EXPERIMENTAL STUDY OF PACK CARBURIZING OF CARBON STEEL

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ABSTRACT

The main purpose of this project is experimental study of pack carburizing of carbon steels by using two parameters (holding time and carburizing temperature). This study was conducted by using furnace. This process is carried out at temperatures from 850°C to 950°C (1123 – 1223K) for three various durations time which are 4, 8 and 16 hours. From the experiment, the surface hardness and thickness of carbon layer was different according to the parameters used. The quenching medium that use in this experiment is water. For carburizing temperature at 950°C, the highest of surface hardness value is 395.7 HV that carburized for 16 hours. For carburizing temperature at 900°C, the highest of surface hardness value is 373.4 HV that carburized for 16 hours and for carburizing temperature at 850°C which is the highest of surface hardness value is 345.5 HV. The thickness of carbon layer for 950°C was between 40μm to 120μm. The thickness of carbon layer for 900°C was between 40μm to 80μm and for 850°C was between 20 μm to 60 μm. Activation energy was determined which is 142.55 kJ/mol. The 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.

ABSTRAK

Tujuan utama kajian ini adalah untuk mengkaji eksperimen karburisasi baja karbon dengan menggunakan dua (masa penahanan dan suhu karburasi). Kajian ini dijalankan dengan menggunakan kebuk pembakaran. Proses ini dilakukan pada suhu 850°C sehingga 950°C (1123 – 1223K) untuk tiga masa berbeza iaitu 4,8 dan 16 jam. Daripada eksperimen ini, kekerasan permukaan dan ketebalan lapisan karbon berlainan mengikut pembolehubah yang digunakan. Agen pnyejuk yang digunakan dalam eksperimen ini adalah air. Bagi karburasi pada suhu 950°C, nilai kekerasan permukaan yang paling tinggi ialah 395.7 HV yang dikarburasi selama 16 jam. Bagi karburasi pada suhu 900°C, nilai kekerasan permukaan yang paling tinggi ialah 373.4 HV yang dikarburasi selama 16 jam dan bagi karburasi pada suhu 850°C dimana bacaan kekerasan permukaan yang paling tinggi ialah 345.5 HV. Bagi ketebalan lapisan karbon pada suhu 950°C ialah 40μm hingga 120μm. Bagi ketebalan lapisan karbon pada suhu 900°C ialah 40μm hingga 80μm dan bagi suhu 850°C ketebalan lapisan karbonnya antara 20 μm hingga 60 μm. Tenaga pengaktifan dikirakan iaitu 142.55 kJ/mol. Keputusan ini menunjukkan proses karburasi mempercepatkan kemasukan atom karbon ke dalam lapisan lalu meningkatkan ketebalan lapisan karbon begitu juga dengan kekerasan lapisan.

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CHAPTER 1

INTRODUCTION

1.1   INTRODUCTION

Low-carbon steel used in many mechanical components is tough, but also soft and flexible. There are advantages to its ductility. However its very nature means that the low-carbon steel's surface is susceptible to battering and wear. Generally, surface treatment processes will apply to produce ductile but tough components. After a component has been produced, it may still not have good condition in surface properties (Parrish G, 1999).

Case hardening is ideal for parts that require a wear-resistant surface and must be tough enough internally to withstand heavy loading. Steels best suited for case hardening are the low-carbon and low-alloy series. When high-carbon steels are through hardening, the hardness penetrates the core and causes brittleness. In case hardening, the surface of the metal is change chemically by introducing a high carbide or nitride content. The core remains chemically unaffected. When heat-treated, the high-carbon surface responds to hardening, and the core toughens. Typical applications for case hardening are gear teeth, cams, shaft, bearing, fasteners, pins, automotive clutch plates, tools, and dies (Parrish G, 1999).

Case hardening-also known as "pack carburising"-involves putting carbon (or a combination of carbon and nitrogen) into the surface of the steel to make it a high-carbon steel which can be hardened by heat treatment, just as if it were tool steel or any other high-carbon steel. Only the outer skin of the steel gets hard in case hardening,

while the center remains tough and malleable. This makes for a strong part with a very tough, durable surface (Parrish G, 1999).

Carburising is a case-hardening process by which carbon is added to the surface of low-carbon steel. This results in carburized steel that has a high-carbon surface and a low-carbon interior. When the carburized steel is heat-treated, the case becomes hardened and the core remains soft and tough. Two methods are used for carburizing steel. One method consists of heating the steel in a furnace containing a carbon monoxide atmosphere. The other method has the steel placed in a container packed with charcoal or some other carbon rich material and then heated in a furnace.

1.2   PROBLEM STATEMENT

The case depth is controlled by the adjustment of the carburizing time and temperature. There is a limit to which temperature can be increased in case hardening. At high temperatures, the structure of the core can be worse and it can affect the diffusion process. At elevated temperature, the rate at which the diffusing element is deposited on the surface of the specimen is greater than the rate at which it diffuses towards the core of the steel. This leads to uneven distribution of the concentration of the element and a high concentration which may lead to the formation of networks of chemical compounds such as carbides and nitrides, which impacts high brittleness to the surface layer. The yield strength of the core of a carburized component may be exceeded, particularly as the core is in a state of tensile stress. It very difficult to control case depth during carburizing to close tolerances because there have relative with heating and cooling times involved, which make the accurate control of actual carburizing temperature and time difficult.

