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THE EFFECT OF TEMPERING TEMPERATURES ON A FATIGUE LIFE OF AISI 4130

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of UTeM as a partial fulfilment of the requirements for the degree of Master of Manufacturing (Manufacturing System Engineering). The member of supervisory committee is as follow:

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DECLARATION

I declare that this thesis entitle "**The Effect of Tempering Temperatures on a Fatigue Life of AISI 4130**" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....
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DEDICATION

To my beloved husband, Mohammad Nasir Bin Hussin, my parents, Haji Jamal Bin Md Aleh and Hajah Rakiah Binti Musa and all my friends. Thank you for the continuous support and encouragement.

ABSTRAK

Proses rawatan haba boleh digunakan untuk mengubah sifat-sifat mekanikal bahan tanpa mengubah bentuk bahan tersebut. Jenis proses rawatan haba yang akan digunakan adalah bergantung kepada sifat mekanik yang ingin diubah. Kajian ini dilakukan untuk menilai hubungan di antara jangka hayat lesu keluli AISI 4130 dengan tiga suhu pembajaan iaitu 100 °C, 350 °C and 700 °C. Keluli ini adalah keluli aloi rendah yang mengandungi molybdenum dan kromium sebagai agen pengukuhan. Proses rawatan haba yang dijalankan adalah pengerasan dan diikuti dengan pembajaan. Ujian kelesuan dilakukan dengan mesin ujian kelesuan lenturan berputar untuk mendapatkan jangka hayat lesu bahan ini. Mikrostruktur bahan diperiksa dengan Mikroskop Optik (OM). Mikroskop Stereo pula digunakan untuk memeriksa permukaan patah pada bahan. Keputusan menunjukkan dengan menaikkan suhu pembajaan daripada 100°C kepada 350°C telah meningkatkan jangka hayat lesu bahan ini berbanding dengan bahan yang tidak menjalani rawatan haba. Walaubagaimanapun, dengan menaikkan lagi suhu pembajaan kepada 700 °C telah menurunkan jangka hayat lesunya. Daripada analisis mikrostruktur, perubahan jangka hayat lesu bahan ini adalah disebabkan perubahan di dalam mikrostruktur bahan hasil daripada proses pengerasan dan pembajaan. Selain daripada itu, permukaan patah adalah berbeza bagi suhu pembajaan yang berbeza. Perbezaannya adalah dari segi saiz zon patah pantas. Semakin kecil saiz zon patah pantas, semakin rendah jangka hayat lesu bahan ini.

ABSTRACT

Mechanical properties of material can be changed by heat treatment processes without changing its shape. In this research, a relationship between various tempering temperature and fatigue life of AISI 4130 steel has been evaluated. This steel is a low alloy steel containing molybdenum and chromium as strengthening agents. The material has been hardened, followed by tempering with three tempering temperatures, 100 °C, 350 °C and 700 °C. Fatigue tests under rotating bending fatigue testing machine has been carried out to estimate the effect of tempering temperature on its fatigue life. The fatigue life of these materials has been studied as a function of the tempering temperatures. Microstructure of the materials has been analyzed using Optical Microscope (OM). A Stereo Microscope has been used to observe surface fractures on the material. The result show that increasing the tempering temperature from 100°C to 350°C has increased the fatigue life of the heat treated material compared to non-treated material. But, increasing the tempering temperature furthermore to 700 °C has decrease its fatigue life lower than the non-treated material. From microstructure analysis, changes in fatigue life of this material are due to the changes in its microstructure as a result of hardening and tempering processes. Besides that, the surface fractures are different between each others as a result of different tempering temperatures. The difference that can be distinguished is the size of the fast fracture zone. As the size of the fast fracture zone is decreases, the fatigue life is also decreases.

