1-DIMENSIONAL TRANSIENT HEAT TRANSFER AXI-SYMMETRIC MATHEMATICAL MODELLING TO DETERMINE LOWEST HARDNESS POINT OF QUENCHED STEEL BAR

ABDLMANAM. S. A. ELMARYAMI

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Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

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ABSTRACT

One-dimensional (1D) model of any axisymmetric industrial quenched steel bar based on finite element method (FEM) has been applied to investigate the influence of process history on its material properties of seventy-five (75) cases on ten (10) different samples of steel. The lowest hardness point (LHP) and the effect of the radius of any steel bar on its temperature history and on LHP is determined. In this research hardness in specimen points was obtained by calculating characteristic cooling time for phase transformation ($t_{8/5}$) to hardness. The model can be employed as a guideline to design cooling approach to achieve desired microstructure and mechanical properties such as hardness. A computer program of the model is developed, which can be used independently or incorporated into a temperature history software named LHP-software to continuously calculate and display temperature history of the industrial quenched steel bar and thereby calculate LHP and to study the effect of radius on temperature history and on LHP. Also the effect of different austenitizing temperatures and the effect of different quenching medium are studied. This technique (LHP-software) is more effective as compared to the conventional methods (Rockwell, Brinell, Vickers Hardness Tester, ...etc) because they only used hardness calculated at the surface that is higher than LHP, which has negative consequence and can result in bending, deformation and failure of the component, as example it was found that the hardness on the surface of alloy steel 50B46H [R=12.5mm, 850 °C, water quenched] = 52.808, while LHP = 44.953. LHP-Software can be used instead of a number of real tools in steel industrial applications and is useful in a wide range of steel industrial field. The developed sofware based on (1-D) FEM model has been verified by comparing its hardness results with commercial finite element software results and also validated by experimental results. The comparison indicates its validity and reliability.

ABSTRAK

Model Satu-Dimensi (1D) bagi bar keluli industri simetrik, berdasarkan kaedah unsur terhingga (FEM), telah digunakankan untuk menyiasat kesan proses pembuatan pada sifat bahan untuk tujuh puloh lima (75) kes bagi sepuloh (10) sampel keluli yang berbeza. Titik kekerasan terendah (LHP) dan kesan jejari bar keluli pada sejarah suhu dan LHP di tentukan. Dalam kajian in, kekerasan pada titik titik spesimen di perolehi dengan mengambil kira ciri masa penyejukkan untuk transformasi fasa $t_{8/5}$ dengan kekerasan. Model ini boleh di gunakan sebagai panduan untuk menentukan kaedah penyejukkan keluli bar yang sesuai bagi mendapatkan struktur mikro dan sifat bahan yang dikehendaki. Satu perisian komputer telah di bangunkan, yang boleh di gunakan secara berasingan ataupun boleh di gabungkan dalam perisian sejarah suhu, dinamakan Perisian-LHP, yang berkebolehan mengira dan memaparkan sejarah suhu secara berterusan untuk bar keluli industri dan seterusnya dapat mengira LHP dan dengan itu berkebolehan menunjukkan kesan jejari bar pada sejarah suhu dan pada LHP. Selain itu, kesan beberapa suhu austenite dan kesan beberapa media celup berbeza juga di kaji. Teknik ini (Perisian-LHP) adalah lebih berkesan berbanding kaedah konvensional (Rockwell, Brinell, Vickers, dll) kerana kaedah kaedah ini hanya mengira kekerasan pada permukaan sahaja, yang mana kekerasan ini adalah lebih tinggi dari LHP, dan berkemungkinan memberikan kesan negatif, seperti lenturan, deformasi dan kegagalan komponen, seperti yang di tunjukkan dalam contoh kekerasan permukaan keluli aloi 50B46H [R=12.5mm, 850°C, celupan air] = 52.808 dan LHP = 44.953. Perisian-LHP ini boleh digunakan menggantikan beberapa alatan di industri keluli dan juga berguna untuk berbagai bidang industri keluli. Perisian yang dibangunkan berdasarkan model 1D FEM ini juga telah disahkan dengan membandingkan hasil kekerasan bar tersebut dengan keputusan dari eksperimen dan juga dengan perbandingan dengan keputusan dari perisian unsur terhingga komersial dan juga keputusan ujikaji makmal. Perbandingan ini menunjukkan kesahihan dan kebolehpercayaan keputusan dari kajian ini.

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CHAPTER 1

INTRODUCTION

1.1 THESIS BACKGROUND

It would be unjust to state that any one metal is more important than another without defining parameters of consideration. For example, without aluminium and titanium alloys, current airplanes and space vehicles could not have been developed. Steel, however, is by far the most widely used alloy and for a very good reason. The reason for steel's dominance is usually considered to be the abundance of iron ore (iron is the principal ingredient in all steels) and/or the ease by which it can be refined from ore. Iron is by no means the most abundant element, and it is not the easiest metal to produce from ore. Copper, for example, exists as nearly pure metal in certain parts of the world. Steel is such an important material because of its tremendous flexibility in metal working and heat treatment to produce a wide variety of mechanical, physical, and chemical properties [1].

Steel is still the preferred material for framing commercial buildings and is commonly used for residential construction [2].

Steel is both the most widely used and most recycled metal material on earth. From stainless and high temperature steels to flat carbon products, steel's various forms and alloys offer different properties to meet a wide range of applications. For these reasons, as well as the metal's combination of high strength and a relatively low production cost, steel is now used in countless products [3].

Heat treatment is a process where solid steel or components manufactured from steel are subject to treatment by heating to obtain required properties, e.g. softening, normalising, stress relieving, hardening [4].

It is a process in which a metal is heated to a certain temperature and then cooled in a particular manner to alter its internal structure for obtaining the desired degree of physical and mechanical properties such as brittleness, hardness, and softness [5].

