A STUDY ON HEAT TREATMENT OF CARBURIZING CARBON STEEL

MOHD MARHAN BIN ASARI

BACHELOR OF ENGINEERING
UNIVERSITI MALAYSIA PAHANG

2010

BORANG PENGESAHAN STATUS TESIS

JUDUL: A STUDY ON HEAT TREATMENT OF CARBURIZING CARBON STEEL

SESI PENGAJIAN: 2010/2011

Saya **MOHD MARHAN BIN ASARI (881210-11-5619)**
(HURUF BESAR)

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

1. Tesis ini 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:	
LOT 4111, KG JENAGOR, **21700 KUALA BERANG,** **TERENGGANU DARUL IMAN.**	**PN. NUR AZHANI BINTI** **ABD RAZAK** **(**Nama Penyelia)
Tarikh: 6 DISEMBER 2010	Tarikh: 6 DISEMBER 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 SULIT atauTERHAD.

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).

UNIVERSITI MALAYSIA PAHANG
FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled "*A study on heat treatment of carburizing carbon steel*" is written by *Mohd Marhan bin Asari*. I have examined the final copy of this project and in my opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I here with recommend that it be accepted in partial fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

Mr. Nasrul Azuan bin Alang

Examiner Signature

A STUDY ON HEAT TREATMENT OF CARBURIZING CARBON STEEL

MOHD MARHAN BIN ASARI

Thesis submitted in fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering with Manufacturing Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

DECEMBER 2010

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 with Manufacturing Engineering.

Signature
Name of Supervisor: MDM. NUR AZHANI BINTI ABD RAZAK
Position: LECTURER
Date: 06 DECEMBER 2010

Dedicated to my beloved parents

ASARI BIN MUSA

NORAINI BINTI TAIB

ABSTRACT

The main purpose of this study is to study the effect of heat treatment of carburizing carbon steel by using three parameters (carburizing hour, carburizing temperature, and quenching medium). This study was conducted using a furnace. This process is carried out at temperatures from 850°C to 950°C (1123 – 1223K) for three various duration time which are 8, 10 and 12 hours. From the experiment, the thickness of carbon layer varied according to the parameters that been used. For carburizing temperature at 950°C, the thickness of carbon layer was between 40µm to 80µm for oil as quenching medium, 60µm to 100µm for water as quenching medium and 20µm to 60µm for air as quenching medium. This experiment also been conducted for different carburizing temperature but with one quenching medium which is oil. The thickness of carbon layer was between 20µm to 60µm for 850°C, 30µm to 70µm for 900°C and 40µm to 80µm for 950°C. For carburizing temperature at 950°C, surface hardness values of carburized specimens were between 185.9 HV and 386.2 HV for oil as quenching medium, 234.7 HV and 398.4 HV for water as quenching medium and 120.7 HV and 241.5 HV for air as quenching medium. For different carburizing temperature, surface hardness values of carburized specimens were between 149 HV and 323.4 HV for 850°C, 166.4 HV and 345.9 HV for 900°C and 185.9 HV and 368.2 HV for 950°C. Activation energy was determined by 47.34 kJ/mol. The lower value of activation energy means less energy required for carbon atoms to diffuse into carbon steel, thus provide a more effective and efficient process.

ABSTRAK

Tujuan utama kajian ini adalah untuk mempelajari kesan-kesan rawatan haba terhadap penyusukkarbonan besi karbon dengan menggunakan tiga pembolehubah (jam penyusukkarbonan, suhu karburasi dan agen penyejukan). Kajian ini dijalankan dengan menggunakan kebuk pembakaran. Proses ini dilakukan pada suhu 850°C sehingga 950°C (1123 – 1223K) untuk tiga masa berbeza iaitu 8,10 dan 12 jam. Daripada kajian ini, ketebalan lapisan karbon berubah-ubah mengikut pembolehubah yang digunakan. Bagi penyusukkarbonan pada suhu 950°C, ketebalan lapisan karbon adalah diantara 40µm sehingga 80µm bagi minyak sebagai agen penyejukan, 60µm sehingga 100µm bagi air sebagai agen penyejukan dan 20µm sehingga 60µm bagi udara sebagai agen penyejukan. Kajian ini juga dilakukan untuk suhu penyusukkarbonan yang berbeza tetapi dengan hanya menggunakan satu agen penyejukan iaitu minyak. Ketebalan lapisan karbon adalah diantara 20µm sehingga 60µm bagi 850°C, 30µm sehingga 70µm bagi 900°C dan 40µm sehingga 80µm bagi 950°C. Bagi suhu penyusukkarbonan pada 950°C, nilai kekerasan lapisan bahan yang disusukkarbonan adalah diantara 185.9 HV dan 386.2 HV bagi minyak sebagai agen penyejukan, 234.7 HV dan 398.4 HV bagi air sebagai agen penyejukan dan 120.7 HV dan 241.5 HV bagi udara sebagai agen penyejukan. Bagi suhu penyusukkarbonan yang berbeza, nilai kekerasan lapisan bahan yang disusukkarbonan adalah diantara 149 HV dan 323.4 HV bagi 850°C, 166.4 HV dan 345.9 HV bagi 900°C and 185.9 HV dan 368.2 HV bagi 950°C. Tenaga pengaktifan dikirakan iaitu 47.34 kJ/mol. Semakin rendah nilai tenaga pengaktifan bermaksud kurang tenaga diperlukan bagi atom karbon masuk ke dalam besi karbon lalu menyediakan satu proses yang efektif dan cekap.

ACKNOWLEDGEMENT

First of all I am grateful to ALLAH S.W.T for blessing me in finishing my final year project (PSM) with success in achieving my objectives to complete this project.

Secondly I want to thank my family for giving morale support and encouragement in completing my project and also throughout my study in UMP as they are my inspiration for me to success. I also would like to thank my supervisor Mdm. Nur Azhani Binti Abd Razak for guiding and supervising my final year project throughout these two semesters. She has been very helpful for me in finishing my project and I appreciate every advice that she gave me in correcting my mistakes. I apologize to my supervisor for any mistakes and things that I had done wrong while doing my project. The credits also goes to all lecturers, tutors, teaching engineers (JP) especially Mr. Jamil and assistant teaching engineers (PJP), Mr Azuwar for their cooperation and guide in helping me finishing my final year project.

Last but not least I want to thank all my friends that have given me advice and encouragement in completing my project. Thank you very much to all and may ALLAH S.W.T. bless you.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 METHODOLOGY

CHAPTER 4 RESULT AND DISCUSSION

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Generally, heat treatment processes apply primarily to steels. After a component has been produced, it may still not have acceptable surface properties. There are few reasons why the surface properties may need altering such as improving wear, corrosion and fatigue resistance, and changing the aesthetic appearance. There are various ways these aims can be achieved.

Heat treatment is a method used to alter the physical and sometimes chemical properties of a material. The most common application is metallurgical. Heat treatments are also used in the manufacture of many other materials, such as glass. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve a desired result such as hardening or softening of a material.

Case hardening is a process in which an alloying element, most commonly carbon or nitrogen, diffuses into the surface of a monolithic metal. The resulting interstitial solid solution is harder than the base material, which improves wear resistance without sacrificing toughness (Prabudev, 1988).

1.2 PROBLEM STATEMENT

Optimum structural material is a great concern in manufacturing environments, where demands for high performance in mechanical properties such as hardness.

The influence of heat treatment on the mechanical properties of the carbon steel is studied. Choosing the best carburizing time, quenching medium and carburizing temperature is the main priority in this research because with the suitable carburizing time, quenching medium and carburizing temperature, it can give precise results in mechanical properties such as hardness.

1.3 PROJECT BACKGROUND

In order to make strong structural material, the material for this research is low Carbon Steels (0.4 wt. %). In general, carburizing process increases the grains size due to permanence for a long time in the austenite region of the phase diagram, and makes necessary a posterior heat treatment to refine the grains. The process that generally involved in heat treatment is quenching. The material is heated to certain temperatures and then rapidly cooled (quenched) in water, oil, and air. This results in martensite structure which is a form of steel that possesses super-saturated carbon content in a deformed body-centered cubic (BCC) crystalline structure, properly termed body-centered tetragonal (BCT), with much internal stress. Thus, quenched steel is extremely hard but brittle, usually too brittle for practical purposes. These internal stresses cause stress cracks on the surface (Prabudev, 1988).

The increasing in the mechanical properties because of the modified microstructures confirmed the efficiency of the method. The surface hardness in carburizing process is increased. This can be proved from Vickers Hardness Test. The Vickers Hardness (HV) number increase after carburizing process. From the reading, the edge gives smaller HV number then the center for all specimens. The smaller HV value indicates that the part is hard (Ray et. al., 2003).

1.4 RESEARCH OBJECTIVES

The objectives of this study are to:

(i). Determine the effectiveness on hardness of carburized carbon steel by using heat treatment.
(ii). Determine the activation energy on carburized layer.

1.5 SCOPE OF THE RESEARCH

The scopes of this study are:

(i). Packing method is used in carburizing process.
(ii). 3 different carburizing times are used in carburizing processes which are 8 hours, 10 hours and 12 hours.
(iii). 3 different carburizing temperatures are used in carburizing processes which are 850°C, 900°C and 950°C.
(iv). 3 different quenching mediums are used which are air, oil and water.
(v). Vickers Hardness Test is used to determine the hardness of certain part on the carbon steel.
(vi). Oil is used as quenching medium for activation energy determination.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

From the early stage of the project, various literature studies have been done. Research journal, reference books, printed or online conference article were the main source in the project guides as they contain the current knowledge on particular research. The reference sources emphasize on effect of heat treatment on surface hardness when carburizing carbon steel. Then, the value of hardness on the surface of carbon steel will be justified using Vickers Hardness Test.