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CHAPTER 1

INTRODUCTION

1.1 Background

Failure of structural components in service is caused by many factors such as fatigue, creep and stress corrosion. Fatigue failure can gives major problem because it can occur due to repeated or fluctuating loads below the static yield strength. It will starts at the surface of a component in the form of crack and propagates to the core of the component until sudden rupture occurs. This can result in an unexpected and catastrophic failure in use. Fatigue life of a component can be expressed as the total number of stress cycles a material can endure before failure (McGraw Hill Science & Technology Dictionary). Fatigue strength is the highest stress that a material can withstand for a given number of cycles without breaking (Merriam-Webster). It is also called endurance strength for a material.

For all this while, heat treatment is used to alter mechanical properties without changing the material shape. The type of heat treatment processes that can be used is depends on mechanical properties that need to be changed. For the purpose of this research, hardening and tempering will be used on the material. The purpose of hardening is to increase material hardness and followed with tempering to relieve internal stress, to reduce brittleness and to make it tough to resist shock and fatigue. Various tempering temperature will be chosen for this material. After the material has been treated by heat treatment processes, it will be tested to get its fatigue life. The effect of various tempering temperature on fatigue life of AISI 4130 steel will be studied.

AISI 4130 is categorized as low carbon steel. It is commonly called AISI 4130 Chromium-molybdenum steel. The base metal is iron and its alloying element is shown in Table 1.1. The '41' indicates a low alloy steel containing chromium and molybdenum as its strengthening agents and the '30' indicates a carbon content of 0.30 percent. This alloy has an excellent strength to weight ratio, is easily welded and is considerably stronger and harder than standard 1020 steel. Its mechanical properties are shown in Table 1.2.

Table 1.1: Percentage of alloying element in AISI 4130 (Bultel and Vogt, 2010)

Number	**Element**	**Weight percentage %**
1	Carbon	0.28 – 0.33
2	Manganese	0.40 – 0.60
3	Phosphorus	0.025
4	Sulphur	0.025
5	Silicone	0.15 – 0.35
6	Chromium	0.80 – 1.10
7	Molybdenum	0.15 – 0.25

Table 1.2: Mechanical Properties of AISI 4130

Tensile Strength (ultimate)	**Tensile Strength (yield)**	**Young's Modulus**	**Hardness (Brinell)**	**Melting point**
670 MPa	435 MPa	190-210 GPa	197	1432°C

Examples of applications for these alloys include structural tubing, bicycle frames, firearms receivers, clutch and flywheel components, roll cages, high strength steel shafts, gears, and pins. It also can be used in automotive parts, race cars, off road, hydraulic tools, and machine tool applications. It is an intermediate strength material. Lighter gauges offer lighter weight but still maintain great strength, making it excellent for auto racing and aerospace.

1.2 Problem statement

Under dynamic loading condition, fatigue failure is considered as the main problem affecting many components. Fatigue had caused that almost ninety percent of failure conditions in mechanical components, Chawla (1998). The factors that affected fatigue had been investigated by many researchers to find solutions to enhance the service life of any components.

For centuries, heat treatment processes have been used to alter mechanical properties of a component without changing its shape. Steels are particularly suitable for heat treatment, since they respond well to heat treatment and the commercial use of steels exceeds that of any other material. Fatigue is one of a mechanical property for a material. There have been some researches about the way it responds to heat treatments. Tempering is one of a heat treatment processes. There are many papers available on the heat treatment that will affect the mechanical properties of steels. Therefore, this study will investigate the effect of tempering temperature on the fatigue life of a material. With this information, a suitable tempering temperature can be chosen to maximize materials service life. The relationship between them can be manipulated according to our need.

1.3 Objectives

The project is about hardening and tempering AISI 4130 Chromium-Molybdenum steel at three tempering temperatures. The objectives of the project are;

i. To analyze the effect of tempering temperatures on microstructure and its relationship with fatigue life of AISI 4130.

ii. To evaluate the relationship between surface fractures on the material and the tempering temperatures.

1.4 Scopes

Target material for this project is AISI 4130 Chromium-molybdenum steel. The heat treatment processes that will be used are hardening and tempering at three tempering temperatures, which are 100°C, 350°C and 700°C. Fatigue test are carried out using the BRAND-TERCO, MODEL-MT 3012E. Microstructure of the materials will be analyzed using Optical Microscope (OM). Fracture surfaces are analyzed using Stereo Microscope.