1.3   RESEARCH OBJECTIVES

The objectives of this study are to:

    i.   Investigate the influence of time and temperature on pack carburizing

    ii.   Examine the activation energy on carburized layer based of varying time and temperature.

1.4   SCOPE OF THE RESEARCH

The scopes of this study are:

    i.   Pack carburizing using commercial grade carbon granule

    ii.   Using material which is AISI 1045.

    iii.   Using 3 different temperatures which are 850°C, 900°c and 950°C for carburizing.

    iv.   Using 3 different times which are 4 hours, 8 hours and 16 hours in carburizing.

    v.   Using one medium which is water in quenching.

    vi.   Using Vickers test to determine the hardness of certain part on the carbon steel.

    vii.   Using optical microscope to determine the thickness of carburizing layer.

CHAPTER 2

LITERATURE REVIEW

2.1   INTRODUCTION

Pure iron is not suitable for use as a structural material. It is weak, soft, is very ductile and does not respond to heat treatment to any appreciable degree. Steel, which is basically iron, alloyed with carbon and a few percent to a few tens of percent of other alloying elements can be heat treated to a wide range of strengths, toughnesses and ductilities. Carbon is the most important of these alloying elements in terms of the mechanical properties of steel and most heat treatments of steel are based primarily on controlling the distribution of carbon. Heat treatment is a process to change certain characteristics of metals and alloys like physical properties by either heating or cooling in order to make them more suitable for a particular kind of application. When heat treatment process occurs, the mechanical properties of metal will influence such as strength, hardness, ductility, toughness, and wear resistance.

2. 2   HEAT TREATMENT OF CARBON 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 happen because heat treatment fundamentally altering the microstructure of the carbon steel (Parrish G, 1999).

Firstly, 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 because of an increase in interstitial sites where carbon can sit between the iron atoms. During the alloying process elements, carbons are introduced to the metal that makes crystal structures changing to be more strength. That mean heat treatment makes increasing strength in crystal structure (D. R. Askeland, 1984).

Carbon steel can exist in various phases which are ferrite, austenite, and cementite. Figure 2.2 shows the phase in steel when heat treatment occur. The Y-axis (vertical) is a measurement of temperature while the X-axis (horizontal) is a measurement of the carbon content of the carbon steel. The far left hand side of the X-axis represents the ferrite phase of carbon 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 phase lines and occurs only above 1333 °F (D. R. Askeland, 1984).
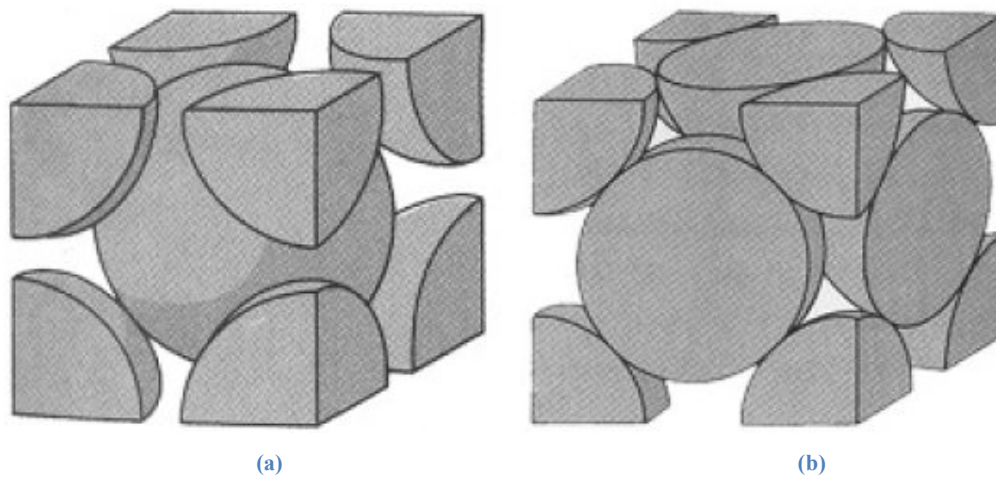
Figure 2.1: (a) Body-Centered Cubic (BCC), (b) Face-Centered Cubic (FCC)

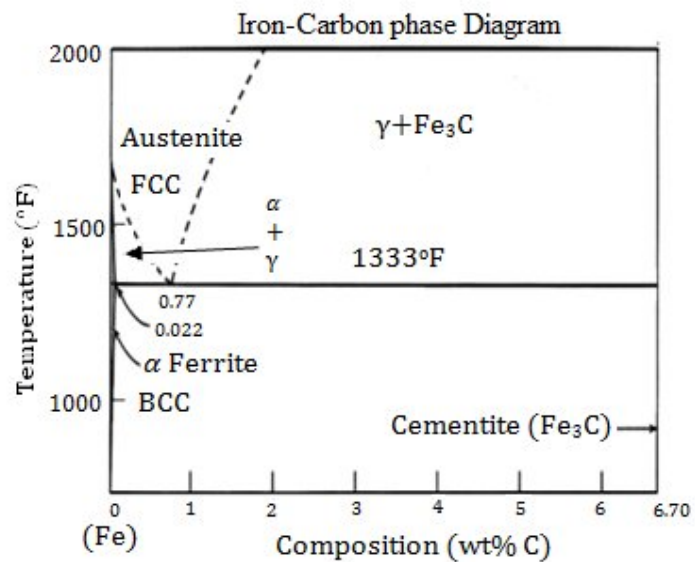Source: William D. Callister Jr., 1994

Figure 2.2: Iron-Carbon phase diagram

Source: William D. Callister Jr., 1994

Based Figure 2.2, ferrite is above the lined 1333°F. When ferrite (low carbon steel) is at room temperature, the crystal structure is a body-centered cubic structure, which is can only absorb a low amount of carbon. The un-absorbed carbon separates out

