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Study of Low Carbon Steel in Rapid Cooling Process: A Short Review

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ABSTRACT

One of the latest technologies used in sheet metal production is hot stamping. It is a mixture of shaping and rapid cooling to create stronger components in the sheet metal products. To handle a wide range of sheet metal that is suitable for hot forming, this research was held to study the microstructure changes during rapid cooling on three different sheet metal thickness of low carbon steel. The mechanical properties like hardness, toughness and ductility can be altered by intense heat treating on steel and rapid cooling it to produce different mechanical properties. To change the characteristics of steels is by heat treating whereby altering the diffusion and cooling rate within its microstructure by adjusting the size of the grain at various stages and changes the molecular arrangement. The mechanical properties of the low carbon steel with different thickness may be different due to the microstructure behaviour after heat treating. Finally, the behaviour of the microstructure of low carbon steel changes with different thickness that is affecting the mechanical properties after heat treating and quenching process.

INTRODUCTION

The essential design criteria of strong, durable and low-cost material to be used in industries including transportation industries such as aircraft, railway and automotive which to produce high quality with good performance vehicles with reasonably price. Low carbon steel steels are used vastly in these industries due to the good formable and weldable [1].

Low carbon steel and medium carbon steel have insufficient carbon content to change their crystalline structure, as the results, the steel unable to tempered or hardened. Medium carbon steel become tougher even if it is hard and are unable to cut using a hacksaw. When the steel is heated until blazes fiery and then is immersed in clean water immediately, the steel becomes hard but brittle. As for soft or easy to cut with hacksaw steel, the blazing steel is cooled slowly using surrounding air [2]. The mechanical properties of a metal are depending on the microstructure behaviour in the steels [3]. The goal of heat treatment is to develop and to control the mechanical properties by manipulating the microstructure for industrial usage. The different mechanical properties of carbon steels will be resulted as different microstructures formed during cooling processes. Furthermore, the diffusionless transformations obtain the martensite formation which is the highest hardness in iron-carbon system and lowest hardness is hardness obtains which cause the pearlite or ferrite formation by a eutectoid reaction. Ferrite and pearlite obtained from austenite during slow cooling near the equilibrium while martensite is obtained during rapid cooling. Low carbon steel is one of the types of carbon steel which has low carbon content itself [4,5]. As this type of materials has been selected in this study to examine the effect of rapid cooling process on low carbon steel and the mechanical properties after undergo heat treatment processes. Therefore, the present-day work was planned to study the relationship among the microstructure, heat treatment and mechanical properties for rational selection of manufacturing process, properties, and application for certain function [6,7,8].

Rapid cooling is essential during industrial production processes. A type of heat-treating process, where immersed a work piece in water, or any fluids to acquire certain material properties. Rapid cooling process is to maintain mechanical properties with a crystalline structure and the phase distribution that would loss during slow cooling process. Steel with low carbon has same properties as iron [9], which is easily to be formed and soft. As the carbon acts as a hardening agent, the strength of steel generally increases with the percentage of carbon contain. This made the metal becomes difficult to weld and less ductile but harder and stronger [10]. Since low carbon steel cannot be strengthened by heat treating which can be only accomplished through cold working. This steel is machine able and weld able due to its softer and the outstanding ductility.

Table 1: Application of Low Carbon Steel based on carbon content

Carbon Percentage (%)	Applications
0.08-0.15	Cold headed fasteners and bolts
0.15-0.30	Case hardened, shafts, spindles and rods

MICROSTRUCTURE THEORY

With every different heat treatment process of steels, the microstructure of the steel will have changed. The study of microstructure also known as metallography or microscopy. The microstructures are the presentation of the structural characteristics of steel under microscopic state. A variety of microstructures of carbon steels are known as ferrite, cementite, pearlite, martensite and austenite. Resulting in partial transformations and the reaction of metastable phases from most of the phase transformations of interest will involve deviations from equilibrium microstructures [11]. Ferrite, cementite and austenite can exist in equilibrium at the eutectoid temperature while pearlite forms by the solid-state transformation. The three stages, cementite, pearlite and ferrite are in this manner the vital constituents of the microstructure of plain carbon steels. To prevent the formation of transient phases, they are put into slow cooling rates. Therefore, it is important to observe these phases and nucleation development and to decide the features which alter their morphology [1-6].