2.2 HEAT TREATMENT

Heat treatment is a process utilized to change certain characteristics of metals and alloys in order to make them more suitable for a particular kind of application. In general, heat treatment is the term for any process employed which changes the physical properties of steel by either heating or cooling. When properly performed, heat treating can greatly influence mechanical properties such as strength, hardness, ductility, toughness, and wear resistance (Zakharov, 1998).

2.2.1 Heat Treatment of Carbon Steels and Carbon Alloy Steels

Most carbon steels and carbon alloy steels can be heat treated for the purpose of improving mechanical properties such as hardness, tensile and yield strength. This is accomplished due to the heat treatment fundamentally altering the microstructure of the steel.

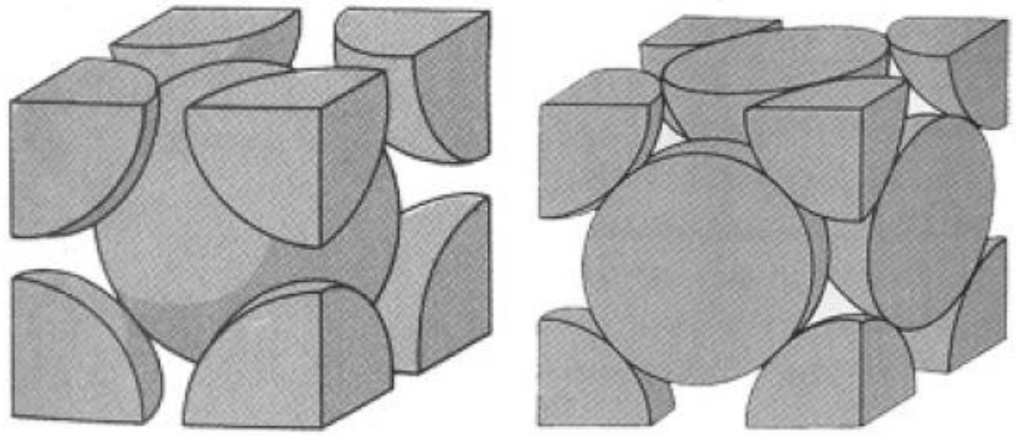
When discussing about heat treating, it must begin with the understanding of the structure and phases of metals.

The structure of steel is composed of two variables:

(i). Grain Structure - The arrangement of atoms in a metal.
(ii). Grain Size - The size of the individual crystals of metal. Large grain size is generally associated with low strength, hardness, and ductility.

The crystals in steel have a defined structure that is determined by the arrangement of the atoms. There are two common crystal structures in iron which are body-centered-cubic (BCC) and face-centered-cubic (FCC). When the iron is arranged in the FCC structure, it is able to absorb higher amounts of carbon than a BCC structure. It is because of the increasing in interstitial sites where carbon can sit between the iron atoms. During the alloying process elements, carbons are introduced to the steel. These alloying elements interrupt the geometry of the individual crystal structures therefore it increase the strength. Thus, the change in crystal structure is critical to successful heat treatment (Askeland, 1984).

Steel can exist in various phases which are ferrite, austenite, and cementite. These phases can be explained by referring Figure 2.2. The Y-axis (vertical) is a measurement of temperature while the X-axis (horizontal) is a measurement of the carbon content of the steel. The far left hand side of the X-axis represents the ferrite phase of steel (low carbon content) while the far right hand side represents the cementite phase of steel (high carbon content), which is also known as iron carbide. The austenite phase is located between the dashed phase lines and occurs only above 1333 °F or 723 °C (Askeland, 1984).



(a) **(b)**

Figure 2.1: (a) Body-Centered Cubic (BCC), (b) Face-Centered Cubic (FCC)

Source: William D. Callister Jr., (1994)

The transformation from BCC to FCC provides more points (spaces between spheres) for carbon to interact with the iron.

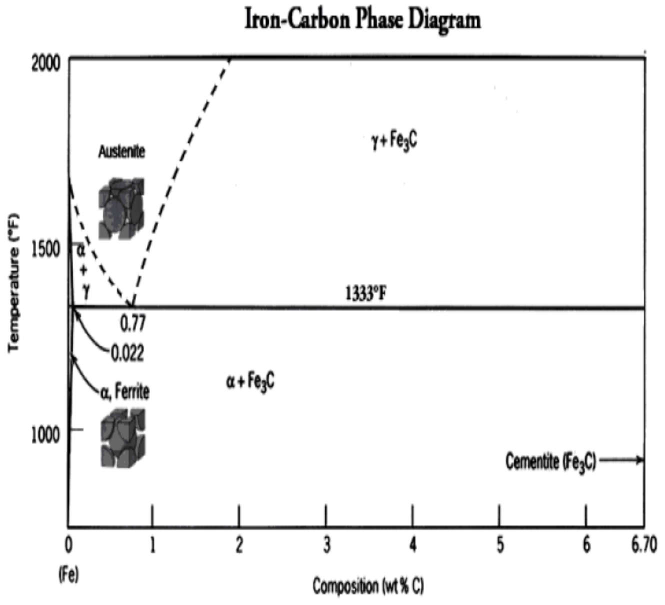


Figure 2.2: Iron-Carbon phase diagram

Source: William D. Callister Jr., (1994)

When ferrite is at room temperature, it has a BCC structure, which can only absorb a low amount of carbon. Because ferrite can only absorb a very low amount of carbon at room temperature, the un-absorbed carbon separates out of BCC structure to form carbides which join together to create small pockets of an extremely hard crystal structure within the ferrite which is cementite. However, when ferrite is heated to a temperature above the transformation line (723ºC), the BCC structure changes to FCC structure known as austenite which is allowing the absorption of the carbon into the crystal structure (Parrish, 1999).

Once the steel enters the austenitic phase, all of the cementite dissolves into austenite. If the steel is allowed to cool slowly, the carbon will separate out of the ferrite as the cubic-structure reverts from face-centered back to body-centered. The islands of cementite will reform within the ferrite, and the steel will have the same properties that it did before it was heated. However, when the steel is rapidly cooled, or quenched, in a quenching medium such as oil, water, or air room temperature, the carbon does not have time to exit the cubic structure of the ferrite and it becomes trapped within it. This leads to the formation of martensite which is the microstructure that produces the most sought after mechanical properties in steel fasteners (Parrish, 1999).

During quenching, it is impossible to cool the specimen at a uniform rate throughout. The surface will always cool more rapidly than the interior of the specimen. Therefore, the austenite will transform over a range of temperatures, yielding a possible variation of microstructure and properties depending on the position within the material. The successful heat treatment of steels to produce a predominantly martensitic microstructure throughout the cross section depends mainly on three factors (Prabudev, 1988):

(i). The composition of the alloy
(ii). The type and character of the quenching medium
(iii). The size and shape of the specimen

Hardenability is the ability of steel to transform into martensite with a particular quenching treatment. This is directly affected by the alloy composition of the steel. For every different steel alloy there is a specific relationship between its mechanical properties and its cooling rate. Hardenability is not “hardness” which is a resistance to indentation but hardness measurements are utilized to determine the extent of a martensitic transformation in the interior of the material. A steel alloy that has a high hardenability is one that hardens, or forms martensite, not only at the surface but also to a large degree throughout the entire interior. In other words, hardenability is a measure of the degree to which a specific alloy may be hardened (Askeland, 1984).

The newly formed martensite is considered as a grain structure but not a phase and it is very hard and brittle. Due to the brittleness inherent in martensite, steel that has been quenched from austenitizing temperatures will require tempering before it can be placed into service. Tempering involves heating the steel to a specific temperature below that of the transformation line and allowing it to cool slowly. This causes the crystal structure to relax, thereby increasing the ductility and decreasing the hardness to specified levels. The specific tempering temperature will vary based on the desired results for the steel (Parrish, 1999).

The following example will demonstrate the effectiveness of tempering:

ASTM A193 Grade B7, SAE J429 Grade 8 and ASTM A574 Socket Head Cap Screws are all made from alloy steels. In fact some alloy steel grades can be used to manufacture any of the three final products such as 4140 and 4142 alloy steel. The final mechanical properties appear in the table.

The initial heat treating process is relatively the same for all three products. The parts are heated until fully austenitized and then are quenched in oil and tempered (Chokshi, 2005).

This tempering temperature dictates the final mechanical properties. The following are the minimum tempering temperatures and it specification:

Table 2.1: Fasteners produced from AISI 4140 & 4142 Steel

Fastener	**ASTM A193 B7**	**SAE J429 Gr. 8**	**ASTM A574 SHCS**
Tempering Temperature	1150°F	800°F	650°F
Tensile Strength	125,000 PSI min. (2½in. and under)	150,000 PSI min.	180,000 PSI min. (through ½in.) 170,000 PSI min. (above ½in.)
Yield Strength	105,000 PSI min. (2½in. and under)	130,000 PSI min	153,000 PSI min
Proof Strength	N/A	120,000 PSI	140,000 PSI (through ½in.) 135,000 PSI (above ½in.)
Hardness	HRC 35 max.	HRC 33-39	HRC 39-45 (through ½in.) HRC 37-45 (above ½in.)

A lower tempering temperature will produce a harder and higher tensile strength part for these alloy steels. However, the lower tempering temperatures will also mean lower ductility, impact strength, operating temperature, and possibly lower fatigue life. For example, socket head cap screws and Grade 8's have an operating temperature limitation of approximately 450 °F, whereas B7 is able to function properly up to approximately 800 °F (Chokshi, 2005).