of the body centered-cubic structure to form carbides which join together to create small pockets of an extremely hard crystal structure within the ferrite called cementite because of low amount of carbon. When ferrite is heated to a temperature above the transformation line at 1333 ℉ (refer Figure 2.2), the body centered-cubic structure changes to a face-centered-cubic structure known as austenite. That mean amount of carbon absorbs in the crystal structure and make arrangement atom

When the carbon steel heat more than 1333 ℉, it in the austenitic phase and 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 will change from face-centered back to body-centered. Cementite will reform within the ferrite, and the carbon steel will have the same properties that it did before it was heated but when the steel is rapidly cooled, or quenched, in a quenching medium (such as oil, water, or cold air) the carbon does not exit the cubic structure of the ferrite and it becomes bond with the structure. This leads to the formation of martensite which is the microstructure that produces the most sought after mechanical properties in steel fasteners (Parrish G, 1999).

The successful heat treatment of steels to produce a predominantly martensitic microstructure throughout the cross section depends mainly on three factors

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

Carbon steel's ability to transform into martensite with a particular quenching treatment is called hardenability. This is due to the composition of alloy in the carbon steel. Each steel alloy has a specific relationship between its mechanical properties and its cooling rate. It is to be noted that hardenability is not some kind of resistance to indentention but it is actually a hardness measurement which is used to estimate the extent of martensitic transformation inside the material. A steel alloy which formed into martensite has a high ability at the surface and also a large degree throughout the entire

interior. In much simply words, hardenability is a measure of the degree to which a specific alloy may be hardened (D. R. Askeland, 1984).

The martensite newly formed is considered as a grain structure and it is very hard and brittle. The steel which has been quenched from austenitizing temperatures requires tempering before it can be placed into service due to the brittleness property in martensite. Tempering is a process of heating the carbon steel to a specific temperature below that of transformation line and the carbon steel is allowed to cool slowly. The slow cooling process will increase the ductility and decrease the hardness to specified level of the crystal structure. Based on the desired results for the steel the specific tempering temperature will be varied (Parrish G, 1999).

2.2.1 Carburizing

The addition of carbon to the surface of low carbon steel at temperature generally 850-950 degree Celsius is called carburization. Carburization is the most widely used method of surface hardening. It consists of enrichment of surface layers of low carbon or mild steel with carbon up to 0.8 % to 1%. This will superimposed the good wear and fatigue resistance on a tough low carbon steel core. It usually has 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, due to high carbon content it can results in retained austenite and brittle martensite which is the main reason it is often limited to 0.9%.

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 order 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 G, 1999).

The following carburizing processes are commonly used in industrial application:

1. Pack carburizing
2. Gas carburizing
3. Liquid carburizing

2.2.2 Pack Carburizing

Pack carburizing is a process of packing parts in a high carbon medium such as carbon powder or cast iron shavings and heated in a furnace for 12 to 72 hours at 900 ºC (1652 ºF). CO gas is produced at this temperature which is a strong reducing agent. Due to high temperature, carbon is diffused into the surface as the reduction reaction occurs on the surface of the steel. Based on experimental and theoretical calculations on diffusion theory the parts are removed and can be subject to the normal hardening methods when enough carbon is absorbed inside the part (Krauss G, 1991)

During the process the part which needed to be carburized is packed in a steel container and surrounded by granules of charcoal. The charcoal is treated with an activating chemical such as Barium Carbonate ($BaBO_3$) that promotes the formation of Carbon Dioxide (CO_2). CO_2 will then react with the excess carbon in the charcoal to produce carbon monoxide (CO). Next, carbon monoxide will react with low carbon steel surface to form atomic carbon which diffuses into the steel. Carbon gradient supplied by Carbon Monoxide is necessary for diffusion. It is to be noted that, carburizing process does not harden the steel but it just only increases the carbon content to some predetermined depth below the surface to a sufficient level to allow subsequent quench hardening. Figure 2.3 below show that about the carburizing process.

