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Influence of Quenching Conditions on Microstructure Evolution and Hardness of 42CrMo4 Alloy Steel

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Abstract

Evolution of microstructure and hardness in 42CrMo4 steel during quenching under the different cooling conditions were investigated. Mineral oil, polymer solution and water were selected as quenchants to provide different cooling conditions. Quenching experiments were also conducted under magnetic stirring and ultrasonic agitation of polymer solution. Cooling conditions during quenching had significant effect on phase transformation and hardness of 42CrMo4 steel. The quench hardened samples show martensite microstructure along with other micro-constituents. Needle like/acicular ferrite was observed with water quenching due to diffusion less transformation. Sample quenched under ultrasonic agitated medium showed formation of network of carbides. Higher hardness values were obtained with water quenching and ultrasonic agitated polymer quenching.

Keywords: Cooling Condition, Hardening, Hardness, Microstructure, Quenchants, 42CrMo4 Steel

1.0 Introduction

Steels offer wide spectrum of metallurgical and mechanical properties through successful alloying and heat treatment. Alloying of steel is the process of addition of one or more chemical elements for specific purpose during steelmaking. Based on the amount of alloying element, alloy steels are classified as low alloyed steels (less than 5 wt% of alloying elements) and high alloyed steels (more than 5 wt%). The important alloying elements to the steel (apart from carbon) are Chromium (Cr), Nickel (Ni), Manganese (Mn), Silicon (Si), Tungsten(W), Molybdenum (Mo), Vanadium (V), Cobalt (Co), Titanium (Ti), Aluminium (Al), Copper (Cu), Niobium (Nb), Zirconium (Zr), Boron (B), Nitrogen (N), Beryllium (Be) and Tantalum (Ta). The main purposes of alloying elements addition into the steel are to alter the mechanical properties (room temperature strength, hardenability, fatigue resistance, creep resistance), service properties (heat resistance, toughness and cold resistance, corrosion/oxidation resistance, wear resistance), processing properties (Castability, weldability, formability, machinability) and physical properties (elastic modulus, density, magnetic properties, electrical properties, thermal expansion properties, colour)[1]. The engineering components are produced/fabricated through casting and/or metal working operations. The as cast and fabricated components are to be subjected to heat treatment process in order to improve the physical,

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chemical, thermal and mechanical properties by altering the microstructure. Heat treatment is a solid-state thermal process which involves heating of components to predetermined temperature, soaking at that temperature for a certain period followed by controlled cooling. Based on cooling rate, heat treatment process is classified as annealing, normalizing and hardening. Quench hardening involves rapid cooling of steel components from austenitizing temperature resulted in formation of martensite[2]. Alloying elements present in the steel have significant effect on phase transformation during quench hardening process. 42CrMo4 alloy steel is typical medium carbon low alloy steel contains major alloying elements Cr (0.80 - 1.10 %) and Mo (0.15 - 0.25 %) and widely used in gas and automobile industries. This steel is quench hardened and tempered to get good balanced tensile strength, toughness and wear resistance. Different liquid cooling media such as water, brine, polymer solution and mineral oils are used for quenching hardening which control heat transfer and wetting phenomenon and in turn control the phase transformation[3]. Ramesh and Prabhu have compared cooling performance of brine and polymer solution by using cooling curve analysis and online video imaging. They reported that brine quenching resulted in rapid and non-uniform rewetting while polymer quenching resulted in slow and uniform rewetting[4]. Another study by Ramesh and Prabhu involved prediction of quenching performance of quench media. They have carried out cooling curve analyses with water, polymer, brine, vegetable oils and mineral oil using Inconel 600 probe. It has been reported that higher cooling rate was obtained with higher thermal conductivity, solid–liquid interfacial tension, and lower viscosity of quenchant[5]. ZUO Xun-wei, *et al.*, have proposed alternately timed quenching technology for thick AISI 4140 steel shaft to reduce cracking tendency. This method involves quenching of AISI 4140 steel shaft using several water-air cooling cycles[6]. A.H. Meysami *et al.*, have prepared AISI 4140 steel rods with different diameter through rolling process and subsequently subjected to direct quenching process and reheating-quenching process. The increase in diameter of the rod resulted in decrease of tensile strength and increase of impact energy in both direct quenching and reheating-quenching processes. The direct quenching process resulted in higher tensile strength and lower impact energy compared to reheating-quenching processes[7]. B.M. Gurumurthy, *et al.*, investigated microstructure and mechanical properties of normalized duplex steels at varying the intercritical temperature holding followed by water quenching. The process resulted in varying amount of martensite in a fine ferrite matrix[8]. Jian Zhu, *et al.*, studied the effect of isothermal temperature on dislocation density in bainite transformation of 4140 steel. They observed that decreased in dislocation density with increase of isothermal temperature due to reduction in plastic deformation in austenite[9]. G.E. Totten illustrated that polymer quenchant with agitation provides uniform and superior properties than mineral oil. The research works are clearly indicating that quench media and quenching conditions have significantly control the cooling rate during hardening and thus superior metallurgical and mechanical properties of the steel are obtained[10].