Annealing is a heat treating process used to soften previously cold-worked metal by allowing it to re-crystallize. The term annealing refers to a heat treatment in which a material is exposed to an elevated temperature for an extended time period and then slowly cooled. Ordinarily, annealing is carried out to relieve stresses (often introduced when cold-working the part), increase softness, ductility and toughness and produce a desired microstructure. A variety of annealing heat treatments are possible (Krauss, 1991).

Any annealing process consists of three stages:

(i). Heating to the desired temperature
(ii). Holding or "soaking" at that temperature
(iii). Slowly cooling, usually to room temperature

Time is the important parameter in these procedures. Process annealing is a heat treatment that is used to negate the effects of cold work that is to soften and increase the ductility of a previously strain-hardened metal.

Stress relieving is an annealing process that is utilized when internal residual stresses develop in metal pieces in response to such things as cold working. Failure to remove these internal stresses may result in distortion and warping. The internal stresses are relieved by bond relaxation as a result of heating. A stress relief is carried out by heating the piece to a recommended temperature (approximately 165 °F or 74°C below the transformation temperature for carbon steels), holding the work piece at temperature long enough to attain a uniform temperature throughout the part, and finally cooling to room temperature in air. Stress relieving can eliminate some internal stresses without significantly altering the structure of the material (Krauss, 1991).

Steels that have been plastically deformed consist of grains of pearlite, which are irregularly shaped and relatively large, but substantially in size. Normalizing is an annealing heat treatment used to refine the grains and produce a more uniform and desirable size distribution (Parrish, 1999).

2.2.2 Carburizing

In general, carburizing is the addition of carbon to the surface of low carbon steels at temperatures generally between 850 and 950°C (1560 and 1740°F) at austenite region that had high solubility for carbon and the stable crystal structure. Hardening is accomplished when the high-carbon surface layer is quenched to form martensite so that a high-carbon martensitic case will have good wear and fatigue resistance. Carburizing steels for case hardening usually have base-carbon contents of about 0.2%, with the carbon content of the carburized layer generally being controlled at between 0.8 and 1% C. However, surface carbon is often limited to 0.9% because too high a carbon content can result in retained austenite and brittle martensite. Carburizing process increases the grains size due to permanence for a long time in the austenitic region of the phase diagram, and makes necessary a posterior heat treatment to refine the grains. Classic quenching generates a martensitic hard but brittle material. On the other hand, intercritical quenching transforms the outward carbon-rich solid solution into martensite, while the internal microstructures present a mixture of martensite, producing a less-brittle material (Parrish, 1999).

Parts are packed in a high carbon medium such as carbon powders are heated in a furnace for 8 to 12 hours at 850°C, 900°C and 950 ºC. At this temperature CO gas is produced which is a strong reducing agent. The reduction reaction occurs on the surface of the steel releasing carbon, which is then diffused into the surface due to the high temperature. When enough carbon is absorbed inside the part (based on experience and theoretical calculations based on diffusion theory), the parts are removed and can be subject to the normal hardening methods (Krauss, 1991).

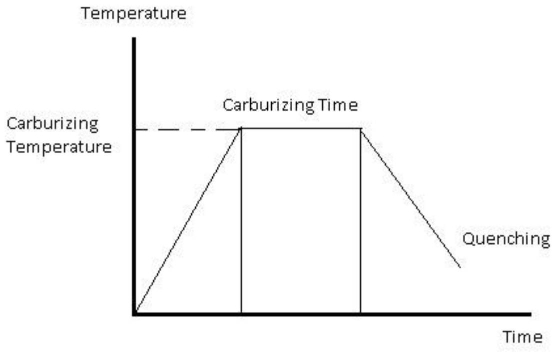


Figure 2.3: Process diagram of carburizing

Figure 2.4: Specimens container (furnace)

2.2.3 Quenching

Usually when hot steel is quenched, most of the cooling happens at the surface, as does the hardening. Different quenching media provide a variety of cooling rates.

Quenching can be done by plunging the hot steel in water. The water adjacent to the hot steel vaporizes, and there is no direct contact of the water with the steel. This slows down cooling until the bubbles break and allow water contact with the hot steel. As the water contacts and boils, a great amount of heat is removed from the steel. With good agitation, bubbles can be prevented from sticking to the steel, and thereby prevent soft spots. Water is a good rapid quenching medium, provided good agitation is done. When the fastest cooling rate is required, water solutions are used as quenching media. When suddenly quenched, the martensite is formed. This is a very strong and brittle structure. However, water is corrosive with steel, and the rapid cooling can sometimes cause distortion or cracking (Prabudev, 1988).

Oil is used when a slower cooling rate is desired. Since oil has a very high boiling point, the transition from start of martensite formation to the finish is slow and this reduces the likelihood of cracking. When slowly quenched it would form austenite and pearlite which is a partly hard and partly soft structure but oil quenching results in fumes, spills, and sometimes a fire hazard. Oils also are intermediate quenching media and they are ideal for quenching steels (Prabudev, 1988).

Quenches are usually done to room temperature. Most medium carbon steels and low alloy steels undergo transformation to 100% martensite at room temperature. When the cooling rate is extremely slow then it would be mostly pearlite which is extremely soft. However, high carbon and high alloy steels have retained austenite at room temperature. To eliminate retained austenite, the quench temperature has to be lowered. This quenching media produces the lowest cooling rate (Prabudev, 1988).

2.2.4 Mounting

Hot mounting uses a thermosetting compound, cured in amounting press which exerts both heat and high pressure. This mounting method produces hard mounts in a short space of time. However the heating (generally in the order of 120 °C) and considerable pressure applied may be unsuitable for delicate, soft or low melting point specimens (Unterweiser et.al., 1982).

Figure 2.5: Mounting machine

Techniques may be used to protect a delicate sample from the effects of pressure, such as placing the sample under supporting structure can protect the sample from initial pressure applied when the mounting material is in a granular form, and most likely to inflict damage. When the mounting material becomes fluid, infiltration should occur to encapsulate the sample which will then be subject to hydrostatic pressure. Hydrostatic pressure can be applied to all but the most delicate of samples without problem. In the case of very soft or thermally sensitive materials, hot mounting is not appropriate. Conductive mounting resins are available, which are good for Scanning Electron Microscopy (SEM) examination, although the adhesion and hardness characteristics are not as good as those of epoxy hot set compounds. If the edges of the specimen are not of interest, then non conductive mounting materials can be used. In general, hot mounting is preferable to cold setting resins, when the sample is not affected by temperature and pressure (200° C & 50kN). However, not all specimens can tolerate this (Unterweiser et.al., 1982).

Non-conductive mounts must be covered with adhesive conductive tape or coated with a conductive medium (the sample are can be masked if sputter coating, or using an evaporator). Aluminium foil or glass cover slips are useful for this purpose. Note that many adhesive metals tape have non-conductive adhesive, so the use of carbon or silver conductive paint may be required at seams. Whilst very thin films of carbon can be tolerated on the sample, the ideal is that is that the sample surface should be bare (Unterweiser et.al., 1982).

Hot mounting may be unacceptable, if the effect of temperature and pressure are expected to be inappropriate for the sample under investigation.

2.2.5 Grinding

Grinding is a finishing process used to improve surface finish, hard materials, and tighten the tolerance on flat by removing a small amount of material (Prabudev, 1988).

The specimens must be grind with the silicon carbide sand paper with the 240 grit first then followed with 320 grit then 400 grit and lastly 600 grit. Then the specimens were grinded with diamond grid.

Figure 2.6: Grinding machine

2.2.6 Polishing

Polishing is the process of creating a smooth and shiny surface by rubbing it or using a chemical action, leaving a surface with minimal diffuse reflection and significant specular reflection (Unterweiser et.al., 1982).

A specimen must be polish with slurry of alumina, silica or diamond on a wheel polisher to produce a scratch-mirror finish, free from smear, drag or pull-outs and with minimal deformation remaining from the preparation process.

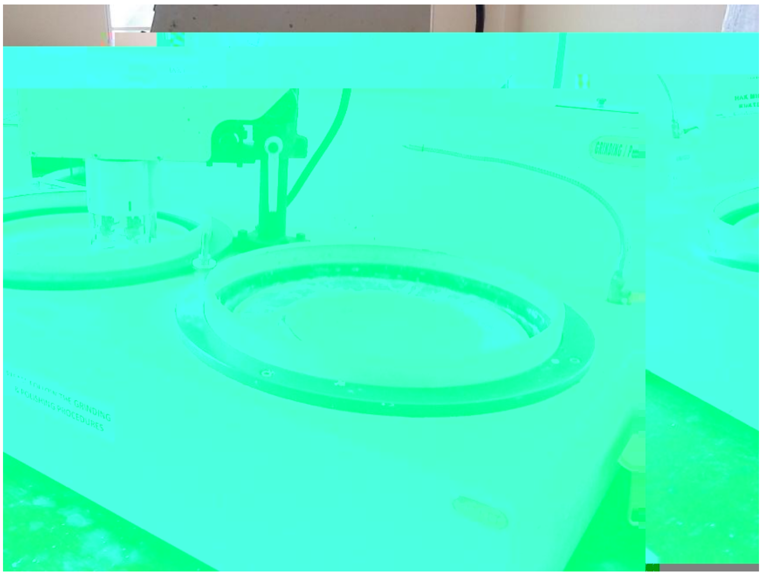


Figure 2.7: Polishing machine

2.3 HARDNESS TEST

The usual method to achieve a hardness value is to measure the depth or area of an indentation left by an indenter of a specific shape, with a specific force applied for a specific time. There are three principal standard test methods for expressing the relationship between hardness and the size of the impression which are Brinell, Vickers, and Rockwell (Ray et.al., 2003). For practical and calibration reasons, each of these methods is divided into a range of scales, defined by a combination of applied load and indenter geometry.

