SciEn

Proceedings of 7th International Conference on Mechanical, Industrial and Energy Engineering-Part I
22-24 December, 2022, Khulna, BANGLADESH

SciEn Conference Series: Engineering Vol. 1, 2025, pp 52-56 https://doi.org/10.38032/scse.2025.1.10

Effect of Cyclic Heat Treatment on the Hardness and Microstructures of High Carbon Tool Steel

M.S. Haque[1,], A. Wafa[2] and M.A. Islam[3]*

[1] Lecturer, Materials Science and Engineering Department, Khulna University of Engineering and Technology (KUET), Khulna-9203, Bangladesh and
Postgraduate Student, Materials and Metallurgical Engineering (MME) Department, Bangladesh University of Engineering and Technology (BUET), Dhaka-1000
[2]Undergraduate Student, MME Department, BUET, Dhaka-1000, Bangladesh
[3]Professor, MME Department, BUET, Dhaka-1000, Bangladesh

ABSTRACT

For any tool, abrasion or friction is obvious that causes high wear and ultimately determines its service life. As a result, special focus on the wear resistance of the tool steel is essential. The high wear resistance of tool steel is mostly due to its high hardness achieved by proper heat treatment. In this regard, there is no doubt that alloying elements like Cr, Mn, W, Ni, V, Mo, etc. also play vital roles. However, like alloying elements, final microstructures of tool steels are also very important to ensure the hardness as well as wear resistance. In the case of traditional heat treatment, the steel is heated to a proper austenitizing temperature, soaking there for a predetermined time and quench it into a suitable media. In contrast, in cyclic heating steel is cooled from austenitizing temperature in several steps for modified microstructures. In this study, high carbon tool steel was heat treated by conventional as well as modified cyclic method. After heat treatment, the resulted microstructure and hardness of the heat-treated steel was studied. Experiment results suggest that cyclic heat treatment has a synergistic action in modifying microstructures hence the hardness.

Keywords: High carbon steel, Microstructure, Traditional heat treatment, Cyclic heat treatment, Martensite, Quenching

1. Introduction

Steel is an alloy of iron and carbon with a few percent of phosphorous, sulfur, silicon, manganese, nickel, chromium, etc. to improve its strength and fracture resistance compared to plain iron. Steel is utilized in various structures, infrastructures, tools, ships, trains, cars, machineries, electrical appliances, weapons and so on due to its good combination of essential properties, low cost and availability. Steel is 100% recyclable, has a high durability, and easy to shape [1-2].

Carbon content in high-carbon steels ranges from 0.60 percent to 2.00 percent. Cutting tools, springs and abrasion-resistant components are the most common uses for this type of steel, which is less likely to be welded. Because when this type of steel cools after welding, hard and brittle martensite phase is developed [3]. To change the hardness and grain size of tool steel, special alloying elements like molybdenum, chromium, tungsten, etc. are added. As they form metal carbide, the hardness of the tool steels is also increased [4].

Heat treatment is the process of applying heat to a material to get desired material qualities such as optimum strength, corrosion resistance, thermal conductivity, ductility, toughness, wear resistance, etc. Typically, microstructural, and crystallographic changes occur throughout the heat treatment procedure [5-7]. In general, traditional heat treatment (THT) process is completed in three distinct steps. The material is heated in the first stage, in second stage the component is held at austenitizing temperature isothermally, in 3rd stage it is cooled in suitable media. The mechanical properties of high carbon steel, such as ductility, hardness, and strength, can be considerably customized by heat treatment. The most frequent heat treatment methods for this type of steel are annealing, quenching, and tempering [8].

The rate at which metal cools from its austenitic temperature range has a significant impact on the material's microstructures. Fast cooling rates cause phase change to occur at lower temperatures, resulting in finer grain structure than slow cooling rates. The cooling rate is adjusted during quenching to avoid the production of soft pearlite or bainite. As a result, the quenching process is mostly determined by the steel grade, section thickness, distortion allowed, and the characteristics of the steel [9-10].

*Corresponding Author Email Address: salmanhaque@mse.kuet.ac.bd Published By: SciEn Publishing Group

A cyclic heat treatment (CHT) is distinct from conventional heat treatments in that it yields improved mechanical qualities. A CHT entails a series of heating and cooling cycles around (or above) the critical temperature, as well as a short soaking period at that temperature [11]. The number of cycles has an impact on the heat treatment results. Structure refining may not be possible if the cycle number is insufficient, while too many cycles may result in flaws owing to micro-deformation processes that are expected to be present in high quality load bearing components [12]. The goal of this experiment is to study how the microstructures and hardness of high carbon steel are affected by THT and CHT processes.

