Vietnam Journal of Agricultural Sciences

ISSN 2588-1299

VJAS 2021; 4(4): 1283-1292
https://doi.org/10.31817/vjas.2021.4.4.07

Effects of Heat Treatment Process on Mechanical Properties of Medium Carbon Steel

Pham Thi Hang

Faculty of Engineering, Vietnam National University of Agriculture

Abstract

In order to select an appropriate heat treatment process for an industrial application of S45C medium carbon steel, it is necessary to investigate the influence of technological parameters during the heat treatment process such as heating temperature, holding time and cooling medium on the microstructure and mechanical properties. In this study, the experiments were conducted in various heating temperatures, holding times and cooling mediums for specimens made of S45C steel. Then, the relationship between the microstructure and the hardness of the steel was examined. The obtained results show that the heating temperature and cooling medium strongly affect the microstructure of this steel, leading to considerable changes in the hardness. The hardness of S45C steel was markedly improved when heated above 800^{o}C and cooled in water. Moreover, the holding time needs to be carefully calculated to obtain finer grain structure to prevent an increase in the brittleness.

Keywords

Hardness, heat treatment, mechanical properties, microstructure, S45C steel

Introduction

Carbon steel is defined as a combination of iron, carbon, and some other impurity elements with a quantity of carbon of less than 2.4%. Nowadays, carbon steels are widely applied in industrial manufacturing applications because of their low cost and ease of fabrication (Callister & Rethwisch, 2007). Carbon steels can be classified into four main groups as low carbon steel, medium carbon steel, relatively high carbon steel, and high carbon steel depending on the percentage of the carbon in the steel.

Among the medium carbon steel grades, grade S45C (JIS) or AISI 1045 (ASTM) steel is good quality steel with about 0.45% carbon. Type-S45C steel possesses favorable mechanical properties such as acceptable strength, hardness, and good ductility (Ibrahim & Sayuti, , 2015). In addition, it can achieve the desired hardness and

Received: October 27, 2020
Accepted: December 29, 2021

Correspondence to
pthang@vnua.edu.vn

ORCID
Hang Pham
https://orcid.org/0000-0002-1216-9060

an improved strength through the heat treatment process because of its high heat treatment efficiency. Therefore, this steel is suitable for mechanical processing as well as manufacturing machine parts as rolling thread, bolts, shafts, gears, steel flanges, sickles, hollows, drills, and knives, etc. (Yoo *et al.*, 2004).

As above mentioned, to meet the mechanical requirements of high wear resistance and increase in durability of machinery parts, S45C steel needs to be treated by heat treatment process to obtain a high value of hardness of about 56-60HRC. The heat treatment method involves heating the steel to a hardening temperature and holding it at that temperature for a certain period of time, and then cooling at a cooling rate to obtain the desired microstructure and mechanical properties (Liu *et al.*, 2003). Therefore, during the heat treatment process, the three most important factors to consider are the heating temperature, the holding time at heating temperature, and the cooling medium (Bhosale *et al.*, 2016; Fadare *et al.*, 2011). The first important factor of the heat treatment process is the value of heating temperature. It is the highest temperature during the heat treatment process. The theoretical basis for determining the heating temperature for carbon steel is the $Fe-Fe_3C$ phase diagram (Callister & Rethwisch, 2007). From the $Fe-Fe_3C$ phase diagram, the critical points where the phase transformation occurs for S45C steel (with 0.45% carbon) are determined. Another important parameter of heat treatment is the holding time. During the holding time at the highest temperature of the heat treatment, a new phase transformation has not occurred. However, this stage is necessary to evenly uniform the temperature between the core and the surface of the specimen, so that the same phase transformation can occur in the core as it does in the surface. In addition, in order to complete the phase transformation, the holding time needs to reach a certain level. On the other hand, if the holding time is too long, the austenitic phase might become larger, leading to more brittle in the steel. Thus, the holding time must be carefully calculated. The heat holding time depends on the size and shape of the specimen, the heating temperature, the heat treatment method, and the grade of the steel (Bouissa *et al.*, 2019).