2.3.1 Vickers Test

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136° between opposite faces subjected. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kg load by the square mm area of indentation (Ray et.al., 2003).

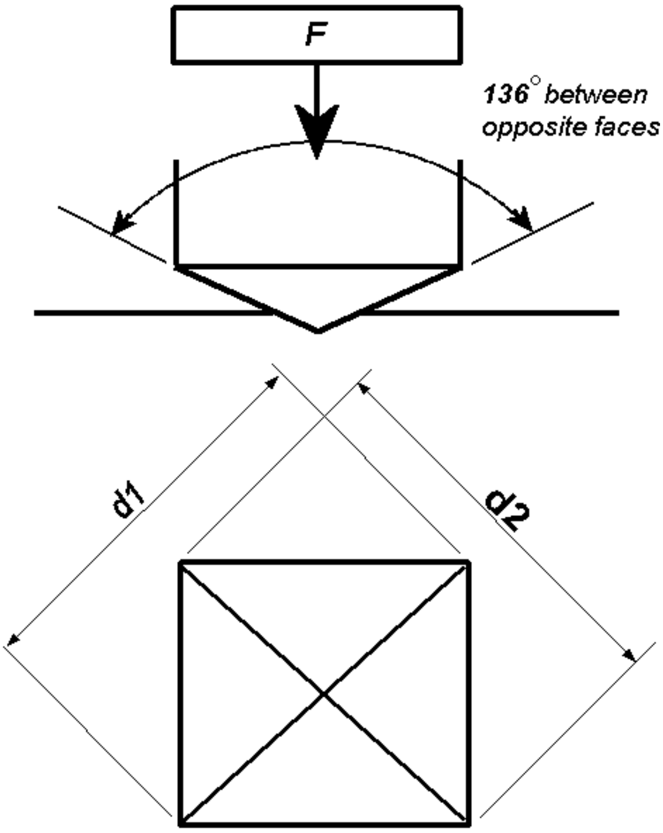


Figure 2.8: Diamond Indenter

Source: Ray et.al., (2003).

$$\mathrm{HV} = \frac{1.854\mathrm{F}}{\mathrm{L}^2} \tag{2.1}$$

where:

L = mean of the two diagonals, *D1* and *D2* in mm

$= \frac{D1+D2}{2}$

F = Load in kg

When the mean diagonal of the indentation has been determined the Vickers hardness may be calculated from the formula. Several different loading settings give practically identical hardness numbers on uniform material, which is much better than the arbitrary changing of scale with the other hardness testing methods. The advantages of the Vickers hardness test are that extremely accurate readings can be taken, and just one type of indenter is used for all types of metals and surface treatments. Although thoroughly adaptable and very precise for testing the softest and hardest of materials, under varying loads, the Vickers machine is a floor standing unit that is more expensive than the Brinell or Rockwell machines (Ray et.al., 2003).

Figure 2.9: Vickers Hardness tester

2.4 ACTIVATION ENERGY

Activation energy, in chemistry is defined as minimum energy needed to cause a chemical reaction. A chemical reaction between two substances occurs only when an atom, ion, or molecule of one collides with an atom, ion, or molecule of the other. Only a fraction of the total collisions result in a reaction, because usually only a small percentage of the substances interacting have the minimum amount of kinetic energy a molecule must possess for it to react. When the reactants collide, they may form an intermediate product whose chemical energy is higher than the combined chemical energy of the reactants. In order for this transition state in the reaction to be achieved, some energy must enter into the reaction other than the chemical energy of the reactants. This energy is the activation energy (Jauhari et.al., 2007).

If the activation energy is low, a greater proportion of the collisions between reactants will result in reactions. If the temperature of the system is increased, the average heat energy is increased, a greater proportion of collisions between reactants result in reaction, and the reaction proceeds more rapidly. The thickness of carburized layer is mainly depends on the diffusion of carbon atoms into the substrate material. Thus, the activation energy of carburizing process can be determined by using the thickness of carburized layer formed.

The thickness of carbon layer varies with time as illustrated in Figure 4.4 and follows parabolic law as below:

$$\mathrm{d}^2 = \mathrm{Kt} \tag{2.2}$$

where;

d = the carbon layer thickness (µm)
K= carbon growth rate constant
t = carburizing time (s)

Figure 4.5 shows that the square of carbon layer thickness is directly proportional with carburizing time. Therefore, the relationship between diffusion coefficients, K (m^2s^{-1}), activation energy, Q (J mol^{-1}) and carburizing temperature, T (K) can be expressed by Arrhenius equation as follow:

$$K = K_o\, e^{-}\left(\frac{Q}{RT}\right) \qquad (2.3)$$

where;

K_o = pre-exponential constant

R = gas constant (8.314 J mol^{-1} K^{-1})

Taking from the natural logarithm of Eq. (2.2), Eq. (2.3) can be derived:

$$\ln K = \ln K_o + (-\,Q\,R^{-1})(T^{-1}) \qquad (2.4)$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter describes the results and discussion based on the experiment conducted. The experimental results will be presented in the table to facilitate the process of analyzing those results. Then the experimental results will be compared to each parameter. Recommendation will be given for future improvements. Surface hardness is the measure of the surface that gives high Vickers hardness (HV) value. The ability of carburizing operation is based on many factors. The surface hardness depends on the carburizing time, carburizing temperature, and quenching time.

4.2 HARDNESS PROFILE

4.2.1 Vickers hardness results for carburizing

After all experiment had been conducted, the result for carburizing at 950°C (1223 K) is shown in Table 4.1, Table 4.2 and Table 4.3. Each table shows the results for carburizing time which are 8 hours, 10 hours and 12 hours and quenching medium which are water, oil and air. There are 20 HV readings for each table that can be used in surface hardness determination. From the table, the cross-section hardness profiles can be determined.

Table 4.1: Carburizing for 8 hours

POSITION(μm)	HV(Oil)	HV(Water)	HV(Air)
0	281.3	311.7	221.9
20	277.1	309.7	220.5
40	271.6	308.5	206.4
60	263.8	304.1	195.4
80	255.1	296.5	185.4
100	245.3	291.2	170.8
120	241.8	288.4	164.4
140	238	285.6	157.6
160	235.9	283.1	154.8
180	231.4	279.6	149.7
200	225.6	275.1	141.7
220	219.8	272.2	139.3
240	215.2	266.2	136.3
260	211.7	260.3	132.3
280	207.5	255.4	129.8
300	199.1	249.1	128.5
320	194.5	245.6	125.7
340	188.8	238.5	123.4
360	185.9	234.7	120.7
380	185.9	234.7	120.7
400	185.9	234.7	120.7

Table 4.1 shows the position of carburizing layer for three different quenching medium. Each position gives different value of Vickers hardness. The reading from 0 μm to 400 μm position shows the HV value decreasing to a same value. This happened because the thickness of carbon layer is decreasing from the edge to the center. At the center, there is no carburized layer occurred.

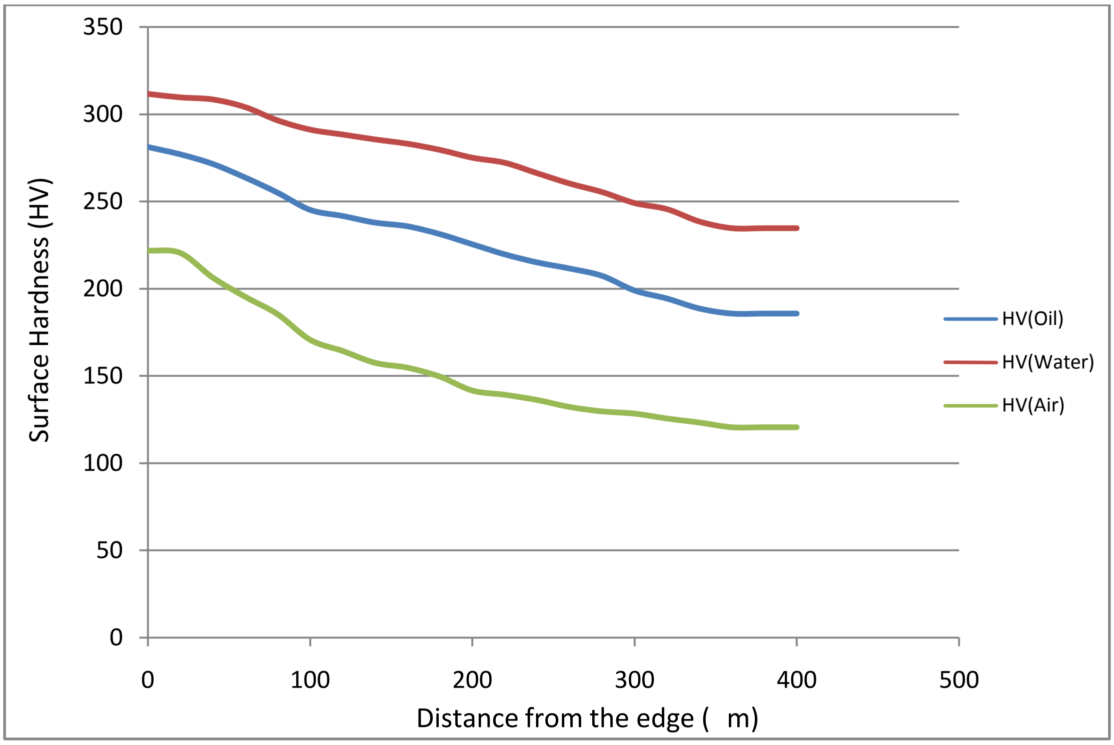


Figure 4.1: Graph of surface hardness vs. distance from the edge (cross-section hardness profiles)