2. Materials and Experimental

2.1 Materials

Two separate high carbon file steels (A and B) were collected from the local market, Fig.1. From each of the file steel, two samples were cut. Samples with a diameter of 8.3 mm were prepared. It was difficult to machine the samples since the file tools were composed of high carbon steel. As a result, the samples were annealed for 2 hours at 800°C and then progressively cooled in the furnace. The samples were then ground and polished to analyze their microstructure. The chemical composition of the tool steels was also determined using OES, which is presented in Table 1.

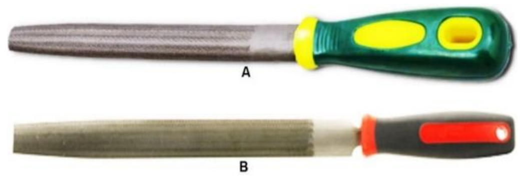


Figure 1: High carbon steel files (A and B).

Table 1: Chemical compositions of the samples

Elements		C	Si	Mn	P	S	Cr	W	V	Fe
Samples	A	1.37	0.19	0.30	0.02	0.03	0.68	0.21	0.03	97.2
	B	1.26	0.16	0.25	0.02	0.02	0.62	0.21	0.03	97.4

2.2 Austenite Temperature Calculation

For proper heat treatment setting of austenitization temperature is very important. To calculate this temperature the following equation was used [13]:

A_{cm}= 224+ 992C -465C^2 +7.5 Mn+ 16 Si+ 47 Cr+ 10 Mo-7Ni + 3.7 C Ni - 2.7 Cr Ni+0.8 Ni^2 +16.7 Si ...(1)

For the file steel used, the austenitization temperature was found to be around 750℃. However, for better compositional homogeneity and carbide dissolution 800ºC was selected as austenitizing temperature for both heat treatments.

2.3 Traditional Heat Treatment (THT)

The Nabertherm furnace (Germany) was used for the THT process. Two samples from each group (samples A_{THT} and B_{THT}) were kept in the furnace and heated. The heating rate was 15°C/min. For three and half hours, the temperature was held at 800°C. After that, the samples were taken out of the furnace and subsequently quenched in hot (55°C) water. The heat treatment cycle is shown in Fig 2. After that, microstructure observation, and hardness tests were performed.

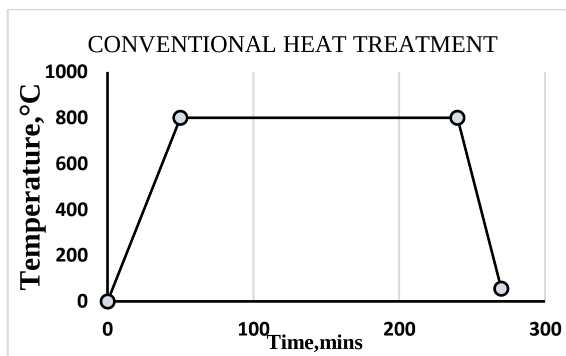


Figure 2: Temperature – Time graph involving traditional heat treatment

2.4 Cyclic Heat Treatment (CHT)

The cyclic heat treatment method was also in the same furnace. In the furnace, two samples from each group (samples A_{CHT} and B_{CHT}) were kept and heated at a rate of 15°C/min. The temperature was kept at 800°C for 20 minutes, then dropped to 650°C in 15 minutes and remained there for 1 minute. The temperature was raised to 800°C once more, and the process was repeated four times. The two samples were promptly quenched in the hot water of same temperature (55°C) when the process was completed (Fig.3). After that, microstructure observation, and hardness tests were performed.

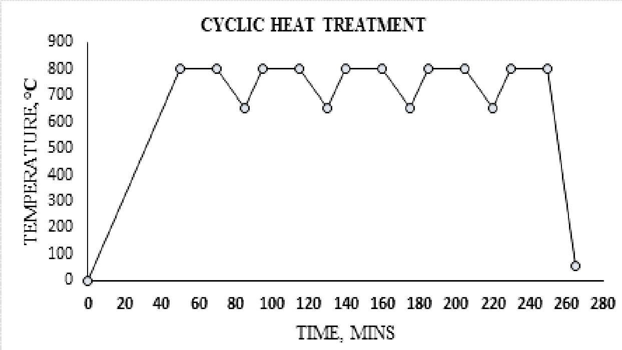


Figure 3: Temperature – Time graph involving cyclic heat treatment.