The high-temperature phase austenite in steel might transform into various phases such as coarse pearlite, bainite, or martensite depending upon the cooling rate (Schindler *et al.*, 2009; Adeyemi & Adedayo, 2009). These phases will considerably change the mechanical properties of the steel after the heat treatment process (Jo *et al.*, 2020). Therefore, this stage becomes very important and needs to be carefully investigated. Indubitably, the results of phase transformation in the cooling stage are strongly affected by the microstructure of the steel obtained in the previous two stages (Bansal *et al.*, 2020). The theoretical basis for considering the cooling medium is the CCT (Continuous-Cooling-Transformation) diagram of the steel (Bouissa *et al.*, 2019).

Depending on the purpose of the application of the material, the appropriate method and the heat treatment regime to change the microstructure are chosen to change the mechanical properties of the material as desired. As a result, it is important to understand and quantify the effect of various parameters during the heat treatment process on the evolution of metallurgical structure, hardness, and residual stress of S45C steel to choose the heat treatment process for the steel for its intended application (Canale *et al.*, 2008). On the other hand, in general, for a real application in manufacturing companies, the mechanical engineers have attention only on the hardness or strength of materials. Meanwhile, according to Ibrahim *et al.* (2015), the microstructure of materials, especially grain size, and its importance for the longevity of materials are often ignored. In many cases, even though the hardness of the steel might achieve the desired value, the grain size observed in the microstructure image is still too coarse, leading to an increase in the brittleness of the materials (Sun *et al.*, 2020; Bouissa *et al.*, 2019). This might reduce the fracture toughness of materials. Therefore, it is necessary to pay attention to the microstructure of the materials and clearly understand the relationship between microstructure and mechanical properties

(Johnson *et al.*, 2019; Odusote *et al.*, 2012; Uyama *et al.*, 2006).

In this paper, the experiments were conducted in different conditions to investigate the influence of the heat treatment factors such as heating temperature, holding time, and cooling medium on the microstructure and mechanical properties of S45C steel. Then, the relationship between the microstructure and the hardness of the steel was explained. Finally, some conclusions on the appropriate condition for the heat treatment process for S45C were induced.

Materials and Methods

Specimen for experiment

The specimen made of S45C steel had a cylindrical shape with a diameter of 22mm and a length of 15mm as shown in **Figure 1**. The chemical composition of S45C steel is shown in **Table 1** (Long *et al.*, 2018). The surfaces of specimen were prepared by an application of grinding and polishing techniques before the heating treatment process.

Experimental setup

In order to investigate the effect of heating temperature, holding time, and cooling medium on the microstructure and mechanical properties of S45C steel, the experiments were carried out in different conditions (**Table 2**). Noticeably, the air media was in static condition. The quenching media of water or servo oil was prepared at room temperature. The cooling rates of water and servo oil were 177^oCs^{-1} and $60^oC\ s^{-1}$, respectively (Mathews *et al*., 2019). The specimen was heated in the electric resistance furnace device SX2-5-12.

After the heat treatment, the specimens were polished, then etched with acid HNO3 3% solution for microscopic examination by metallurgical microscope ECLIPSE L150. In the next step, the HRA and HRC hardness of the specimen were measured using Rockwell hardness tester AR-20. The diamond spheroconical indenter was used for the hardness measurement. The load was set up as 600N and 1500N for HRA and HRC hardness, respectively, during an automatic duration. For the results of hardness, at least five indentations were made under similar conditions, and the average values were obtained.

Results and Discussion

The effects of heating temperatures

Figure 2 shows a microstructure of the S45C steel before the heat treatment. From this figure, S45C steel had a microstructure including dark pearlite phase and light ferrite particles. Due to the considerable amount of ferrite phase, the hardness of this steel before heat treatment was quite low with a value of about 12HRC on average. For the application of S45C steel in machinery parts that required high wear resistance, this level of hardness was insufficient.

Figure 1. Specimens after polishing

Table 1. Chemical composition of S45C steel (Wt.%)

C	Si	Mn	P	S	Ni	Cr	Cu	Fe
0.45-0.47	0.2-0.21	0.63	<0.014	0.006	<0.05	<0.008	<0.012	In balance

Table 2. Testing conditions in experimental work

Heating temperature (°C)	Holding time (minutes)	Cooling medium
670	10	Water
720	10	Water
750	10	Water
770	10	Water
800	10	Water
850	10	Water
850	20	Water
850	10	Servo oil
850	10	Static air
900	10	Water
950	10	Water
1000	10	Water