CHAPTER 2

LITERATURE REVIEW

2.1 Heat Treatment

Heat treatment is the controlled heating and cooling of metals for the purpose of altering their properties. By implying heat treatment, grain size of a metal can be changed resulting a different properties and to relieve the stress set up in the metal after hot and cold working processes. It also can improve product performance by increasing strength or other desirable characteristics (DeGarmo, et.al 1988). Most of the heat treatment processes involve slow cooling at elevated temperature. An equilibrium diagram can be used to predict the resulting structures from the temperatures that have been used. However, the diagram can be only be used for equilibrium condition. Thus a T-T-T diagram as shown in Figure 2.1 should be used for understanding the heat treatment processes that were nonequilibrium in nature. T-T-T diagram stand for Time- Temperature –Transformation diagram or also called Isothermal- Temperature –Transformation diagram.

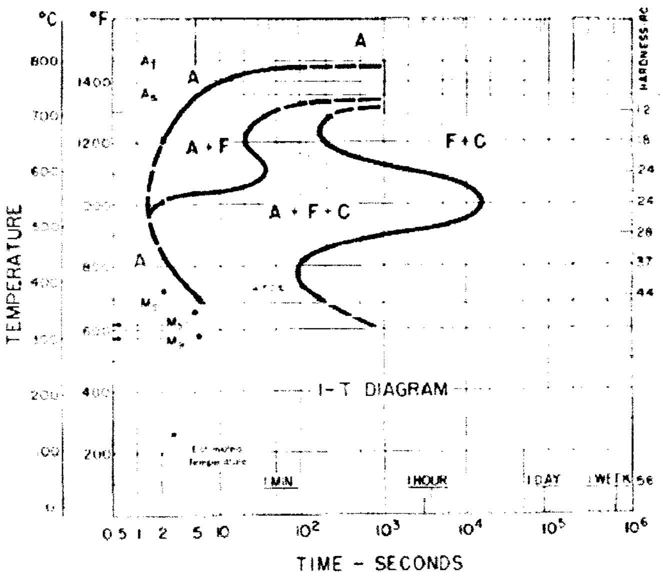

Figure 2.1: T-T-T diagram for AISI 4130 steel (DeGarmo, et.al 1988)

From the diagram, above 727°C, austenite is in the stable phase. Below this temperature, the austenite will transform to ferrite and cementite. If the austenite is now quenched to below the M_s temperature, it will transform into martensite, and with sufficient carbon, it is exceptionally strong, hard and brittle. The hardness and strength of the steel in the martensitic condition clearly depends on the carbon content. From 0.3% to 0.7% carbon, the hardness increase rapidly. The amout of martensite formed on cooling is a function of the lowest temperature encountered and not of the time at that temperature (DeGarmo, et.al 1988).

If no further cooling is undertaken, the untransformed austenite can remain within the structure indefinitely. This retained austenite can cause loss of strength or hardness, dimensional instability or cracking, or brittleness. Since most of quenches are to room temperature, retained austenite problems become significant when the martensite finish, or 100% martensite, temperature lies below room temperature. Higher carbon contents and alloy additions decrease all martensite-related temperatures (DeGarmo, et.al 1988).

Because it lacks good toughness and ductility, medium or high-carbon martensite is not a useful engineering microstructure, despite its great strength. A subsequent heating, known as tempering is usually required to restore some desired degree of toughness at the expense of a decrease in strength and hardness. Martensite is supersaturated solid solution of carbon in alpha ferrite and therefore is a metastable structure. When reheated into the range of 100-700°C, carbon atoms are rejected from solution, and the structure moves towards a mixture of the stable ferrite and cementite phases. This decomposition of martensite into ferrite and cementite is a time and temperature dependent (DeGarmo, et.al 1988).