Here it is to be noted that for all heat treatment, holding (cyclic heating-cooling at high temperature) and cooling time for both cases were almost identical.

3. Result and Discussion

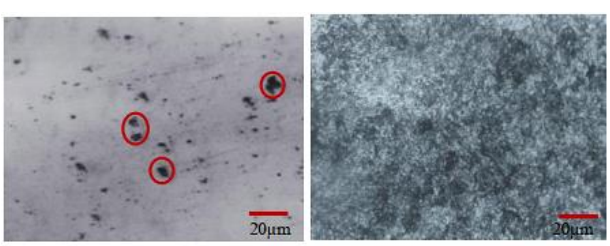
3.1 Annealed Samples

Initially, the two samples were annealed at 800°C to achieve consistency in hardness and chemical composition. High carbon steel undergoes phase transformations to austenite, during heating process. For the subsequent complete austenite phase, the samples were held at a steady temperature. Afterwards, the samples went through a furnace cooling process.

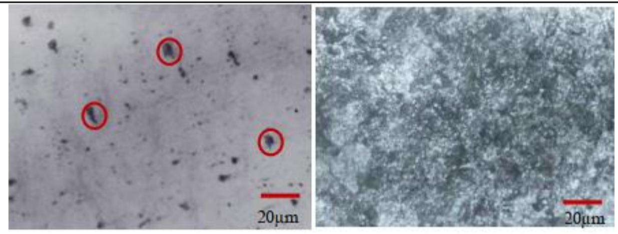
Table 2: Hardness Values after Annealing process

Sample Description	Hardness, HRB
A	91.1
B	90.2

Hardness was measured once the annealing procedure was complete. The hardness was found to be 91.1 HRB for A, and 90.2 HRB for B sample (Table 2). Slow cooling allowed pearlite and cementite to form from austenite, preventing other phases forming and allowing the coarsening of carbides (Fig 4). Coarse and inhomogeneous carbide is not ideal for boosting hardness or wear resistance. However, its brittle properties may cause the mechanical property to degrade [14-16].



Sample A (left: unetched; right: etched) 500X magnification



Sample B (left: unetched; right: etched) 500X magnification

Figure 4: Micro-structure of post-annealed tool steel (Carbide are marked by circle)

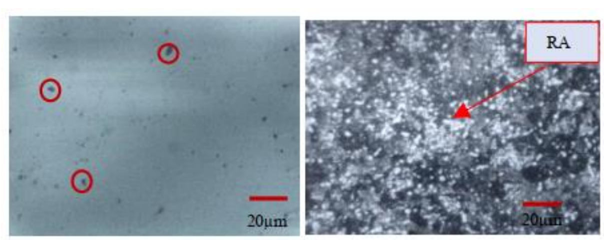
3.2 Hardening by Tradition and Cyclic Heat Treatments

After traditional heat treatment, hardness values were measured on both samples in Rockwell C scale. The results thus obtained are shown in Table 3.

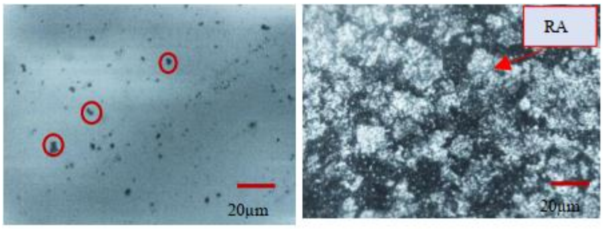
Table 3: Hardness values after Traditional Heat Treatment

Process	Traditional Heat Treatment (THT)			
Sample Description	A_{THT}		B_{THT}	
Hardness Values (HRC scale)	41.2	41.4	40.5	40.9
Average value	41.3		40.7	

Following the traditional hardening heat treatment, the hardness values for samples A_{THT} and B_{THT} has been improved to 41.3 HRC and 40.7 HRC, respectively. During the heating process, the high carbon steel passes through phase transitions from pearlite-cementite to austenite, body-centered cubic to face-centered cubic. When quenching took place, the austenite converted into martensite. The hardness levels were raised as a result of the martensite development. However, a lot of soft, retained austenite was seen, which affected the hardness's value (Fig. 5). A homogenous precipitation of carbide was typically responsible for the increase in hardness as well. However, the carbide particles were of a coarse size, which prevents them from perfectly boosting the hardness levels. As fine carbide is preferred over coarse carbide in terms of enhancing hardness and wear resistance. [17]