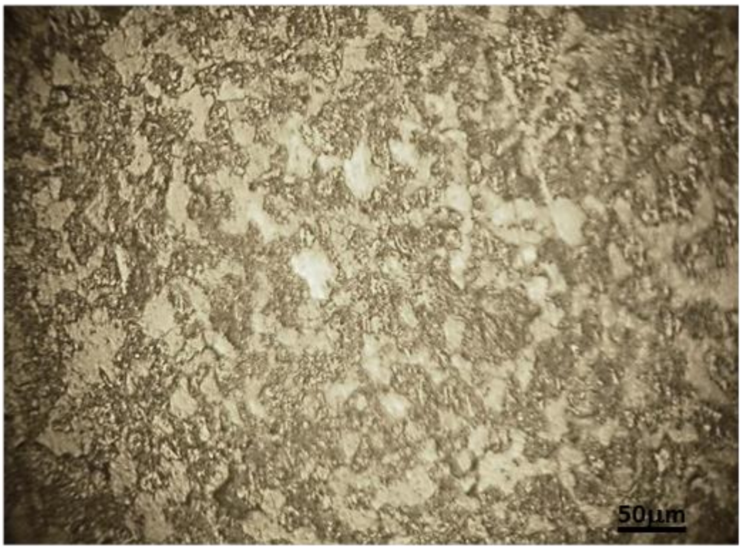
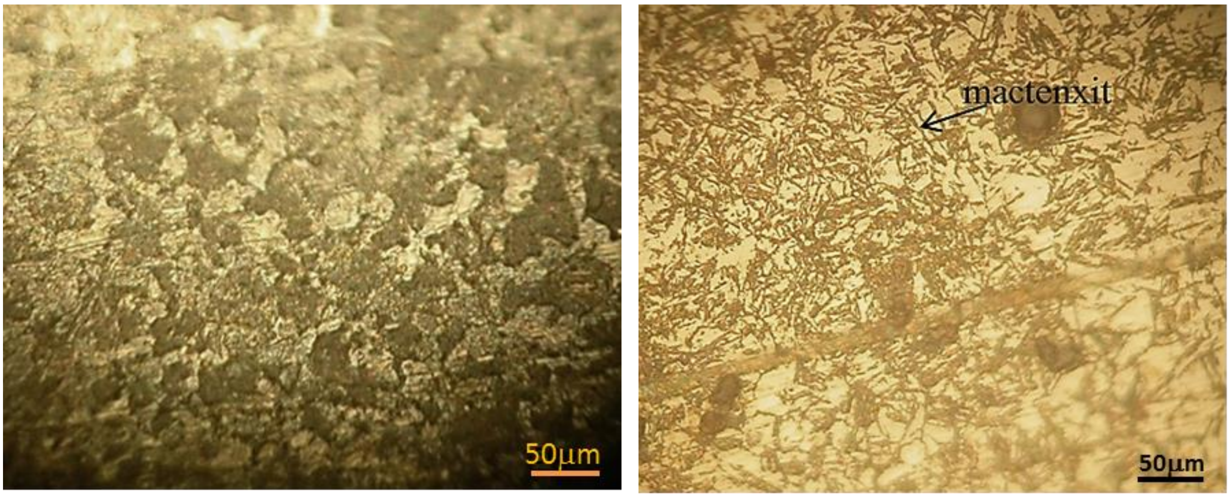


Figure 2. Microstructure of S45C steel before the heat treatment

Next, in order to consider the effect of temperature, S45C steel specimen were heated at different temperatures at the same condition of a heat holding time of 10 minutes and the cooling medium of water. The microstructure examinations of the steel after heat treatment at different heating temperatures are shown in **Figure 3**. In the case of 670°C, the temperature was lower than the critical value of temperature for austenitic phase transformation, pearlite had not yet transformed into austenite during heating. Therefore, the received microstructure after heat treatment was still a combination of pearlite and ferrite, although microscopic observation



(a) Heating temperature of 670°C

(b) Heating temperature of 850°C

Figure 3. Effect of heating temperatures on the microstructure of S45C steel

showed that the bright ferrite particles were more evenly distributed and the shape of the particles was slightly changed.

On the other hand, at a higher heating temperature of 850°C, the microstructure of S45C steel changed considerably after the heat treatment process. The needle-shaped martensitic phases appeared rather densely interspersed with residual austenitic phases. This could be explained by the fact that when S45C steel was heated to 850°C, the pearlite phase in the initial steel had been transformed into austenite, and at the same time, the ferrite phase had completely dissolved into austenite. The microstructure received after the completely heating process was austenite. Then, during quenching rapidly in water, the austenite phase was transformed into needle-shaped martensite. Since this was an incomplete transformation, the residual austenitic phase could still be observed in the microscopic image of the steel. It was expected that the hardness of this steel at low heating temperature would not change much. Meanwhile, at 850°C, the hardness of steel would change markedly.