Carbon Monoxide reaction:

$$+ \quad \rightarrow 2$$
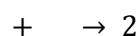
Reaction of Cementite to Carbon Monoxide:

$$2 \quad + 3 \quad \rightarrow \quad +$$

PACK CARBURIZING PROCESS
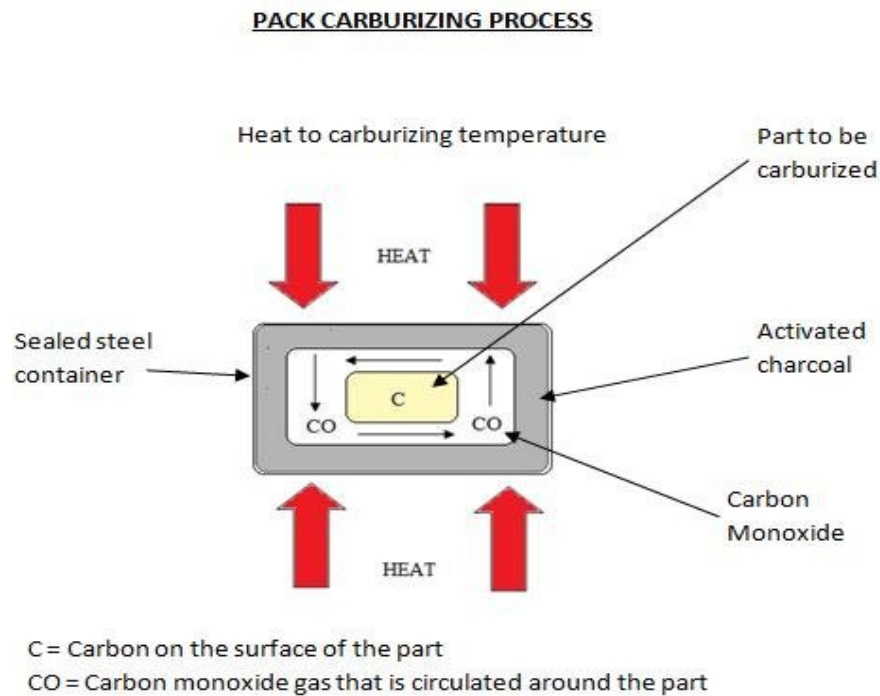
Figure 2.3: Pack carburizing process

Source: Romesh C.Sharma, 2003

2.2.3   Gas Carburizing

Gas carburizing consists of introducing carbon into the ferrous base material by heating in a gaseous atmosphere. Commercial gases, natural and propane, and easily vaporized hydrocarbon liquids are used to supply the desired quantity of carbon.

Batch type furnaces are used in this process. This furnace consists of an inner cylinder, made from noncarburizing alloy steel, and heated-insulated outer cylinder. The parts are placed in the inner cylinder. After that carburizing gas or oil will introduced, circulated by a fan. The furnace is sealed and the parts are soaked at the carburizing temperature for the required time for the depth of case desired. The carburizing temperature required is about 1700°F for case depths of 0.020″ to 0.030″. Longer carburizing periods will produce greater depths.

The parts are then quenched. Finally, they are reheated to a point above the transformation range of the case and quenched (Vijaya and Ranganjaran, 2004).

2.2.4 Liquid Carburizing

Liquid carburizing is a method of case-hardening or carburizing steel in molten baths. The baths are mixtures of cyanides, chlorides, and carbonates. The case that is produced is comparable with one resulting from pack or gas carburizing. The salts produce carbon and nitrogen that penetrate the surface.

The carburizing action depends upon sodium cyanide or barium cyanide, which supplies the carbon and some nitrogen. Non-cyanide carburizing applications are available. They produce excellent results.

Liquid carburizing temperatures usually range from 1500°F to 1750°F. Faster penetration can be obtained if higher temperatures are used. However, this method increases material cost and causes rapid deterioration of equipment. Cases as deep as 0.30″ can be obtained with a cyanide content of 20% using carburizing temperatures from 1550°F to 1650°F (Vijaya and Ranganjaran, 2004).

This advantage of this method can be summarized as follows:

     i.   Uniform case depth and carbon content
    ii.   Rapid penetration depth
   iii.   Rusting, pitting, and corrosion minimized
    iv.   Reduction of time required for steel to reach carburizing temperature
    v.   Low installation cost.

2.2.5 Quenching

The process to improve the mechanical properties of steel products, such as hardness, stiffness, and strength, by the means of opportune solid–solid phase changes, induced by a heating, holding, and cooling thermal cycle is called quenching process it is widely used and the main purpose of the heating and the holding stages is to transform starting material structure into a homogeneous austenitic phase. During the process, workpiece is undergoing forced cooling to induce the opportune decomposition of austenite into several microstructures such as martensite, pearlite, ferrite and Fe-carbide that depending on the chemical composition of the processing carbon steel and the local cooling rate. (K.H. Prabudev, 1988).

The timing of each step such as heating, cooling rates and the holding temperature are very important. This is because high heating rates could results to excessive temperature gradients which will then causes internal stresses, deformations or cracks. For non-homogeneous austenite formation, the temperature and duration of the holding stage should be carefully planned to obtain a fully austenitic structure, avoiding excessive grain size, and reducing energy consumption and costs, due to extended holding at relatively high temperature. Finally, in order to induce the austenite decomposition into desired microstructures by reducing residual stresses and part distortions, the choice of cooling medium, cooling temperature and cooling technique is very crucial for the cooling stage. (K.H. Prabudev, 1988).

The most commonly used quenching media are:

1. Water (plain or salt water)

2. Oil

3. Air

After carburizing, carburized components are normally quenched from the austenite temperature range to obtain maximum hardness at the surface. A carburized component may either be quenched directly from carburizing temperature, or reheated (after slow cooling) to appropriate austenitizing temperature and quenched. Mildest possible quench, consistent with desired hardening, is normally used to minimize the possibility of quenching cracks and distortion of the components during quenching. Whenever possible, direct quenching from carburizing temperature is done to minimize operational time and costs. After pack carburizing, direct quenching is not possible, and hence, the components have to be reheated for quench hardening (Romesh C.Sharma, 2003).