Heat treating of steel is the process of heating and cooling of carbon steel to change the steel's physical and mechanical properties without changing the original shape and size. Heat treating is often associated with increasing the strength of the steel, but it can also be used to alter certain manufacturable objectives such as, to improve machinability and restore ductility etc. Thus, heat treating is a very useful process to help other manufacturing processes and also improve product performance by increasing strength or provide other desirable characteristics. High carbon steels are particularly suitable for heat treatment, since carbon steel responds well to heat treatment and the commercial use of steels exceed that of any other material. There are many different types of heat treating processes; each individual process provides different desirable characteristics to the product [6].

Quenching technology is a highly non-linear process in which temperature, phase-transformation, and stress/strain affect each other [7].

Quenching refers to the process of rapidly cooling metal parts from the austenitizing or solution treating temperature at which austenites are formed, typically from within the range of 815 to 870 °C (1500 to 1600 °F) and then quenching, or cooling it rapidly in medium such as water or oil. The ultimate goal of the quenching process is to transform the austenite to the martensite form by cooling steel rapidly under this condition [8].

The hardness prediction is an integration of Jominy end quenched test data [9].

Many methods for quenching exist, including: cooling in air, water, oil, and salt. The type of cooling process used helps to determine how fast or how slowly the steel cools. Ultimately, the rate of cooling helps determine many of the important characteristics of the steel [10].

By corresponding the cooling rate from 800 °C to 500 °C with hardness of Jominy end quenched test curve, one is able to predict the hardness [11].

Steel is an alloy of iron with approximately 2 % or less carbon. Pure iron is soft and thus, not good for structural applications, but the addition of even small amounts of carbon to iron hardens it and transforms it into 'steel' with better mechanical properties, such as greater strength. Adding other elements such as nickel, chromium, manganese, tungsten, and silicon can modify the properties of steel. For example, chromium is used to increase the resistance of steel to corrosion [12].

The hardness of the quenched-steel depends on both cooling speed and on the composition of the alloy. Steel with a high carbon-content will reach a much harder state than steel with a low carbon-content [13].

A larger diameter rod quenched in a particular medium will obviously cool more slowly than a smaller diameter rod given with similar heat treatment. [14]

1.2 PROBLEM STATEMENT

Simulation of steel quenching is a complex problem, dealing with estimation of microstructure and hardness distribution [15], and with evaluation of residual stresses and distortions after quenching [16]. The mechanisms of reactions during rapid quenching have given rise to much controversy and exact explanation of the transformation processes is still lacking. In order to predict the structural constitution and hardness after cooling, a continuous cooling diagram (CCT) can be used to represent the structural transformation during steel cooling. However, the CCT diagram is expensive to prepare and it is strictly for the determination of elemental composition and temperature of austenization. The simplest way of characterizing the microstructure transformations is to measure the hardness of steel [17]. When the indentor is forcing over the sample, the surface under sample deforms both elastically and plastically. Plastic deformation begins when mean pressure is 1.1 yield stress. Fully plastic deformation is when mean pressure is equal to 3 x yield stress, after that if the force increase, pressure doesn't increase, as contact area between indentor and sample increases proportional to force. The mean pressure when deformation is fully plastic is Hardness; the relationship between the hardness HV and yield strength σ_y approximately follows the form of Tabor's formula as below:

$HV \approx 3 \times \sigma_u$ [18].

It is much simpler than the tensile test and can be non-destructive because the small indentation of the indenter may not be detrimental to the use of an object; consequently the hardness test is used extensively in the industry for quality control [19]. With the evolution of digital computer in recent years, there is a growth in research on computational prediction of steel hardening [20]. Bozidar Liscic et al. (2010) reported that simulating the hardness of as-quenched steel specimen can be done using a rather simple method whereby a characteristic cooling time is the main variable in determining the hardness [15].

LHP calculation experimentally is an almost impossible task using manual calculation techniques. Furthermore, earlier methods such as Rockwell, Brinell, Vickers hardness testers ...etc only used hardness calculated at the surface, which is higher than LHP, where this can have negative consequences resulting in bending, deformation and failure of the component. This simulated hardness can be used as a guideline to mark the quality of steel bar, where designers and engineers may be able to justify its use in steel industries globally to determine the lowest hardness point (LHP) and predict the hardness ability of steel.

1.3 THESIS AIM

To calculate the lowest hardness point [LHP] and to predict the hardness ability of any quenched steel bar in the radial axis from the centre to the surface. Various different types of steel will be studied by developing (1-D) unsteady state heat transfer mathematical model, and a (LHP)-Software to reflect the mathematical model. The effects of radii, quenching media and the austenitizing temperatures on the hardness of the LHP will be determined.

1.4 THESIS OBJECTIVE

The objectives of this thesis work are:

1. To model 1-D heat transfer mathematical model formulations in order to predict temperature history for efficient production of high quality component.
2. To apply 1-D unsteady state heat transfer mathematical models to the case of axi-symmetric cylindrical steel bar during quenching.
3. To transform the proposed mathematical formulation into a user friendly computer program.
4. To simulate the temperature and time history and to analyze the thermal behavior of any heat treated transient cylindrical steel bar during quenching.
5. To evaluate the simulation hardness results on the surfaces with respect to experimental results and commercially established data and hence, assesses the accuracy of proposed methodology.
6. To predict the hardness at any point (node) and determine LHP, LHP's microstructure, LHP's surrounding microstructures and to study the effect of radius and quenching medium on temperature history and LHP.

1.5 THESIS SCOPE

The scopes of this thesis work are:

1. Mathematical modelling of 1-Dimensional radius will be developed which will then be converted to a computer program. The program can be used independently or incorporated into (LHP)-software to continuously calculate and display temperature history and thereby calculating LHP.
2. Seventy five (75) cases on ten (10) different samples of steel will be analyzed.
3. The affect of several quenching media (water, sea water and oil), several austenitizing temperatures (850, 900 and 950 °C) on the cooling process and the affect of different radii (12.50, 25, 50 and 100 mm) on temperature history and LHP will be analysed.
4. (LHP)-Software results will be verified with commercial finite element software results and will also be validated by experimental work results.