Sample A_{THT} (left: unetched; right: etched) 500X magnification

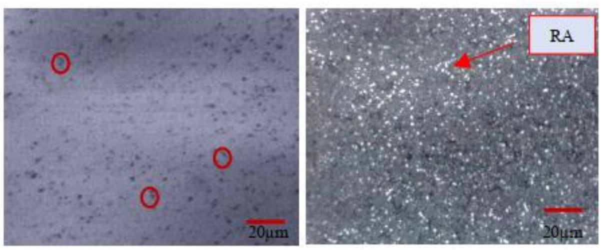


Sample B_{THT} (left: unetched; right: etched) 500X magnification

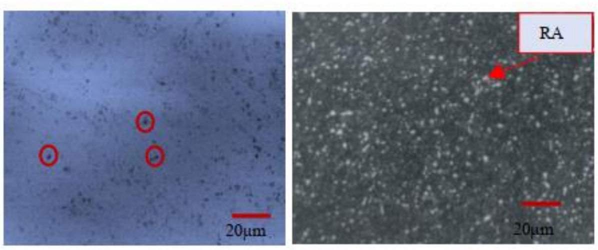
Figure 5: Micro-structure of Traditional heat-treated tool steel (Carbide are marked by circle)

Table 4: Hardness values after Cyclic Heat Treatment

Process	Cyclic Heat Treatment (CHT)			
Sample Description	A_{CHT}		B_{CHT}	
Hardness Values (HRC scale)	64.6	66.9	63.4	62.3
Average value	65.75		62.85	



Sample A_{CHT} (left: unetched; right: etched) 500X magnification



Sample B2 (left: unetched; right: etched) 500X magnification

Figure 6: Micro-structure of cyclic heat-treated tool steel (Carbide are marked by circle)

After undergoing cyclic heat treatment, both the A_{CHT} and B_{CHT} samples showed considerable increases in hardness, reaching 65.75 and 62.85 HRC, respectively (Table 4). During the first three cycles of heat treatment, the high carbon steel underwent phase transformations from pearlite-cementite to austenite during the heating period and from austenite to pearlite-cementite during the cooling period. With no composition variation, the crystal structure of steel that underwent phase transformation during heating converted from face-centered cubic to body-centered cubic, resulting in a variation in atom position of less than one atomic spacing. The CHTs stimulated nucleation in non-nucleated regions, allowing for the refining of martensite grains following water quenching [18]. The structure was composed of very fine spheroidal carbides particles in the martensite matrix (Fig 6). After being quenched, the material gained a greater resistance to plastic deformation because of the increased number of grain boundaries. Therefore, the hardness has been increased [19].

It is obvious that the spheroidal carbides particles became finer after cyclic heat treatment as compared to traditional heat treatment, leading to increased hardness values (Tables 3 and 4). Moreover, in the cyclic heat treatment, a continuously shifting atom position induced more nucleation sites for the development of fine austenite grains (Fig.7). When it was quenched, generated finer martensite grains with more grain boundaries. As it prevented the samples from becoming plastically deformed, the fine martensite contributed to an increase in the hardness of the material. Additionally, the soft phase of the retained austenite has been reduced, which contributed to an increase hardness value as well (Fig.6).

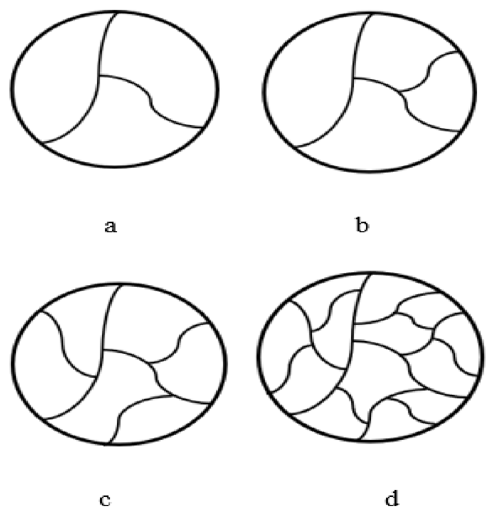


Figure 7: Schematic diagram of increasing number of austenite grain boundry with clycle of heat treatment. Austenite phase after a) 1st cycle, b) 2nd cycle, c) 3rd cycle and d) 4th cycle.