In this paper, effect of cooling conditions on evolution of microstructure and hardness in 42CrMo4 alloy steel was investigated. Water, mineral oil, polymer solution (with and without agitation) was used to provide different cooling rate during immersion quenching.

2.0 Experimental Work

Cylindrical specimens of diameter 1 inch and height 1 inch were prepared from 42CrMo4 alloy steel which was procured from local market. The chemical composition of the steel was analysed using spectrometer and shown in Table 1.

Mineral oil, polymer solution, water was used as quench media for immersion quenching. The mineral oil (Thermol 32) was procured from Bharat Petroleum Corporation ltd, India. The polymer solution was prepared by homogenous dissolution of 5 wt% Starch into water. Quench tank of 115mm internal diameter and 200 mm of height with 2 liters of quench was used. Hardening of the prepared specimen was carried out by heating a specimen into 890˚C in a muffle furnace, holding at that temperature for 1 hour and then rapidly cooled in different quench media. Heating rate of the furnace was kept at 10 ˚C/min. Quenching experiments were also carried out with polymer solution under magnetic stirring (500 rpm) and ultrasonic agitation (50Hz)

Table 1. Chemical composition of 42CrMo4 alloy steel

C	Mn	Cr	Mo	Si	P	S	Fe
0.42	0.92	1.05	0.23	0.20	0.007	0.006	Bal

conditions. All quenched samples were then subjected to low temperature tempering process at 100 ˚C for 30 min.

The quenched samples were sectioned using low speed cutting machine for microstructural study. The sectioned samples were polished using 180#, 220#, 400#, 600#, 1000# and 1200# silica carbide emery papers and finally with disc polishing using 3µm granulation diamond paste to obtain mirror finish. The polished samples were etched using 5% Nital solution and then microstructures of the samples were analysed using Leica DM5000 Metallurgical Microscope.

The hardness of the quenched samples was determined using Brinel Hardness tester with 10mm diameter (D) steel ball indenter and 3000 kg load (P). The Brinel Hardness Number (BHN) was determined by using the following equation.

$$BHN = \frac{2P}{\pi D(D - \sqrt{D-d}}$$

where D is impression diameter (mm).

3.0 Results and Discussion

Figure 1 shows the microstructure of as received 42CrMo4 alloy steel. Microstructure clearly shows ferrite and pearlite constituents.

Figure 2 (a-c) shows microstructure of 42CrMo4 alloy steel hardened with mineral oil, polymer solution and water. Microstructures show quench hardened structure i.e. Martensite with all quench media. It indicates the diffusion less phase transformation of austenite under a thermal condition due to rapid cooling. The rapid cooling resulted in restriction of carbon diffusion during cooling and transformation of FCC austenite to BCT martensite with trapped carbon atoms.

The displacive movement of trapped carbon atoms by shear resulted in tilt surface, plastically deformed region near to tilt surface and increased internal stress. It makes material to be hard and brittle by martensite formation. Microstructures of quenched samples show that coarse structure with mineral oils and polymer solution quenching and fine structure with water quenching. The earlier works of current author involved the determination of cooling performance of liquid quenchants using cooling curve analysis[11,12]. The thermal history measurement and video imaging of immersion quenching of Inconel probe showed occurrence of three stages of cooling i.e. vapour blanket, nucleate boiling and convective cooling during immersion quenching in liquids. Uniform and slow rewetting with mineral oil quenching, formation thick polymer insulating layer and explosive like wetting with polymer solution quenching and lower vapour blanket stage and fast rewetting with water quenching were reported. Accordingly higher cooling rates at maximum and 300˚C were reported with water than mineral and polymer solution. Hence, it is expected that higher amount of undercooling during phase transformation with water quenching compared to mineral and polymer solution quenching. It resulted in fine structure with water quenching and coarse structure with mineral and polymer solution quenching. The presence of other micro constituents along with martensite structure were observed with quenched samples. The samples quenched into mineral oil and polymer solutions show presence of bainite along with martensite. Generally, the bainitic formation is obtained by isothermal holding of austenite in a bainitic transformation temperature range and is diffusion-controlled nucleation and growth process. The rapid cooling of quenching is expected to be prevent the diffusion process. However, Kolmskog, *et al.*, have discussed growth of bainite even below the martensitic transformation temperature[13]. The Cr and Mo present in the 42CrMo4 steel are ferrite former and are carbide forming elements. They decrease the eutectoid carbon composition and increase the eutectoid transformation temperature. Further the presence of Cr and Mo delay the austenite decomposition, retard the pearlite transformation, decrease the bainitic start temperature and promote the formation of bainite in steel. Hence,