1.6 THESIS ORGANIZATION

The thesis is organized as follows:

Chapter 1: Introduction

This chapter discusses on all aspects; statements of the problems, the outline of the thesis objective, scope of study and the thesis methodology.

Chapter 2: Literature Review

This chapter focuses on the quenching process and hardness. Past researches will also be studied and discussed.

Chapter 3: Developing of unsteady state heat transfer axisymmetric 1-D FEMM to determine LHP and to study the effect of radius on temperature history and on LHP of industrial quenched steel bar.

Chapter 4: Result and discussion

In this chapter, the 1-D mathematical modelling (transient), (LHP)-Software, commercial finite element software (ansys) and experimental work results will be analysed and discussed. The unsteady state mathematical model will also be verified with commercial finite element software (Ansys) and validated with experimental work.

Chapter 5: Conclusion, contribution and recommendation

This chapter reviews the work presented in this work and presents the conclusion that can be drawn from it. Possible areas that warrant further research efforts will be suggested.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is a description of steel, the iron carbon equilibrium diagram, the steel section of the Iron - Carbon Diagram, heat treatment, quenching, TTT diagram, steel manufacturing and steel bar production procedure. A literature survey of past researches into the numerical techniques in the steel processing industry is also discussed. Relevant numerical methods and finite element methods used are presented. Brief insights into the commercial uses of the methods are also discussed.

2.2 Background of steel

Steel is everywhere in our lives; in cars, houses, trains, applications that make lives easier. Steel is strong and light, durable and corrosion-resistant, adaptable and completely recyclable.

Nearly 150 years ago, steel sparked the industrial revolution, "steel has been part of some of the greatest achievements in history: It was the "iron horse" and steel rails that helped carve a nation out of the frontier. Steel is the backbone of bridges, the skeleton of skyscrapers, and the framework for automobiles. Today, it is still revolutionizing the way of the live. It is the high-strength, lighter-than-plastic frames for eyeglasses; more durable frame in housing; it is the high-tech alloy used in the Space Shuttle's solid fuel rocket motor cases; and it is the precise surgical instruments used in hospital operating rooms around the world." [21]. Steel is in just about everything that is used today.

2.3 Definition of steel

Steel is the most common and widely used metallic material in today's society. A prime example of the versatility of steel is in the automobile, where it is the material of choice and accounts for over 60 % of the weight of the vehicle. It is strong and is used in the body frame, motor brackets, driveshaft, and door impact beams of the vehicle. Steel is dent resistant compared to other materials and provides exceptional energy absorption in a vehicle collision. It is inexpensive compared to other competing materials such as aluminium and various polymeric materials [22].

In the past, steel has been described as an alloy of iron and carbon. Today, this description is no longer applicable since in some very important steels, e.g., interstitial-free (IF) steels and type 409 ferritic stainless steels, carbon is considered an impurity and is present in quantities of only a few parts per million. By definition, steel must be at least 50 % iron and must contain one or more alloying elements. Each chemical element has a specific role to play in achieving particular properties or characteristics, e.g., hardness, strength, corrosion resistance, magnetic permeability, and machinability [22].

Carbon in steel may be present up to 2 %. Steels with carbon content from 0.025 percent to 0.8 percent are called hypo-eutectoid steel. Steel with a carbon content of 0.8 percent is known as eutectoid steel. Steels with carbon content greater than 0.8 percent are called hyper-eutectoid steel. There are three major categories of steel which are as follows [23]:

2.3.1 Low carbon steel

Low carbon steel [LCS] has a carbon content that ranges between 0.02 % and 0.30 %, making up the highest tonnage of all steels produced in a given year [24].

2.3.2 Medium carbon steel

Medium carbon steel [MCS] is carbon steel that contains between 0.3000 and 0.7000 percent carbon and is capable of being quenched to form martensite and tempered to develop toughness with good strength [25].

2.3.3 High carbon steel

The high carbon steel [HCS] (0.70-1.70 C%) is usually quench hardened and lightly tempered at 250 °C to develop considerable strength with sufficient ductility for springs, cutting tools and dies [26].

Tempering at a temperature up to 200 °C only relieves stresses to some extent, but between 250 and 400 °C the martensite changes to troostite, and tempering to above 400 °C the martensite changes to a softer structure known as sorbite, which has less strength, weaker but more ductile than troostite [27].

Increased carbon means increased hardness and tensile strength, and more difficult machining [28].

Alloy steels [AS] are basically carbon steels with certain chemical elements added to improve the properties of the metal for specific applications or end products. Alloying elements include carbon, sulphur, copper, phosphorus, manganese, nickel, boron, molybdenum and chromium, and the resulting material is called an alloy steel [29].

A study of the constitution and structure of all steels and irons must first start with the iron-carbon equilibrium diagram [ICED] followed by the TTT diagram. Many of the basic features of this system (Figure 2.1 and Figure 2.2) influence the behaviour of even the most complex alloy steels. For example, the phases found in the simple binary Fe-C system persists in complex steels, but it is necessary to examine the effects that alloying elements have on the formation and properties of these phases. The iron-carbon diagram provides a valuable foundation on which to build knowledge of both plain carbon and alloy steels in their immense variety [30].