Figure 4.1 shows the result for water quenching gives the highest HV value. The highest HV value for water is 311.7 while the lowest value is 234.7. The second highest HV value is using oil quenching which is 281.3 while the lowest HV value is 185.9. Air quenching gives the lowest HV values which are 221.9 and 120.7. From the data, the HV value shows using water quenching gives the highest HV value. It is because fastest cooling rate happens. When suddenly quenched, the martensite is formed. It is a very strong and brittle structure. For oil quenching, the cooling rate is slower than water quenching. Since oil has a very high boiling point, the transition from start of martensite formation to the finish is slow. When slowly quenched it would form austenite and pearlite which is a partly hard and partly soft structure. Air quenching gives very slow cooling rate. Most medium carbon steels and low alloy steels undergo transformation to 100% martensite at room temperature. When the cooling rate is extremely slow then it would be mostly pearlite which is extremely soft.

Table 4.2: Carburizing for 10 hours

POSITION(µm)	HV(Oil)	HV(Water)	HV(Air)
0	350.2	386.3	194.3
20	349.7	386.3	193.4
40	349.4	385.6	192.4
60	348.7	384.2	185.6
80	340.1	382.1	179.2
100	335.2	372.1	170.1
120	332.1	365.2	164.1
140	325.4	359.2	155.6
160	321.3	350.6	145
180	315.3	343.5	140.3
200	311.1	337.2	136.2
220	305.2	332.3	134.8
240	298.1	321.3	130.6
260	294.5	316.4	128.3
280	288.7	311.3	126.4
300	283.2	306.7	120.3
320	279.1	302.1	118.7
340	275.5	294.6	115.3
360	271.2	290.1	113.6
380	271.2	290.1	113.6
400	271.2	290.1	113.6

Table 4.2 shows the position of carburizing layer for three different quenching medium. Each position gives different value of Vickers hardness. The reading from 0 µm to 400 µm position shows the HV value decreasing to a same value. This happened because the thickness of carbon layer is decreasing from the edge to the center. At the center, there is no carburized layer occurred.

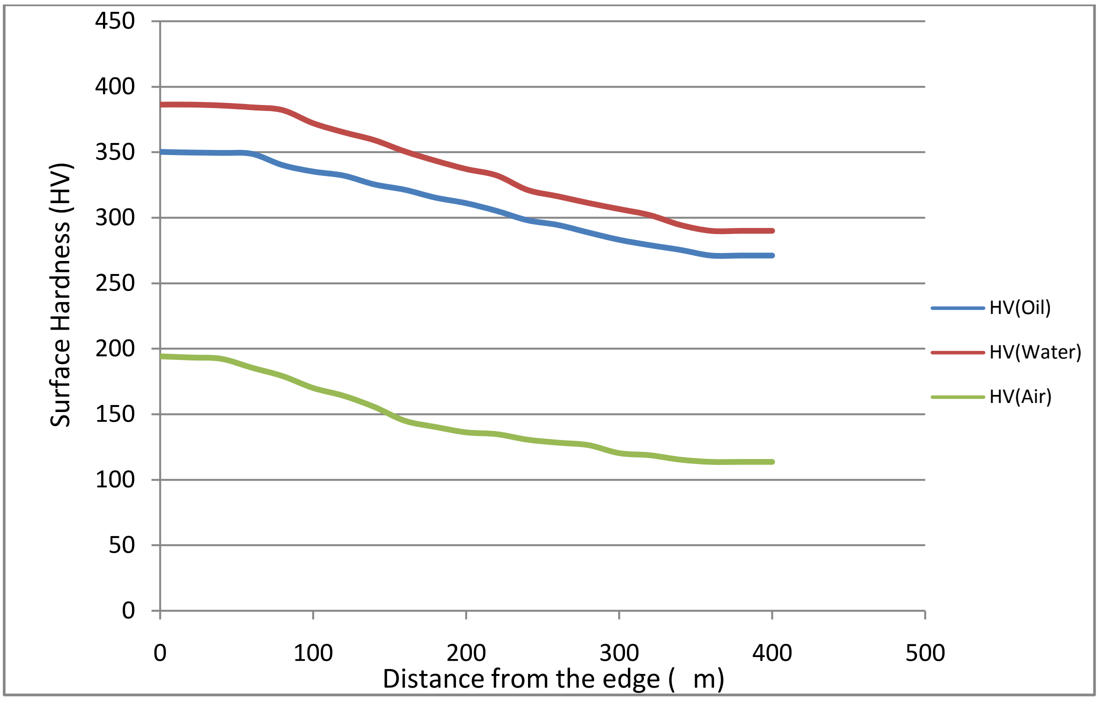


Figure 4.2: Graph of surface hardness vs. distance from the edge (cross-section hardness profiles)

Figure 4.2 shows the result for water quenching gives the highest HV value. The highest HV value for water is 386.3 while the lowest value is 290.1. The second highest HV value is using oil quenching which is 350.2 while the lowest HV value is 271.2. Air quenching gives the lowest HV values which are 194.3 and 113.6. From the data, the HV value shows using water quenching gives the highest HV value. It is because fastest cooling rate happens. When suddenly quenched, the martensite is formed. It is a very strong and brittle structure. For oil quenching, the cooling rate is slower than water quenching. Since oil has a very high boiling point, the transition from start of martensite formation to the finish is slow. When slowly quenched it would form austenite and pearlite which is partly hard and partly soft structure. Air quenching gives very slow cooling rate. Most medium carbon steels and low alloy steels undergo transformation to 100% martensite at room temperature. When the cooling rate is extremely slow then it would be mostly pearlite which is extremely soft.

Table 4.3: Carburizing for 12 hours

POSITION(μm)	HV(Oil)	HV(Water)	HV(Air)
0	368.2	398.4	241.5
20	367.9	395.9	241.4
40	367.4	389.4	238.2
60	366.8	387.2	236.4
80	361.2	383.4	227.9
100	350.5	379.1	220.3
120	346.1	369.5	212
140	341.1	366.4	211.2
160	335.5	363.5	209.3
180	331.2	358.1	206.7
200	326.7	350.4	203.6
220	321.9	346	200.7
240	314.7	342.1	195.4
260	308.7	339.7	190.2
280	299.5	335.2	185.7
300	294.8	331.6	181.2
320	286.5	329.4	182.1
340	280.5	327.5	179.6
360	272.7	326.1	178.2
380	272.7	326.1	178.2
400	272.7	326.1	178.2

Table 4.3 shows the position of carburizing layer for three different quenching medium. Each position gives different value of Vickers hardness. The reading from 0 μm to 400 μm position shows the HV value decreasing to a same value. This happened because the thickness of carbon layer is decreasing from the edge to the center. At the center, there is no carburized layer occurred.

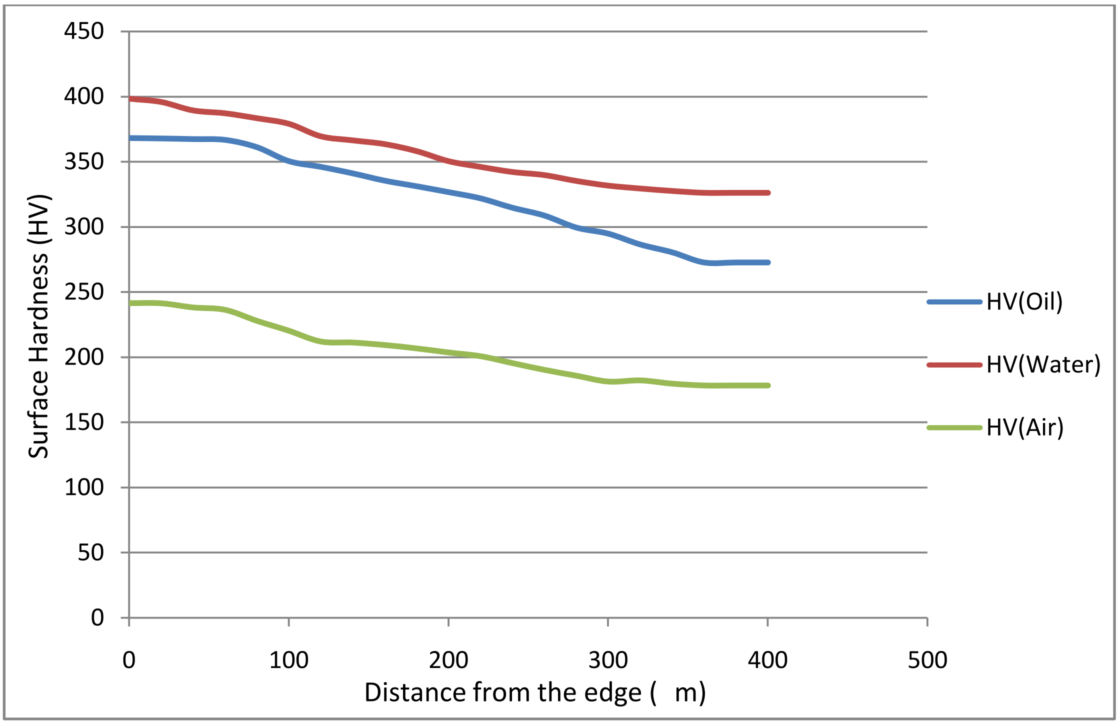


Figure 4.3: Graph of surface hardness vs. distance from the edge (cross-section hardness profiles)