Sometimes, even the parts carburized by gas and liquid carburizing are slow cooled to room temperature, and then reheated for quench hardening. This may be done for one or more of the following reasons:

i.   Some carburized components ay require some machining before the hardening operation. In such cases, parts are slowly cooled and machined in the soft state, before quench hardening.

ii.   When grain coarsening has occurred during carburizing, it is desirable to reheat the components for quench hardening to refine the grain size to some extent.

iii. Surface carbon concentration of pack carburizing components is normally at saturation level, and that may be higher than the desired value. Liquid carburized components may also at the times have higher surface carbon content than desired. Such components, when quenched directly, would have relatively higher retained austenite levels, and consequently lower hardness values, near the surface. Furthermore, high retained austenite levels near the surface lead to problems during the grinding of these components. It may be recalled that retained austenite increases with increasing carbon content. Generally, the retained austenite should be less than 15%. When carburized components are reheated for hardening, carbon gradient near the surface get somewhat moderated by carbon diffusion and the surface carbon concentration is somewhat reduced, leading to reduced retained austenite.

2.3   HARDNESS ANALYSIS

2.3.1   Activation Energy

The activation energy is determined by measuring the effect of temperature on the rate of the reaction. At a higher temperature there is greater proportion of reactants with the required activation energy (E $\geq$ Ea), increasing the rate of the reaction. However change of temperature does not depend to activation energy. It only changes the frequency of collisions and the proportion of reactants with the kinetic energy, E that is greater than or equal to the activation energy, Ea (E $\geq$ Ea). Arrhenius proposed an equation to represent the proportion of molecules with E $\geq$ Ea (John M. Coulson, John Francis Richardson, 1995).
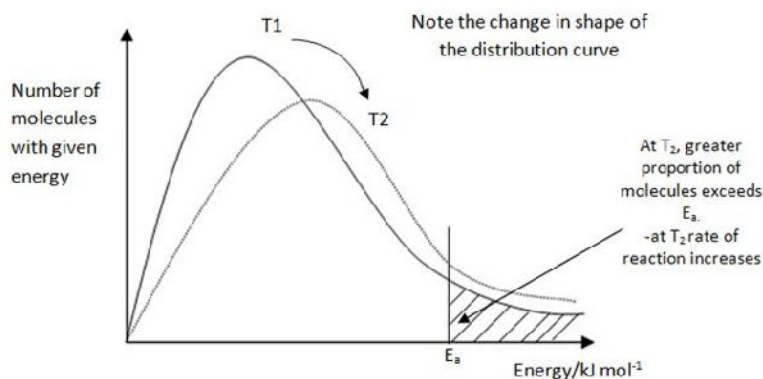
Figure 2.4: Graph number of molecules versus Energy

Figure 2.4 shows the relationship for equation 2.1.

$$= \frac{\rule{3cm}{0.4pt}}{} = \overline{}$$

(2.1)

This mathematical model developed into now what is called the Arrhenius equation.

$$= \quad (\text{—}) \tag{2.2}$$

Where;

= the Arrhenius constant or frequency factor. It is related to the collision frequency and the probability that the molecules have the correct orientation/geometry at the point of collision.

= the activation energy in $Jmol^{-1}$

= the gas constant ($8.314\ JK\text{-}1mol^{-1}$)

= the absolute temperature (K)

= the rate constant (s^{-1})

From the Arrhenius equation, add natural log and the activation energy can be determined.

$$= \text{—} + \tag{2.3}$$

And then plot ln k versus 1/T (called an Arrhenuis plot) a straight line is obtained.

$$= \frac{\quad}{/} \tag{2.4}$$

The activation energy can be determined from the slope/gradient of the line using:

$$= \frac{\text{—}}{\quad}$$

$$\tag{2.5}$$

This is example using Arrhenius equation to determined activation energy in pack carburizing. The activation energy of carburizing process can be determined by using the thickness of carburized layer formed. Figure 2.5 shows the cross-sectional microstructure of superplastically carburized DSS at 1223K with 8 hours carburizing time. From Figure 2.5, the carburizing layer can be observed clearly with dropping hardness value (I. Jauhari, 2007).
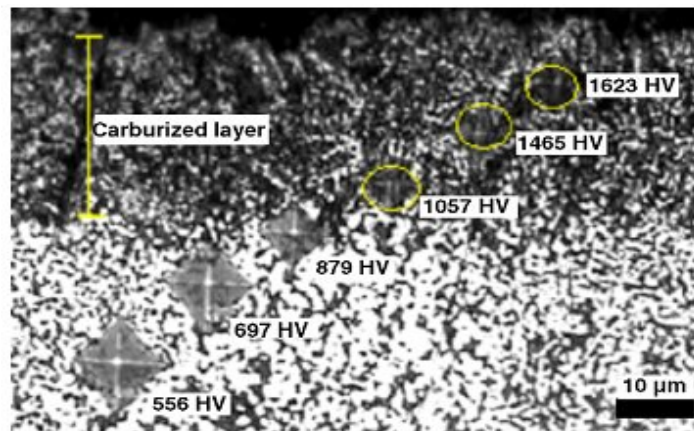

Figure 2.5: Optical micrograph showing the hardness indentation variation from the outer layer to the interior of superplastically carburized DSS at 1223K for 8 h.