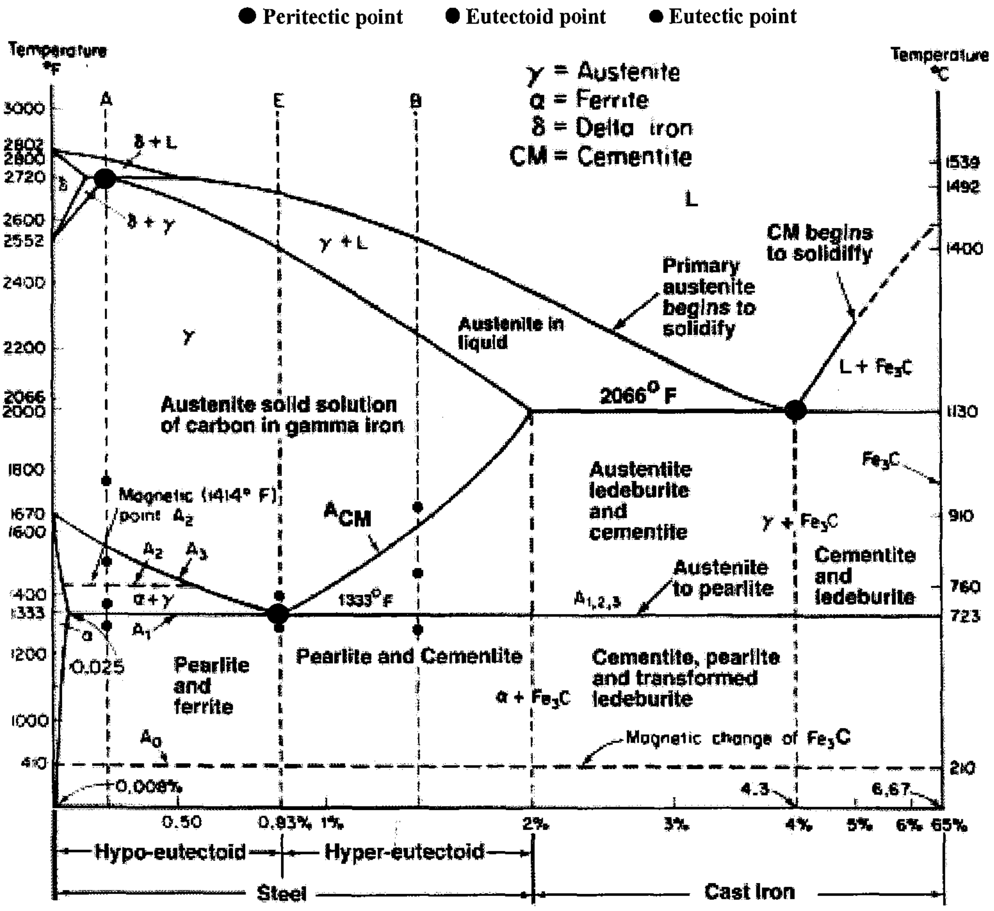

Figure: 2.1: Fe-Fe$_3$C Phase Diagram [31].

(i) Peritectic reaction equation may be written as

Delta (δ) + Liquid (L) -->Austenite

(ii) Eutectoid reaction equation may be written as

Solid (γ) --> Ferrite + Fe$_3$C (Cementite) (Heating Eutectoid mixture (Pearlite))

(iii) Eutectic reaction equation may be written as

Liquid (L) --> Austenite + Cementite (Eutectic mixture (Ledeburite))

2.4 Heat Treatment of Steel and TTT Diagram

Heat Treatment may be defined as the heating and cooling operations applied to metals and alloys in the solid state so as to obtain the desired properties. Heat treatment is sometimes done inadvertently due to manufacturing processes that either heat or cool the metal such as, welding or forming. In this research, the heat treatment of steel will be considered. Heat treatment is often associated with increasing the strength of material, but it can also be used to refine the grain size, relieve internal stress, to improve machinability and formability and to restore ductility after a cold working process [23].

Heat treatment is a combination of timed heating and cooling operations applied to a metal or alloy in the solid state so as to produce certain microstructures and desired properties. Annealing, Normalizing, Quench Hardening (as in this research), Tempering, and Austempering are five of the important heat treatments often used to modify the microstructure and properties of steels. The microstructure produced by any of the above heat treatments can be deduced using Continuous Cooling Transformation (CCT) diagrams, which are directly related to the Time Temperature Transformation (TTT) diagrams for the specific steel being treated. A TTT diagram for steel is shown in Figure 2.2. The microstructures that result from various heat treatments are dependent on the cooling rate from the austenite range; they are predicted using the TTT diagram with superimposed cooling curves for the selected material [32].

2.4.1 The main types of heat treatment of Steel

The main types of heat treatment applied in practice are: annealing, normalization, quenching (hardening), tempering and austempering as shown in Figure 2.2.

2.4.1.1 Quenching

Quenching as shown in Figure 2.2 refers to the process of rapidly cooling metal parts from the austenitizing temperature, typically from within the range of 815 to 870 °C (1500 to 1600 °F) for steel. Stainless and high-alloy steels may be quenched to minimize the presence of grain boundary carbides or to improve the ferrite distribution but most steels including carbon, low-alloy, and tool steels, are quenched to produce controlled amounts of martensite in the microstructure. Successful hardening usually means achieving the required microstructure, hardness, strength, or toughness while minimizing residual stress, distortion, and the possibility of cracking. The selection of a quenchant medium depends on the hardenability of the particular alloy, the section thickness and shape involved, and the cooling rates needed to achieve the desired microstructure. The most common quenchant media are liquids. The liquid quenchants commonly used include: Oil, water or water that may contain salt. The ability of a quenchant to harden steel depends on the cooling characteristics of the quenching medium. Quenching effectiveness is dependent on the steel composition, type of quenchant, or the quenchant use conditions. The design of the quenching system also contributes to the success of the process [33].