Figure 4.3 shows the result for water quenching gives the highest HV value. The highest HV value for water is 398.4 while the lowest value is 326.1. The second highest HV value is using oil quenching which is 368.2 while the lowest HV value is 272.7. Air quenching gives the lowest HV values which are 241.5 and 178.2. From the data, the HV value shows using water quenching gives the highest HV value. It is because fastest cooling rate happens. When suddenly quenched, the martensite is formed. It is a very strong and brittle structure. For oil quenching, the cooling rate is slower than water quenching. Since oil has a very high boiling point, the transition from start of martensite formation to the finish is slow. When slowly quenched it would form austenite and pearlite which is partly hard and partly soft structure. Air quenching gives very slow cooling rate. Most medium carbon steels and low alloy steels undergo transformation to 100% martensite at room temperature. When the cooling rate is extremely slow then it would be mostly pearlite which is extremely soft (Prabudev, 1988). Compare to carburizing for 8 hours and carburizing for 10 hours, carburizing for 12 hours shows the value of HV is increasing in all quenching medium. It is because the longer carburizing time, more carbon agent can diffuse into the carbon steel. Therefore, more carbon atom interrupts the geometry of the structures, thus increasing the structures strength.

From all the data above, it shows that in certain position from the edge, the HV value drop rapidly for all carburizing hour and quenching medium. It is due to carburized layer had been decreased from the edge to the center. From that, the value of carburized layer can be calculated.

Table 4.4: Thickness of carbon layer at 950°C (1223 K)

Carburizing time (h)	Position/Oil (μm)	Position/Water (μm)	Position/Air (μm)
0	0	0	0
8	40	60	20
10	60	80	40
12	80	100	60

Table 4.4 shows the determination of carbon layer from 8 hours, 10 hours and 12 hours time, oil, water and air quenching and the position from the edge.

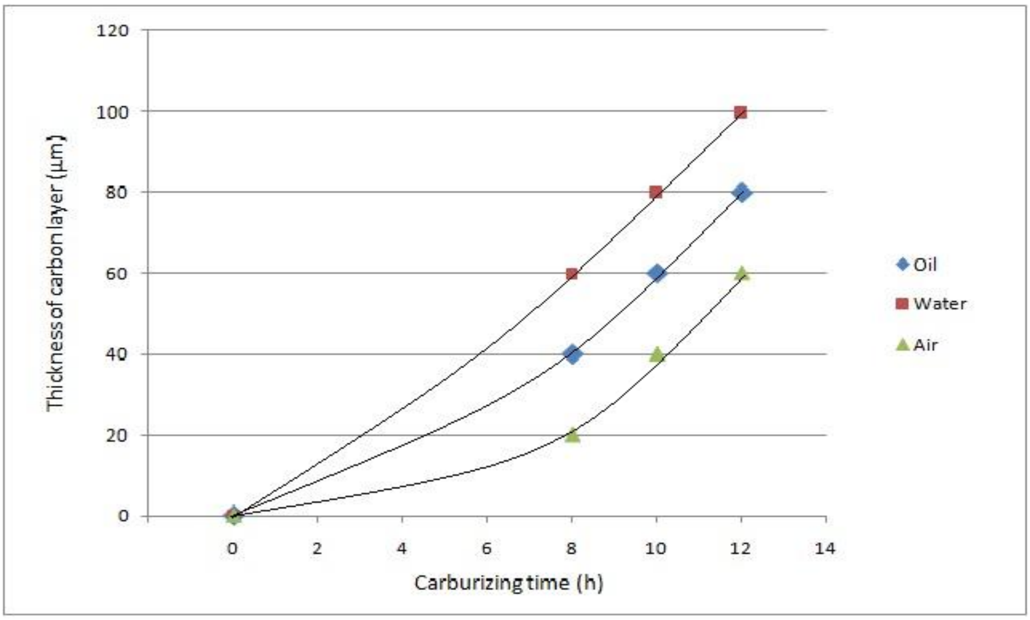


Figure 4.4: Graph of thickness of carbon layer vs. carburizing time

From Figure 4.4, it shows that water quenching gives the highest value of thickness of carbon layer in all carburizing time which are 8,10 and 12 hours. The carbon layer for water quenching in 12 hours carburizing time is 100µm, for 10 hours carburizing time is 80µm and 60µm for 8 hours. For oil quenching, it gives 80µm for 12 hours carburizing time, 60µm for 10 hours carburizing time and 40µm for 8 hours carburizing time. For air quenching, it gives 60µm for 12 hours carburizing time, 40µm for 10 hours carburizing time and 20µm for 8 hours carburizing time. From the results, it shows varied parameter gives different thickness of carbon layer. This happened due to the changing of the parameter which are carburizing temperature, carburizing time and quenching medium. Carburizing for 12 hours gives the highest carbon layer thickness because the longer carburizing time means that more carbon atom can diffuse into the material. Carburizing at 950°C gives the highest carbon layer thickness because when ferrite is heated to a temperature above the transformation line (723ºC), the body-centered-cubic (BCC) structure changes to face-centered-cubic (FCC) structure known as austenite which is allowing the absorption of the carbon into the crystal structure, thus increasing the structures strength. Quenching medium using water gives the highest carbon layer thickness because fastest cooling rate happened. When suddenly quenched, the martensite is formed. It is a very strong and brittle structure.

4.3 ACTIVATION ENERGY DETERMINATION

The thickness of carburized layer is mainly depends on the diffusion of carbon atoms into the substrate material. Thus, the activation energy can be determined by using the thickness of carburized formed (Jauhari et.al., 2007).

4.3.1 Vickers hardness results for carburizing

The results for carburizing in three temperature which are 850°C (1123K), 900°C (1173K) and 950°C (1223K) are shown in Table 4.5, Table 4.6 and Table 4.7. Each table shows the results for carburizing time which are 8 hours, 10 hours and 12 hours and used only one quenching medium which is oil. There are 20 readings for each table that can be used in activation energy determination.

Table 4.5: Carburizing for 8 hours

POSITION(µm)	HV(850°C)	HV(900°C)	HV(950°C)
0	249.2	268.4	281.3
20	246.9	265.1	277.1
40	240.3	252.1	271.6
60	235.8	249.6	263.8
80	230.3	245.3	255.1
100	225.5	240.2	245.3
120	220.1	233.7	241.8
140	215.7	225.2	238
160	210.4	220.4	235.9
180	205.4	214.7	231.4
200	199.4	208.6	225.6
220	193.4	204.5	219.8
240	185.2	198.4	215.2
260	178.9	194.6	211.7
280	172.2	187.7	207.5
300	167.6	181.9	199.1
320	159.2	176.2	194.5
340	153.2	171.2	188.8
360	149	166.4	185.9
380	149	166.4	185.9
400	149	166.4	185.9

Table 4.5 shows the position of carburizing layer for three different carburizing temperatures. Each position gives different value of Vickers hardness. The reading from 0 μm to 400 μm position shows the HV value decreasing to a same value. From the table, the highest and lowest HV values for 950°C carburizing temperature are 281.3 and 185.9. The highest and lowest HV values for 900°C carburizing temperature are 268.4 and 166.4. The highest and lowest HV values for 850°C carburizing temperature are 249.2 and 149.

Table 4.6: Carburizing for 10 hours

POSITION(μm)	HV(850°C)	HV(900°C)	HV(950°C)
0	296.9	339.3	350.2
20	296.9	330.2	349.7
40	294.3	320.1	349.4
60	283.9	310.5	348.7
80	279	291.5	340.1
100	271.1	284.5	335.2
120	265.4	277.7	332.1
140	260	269.8	325.4
160	254.3	264.5	321.3
180	244.2	261.3	315.3
200	230.4	256.7	311.1
220	224.7	251.2	305.2
240	216.2	247.5	298.1
260	210.7	242	294.5
280	201.3	236.9	288.7
300	197.4	230.5	283.2
320	194.5	224.5	279.1
340	189.2	218.7	275.5
360	184.9	215.3	271.2
380	184.9	215.3	271.2
400	184.9	215.3	271.2

Table 4.6 shows the position of carburizing layer for three different carburizing temperatures. Each position gives different value of Vickers hardness. The reading from 0 μm to 400 μm position shows the HV value decreasing to a same value. From the table, the highest and lowest HV values for 950°C carburizing temperature are 350.2 and 271.2. The highest and lowest HV values for 900°C carburizing temperature are

339.3 and 215.3. The highest and lowest HV values for 850°C carburizing temperature are 296.9 and 184.9.

