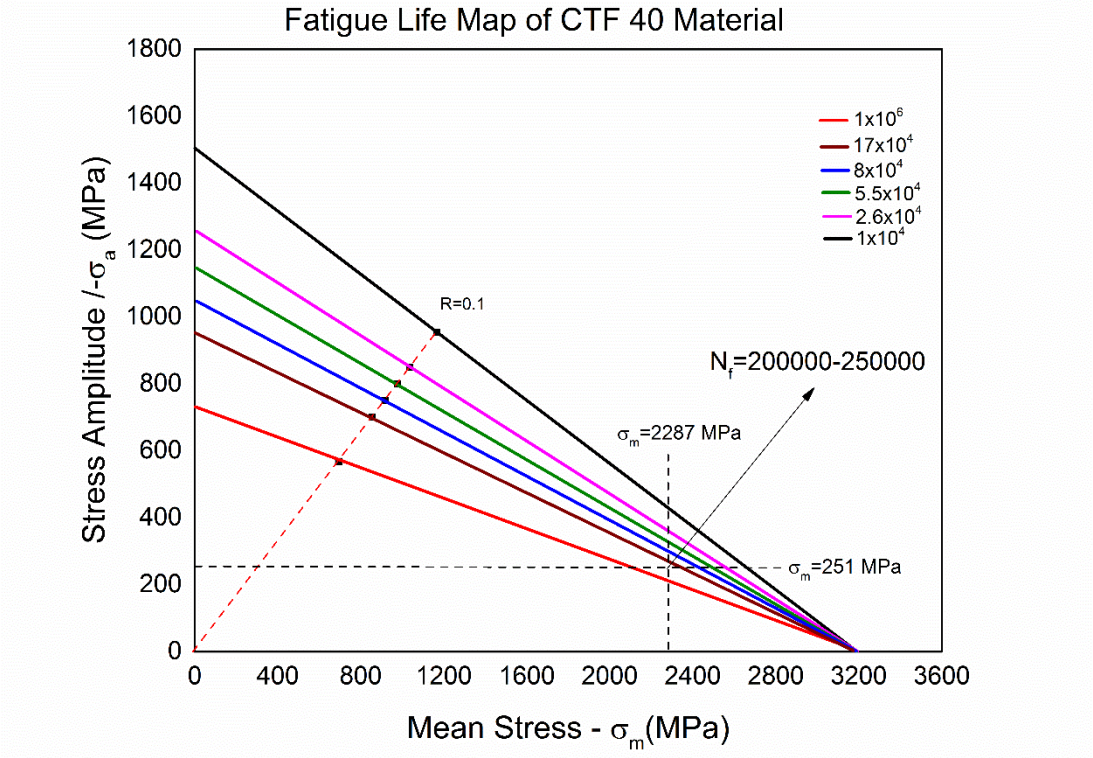


Figure 5.6 Life prediction using CTF 40 life map

CHAPTER SIX
CONCLUSION

Study was based on fatigue behavior of WC-Co material with a different grain sizes and surface conditions. In the first part of the study, literature surveys about forging operations were explained. Also, some literature about fatigue behavior of materials and prediction methods was explained.

In addition to the literature survey, due to lack of the testing standard for fatigue of WC-Co materials, researches were established on determining a fatigue life condition with varied testing systems. Based on ISO standard for determining the rupture strength of hard metals, dynamical fatigue testing of WC-Co material were conducted to fine and coarse grain sized specimens with a polished and unpolished surface conditions.

Experimental result has shown that surface conditions play a key role on fatigue life cycles of the material. Results based on specimen with a polished surface condition has much more life cycle till the fracture occurs. In addition, results of the fatigue test with fine and coarse grain sized specimens has shown that finer grain sized Wc-Co material have less fatigue life compared to the coarse grain sized material.

According to stress-life method, S-N curves has been created for two different cases, which are grain size and surface effects. Comparative S-N result is in a good agreement with the behavior stated in the previous paragraph. In the second part of the experimental results, fatigue life maps based on three point bending fatigue test were created with a help of modified Goodman diagrams.