Figure 4 shows the result of the effect of heating temperatures on the hardness of S45C

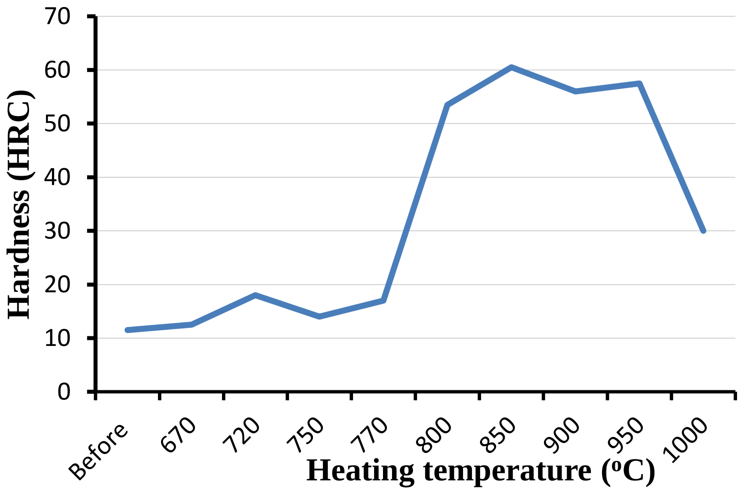


Figure 4. Effect of heating temperatures on the hardness of S45C steel

steel. Noticeably, the hardness of the specimen after the heat treatment at 670°C was almost similar to that before the heat treatment. As can be seen from **Figure 3a**, the temperature of 670°C was lower than the critical value of temperature for pearlite-austenitic phase transformation in the steel, austenite phase could not be obtained during heating and the final achieved microstructure was still a combination of pearlite and ferrite. Since the hardness of these phases was small, an improvement of the hardness of the specimen after heat treatment at 670°C could not be seen.

In heating temperatures lower than 800°C, the hardness of steel did not considerably change compared to that in unheated treatment, under 20HRC. At this level of hardness, the machinery parts still had not met the requirements for wear resistance. This phenomenon could be explained by the existence of the ferrite phase in the steel, although pearlite might transform into austenite during the heating process. Therefore, after the cooling stage, a small amount of martensite could be formed and the ferrite phase was much more flexible, in aggregate. As a result, the hardness of S45C steel increased insignificantly. When the heating temperature reached 800°C, the hardness of steel improved significantly and reached the highest value of about 60HRC at 850°C. Similar result on the hardness value obtained after quenching of S45C steel at the same heating temperature and cooling media could be seen in the past study of Long *et al*. (2018). As observed at the microstructure of the steel after heat treatment at 850°C in **Figure 3b**, the formation of large quantities of martensite induced an increase in the hardness of the steel. The hardness achieved by heating at 850°C completely met the common requirements for machine parts in a range of 56 to 60HRC. However, the value of hardness of the steel decreased when the heating temperature increased to over 850°C, especially 1000°C. This tendency was similar to the result of Ibrahim *et al.* (2015). In the range of high heating temperature, there was no new phase transformation compared to that at 850°C, the obtained microstructure was still a combination of martensite and residual austenite. Meanwhile, due to the temperature, long burning time without any new changes occurring after 850°C, the formed austenitic particles might be merged to make a bigger grain size because of the long heating time without any changes in phase transformation. This led to a slight reduction in the hardness of the steel but adversely affected the strength and made the steel more brittle. Therefore, for the application of S45C steel in manufacture, the temperature of the heat treatment should not exceed 900°C.

Effect of cooling mediums

Figure 5 shows the optical microstructure of S45C steel after heat treatment in different cooling mediums. These specimens were heated at the same heating temperature of 850°C and the same holding time of 10 minutes. At this heating temperature, the austenitic transformation during the heating process had occurred completely. Thus, the microstructure obtained after heating was uniform austenitic phase.