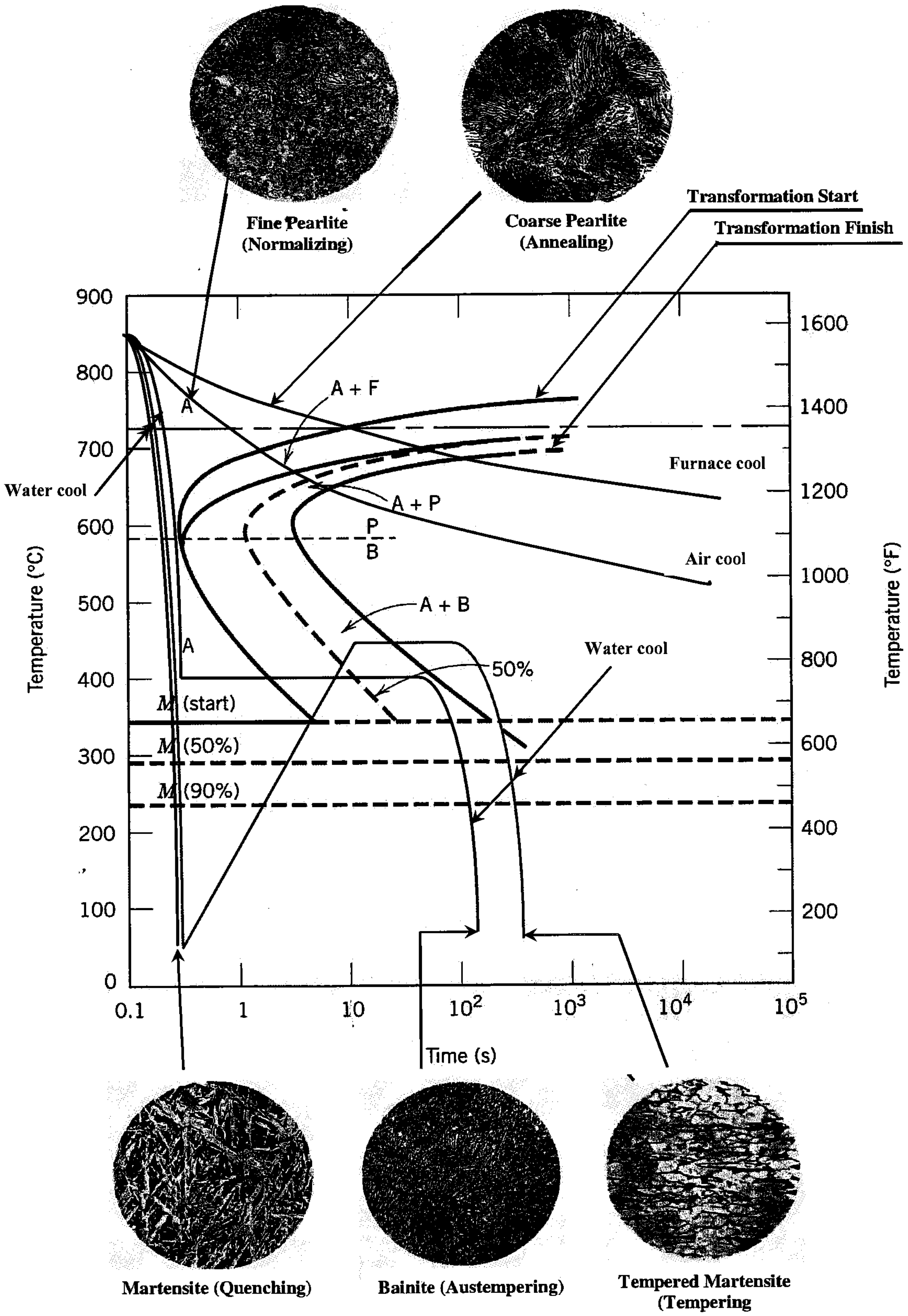

Figure 2.2: TTT diagram [32].

However only quenching will be studied in this research, where it is physically one of the most complex processes in engineering, and very difficult to understand. Simulation of steel quenching is also a complex problem [34].

Quenching technology is a highly non-linear process in which temperature, phase-transformation, and stress/strain affect each other [35]. The soaking of a metal at a high temperature above the recrystallization phase then followed by a rapid cooling process. The quenching of steel creates martensites [36, 37].

Hardening is one of the oldest metallurgical processes known to man, originally in the form of heating a sword in the fire and then throwing it into the lake to make it harder. [38]. The mechanical behaviour of an as-quenched steel directly depends on the steel hardening degree [39].

Quenching is a heat treatment usually employed in industrial processes in order to control mechanical properties of steels such as toughness and hardness. The process consists of raising the steel temperature to above a certain critical value, holding it at that temperature for a specified time and then rapidly cooling it in a suitable medium to room temperature. The resulting microstructures formed, (ferrite, cementite, pearlite, upper bainite, lower bainite and martensite) will depend on the cooling rate and the chemical composition of the steel [40].

Quenching of steels is a multi-physics process involving a complicated pattern of coupling among heat transfer; and because of the complexity, coupled (thermal-mechanical-metallurgical) theory and non-linear nature of the problem, no analytical solution exists. However, numerical solutions are possible by the finite difference method, finite volume method, and the finite element method (FEM) which will be used in this research.

Research of numerical simulation of the hardening degree, i.e. hardness distribution in quenched steel specimen is one which is given high priority in simulation of the phenomena of steel quenching [34].

The quality of a steel quenching process depends on the intrinsic (alloy controlled) hardenability of the steel and the heat transfer rate during the quench, a successful quench is one that develops substantial martensite in the sample with a minimum amount of cracking. Achieving this result requires a careful choice of the steel, the quenching liquid, and the quench conditions. For economic reasons, it is desirable to use the steel with the lowest alloy content to obtain the required hardness and hardenability. Thus, the cooling capacity of the quenching liquid is of vital importance to the quench. An ideal cooling rate for a quench is one that is fast in the high-temperature range where austenite decomposes easily into ferrite and iron carbide, and slow in the low-temperature range where austenite transforms into martensite. A rapid cooling rate in the high temperature range suppresses the formation of ferrite and iron carbide and thereby increases the formation of martensite at lower temperatures; a slow cooling rate in the low-temperature range minimizes thermal stress and suppresses quench cracking [41].