From Vickers test, the dropping hardness value can be determined with graph surface hardness (HV) versus distance from surface (μm) that takes from edge to core. It had been shown in Figure 2.6 (I. Jauhari, 2007).
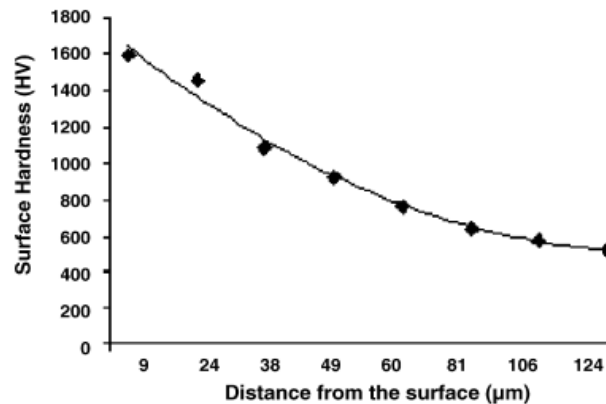
Figure 2.6: Cross-section hardness profiles of super plastically carburized DSS at 1223K for 8 hours.

When the thickness carburizing layer had been found, graph thickness of carbon layer (μm) versus carburizing time (hour) was plotting that shown in Figure 2.7.
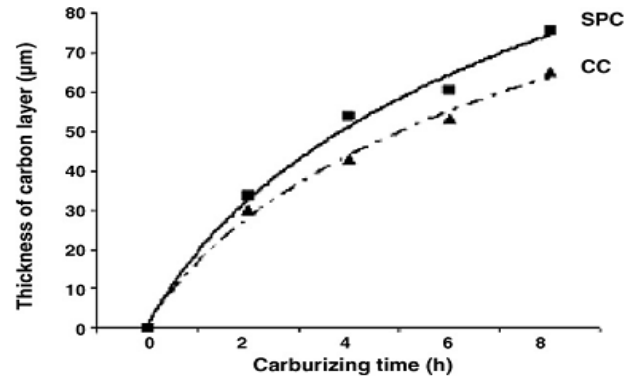

Figure 2.7: The variation of carbon layer thickness with carburizing time at 1223K.

The thickness of carbon layer from the graph increasing with increasing time and follows parabolic law as below:

$$d^2 = Kt \tag{2.6}$$

Where;

        d= the carbon layer thickness (μm)

        K= carbon growth rate constant
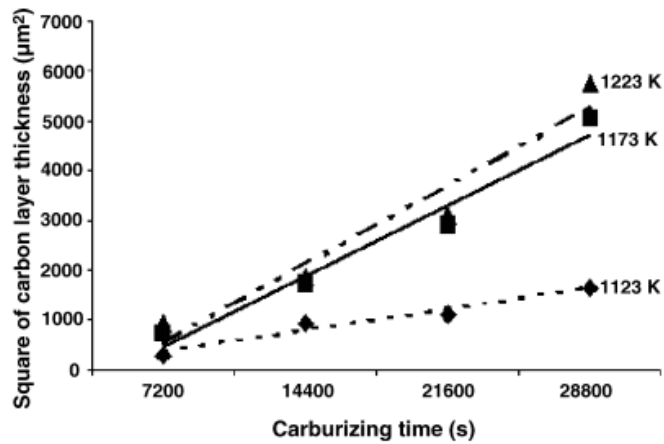
        t= carburizing time (s)

Figure 2.8: Square of carbon layer thickness of superplastically carburized DSS vs. carburizing time.

Figure 2.8 shows the square of carbon layer thickness superplastically carburized DSS changes linearly with time that comes from Figure 2.6 and using parabolic law to make the graph linear. Therefore, the relationship between the diffusion coefficient, K (m^2s^{-1}), activation energy, $Q(Jmol^{-1})$ and carburizing temperature, T (K) can be expressed by Arrhenius equation as follow:

$$= \quad ^{(—)} \tag{2.7}$$

Where;

K_0= pre-exponential constant

$R = 8.314\ Jmol^{-1}\ K^{-1}$

T = temperature (K)

Q= activation energy

Taking the natural logarithm of equation 2.7, equation 2.8 can be derived as follow:
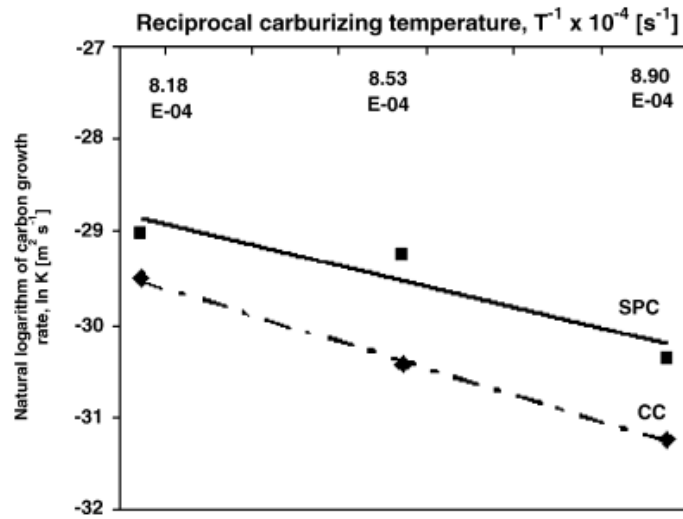
$$= \quad + (— \quad)(\quad) \tag{2.8}$$

Figure 2.9: Natural logarithm of carbon growth rate (ln K) vs. reciprocal carburizing temperature (T−1) for superplastically and conventionally carburized DSS.