When cooled in the air corresponding to the normalizing method, the austenite was transformed into sorbite. As seen in **Figure 5a**, bright ferrite particles were more evenly distributed and finer, while the lattice grids were also more uniform and finer after normalizing compared to the microstructure of the steel at the un-heated treatment stage. On the other hand, when the specimen was cooled in the oil medium with a higher cooling rate than that in the air, a clear difference in the microstructure of the steel can be seen in **Figure 5b**. In the oil medium, a combination of a large amount of residual austenite and pearlite was formed after the heat treatment process. Theoretically, the microstructure formed after oil quenching would change considerably with the appearance of semi-martensite transformed from austenite. However, in the case of S45C steel, the cooling rate in oil might be insufficient for martensitic transformation (Hajek *et al.,* 2021). Therefore, the obtained microstructure was observed without an appearance of martensitic phase but a combination of residual austenite and pearlite was clearly seen. Additionally, the martensitic phase could only be seen in the microstructure of S45C steel when the steel was quenched in water as explained above. Consequently, the cooling rate played a vital role in phase transformation in the steel. Thus, it could be said that the mechanical properties of the steel would be strongly affected by the cooling medium during the heat treatment process.

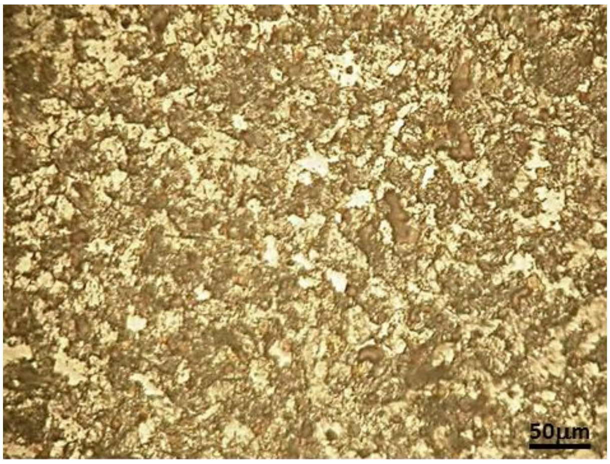
The differences in the hardness of S45C steel after heat treatment in different cooling mediums are shown in **Figure 6**. Obviously, due to the appearance of martensitic phase in microstructure, S45C steel had a relatively high hardness by quenching in water than in other cooling mediums. Meanwhile, the values of hardness in case of cooling mediums of air and oil were still small.

Effect of holding times

Figure 7 shows the image of the microstructure of S45C steel after the heat treatment at 850^{o}C, holding time of 20 minutes, austenite obtained in this case of a longer holding time was considerably larger compared to that in **Figure 5c**. This phenomenon not only affected the formation of martensite during quenching in water but also induced the brittleness of the steel. Thus, the ductility of the steel would significantly decrease. In the actual situation, this phenomenon should be avoided during the heat treatment for the steel since micro-cracking might appear because of excessively high brittleness.

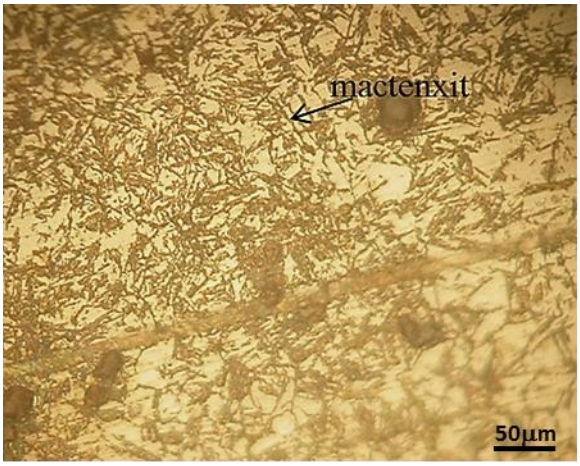
Effect of tempering after quenching

The specimen after quenched at 850^{o}C and cooled in water was tempered at 250^{o}C. With this low tempered temperature, the hardness of S45C steel slightly decreased compared to that after