Table 4.7: Carburizing for 12 hours

POSITION(µm)	HV(850°C)	HV(900°C)	HV(950°C)
0	323.4	345.9	368.2
20	318.4	342.4	367.9
40	312.6	340.9	367.4
60	295.4	337.1	366.8
80	272.9	325.2	361.2
100	266.4	323.2	350.5
120	258.9	319.5	346.1
140	243.9	315.3	341.1
160	235.6	310.6	335.5
180	230	304.2	331.2
200	223.5	299.3	326.7
220	222.9	289.9	321.9
240	217.6	283.7	314.7
260	208.1	277.7	308.7
280	203.9	271.2	299.5
300	199.3	264.2	294.8
320	194.2	258.7	286.5
340	184.3	254.9	280.5
360	176.2	250.9	272.7
380	176.2	250.9	272.7
400	176.2	250.9	272.7

Table 4.7 shows the position of carburizing layer for three different carburizing temperatures. Each position gives different value of Vickers hardness. The reading from 0 µm to 400 µm position shows the HV value decreasing to a same value. From the table, the highest and lowest HV values for 950°C carburizing temperature are 368.2 and 272.7. The highest and lowest HV values for 900°C carburizing temperature are 345.9 and 250.9. The highest and lowest HV values for 850°C carburizing temperature are 323.4 and 176.2. For all carburizing time, using 950°C as carburizing temperature shows the value of HV increased. It is due to when ferrite is heated to a temperature above the transformation line (723ºC), the body-centered-cubic (BCC) structure changes to face-centered-cubic (FCC) structure known as austenite which is allowing

the absorption of the carbon into the crystal structure, thus increasing the structures strength.

From all the data above, it shows that in certain position from the edge, the HV value drop rapidly for all carburizing hour and carburizing temperature. It is due to carburized layer has been decrease from the edge to the center. From that, the square of carburized layer thickness can be calculated.

Table 4.8: Square of carbon layer thickness (µm²) for oil quenching

	Temperature		
Carburizing time (s)	**1123 K**	**1173 K**	**1223 K**
28800	400	900	1600
36600	1600	2500	3600
43200	3600	4900	6400

Table 4.5 shows the determination of square of carbon layer from 28800 second, 36600 second and 43200 second time, 1123 K, 1173 K and 1223 K temperature and the position from the edge.

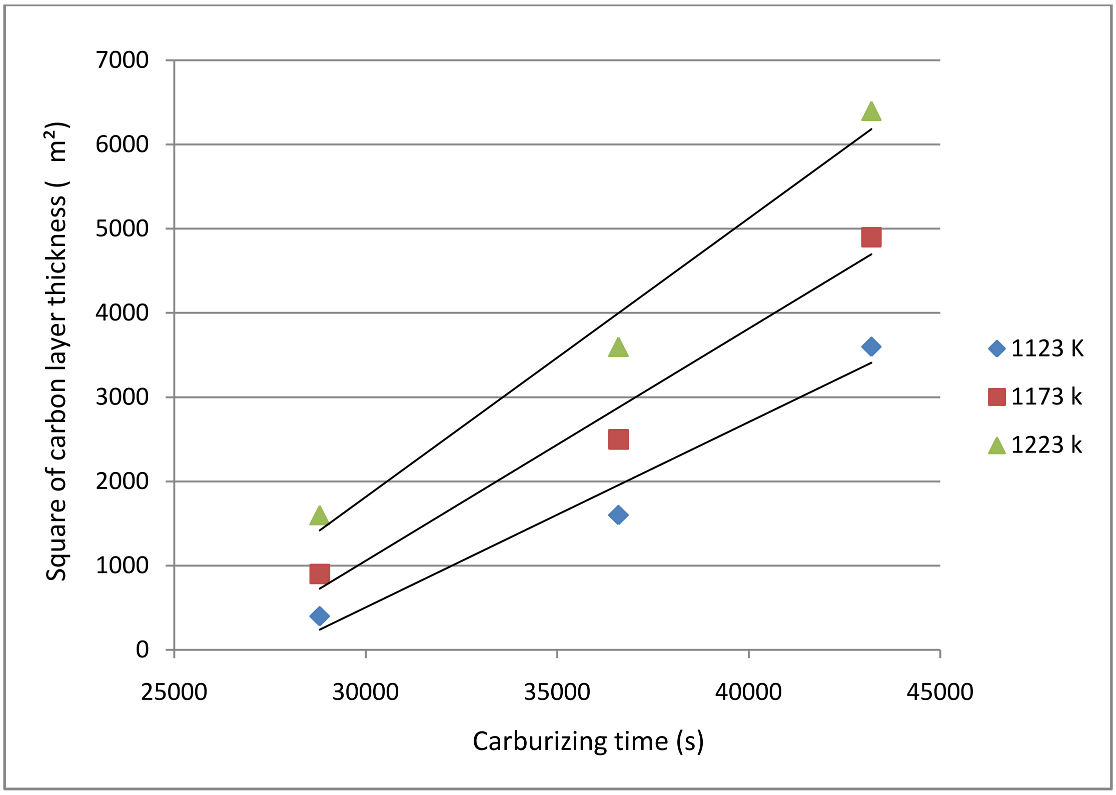


Figure 4.5: Square of carbon layer thickness vs. carburizing time

Figure 4.5 shows that the square of carbon layer thickness is directly proportional with carburizing time. From the slope of Figure 4.5, the diffusion coefficients, K (m^2s^{-1}) can be determined for each carburizing temperature. The data are listed in the table below:

Table 4.9: Value of K and ln K for each carburizing temperature

$K \times 10^{-13}$ $[m^2s^{-1}]$	$T^{-1} \times 10^{-4}$ $[s^{-1}]$	ln K $[m^2s^{-1}]$
2.22	8.9	-29.14
2.78	8.53	-28.91
3.33	8.18	-28.73

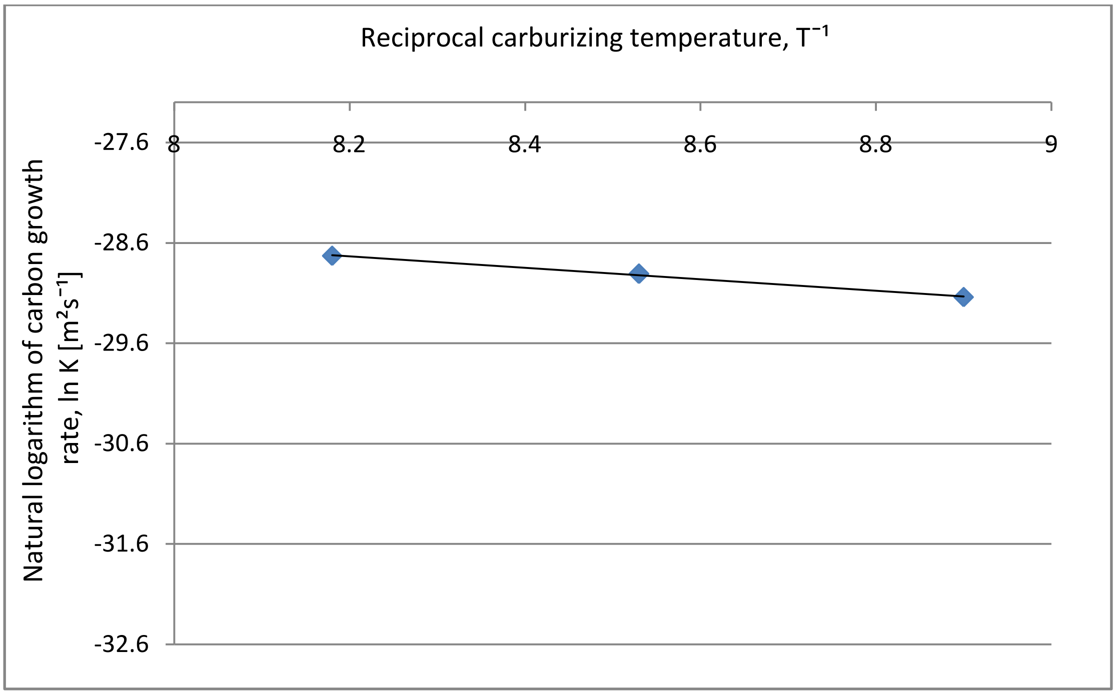


Figure 4.6: Natural logarithm of carbon growth rate (ln K) vs. reciprocal carburizing temperature (T^{-1})

Figure 4.6 shows the straight line, thus the slope will determine the activation energy (Q) of carburizing process. From the slope, the activation energy was determined which is 47.34 kJ/mol. This result indicates the carburizing process accelerates the diffusion of carbon atoms into the surface, thus increasing the thickness of carburized layer as well as the surface hardness.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

In this chapter, all about the whole research has been summarized. The observation and results analysis from the experiment are concluded. Besides that, recommendations also have given in this chapter for the future improvement.

5.2 CONCLUSION

Based on the results, it show that all parameter which are carburizing time, carburizing temperature and quenching medium revealed thick, uniform and dense carburized layer. The varied of each parameter obtained a different thickness of carburized layer. Surface hardness can be improved and increased by altering all the three parameters to the highest value. For carburizing time, the most effective time is 12 hours. For carburizing temperature, the most effective temperature is 950°C and for quenching medium, the most effective medium is water. In the terms of kinetics process, the activation energy was determined by 47.34 kJ/mol which is lower than previous study.

5.3 RECOMMENDATIONS

For every studies and researches that has been done, there is always room for further improvements. From this experiment, there are several suggestions that could be implanted for further improvements when running this research next time. First is the quenching medium, if industries want the strongest structural material which means water is the best answer but remember water is corrosive with steel, and the rapid cooling can sometimes cause distortion or cracking. The best quenching medium is oil because it has a very high boiling point, so that the transition from start of martensite formation to the finish is slow and this reduces the likelihood of cracking. Second, the researchers must follow the procedure effectively; there should be no mistake in carburizing time and carburizing temperature. If errors happened, which mean the temperature and time for the carburizing is over a certain limit, the experiment results will be wrong. Finally, the specimen to be carburized should be less carbon contain (0.02-0.10 wt. %) due to the less of carbon contain in a specimen, it is easier for carbon agent to diffuse into the material surface.