This work aims to generate a knowledge base, both fundamental and applied, on developing finite element mathematical model of the heat treated quenched steel bar to determine LHP and to study the effect of radii on temperature history and on LHP. The hardness in specimen can be estimated by the conversion of time cooling for phase transformation results by using both, the relation between cooling time and distance from the quenched end of the Jominy specimen and the Jominy hardenability curve. The characteristic cooling time relevant for phase transformation in most structural steels, is the time of cooling from 800 to 500 °C (time $t_{8/5}$) [42-47].

No published information is available till date to calculate the lowest hardness point [LHP] except the publications from this research (twenty nine article, chapter in a book, two awards and patent under consideration), where it is exactly inside the heat treated quenched steel bar at half length at the centre of the bar (node E) as shown in Figure 3.2 and Figure 3.3, which is experimentally almost impossible. Manual calculation techniques from earlier methods only used hardness calculated at the surface element 4 at (node 5) as shown in Figure 3.11 and 4.18, which is higher than the lowest hardness point (node E) that can have a negative consequence resulting in bending, deformation and failure of the component. The work done here envisages a major contribution towards understanding the behaviour of steel at elevated temperatures during quenching at the lowest hardness point of the steel bar; and this will be very useful in order to obtain the maximum benefit against bending, deformation and failure of the component.

A larger diameter rod quenched in a particular medium will obviously cool more slowly than a smaller diameter rod given with similar heat treatment. [48]

Therefore, it is important to know the lowest hardness point (LHP), and since the radius of the quenched steel bar is large, thus the lowest hardness point will decrease, i.e. lower than the hardness on the surface. This means the increase in radius of the bar will be inversely proportional to the hardness at the lowest point (node E), while the hardness on the surface will be approximately the same.

During the quenching process of the steel bar, the heat transfer is in an unsteady state as there is a variation of temperature with time. The heat transfer analysis in this research will initially be carried out in 3- dimensions.

The three dimensional analysis will then be reduced into a 1-dimensional axisymmetric analysis to save cost and computing time. This is achievable because in axisymmetric conditions, there is no temperature variation in the theta (Θ) and (z) directions, thus the temperature deviations is only in (r) direction. The Galerkin weighted residual technique will be used to derive the mathematical model.

1-D line (radius) element will be used. A 1-D element is defined by two nodes. Therefore, the variation of the dependent variable can be represented as temperature at any point (node) even inside the heat treated quenched steel bar, over the element regions as shown in chapter 3, Figure 3.2, Figure 3.3 and its results by applying FEM shown on chapter 4.

2.5 Previous Researches

In this section review of selected studies done by previous authors regarding finite element methods (FEM) in the steel processing industry are explained as the following and the conclusion shown in Table 2.1.

US Patent 6238087 (2001), disclosed method and apparatus for characterizing a quench for determining a series of heat transfer coefficients. The heat transfer coefficient is used in computer programs for predicting hardness characteristics of a steel part subject to the quench. The method comprises of: determining a difference between information representative of the desired hardness characteristic and information representative of a hardness characteristic produced by a known quench on at least one specimen part having at least one distinguishing characteristic, and if the difference is less than a predetermined value, then producing information representative of a characterization of the known quench, and if the difference is greater than or equal to the predetermined value, then determining and producing information representative of a characterization of a new quench based on the difference. The apparatus comprises of a strong device containing information representative of a hardness characteristic produced by at least one known quench on at least one specimen, information representative of at least one distinguishing characteristic of at least one specimen affecting the hardness characteristic thereof, and information representative of a characterization of at least one known quench, a processor operable for determining a difference between information representative of the desired hardness characteristic and the known quench of at least one specimen [49].

US Patent 2559016 (1951), disclosed methods for determining hardenability of steel and more particularly, determining what alloy elements and how much of each will be necessary to produce a steel having a desired hardenability. The method of determining the hardenability of steel, comprises of making a series of steel having the same basic composition but varying in the content of one alloying element. Then making cylindrical quenching specimens of said steels in various sizes, quenching said specimens under identical conditions, and measuring the diameters of the largest specimen of each said steel. The steels which is hardened throughout, such as the critical diameter at which the quenched specimen is characterized by the absence of a relatively soft core within an external hardened case, thereby obtaining a relation between such critical diameter and the content of the said alloying element giving the hardenability factor of the letter. Then repeating the procedure set forth above for various elements entering into the composition of steel, the hardenability of steel containing known amounts of several elements given by the product of the hardenability factors corresponding to such amounts of all the elements present in the steel. A hardness-testing device similar to Rockwell C hardness tester has been found satisfactory for the purpose, and one-sixteenth-inch intervals provide a sufficient closeness of measurements without unduly complicating testing operations. Hardness figures are recorded and plotted against the distance from the surface [50].

John D. Bernardin, et al, (1995) disclosed a validation of the quench factor technique in predicting hardness in heat treatable aluminium alloys. The article is describing the relationship between the heat transfer mechanisms and metallurgical transformation associated with spray quenching in the heat treating of aluminium alloys. The quench factor technique is used for predicting the hardness and strength of aluminum alloys. Then, a procedure of heat treatment with spray quenching and artificial age-hardening method is used. The input parameter for predicting hardness of a particular alloy is its temperature-time history during quenching. Temperature-time quench data measured both in small specimens and a relatively L-shaped specimen are combined with metallurgical transformation data for aluminum alloy 2024-T6 to predict Rockwell B hardness. The predicted hardness is compared with the values measured for both types of specimens to validate the quench factor technique [51].