Figure 2.9 shows the plot of natural logarithm of carbon growth rate (ln K) versus reciprocal of carburizing temperature (T−1) for both SPC and CC processes is linear. Thus, the slope of the straight line will determine the activation energy (Q) of each carburizing process (I. Jauhari, 2007).

2.3.2   Diffusion Energy

Diffusion is the process by which atoms move in a material. Many reactions in solids and liquids are diffusion dependent. Structural control in a solid to achieve the optimum properties is also dependent on the rate of diffusion. Diffusion can be defined as the mass flow process in which atoms change their positions relative to neighbors in a given phase under the influence of thermal and a gradient. The gradient can be a compositional gradient, an electric or magnetic gradient, or stress gradient (Vijaya and Ranganjaran, 2004).

Diffusion processes can be either steady-state or non-steady-state that are distinguished by use of a parameter called flux. It is defined as net number of atoms crossing a unit area perpendicular to a given direction per unit time. For steady-state diffusion, flux is constant with time and for non-steady-state diffusion, flux varies with time. The graph of concentration gradient with distance for both steady-state and non-steady-state diffusion processes are shown in Figure 2.10 (Vijaya and Ranganjaran, 2004).
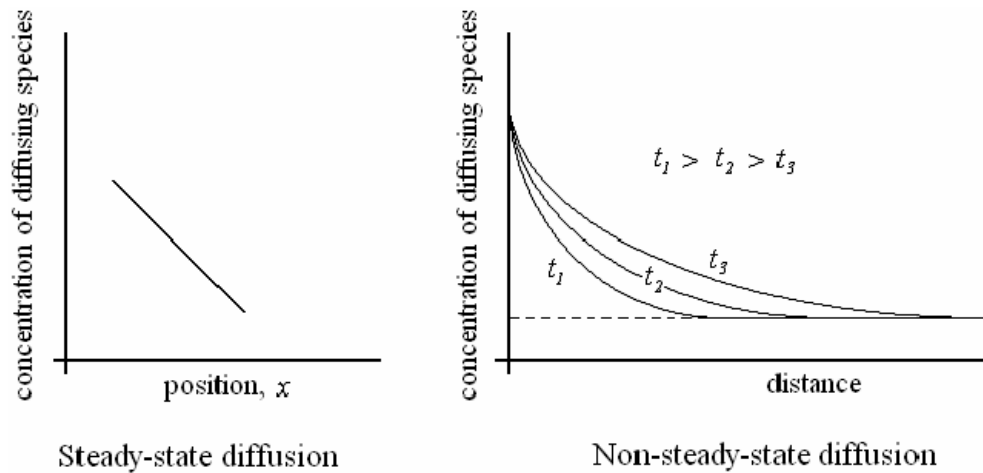

Figure 2.10: Steady-state and Non-steady-state diffusion processes.

Steady-state diffusion is described by Fick's first law which states that fluxes (J), is proportional to the concentration gradient. The constant of proportionality is called diffusion coefficient, D (cm2/sec). Diffusivity is characteristic of the system that depends on the nature of the diffusing species and the temperature at which diffusion occurs. Anyway, when the flux is independent of time and remains the same at any cross-sectional plane along the diffusion direction that is under steady-state flow. For the one-dimensional case, Fick's first law is given by

$$ = - \quad — = \frac{1}{—}— $$

(2.9)

And

$$\neq \quad (\ ,\ ) \tag{2.10}$$

Where;

D= the diffusion constant

$-$= the gradient of the concentration c

$-$= the number atoms crossing per unit time a cross-sectional

plane of area A

For non-steady-state processes there are concentrating to the position changes with time and make the flux changes with time too. This is because of diffusion flux were depends on time which means that a type of atoms accumulates in a region or depleted from a region that may cause them to accumulate in another region. For this process, the Fick's law had been introduced, which is expressed by

$$- = - - = - \quad - $$

$$\tag{2.11}$$

Where;

$-$= the time rate of change of concentration at a particular

position x

If D is assumed to be a constant

$$- = \quad - $$

$$\tag{2.12}$$

During carburizing, temperature has a most profound influence on the diffusivity and diffusion rates. It is known that there is a restriction to diffusion created by atoms those need to move to let the diffusing atom pass. Therefore, the temperature makes the atomic vibrations for assist diffusion. Empirical analysis of the system resulted in an Arrhenius type of relationship between diffusivity and temperature (Vijaya and Ranganjaran, 2004).

$$= \quad \overline{} \qquad\qquad\qquad (2.13)$$

Where;

$\quad$ = Temperature-independent pre exponential (m^2s^{-1})

$\quad$ Q= the activation energy for diffusion ($Jmol^{-1}$)

$\quad$ R= the gas constant (8.31 $Jmol^{-1}$-K^{-1})