APPENDIX B1

Gantt Chart for
Final Year Project 1

Project Activities	**JANUARY**				**FEBRUARY**				**MARCH**				**APRIL**			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Title distribution	▨															
Meet Supervisor	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Brainstorming		▨	▨													
Identify problems statements			▨													
Determine objectives & scope				▨	▨											
Submit draft proposal						▨						▨				
Literature Review						▨	▨	▨	▨							
Methodology										▨	▨	▨	▨			
Log book submission													▨	▨		
Submit full proposal & presentation													▨	▨	▨	

APPENDIX B2

Gantt Chart for
Final Year Project 2

Project Activities	JUNE				JULY				AUGUST				SEPTEMBER				OCTOBER				NOVEMBER				DISEMBER			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Study experiment procedure	▨	▨	▨	▨																								
Specimen preparation					▨	▨	▨	▨																				
Run the experiment					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨									
Finish the experiment																▨	▨	▨	▨									
Collecting data																	▨	▨	▨									
Analyze data collection																		▨	▨									
Results and conclusion																		▨	▨	▨								
Submit draft 1 report to supervisor																			▨	▨								
Submit full thesis to faculty																					▨							
Collect back full thesis and make correction																						▨	▨					
Final presentation on FYP 2																								▨	▨			
Submit final full thesis to faculty																									▨			

REFERENCES

This research is prepared based on the following references:

Askeland D.R., *The Science and Engineering of Materials*, Alt. Ed., PWS Engineering, 1984,pp.288-303,351-376.

Chokshi A.H., *Mater. Sci. Eng.* A 410–411 (2005) 95–99.

Iswadi Jauhari, Shaifulazuar Rozali, Nik Rozlin Nik Masdek, Ogiyama Hiroyuki, *Surface properties and activation energy analysis for superplastic carburizing of duplex stainless steel;*466 (2007) 230–234

Jauhari I., Ogiyama H., Tsukuda H., *Mater. Sci. Res. Int.* 9 (2) (2003) 154–159.

Jena P.K., Bidyapati Mishra, RameshBabu M., Arvindha Babu, Singh A.K., SivaKumar K., Balakrishna Bhat T., *Effect of heat treatment on mechanical and ballistic properties of a high strength armour steel*; 37 (2010) 242–249

Krauss G., *Microstructure and properties of carburized steel. In: Metals handbook. Heat treating, vol. 4.* Materials Park, OH: ASM International; 1991.p. 363–75.

Krauss G., *Principles of Heat Treatment of Steels, American Society for Metals, Vol. 1*, pp. 251

Parrish G., *Carburizing: microstructures and properties.* Materials Park, OH: ASM International;1999.

Prabudev K.H., *Handbook of Heat treatment of Steels*, Tata McGraw-Hill, Inc., New Delhi, 1988.

Ray P.K., Ganguly R.I., Panda A.K., *Optimization of mechanical properties of an HSLA-100 steel through control of heat treatment variables.* Mat Sci Engg A 2003;346:122–31.

Sieurin H., Sandstrom R., *Eng. Fract. Mech.* 73 (2005) 377–390.
Smith W.F., Hashemi J., *Foundatios of Materials Science and Engineering, McGraw-Hill, Inc, 4th Edition,* 2006.

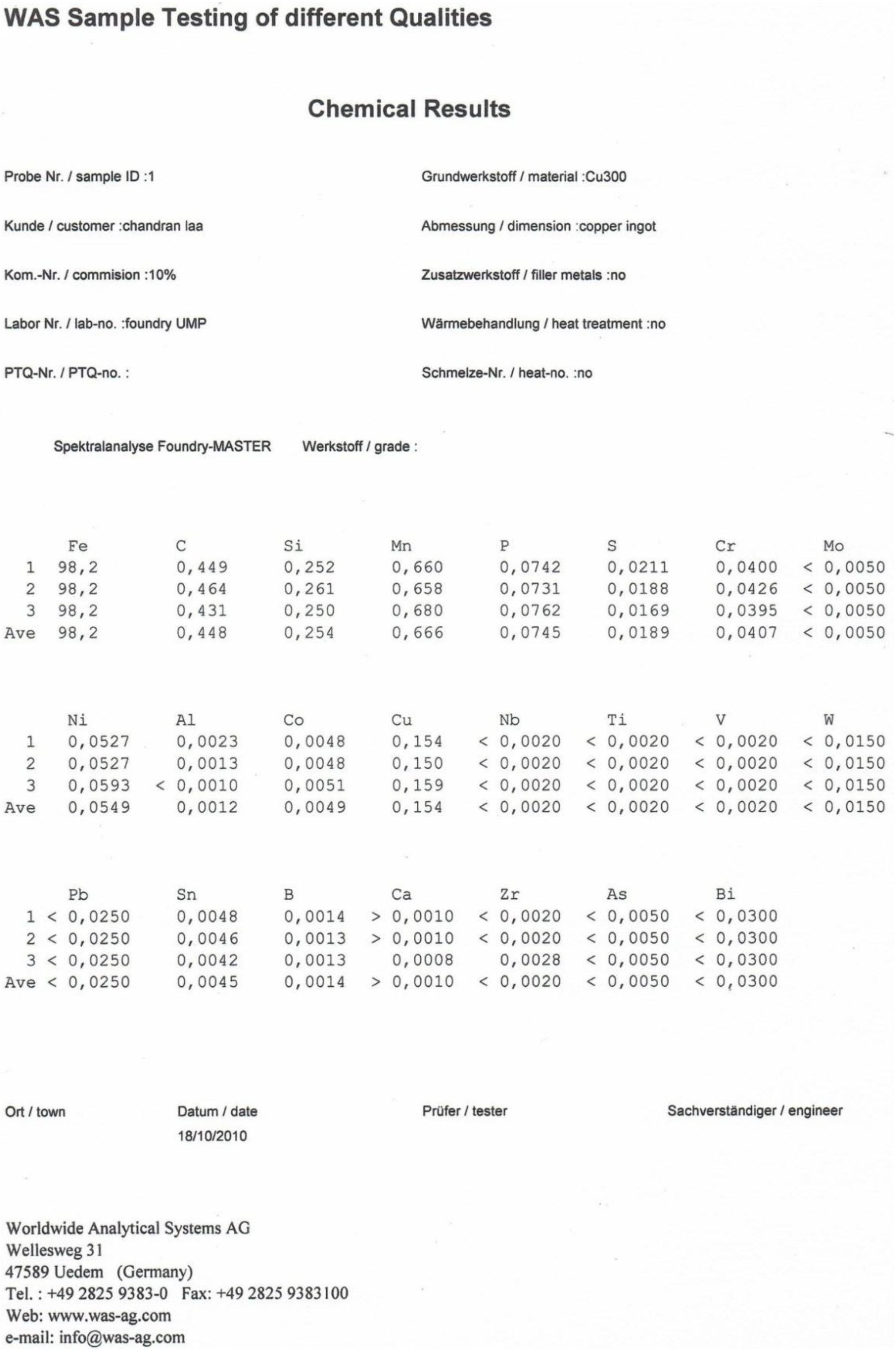
Sun Z., Kuo M., Annergren I., Pan D., *Mater. Sci. Eng.* A 356 (2003) 274–282.

Unterweiser P.M., Boyer H.E., and Kubbs J.J., *Heat Treaters Guide: Standard Practice and Procedure for Steel*, eds., ASM, Metals Park, Ohio, (1982). (UCD PSL: TN751.H4 1982(REF))

Zakharov B., *Heat treatment of metals.* New Delhi: CBS Publishers and Distributors; 1998. p. 81.

APPENDIX A

Table of chemical composition results



WAS Sample Testing of different Qualities

Chemical Results

Probe Nr. / sample ID :1	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	98,2	0,449	0,252	0,660	0,0742	0,0211	0,0400	< 0,0050
2	98,2	0,464	0,261	0,658	0,0731	0,0188	0,0426	< 0,0050
3	98,2	0,431	0,250	0,680	0,0762	0,0169	0,0395	< 0,0050
Ave	98,2	0,448	0,254	0,666	0,0745	0,0189	0,0407	< 0,0050

	Ni	Al	Co	Cu	Nb	Ti	V	W
1	0,0527	0,0023	0,0048	0,154	< 0,0020	< 0,0020	< 0,0020	< 0,0150
2	0,0527	0,0013	0,0048	0,150	< 0,0020	< 0,0020	< 0,0020	< 0,0150
3	0,0593	< 0,0010	0,0051	0,159	< 0,0020	< 0,0020	< 0,0020	< 0,0150
Ave	0,0549	0,0012	0,0049	0,154	< 0,0020	< 0,0020	< 0,0020	< 0,0150

	Pb	Sn	B	Ca	Zr	As	Bi
1	< 0,0250	0,0048	0,0014	> 0,0010	< 0,0020	< 0,0050	< 0,0300
2	< 0,0250	0,0046	0,0013	> 0,0010	< 0,0020	< 0,0050	< 0,0300
3	< 0,0250	0,0042	0,0013	0,0008	0,0028	< 0,0050	< 0,0300
Ave	< 0,0250	0,0045	0,0014	> 0,0010	< 0,0020	< 0,0050	< 0,0300

Ort / town	Datum / date	Prüfer / tester	Sachverständiger / engineer
	18/10/2010		

Worldwide Analytical Systems AG
Wellesweg 31
47589 Uedem (Germany)
Tel. : +49 2825 9383-0 Fax: +49 2825 9383100
Web: www.was-ag.com
e-mail: info@was-ag.com