NORMALIZING PROCESS

Normalizing process is a heat-treating process to make softer material and to adjust desired mechanical properties. To produce a uniform and fine-grained structure is normalising goals. After hot rolling, casting and forging a steels microstructure normally getting unhomogenous [12] consists of unwanted particle and large grains such as bainite or carbides. Through Normalising, this process can be done to austenite phase by heating the steel and cooling it in surrounding air. In industrial, to gain assurance of the steel mechanical properties, and improving the machinability of low carbon steel by the used of this process. In normalizing process, complete austenite transformation occurs when steel is uniformly heated to a certain temperature. The result of this process is pearlite or pearlite with left-over ferrite or cementite. It is dependent on the compositions of the steel. There are different form of structures resulting after annealing process. There is less of excess ferrite or cementite and the pearlite is finer. For steels with same carbon content in the hypoeutectoid or hypereutectoid ranges. Due to the higher cooling rate, the austenite transformation occurs at a very low temperature than in annealing process. Decrease of ferrite grain size and increase the strength and hardness of steel is by using a higher cooling rate. Whereas formations of soft, coarse and less dislocated phases like polygonal ferrite is by using slow cooling rates. The difference value of pearlite occurs due to the changing of eutectoid composition to a lower value.

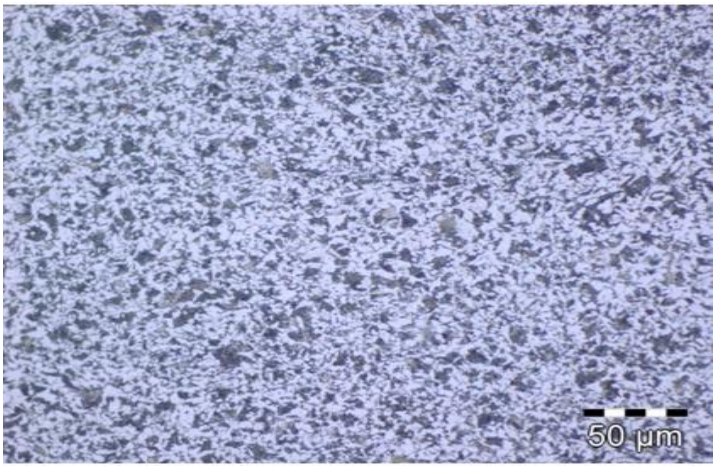

Figure 1: The microstructure of medium carbon steel 35C8 after air cooled. Coarse ferrite and pearlite grains with volume fraction of pearlite content around 40% Israr (2016).

QUENCHING PROCESS

Quenching is one of the hardening processes of steel that defined as a rapid cooling process from the austenite phase to formation of martensite. To avoid from sudden microstructure changes, quenching is a way to bring back the steel to room temperature. Quenching undergo by immersing the steel in water, oil and any liquid substance to obtain desired material properties, increase strength, hardness and wear resistance. During quenching process, the outer surface of the steel cool at faster rate than the internal area. Since not all austenite is transformed into martensite, the untransformed austenite called as retained austenite [13]. The formation of pearlite, ferrite and bainite may occur before martensite forming completely, if the cooling rate is low. The mechanical properties of steels such as strength increase, when the concentration of carbon dissolved in austenite during heating which is because of transformation of austenite into martensite [14]. Therefore, mechanical strength can be improved by quenching in right medium, type of heat treatment, the composition of steel, duration the steel immersed in [15].