$\quad$ T= absolute temperature (K)

Taking the natural logarithm of equation 2.13, equation 2.14 can be derived as follow;

$$= \quad + (- \quad)(\quad) \qquad\qquad\qquad (2.14)$$

From this equation, the graph In D versus T^{-1} will plot to find the activation energy which is from the gradients that shows in Figure 2.11.
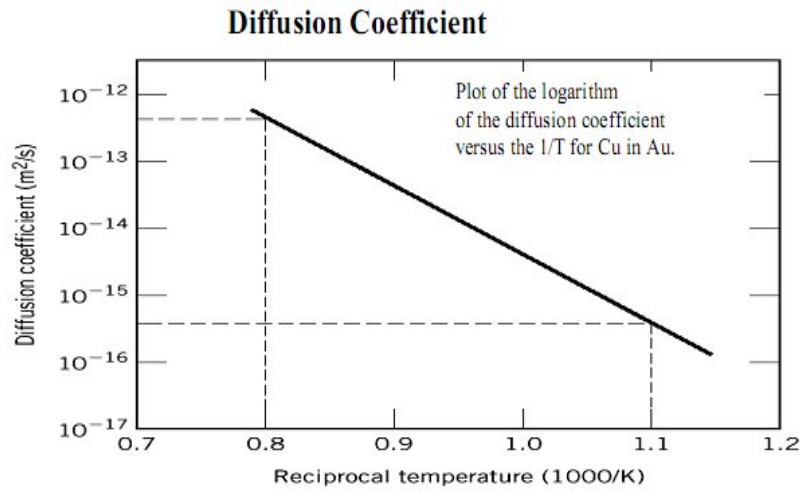
Figure 2.11: In D versus T^{-1}

This is example using diffusion energy to determined activation energy in pack carburizing. The carbon profiles along with case depth of the pack carburizing will derive by using Fick's second law. A two-step optimization procedure will develop in order to compute the optimum values of the activation parameters (activation energy for diffusion and diffusivity coefficient) of carbon in austenite as well as carbon potential that is form at the surface of the carburizing specimen under different conditions of temperature, time and coke-catalysts mixtures. This experiment will use SAE 8620 H steel and three different mixtures that will use for agent carbon in pack carburizing. Table 2.1 shows the mixture that use in this experiment

Table 2.1: Composition of the pack carburizing mixtures

Composition	Mixture A	Mixture B	Mixture C
Coke	90	100	85
$BaCO_3$	5	-	10
$NaCO_3$	5	-	5

The carbon profile after carburizing was determined from chips obtained at 0.1 mm intervals from the outer face of the samples until the chemical analysis was found close to the carbon composition of the base steel. The machining process was carried

out carefully without lubrication. The determination of the carbon content of the case layer was conducted in a Leco CS-46 analyzer, taking the mean of three samples and the value obtained was then reported in relation to the midpoint of the cemented case, according to the ASTM standard G79-C. The carbon profile of the cemented case was also evaluated by means of SEM techniques (Phillips 505) employing a WDX analyzer (Microspec WDX-2A). In this case, the change in carbon content was evaluated linearly from the outer surface to the center of the samples (H. Jiminez, 1999).
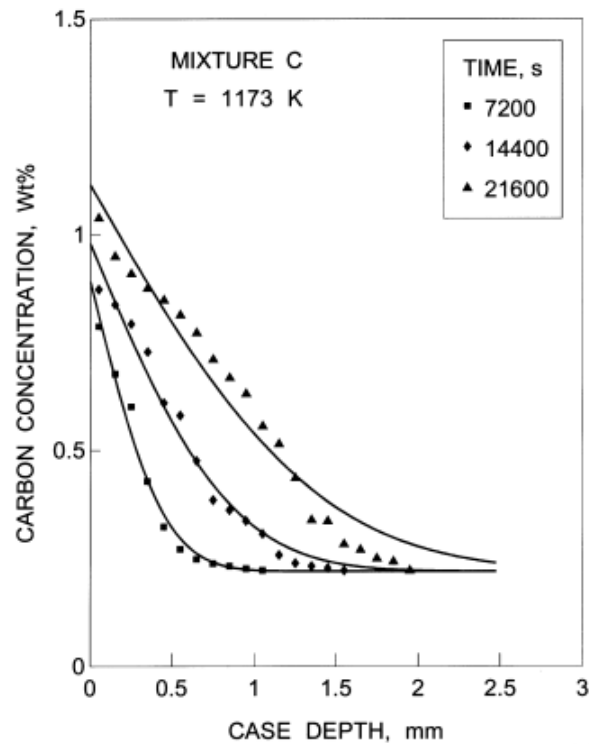

Figure 2.12: Carbon concentration profile obtained with the carburizing compound designated as mixture C, at 1173 K. The solid curve represents the theoretical description obtained by optimization of the parameters CS and D.

The Figure 2.12 shows the amount of carbon after pack carburizing in mixture C for example. The carbon profiles determined by means of chemical analysis of the chips machined from the specimens, after carburizing at 1173 K for 4 hours with mixtures C employed. The carbon concentration is observed to decrease smoothly from the surface to the interior of the work- piece, with the trend to achieve asymptotically the carbon content of the steel. The solid lines shown in these figures correspond to the theoretical