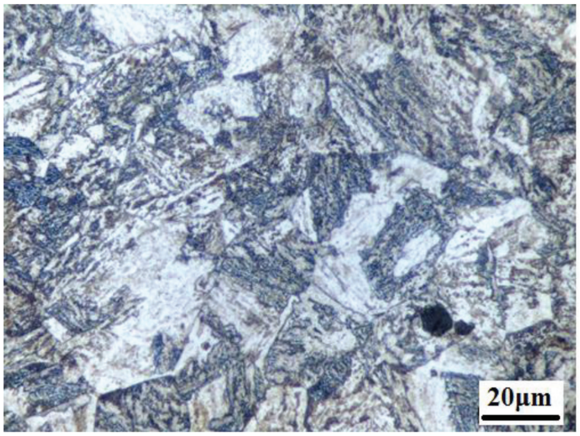

Figure 1. Microstructure of as received 42CrMo4 alloy steel sample.

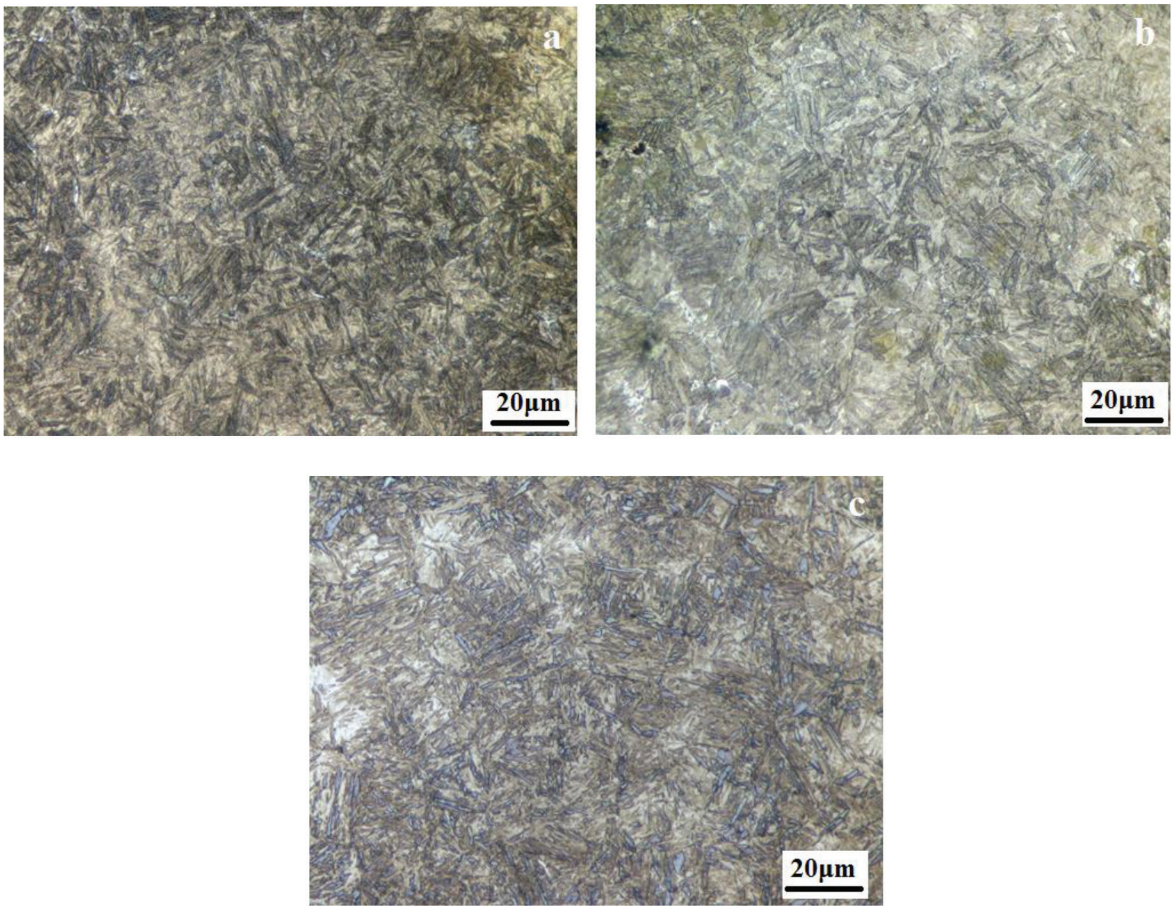

Figure 2. Microstructure of 42CrMo4 alloy steel sample quenched into **(a)** mineral oil **(b)** polymer solution and **(c)** water.