Bozidar Liscic, et al, (2010) disclosed a prediction of Quench-Hardness within the whole volume of axisymmetric workpieces of any shape. The method is based on the temperature gradient method, where a quench probe was used to measure and record cooling curves when quenching real axially symmetric workpieces of any complex shape in liquid quenchants, followed by the calculation of relevant heat transfer coefficients (HTC). To calculate the HTC, a cooling curve measured near the surface of the probe is necessary. A 2-D computer program based on the Finite Volume Method and contains the necessary subroutine for drawing a 2-D contour of every axisymmetric workpiece is used to predict the hardness. The input such as cooling time from 800 to 500 °C ($t_{8/5}$), and the Jominy hardenability curve of the steel grade in question, is used to predict the hardness distribution within the whole volume of the workpiece, all at once, which is a unique feature of this method [52].

Abdlmanam S. A. Elmaryami, (2008) investigated the effect of thermal cycling on hardness of plain carbon steel, where he found that hardness decreased with increasing thermal cycling for both the annealed and tempered samples in all media (water, sea water, and oil), but this decrease in hardness is very small and can be neglected [53].

Abdlmanam.S.A.Elmaryami, (2007) investigated the changes on the Microstructure of plain carbon steel after 10, 20 and 30 thermal cycles. The annealed and the tempered samples were each divided into three groups, and each group was subjected to a different number of thermal cycling (10, 20, and 30 cycles). All samples were subjected to the same heating cycle, in which the samples were heated below A1 to 500 °C and held in the furnace for 15 min. Three samples of each heating cycle were cooled in different media [water, sea water, and oil]. The total time of a single cycle was 40 min. From his results, he found that: for all types of carbon steels, grain size increased with the increase in number of thermal cycling [54].

Abdlmanam.S.A.Elmaryami, (2009) studied the thermal cycling tests that were carried out on carbon steel up to 1.20 C %. A single run was performed at the upper temperature of 500 °C and lower temperature of 30 °C cooled in oil. As many as 30 cycles are necessary for an accurate determination of heating and cooling time. The effect of thermal cycling on the corrosion rate was evaluated. From the obtained results, he found that: the type of corrosion is uniform attack; thermal cycling caused a considerable increase in corrosion rate especially at low cycles. The corrosion rate increases with increasing carbon content for the thermal cycling of annealed samples, and decreases for the thermal cycling of tempered samples [55].

Experimental results of tension, compression, and hardness tests of samples of the S.A.E. 1010 welded steel tubing has been presented by (University of Illinois, Winston. Black, 2007). The tubing from which samples were taken, as originally formed (welded and heat treated), had an outside diameter of approximately one inch; the tubing had been subjected to various amounts of cold working by drawing through dies of different diameters. Tests were made both on the normalized tubing before being cold drawn and on the cold-drawn tubing. The structural behaviour of members, ma-chines, or structures made of the tubing is not discussed in this bulletin [56].

A study on heat conduction with variable phase transformation composition during quench hardening was done by Chen, J., Tao, Y., et al, (1997). This research only involved computer simulation without experimental procedure and proposed it as a time and cost saving method in the steel processing industry. The study was done via Finite Element Method computer simulation of the heat-conduction governing equation set, the shape effect, a subcooling boundary and variable phase transformation composition. First, the phase transformation conditions were analysed based on CCT diagram of carbon steel in correspondence to the requirement for formation of ferrite, pearlite, bainite and martensite. The second step was to obtain equations to calculate the phase compositions. The FEM computer program was executed for carbon steel consisting of (% wt) C 0.44, Si 0.12, Mn 0.66, P < 0.035, S < 0.035 with water as the quenching medium. With the results, the author concluded that the model is feasible to resolve the distribution of the transient temperature and the phase transformation composition of the specimen. Other discovery includes the dependence of temperature upon phase transformation and shape of the specimen; both retarded the cooling velocity. Heat radiation and phase transformation have certain effects on the transient thermal stress. The author recommended the mathematical model as a profitable simulation in heat treatment technology and could be extended to other quenching methods [57].

Sobh & co-authors (2000) used a discontinuous Galerkin model to develop finite element model for precipitate nucleation and growth during the quench phase of aluminium alloy manufacturing. The nucleation and growth of precipitates are determined by chemical composition of the alloy and the thermal history. They considered the thermal response as steady state under continuous cooling. 9-node quadrilateral elements were used resulting in 12.5 hours of computer processing time on a desktop PC [58].

Said, A. et al, (1999) studied the relationship of temperature, roll forces, roll torques and area reduction of hot bar rolling with various simplified rolling formulae and compared with experimentally-measured values. The effect of temperature change and the reduction on the predictive abilities of some of the traditional models, developed for bar rolling, was examined. The experimental procedure on AISI 1018 carbon steel bar (0.19 % Carbon, 0.75 % Manganese, 0.05 % Silicone, 0.007 % Sulphur, and 0.009 % Phosphorus) of 80 x 16 x 16 mm was performed with thermocouples embedded in 25 mm deep holes at the tail. The steel bar was rolled in laboratory rollers with four passes. It was discovered that temperatures, roll forces and roll torques were measured and reported as a function of the reduction. Only two models proved merely consistent in their predictions. The author recommended the finite element method to determine the distribution of the strains, strain rates, stress and temperature in the deformation zone and the conditions at the roll/metal interface [59].

E.E.U. Haque & P.R. Hampson, (2013), investigated a 3D thermal transient analysis of a gap profiling technique which utilises phase change material (plasticine) in ANSYS. Phase change is modelled by assigning enthalpy of fusion over a wide temperature range based on Differential Scanning Calorimetry (DSC) results. Temperature dependent convection is approximated using Nusselt number correlations. A parametric study is conducted on the thermal contact conductance value between the profiling device (polymer) and adjacent (metal) surfaces. Initial temperatures are established using a liner extrapolation based on experimental data. Results yield good correlation with experimental data.