4. Conclusion

Microstructures and harness values of two types of high carbon steel that have been annealed, conventionally hardened, and cyclically hardened have been compared and presented in this research work.Both samples in annealed condition showed very low hardness values and fine pearlitic structures with undissoled carbide particles. Hardening treatment modified both the microstructures and hardness values. In this regard, hardening by cyclic heat treatment resulted in refined microstructures, lower amount of retained austenite and significantly high level of hardness values. Very high level of retained austenite (soft phase) is found to be resposible for the reduced hardness values of the traditionally hardened steel samples.

5. Acknowledgement

The authors would like to express their gratitude to the Materials and Metallurgical Engineering (MME) Department at Bangladesh University of Engineering and Technology (BUET) for providing access to their laboratories and funding for this study.

Reference

[1] Totten, G., 2007. *Steel Heat Treatment*. 2nd ed. CRC Press, p.2.

[2] Worldsteel.org. 2022. *worldsteel | worldsteel*. [online] Available at: <https://www.worldsteel.org/about-steel/about-steel.html> [Accessed 18 January 2022].

[3] Singh, R., 2016. Stresses, Shrinkage, and Distortion in Weldments. *Applied Welding Engineering*, pp.201-238.

[4] Bayraktar, S., 2021. Dry cutting: a sustainable machining technology. *Sustainable Manufacturing*, pp.231-257.

[5] Daramola, O., Adewuyi, B. and Oladele, I., 2010. Effects of Heat Treatment on the Mechanical Properties of Rolled Medium Carbon Steel. *Journal of Minerals and Materials Characterization and Engineering*, 09(08), pp.693-708.

[6] Rajan, T.V; Sharma, C.P. and Sharma, A. (1989). Heat Treatment Principles and Techniques.Prentice Hall of India Private'Limited, New Delhi. pp. 36-58

[7] Mamoru, O. Yukito, T; Hitoshi, K; and Yuji, F. (1990). Development of New Steel Plates for building structural use, Nippon Steel Technical Report, No 44 pp. 8-15.

[8] Ismail, N., Khatif, N., Kecik, M. and Shaharudin, M., 2016. The effect of heat treatment on the hardness and impact properties of medium carbon steel. *IOP Conference Series: Materials Science and Engineering*, 114, p.012108.

[9] Akinlabi, E.T and Akinlabi, S.A. Characterising the effects of Heat treatment on 3CR12 and AISI316 Stainless Steels. International Journal of Materials and Metallurgical Engineering, 2014, 8(2): 256-261.

[10] Roney, T.J., and Loker, D.R. Evaluation of quenching methods for the purpose of acoustic data collection. Procedia Manufacturing, 2017, 10: 1118-1128.

[11] Singh, J. and Nath, S., 2020. Improved slurry erosion resistance of martensitic 13wt.%Cr–4wt.%Ni steel subjected to cyclic heat treatment. *Wear*, 460-461, p.203476.

[12] Aweda, J., Orhadahwe, T. and Ohijeagbon, I., 2018. Rapid Cyclic Heating of Mild Steel and its Effects on Microstructure and Mechanical properties. *IOP Conference Series: Materials Science and Engineering*, 413, p.012016.

[13] Lee, S. and Lee, Y., 2007. Thermodynamic Formula for the Acm Temperature of Low Alloy Steels. *ISIJ International*, 47(5), pp.769-771.

[14] H., K. Gai, L. He, C. Zhang, H. Cui, and M. Li. Non-isothermal phase-transformation kinetics model for evaluating the austenization of 55CrMo steel based on Johnson-Mehl-Avrami equation. Materials & Design, Vol. 92, 2016, pp. 731–741.

[15] Sherif El-Eskandarany, M., El-Bahnasawy, H., Ahmed, H. and Eissa, N., 2001. Mechanical solid-state reduction of haematite with magnesium. *Journal of Alloys and Compounds*, 314(1-2), pp.286-295.

[16] Prakash, L., 1995. Application of fine grained tungsten carbide based cemented carbides. *International Journal of Refractory Metals and Hard Materials*, 13(5), pp.257-264.

[17] Haque, M., Khan, S. and Kaiser, M., 2022. Effect of Sc and Zr on Precipitation Behaviour of Wrought Al-Bronze. *IOP Conference Series: Materials Science and Engineering*, 1248(1), p.012037.

[18] Kaneko, K., Matsumura, S., Sadakata, A., Fujita, K., Moon, W., Ozaki, S., Nishimura, N. and Tomokiyo, Y., 2004. Characterization of carbides at different boundaries of 9Cr-steel. *Materials Science and Engineering: A*, 374(1-2), pp.82-89.