(a) Cooling in air

(b) Cooling in oil



(c) Cooling in water

Figure 5. Effect of cooling mediums on the microstructure of S45C steel

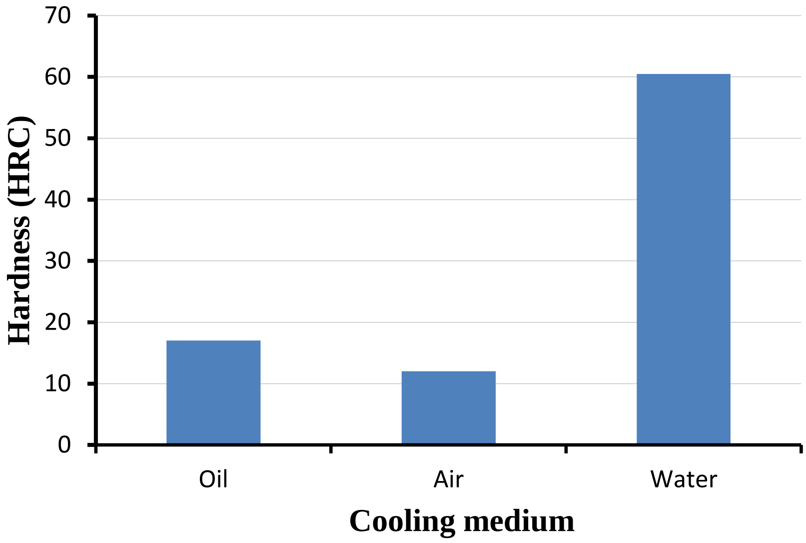


Figure 6. Effect of cooling mediums on the hardness of S45C steel

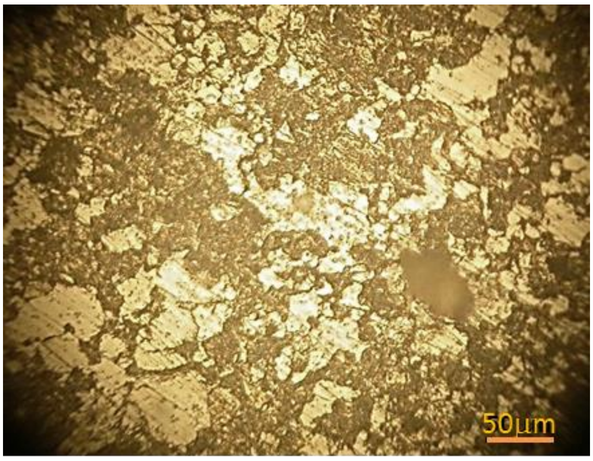


Figure 7. Effect of holding time on the microstructure of S45C steel

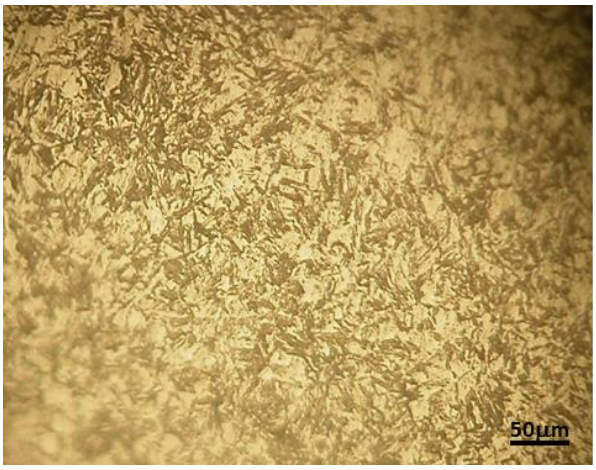


Figure 8. Microstructure of S45C after tempering

quenching. The obtained microstructure is shown in **Figure 8**. It is clearly seen from this figure that the distribution of martensitic phase was more uniform than that after quenching. Also, the grain size of residual austenite was finer than before. Thus, it could be estimated that the residual stress in microstructure, as well as the brittleness of the steel, might be suppressed when tempered at this level of temperature while the value of hardness was still sufficient.

Conclusions

In this study, the influences of factors during the heat treatment process such as heating temperature and cooling medium on the microstructure and mechanical characteristics of S45C medium carbon steel were investigated and discussed. The results obtained from experiments show that the heating temperature and cooling medium greatly affected the microstructure of steel, leading to changes in the hardness of S45C steel. The hardness of S45C steel was only markedly improved when heated above 800^{o}C and cooled in water. Notably, at 850^{o}C, the maximum hardness was achieved due to the martensitic phase formation that occurred during rapid cooling for the steel after quenching. As the heating temperature increased, the hardness of steel did not increase anymore because there was no new phase change that facilitated the austenitic particles to merge, then might induce the brittleness in the steel. Moreover, the holding time needed to be carefully calculated to obtain a finer grain structure in order to prevent an increase in the brittleness of the steel.

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