The initial stage, which occurs at 100-200°C, is the precipitation of an intermediate carbide with the composition of $Fe_{24}C$, known as *epsilon* (ε) carbide. This precipitation allows the matrix to revert to the body-centered-cubic configuration. From 200-400°C, the structure becomes one of ferrite and cementite. Little change is observable in the microscope, however, for the cementite particles are submicroscopic and the original martensite boundaries are retained. Its microstructure appears as a rather mottled mass with little well-defined structure. Electron-microscopic studies reveal fine carbide dispersion, which is responsible for the observed softening and improved ductility. If tempering progresses into the 400-550°C range, the martensite boundaries disappear, and a new ferrite structure nucleates and grows. As the precipitated carbides increase in size, the properties move further in the direction of a weaker, but more ductile material (DeGarmo, et.al 1988).

Above 550°C, the new ferrite grains totally consume the original structure, and the cementite particles have become larger and more spherical. This structure has the highest toughness and ductility and the lowest strength of all tempered martensite. By quenching steel to form 100% martensite and then tempering it at various temperatures, an infinite range of structures and corresponding properties can be produced. This is known as the quench-and-temper process, and the product is called tempered martensite (DeGarmo, et.al 1988).

2.1.1 Type of Heat Treatment

The various heat treatment processes commonly employed in engineering practice are:-

2.1.1.1 Annealing

Annealing is done to reduce hardness, to remove residual stresses, to improve toughness, to restore ductility, to refine grain size and to alter the mechanical, electrical or magnetic properties of a material (DeGarmo, et.al 1988).

2.1.1.2 Normalizing

The purpose of normalizing is to refine grain structure, improve machinability and improve tensile strength, to remove strain and to remove dislocation (DeGarmo, et.al 1988).

2.1.1.3 Hardening

The purposes of hardening are to increase the hardness of the metal and to make suitable cutting tools (Jaypuria, 2009).

2.1.1.4 Tempering

This process consists of reheating the hardened steel to some temperature below the lower critical temperature, followed by any desired rate of cooling. The purpose is to relieve internal stress, to reduce brittleness and to make steel tough to resist shock and fatigue (Jaypuria, 2009).

Variables that affect the microstructure and the mechanical properties of tempered steel are tempering temperature, tempering temperature time, cooling rate from the tempering temperature and composition of the steel including carbon content, alloy content, and residual elements. For those alloy steels that contain one or more of the carbide-forming elements (chromium, molybdenum, vanadium and tungsten) are capable of secondary hardening: that is they may become somewhat harder as a result of tempering (ASM International, 1995).

2.2 Heat Treatment on Low Carbon Steel

Research on Heat Treatment of Low Carbon Steel was done by Jaypuria (2009). The author found that from the various heat treatment processes that have been done, the mechanical properties of low carbon steel will vary. This means that depending upon the properties and applications that are desired, a suitable heat treatment process must be chose. Tempering at high temperature for 2 hours gives the best result among all tempering experiments when ductility is the only criterion that is desired. Besides that, if the hardness of the low carbon steel is desired, tempering process at low temperature for 1 hour or so must be chose. By comparing all the heat treatment processes, austempering should be done to obtain an optimum combination of ultimate tensile strength, yield strength, ductility as well as hardness.

2.3 Effect of Heat Treatment on Fatigue Behaviour of Various Alloys

The effect of nitriding after heat treatment on the fatigue properties of No 20 alloy steel was studied by Guiyun (1989). The author found that nitriding has more effect on the quenched specimens than the normalized specimens. Alloy 20 is an austenitic nickel-iron-chromium based alloy with additions of copper and molybdenum. It is one of the “super” stainless steels developed for maximum resistance to acid attack, because of this; there are various uses for it in both the stainless and nickel industries.

Research carried by Bourass et. al., (1998) studied the effect of heat treatment on the fatigue strength of micro knurled (Ti-6A-4V) alloy. In the research, a rotating-bending fatigue test is used. The researchers reported that the microstructure of the alloy had some benefits. But the heat treatments needed to obtain this microstructure gave the side effect which is reduction in compressive strains imparted to the surface.