In the last part of the study, finite element simulations for determining the stress state behavior of a cold forging punch during forging process has been carried. Based on the results, stress amplitude and mean stress values were calculated. Life prediction was done with implementing stress amplitude and mean stress values on

life map of fine grain sized WC-Co. Result obtained from the map is around 200.000-250.000 cycle which were approximately the same as the manufacturing process in the forming operation of the company.

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APPENDICES

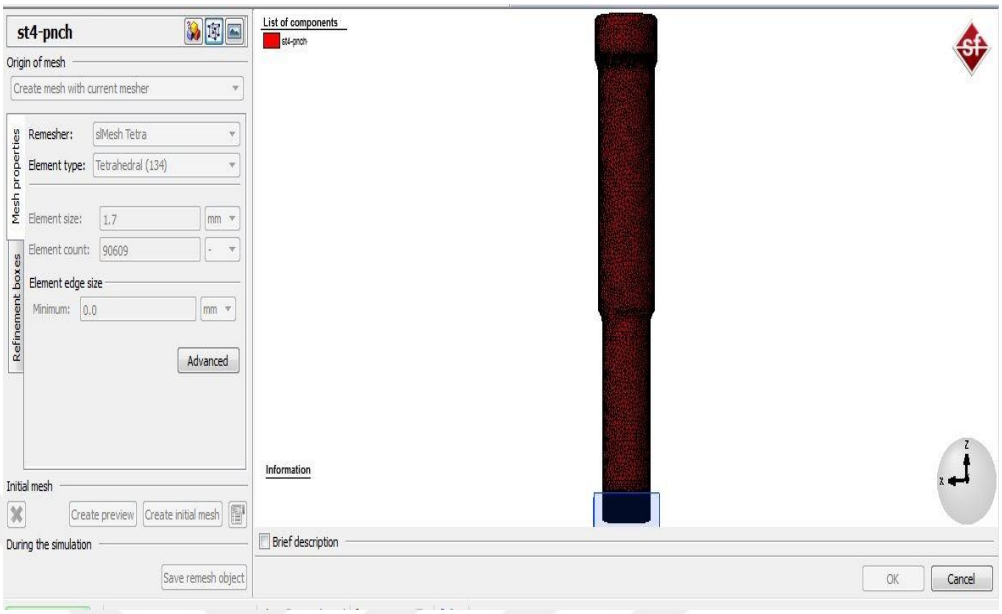


Figure 1 St4 punch meshing properties

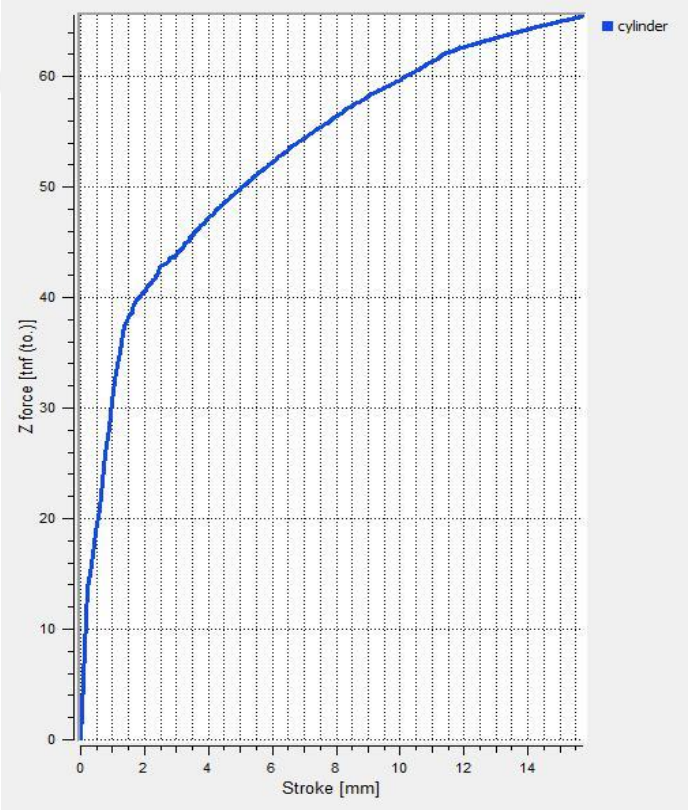


Figure 2 St. 4 Stroke-Force graph