SLOW COOLING OF HYPOEUTECTOID STEEL

Eutectoid deals with a solid to solid transformation. The reaction occurs on cooling a 0.8% of carbon composition at the eutectoid point, slowly through eutectoid temperature. Hypo-eutectoid steel composition has less than 0.8% of carbon. It is containing of α-ferrite and pearlite while hyper-eutectoid contains 0.8% - 2% of carbon, consists of pearlite and cementite. Forms reaction of Austenite→Ferrite + Fe_3C [13-14]. On slow cooling through the critical temperature, free ferrite will first be rejected out until the remaining austenite reaches 0.8% of carbon composition, if the austenite contains less than 0.8% carbon when the synchronized rejection of carbide and ferrite will occur and producing pearlite. At a room temperature, the hypo-eutectoid steel will be composed of areas of free ferrite and pearlite. The higher the carbon contains the more pearlitic in the steel compositions [15].

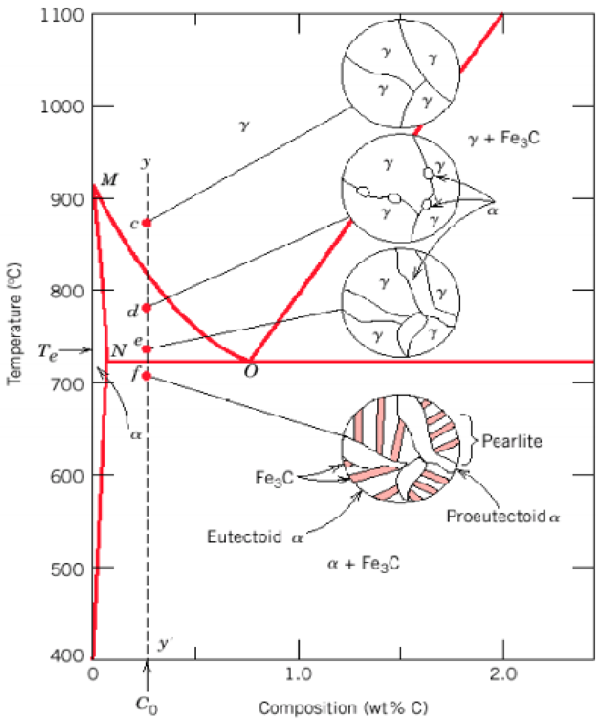

Figure 2: Transformation of 0.4% of carbon hyopoeutectoid steel Callister (2001).

Proeutectoid ferrite is from hypoeuctectoid alloys where its forms up the eutectoid temperature. The eutectoid pearlite is containing with eutectoid ferrite and cementite. If a sample is heated up to 900°C or point c as shown in Figure 2 and held for sufficient time, the structure will become homogenous and gets austenitized which consist entirely grains of austenite (γ). After that, if the steel is slowly cooled down to temperature of point d, it enters the two phases of ferrite and austenite region and proeutectoid ferrite nucleates heterogeneously at austenitic grain boundaries, proeutectoid ferrite is determined as the earlier eutectoid ferrite that formed before the eutectoid reaction. Most of the ferrite particles will aligned along the original austenite boundaries. When the steel is continuously cooling from temperature to e in **Figure 2**, the amounts of proeutectoid ferrite have grows until austenite is transformed. Furthermore, if the steel cooled down again to temperature f from e, the carbon concentrations of the remaining austenite will rise up from 0.4% to 0.8% of carbon [16]. At eutectoid temperature (T_e), austenite has transformed by eutectoid reaction into pearlite. Eutectoid ferrite is from the ferrite (α) in the pearlite. At temperature (T_e), the existing austenite phase will turn to pearlite as the temperature is lowered down below the eutectoid to point f. There is no change into the austenite phase that existed in point e in intersect the eutectoid temperature. For ferrite phase, they are present in both phase in pearlite and the phase of cooled down through ferrite- austenite phase region [17].

In industrial heat treatment operations, most of steel are continuously cooled from austenite to room temperature and temperature exceed the martensite temperature is not isothermally transformed. In continuous cooling of a low carbon steel such as mild steel, the transformation from austenite to pearlite over a range of temperatures instead t at a single isothermal temperature. As a result, the microstructure after the continues cooling will be complex since the reaction of the kinetics changes over the temperature range in which the transformation takes place [18].