They cited manuscript published from this research [55], where they used the Galerkin Weighted Residual Method to integrate around the volume of an element (e), while taking into account the boundary conditions (spatial temporal dependence of temperature, convection and substitution of the shape function of the elements [60].

S. M. Adedayo et al, (2012) presented a two - dimensional finite-difference model capable of predicting temperature history at various points on a solid cylinder in the quenching process. Solution to the Fouriers' heat conduction equation coupled with the boundary condition was numerically solved using Finite-difference and energy balance around a nodal system. They solved the resulting numerical equation by the Gauss–Siedel iterative method. They derived hardness variation from simulated cooling curves and Jominy curves. Computed results were compared with a typical practical model. In the experimental verification, medium carbon solid steel cylinder with an attached Ni-Cr thermocouple was quenched from temperature 650 °C into water at 20 °C. The results show that the model can reasonably predict temperature histories of quenched solid steel cylinders.

However, they cited manuscript published from this research, where they assumed that the internal thermal energy generation is negligible as it is in this work [61].

B. Shaheen. Bachy, (2012) present annealing and normalizing treatment are one of the most important heat treatment for the steel and its alloys. In his present work a mathematical model has been used to simulate this process, the model taken in account the variation in the physical material properties and heat transfer coefficient for the surface of metal. A numerical scheme based on control finite volume method has been used. A computer program with C++ language was constricted to found the final solution of the numerical equations. The model was used to estimate the temperatures distribution and the hardness value at each point of the workpiece. Good agreement has been obtained when compared the result of the present model with other experimental published data.

He cited manuscript published from this research, where he used the relationship between the time from 800 °C to 500 °C and the distance from quenching end of Jumine-specimant to estimate the hardness distribution depending on the cooling rate or cooling curve for the workpiece as it is in this work [62].

Alim Sabur Ajibola, et al, (2012) studied the production and microstructural analysis of as-cast and heat treated aluminium alloy, (Al – 20 % wt Mg). The conclusion from their work is that the Hardness of Al – 20 % wt Mg increased by heat treatment and hardness of Al – 20 % wt Mg increased with increasing cooling rates of quenchant used in cooling. They found that the water quenched sample has the highest hardness, while the used engine oil quenched has the least hardness. This is an indication that the hardness of Al – 20 % wt Mg increases as the material is heat treated, which is in reverse to the ultimate tensile strength. As quenching is carried out on a metal basically in order to harden it, different quenching media have varying cooling rates that affect how the hardness is distributed across the metal cross section as the quenching process is taking place. Water that has a fast cooling rate is observed to have the highest hardness value while the used engine oil quenched has a slower cooling rate to that of water. In annealing, the cooling rate is much slower and has the least value [63].

Sh.E. Guseynov (2007) studied "nonlinear mathematical model for intensive steel quenching and its analytical solution in closed form" he considered nonlinear mathematical model for intensive steel quenching processes. In their work, some analytical procedure for solving of obtained nonlinear equation is proposed. It is proved that this analytical procedure permits finding the unique solution of the original nonlinear model [64].

Sanda Blomkalna, et al, (2012) developed multi-dimensional Mathematical Models of Intensive Steel Quenching for Sphere. Mathematical models for 3-D and 1-D hyperbolic heat equations and construction of analytical solutions for the determination of the initial heat flux for rectangular and spherical samples is developed. They obtained numerical results and examined for spherical sample [65].

Fernandes, F. M. B. et al, (1985) studied "the mathematical model coupling phase transformation and temperature evolution during quenching of steels" and they carried out the temperature field calculation by the resolution of the heat equation using the finite–difference method. They compared the results of the theoretical calculations with those obtained by experiment; also they discussed the validity of the model and the effect of internal stress on the theoretical predictions [66].

Božo Smoljan, et al, (2010) studied "Predictions of Mechanical Properties of Quenched and Tempered Steel". They predicted fatigue crack initiation threshold of quenched and tempered steel. They applied the method of computer simulation of mechanical properties for a workpiece of complex form made of quenched and tempered steel. They also predicted distribution of as-quenched hardness within the workpiece of complex forms by computer simulation of steel quenching using the finite volume method. They predicted microstructure composition and hardness of tempered steel based on as-quenched hardness and fatigue crack initiation threshold of quenched and tempered steel were predicted based on microstructure composition and hardness. They found that the proposed method can be successfully applied in calculating fatigue crack initiation threshold of quenched and tempered steel [67].

Song Dong-li, et al. (2004) studied "Numerical Simulation on Temperature and Microstructure during Quenching Process of Large-sized AISI P20 Steel Die Blocks". They described a model of coupled thermal and phase transformation. They have also been simulated using the finite element method (FEM), the temperature and microstructure during the quenching process for large-sized of AISI P20 steel. Water quenching technology, that is completely austenitizing at 860 °C and cooling in water to room temperature, is simulated [68].

Smoljan Božo, et al, (2011) investigated the engineering and economical aspects of the optimization of steel shaft quenching and tempering. They developed a mathematical model and method of computer simulation for the prediction of fatigue properties of quenched and tempered steel. They applied computer simulation of the fatigue properties of quenched and tempered steel in the optimization of quenching and tempering of steel shafts. The proper heat treatment process was accepted based on economical analysis. Fatigue properties of quenched and tempered steel were predicted based on microstructure composition and yield strength. Microstructure composition and yield strength were predicted based on as-quenched hardness. Also they predicted the distribution of as-quenched hardness in the workpiece through computer simulation of steel quenching using a finite volume method (FVM). They estimated the as-quenched hardness based on time of cooling and on Jominy test results. It was taken into account that the mechanical properties of quenched steel directly depend on the hardness, degree of hardening, and microstructural constituents. Using a numerical simulation of microstructure and mechanical properties, they found that the investigated shaft has the best fatigue properties in

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