Gayda et.al., (2003), studied the effect of heat treatment on the fatigue behaviour of alloy 10. The authors found that, finer grain sizes of the alloy 10 had improved the alloy’s fatigue life.

Fatigue properties of two types of cold-work tool steels tempered at various temperatures has been evaluated by Fukaura et.al., (2004). The authors found that carbide refinement can enhance the fatigue properties of the tool steels.

Effect of Heat Treatment on Fatigue Behaviour of (A193-51T-B7) Alloy Steel had been studied by Somer (2007). Two heat treatment processes were conducted, which are annealing and quenching followed by tempering at 200^{o}C. A rotary bending machine with constant stress ratio, R=-1 was used to carry out all fatigue tests. To measure the crack length propagation, the eddy current probe was used. The author found that quenching followed by tempering decreases the crack growth rate, while annealing increases this rate. It can be observed that fatigue crack growth rate of the quenched and tempered specimens of A193-51T-B7 alloy steel is lower than the standard specimens. While the fatigue crack growth rate of the annealed specimens is higher than the standard specimens. From the obtained result, it can be seen that annealing increases ductility and decreases yield stress, ultimate strength, and hardness. Meanwhile, quenching followed by tempering has a reversed action, which is decreases ductility and increases yield stress, ultimate strength and hardness. The author also found that the annealed specimens have fatigue life less than the standard specimens. Quenching followed by tempering will increase fatigue life and endurance limit of the specimens. Annealing had caused the reduction of strength and endurance limit, and enhancement of ductility due to the formation of soft coarse ferrite grains. Meanwhile, quenching followed by tempering had increased strength and endurance limit while ductility is reduced due to the formation of hard tempered martensite grains.

Ting and Zhao (2010) have made a research on repairing surface fatigue damage of metal by using heat treatment. The authors found that heat treatment can be used in repairing metal's fatigue damage. The metal has temping threshold behaviour. The first tempering temperature after the metal was hardened before it was in fatigue damage is the temping temperature threshold to repair metal fatigue damage.

The study to investigate the effectiveness of fluidized bed peening (FBP) to improve the fatigue behaviour of axial-symmetric stainless steel substrates was done by Barletta (2011). The author found that number of cycles to fracture can be improved by FBP. The fatigue life can be increased for four to five times. Besides that, the fatigue behaviour of the substrates was also found to be influenced by peening time.

Sollich and Wohlfahrt (1996) had studied the improvement of the fatigue strength of differently heat treated steels due to short peening with steel shot, with ceramic beads and also with steel shot plus ceramic beads. The author found that steels in the hardened state will have high resistance against crack initiation. If the surface roughness is low enough, it can prevent the initiation of fatigue cracks at the surface.

Mechanical properties and fracture morphology of NiCrMoV steel that has been austenitized were studied by Salemi and Abdollah-zadeh (2008). The specimens were austenitized at 870 °C for 1 hour, followed by oil quenching, and then tempered at temperatures in the range of 200–600 °C. The authors found out from tensile testing results that the yield strength (YS) and ultimate tensile strength (UTS) decreased with increased tempering temperature.

Haftirman et. al., (2007) have studied the effects of tempering temperature on fatigue strength of Thyssen 6582 steel. They carried fatigue tests using rotating bending fatigue machine to get the fatigue strength of the material as the tempering temperatures were vary from 100 °C to 600 °C. The micro cracks initiation and propagation on the specimen surface were investigated using Scanning Electron Microscope (SEM). The results showed that as the tempering temperature increase from 100 °C to 300 °C, the fatigue strength of the samples are also increased. But, the fatigue strength of 100 °C was lower than the standard specimen at room temperature. In the meanwhile, for the samples with tempering temperatures ranging from 400 °C to 600 °C, the fatigue strength of the samples is decreased. The optimum fatigue strength has been achieved at 300 °C.

The fatigue strength increased as the temperature increased to 300 °C due to decreases of the crack length occurred on the specimen surface. As the tempering temperature is higher than 300 °C the crack length had increased that cause the decreasing of fatigue strength of the specimen.