A very slow cooling curve of full anneal represents slower cooling and the microstructure in this case would be course pearlite. For normalizing, the curve shows rapid cooling. This situation can be obtained by removing an austenitized steel from a furnace chamber and allowed the steel to cool in still air [17]. A fine pearlite microstructure is formed. Cooling curve for oil quench starts with the formation of pearlite, but there is an insufficient time to complete the austenite-pearlite transformation. The excess austenite that does not transform to pearlite at the above temperature will transform to martensite at lower temperature starting at 220°C. Since it takes two steps of transformation, this is called split transformation [18]. The microstructure of this condition are the combination of martensite and pearlite. A fully hardened martensitic structure are produce at critical cooling rate.

TESTING ON MECHANICAL PROPERTIES

Hardness Test

A resistance to indentation, abrasion or cutting are the definition of hardness. Hardness is not a property based on physical but a characteristic of a material which are the results of measuring the depth of the dent. More simply put, the softer the material, the bigger indentation left by the indenter based on its force. By measuring the depth and size of dent obtained using different test methods, the indentation hardness value can be obtained [16-17]. It is generally known that the hardness of metal alloys is greater than the hardness of its individual components. The hardness of a metal depending on the grain size of the microstructure of steel, the smaller the grain size, and the hardest the steel. This is because the bonding forces between molecules that differ from each other are larger than between molecules that are similar to each other. This is why, with the addition of foreign substance to a metal increase their hardness. [19]. Heat treatment and alloying are the other methods used to increase the hardness and strength of the material. Hardness measurements provide a quick and easy ways to check the given strength has been obtained through some particular methods [20].

Rockwell Hardness Test

Comparing different types of hardness testing methods, Rockwell hardness test is much easy process and provide more accurate result results. This approach is used on all metals, except in condition where the dent produce would be too big where the test metal structure or surface conditions would introduce too much variation. Permanent intensity of indentation produced by a pressure on indenter may be measured by this test [21]. First, a sample has applied with a force (preload/minor load) using a diamond or ball indenter. Preload breaks through the surface to lessen the surface finish affects. The baseline depth of indentation is measured after retaining the preliminary test force for a certain time. Then, major load is applied on the surface to get the total required test load where this pressure or force is held for a certain time to allow elastic recovery and major load is released. The final depth is measured and the difference between baseline and final depth measurement is the result derived for Rockwell hardness value. The accuracy of the value is depends on the indentation on a smooth flat surface [21-23].

HEAT TREATMENT EFFECTS ON LOW CARBON STEEL

To give a good combination of toughness and strength from the martensitic phase, quenching and tempering heat treatments process have been used for a few decades applied to steels [3]. The microstructure of low carbon steel includes of ferrite and small amount of pearlite [4] states in their research that the tensile strength of low carbon steel ASTM A-36 mild steel without any heat treated is 402.45 MPa and the hardness is 69.8 BHN, the percentage elongation is 23.6% and reduction 56.24%. The tensile strength and hardness of steel will rise due to mechanical properties while the ductility, elongation and reduction in area lessening.

According to Hasan MF., normalizing does not soften the steel to the maximum and does not restore ductility much more done by annealing. The Brinell Hardness Number (BHN) of normalized is lesser than hardening but higher than annealing. Reheating the specimen to a specific temperature and cooling it at faster rate is a tempering process which reveal toughness at the cost of its hardness to an already hardened piece of steel. The decrease in hardness and strength in the microstructure of the annealed sample by cooling can be linked with soft ferrite matrix [22]. Due of the proper austenizing temperature and faster cooling rate, the increase in tensile strength and hardness compared to annealed and without heat treated. When low carbon steel was rapidly immersed from austenitic phase to room temperature, the austenite will rot into a mixture of martensite and finer pearlite. The hardness of steel increases both with cooling rate and the pearlite percentage. One of the reasons is due to the formation of martensite was the strengthening phases in steel. Due to the delay in the formation of pearlite and martensite at faster cooling rate, increase the hardness value [24].

The microstructures changes affected the mechanical properties of the steels after heat treatment which is to get a better property of the steels. Oil quenching may lead to a development of somewhat pearlite grains and fine pearlite in comparison between forced air cooling and normal air. For fine ferrite, pearlite decrease ductility but increasing the strength of the material. The cooling rate at room temperature has a notable effect on the mechanical properties and microstructure [25]. Ferrite-martensite dual phase structure produced from oil quenching with thin film and fine particle of retained austenite as the microstructure has been studied by microscopy. By cooling treatment, the properties obtained mostly forms a structure composed mainly of bainite. While increasing impact toughness at minus temperature, plastic deformation of the steel following to its controlled cooling additionally also increases its strength characteristics [26]. For slower air cooling, larger amount of remaining austenite combines to the martensite and ferrite phases. In contrast, the changes of the structure develop from self-tempered martensite, lower binite and granular bainite to lastly martensite without self-tempering due to the increasing of applied cooling rate (Qiao et al.,2009). With the increasing of the cooling rate also increase the yield strength of the material while the strain-to-failure and ultimate tensile strength was unchanged. In the previous research, AISI 1060, AISI 1040 and AISI 1020 steels were tested where the specimen samples were heated at the same temperature for certain hours and afterward were cooled by three different methods; room condition water quenching, room condition air cooling and at furnace condition temperature cooling. According to Adnan C. (2009), the percentage of pearlite changes with the change of carbon content of steels.

Table 1: The percentage of phases after heat treatment of AISI 1060, high carbon steels Adnan C. (2009)

Heat Treatment	Ferrite (%)	Pearlite (%)	Martensite (%)	Retained austenite (%)
Water-quenched	5	60	30	5
Air-cooled	30	65	5	-
Furnace-cooled	50	50	-	-

Table 1 shows the percentages of phases obtain by using the optical microstructure photograph of steel after undergo heat treatment process. In this table we can observe that the pearlite and ferrite percentages changes with carbon content and cooling rate. In contrast, to reach a martensitic state, higher cooling rate can be used. It can be said that the carbon content and cooling rate effect on the microstructure of the steels. When the carbon is immediately cooled to room temperature, carbon can spread quite further and the space of the rich carbon phase, pearlite is greater [22,24,25]. The product of pearlite is called as coarse pearlite. For the faster rate of cooling, it produces fine pearlite in carbon steels. The carbon content and cooling rate effects on the microhardness of steels as the microhardness increases when the cooling rate and the carbon content are higher. In addition, the increasing of the pearlite percentage also results on the higher microhardness of the steel. On the other hand, the microhardness also increases rapidly when the martensite percentage is increasing. This is because strengthening phases in steel occurs in martensite phases [27].

CONCLUSIONS

Generally, the increasing of the microhardness is due to the alteration of the primary phases after undergoing rapid cooling process. Also known that construction of a supersaturated solid solution, and openings increase with the carbon content in water quenchant is from the water quenching. So, high-hardness links with dislocation and high resistance to slip. We can conclude that by increasing relative volume of pearlite and martensite after quenching affect the increasing of microhardness with the water quenched steels. Also, the increasing of carbon content risen up sharply the hardness of martensite. Heating or cooling process is a heat treatment that has been done to alter the metal physical and mechanical properties without changing the metal original shapes. Heat treatment also the methods for strengthening materials and can be used to change mechanical properties such as enhancing machining efficiency and improving formability.

Transformation of austenite to martensite only takes place during higher cooling rates which is quenching process. The percentage of martensite forms on the austenite boundaries depends on the time taken the steel to cool. The faster the cooling rate of steel, the more percentage of martensite forms. Formation of pearlite rather than martensite occurs in air normalising process where the cooling rate is lower. Since the cooling rate is depending on the thickness of the steel, the thinner the steel, the faster it takes to cool into equilibrium temperature with high martensite or lower pearlite area forms.

The microstructure development after heat treatment affects the mechanical properties of the steel. The hardness of the steel was mainly influenced by the grain development. However, the thickness also playing a main role in controlling the growth of the grain. Distribution of pearlite grain increase with the lower thickness of steel, whereas the hardness of the steel increase with the decreasing of its thickness.

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