quench hardened 42CrMo4 alloy steel with mineral and polymer quenchants shows low volume fraction of lath like bainite. The sample quenched in water shows presence of more amount of needle-like/acicular micro-constituents along with martensitie. These needles/acicular micro constituents were oriented in randomly and along with materistic plates. It indicates similar like martensitic transformation; these needles were also formed due to shear transformation by displacive motion of atoms. Bhadeshia have explained the formation of bainite by diffusionless growth. It involves formation of supersaturated subunit of ferrite on austenite grain boundary even before cementite had formed. This is known as bainitc ferrite or carbide free bainite[14]. As discussed earlier, Cr and Mo are ferrite former and strong carbide forming elements, they increase the activation energy of carbon diffusion in austenite and decrease the diffusion coefficient of carbon. Simultaneously, the decrease in bainitic transformation temperature due to Cr and Mo and rapid cooling are expected to form bainitic ferrite in austenite by insitu nucleation at the earlier stage of quenching. Figure 3 shows the microstructure of 42CrMo4 alloy steel immersion quenched into polymer solution under magnetic stirring and consists of mixture of bainite and matensite. The structure is finer than polymer quenching without stirring. The stirring during quenching may result in early breakdown of polymer film, uniform rewetting and enhanced cooling rate during quenching. Figure 4 shows the microstructure of 42CrMo4 alloy steel immersion quenched into polymer solution under ultrasonic agitation and shows completed different microstructure that consist of clear network of carbide. John A. Petras and Joseph E. McVicker have studied effect of ultrasonic on kinetic of phase transformation during quenching of 1045 steel[15]. The ultrasonic agitation result in cavitation that significantly destabilize the film boiling stage and increase the rate of heat transfer during immersion quenching. Further, the ultrasonic vibration provides additional activation energy which enhance the carbon diffusion and favours

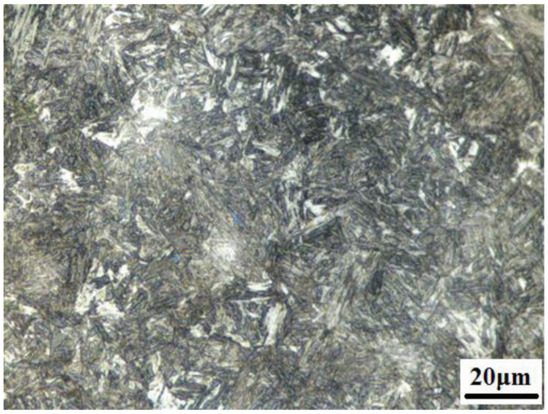

Figure 3. Microstructure of 42CrMo4 alloy steel sample quenched into polymer solution under magnetic stirring.

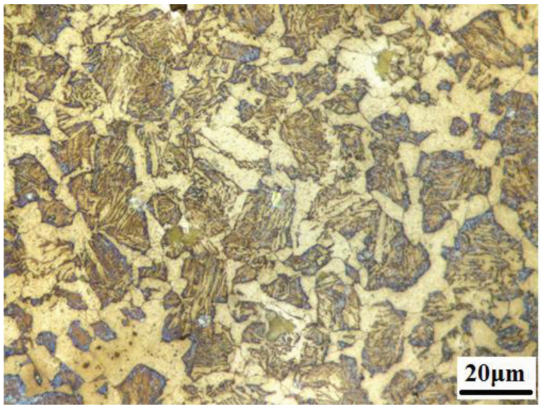

Figure 4. Microstructure of 42CrMo4 alloy steel sample quenched into polymer solution under ultrasonic agitation.

the precipitation of new carbides. 42CrMo4 alloy steel is a medium carbon low alloy steel with strong carbide forming elements Cr and Mo. Hence, it is expected that nucleation and growth of carbide at the austenitic grain boundaries at the earlier stage of quenching. Once the carbide is formed which cannot undergo further phase transformation in the later stage of quenching especially in martensitic transformation temperature range. The remaining austenite undergoes shear displacive transformation. Since most of the carbon atoms are utilized for carbide formation, shear transformation leads to low carbon martensite plates which was clearly evident from the microstructure (Figure 4). The hardness of the samples was measured using Brinell hardness tester. The average of three indentations were used to determine the hardness number and shown in Figure 5. Among the three quenchants, water quenching shows highest harness value due to fine structure of

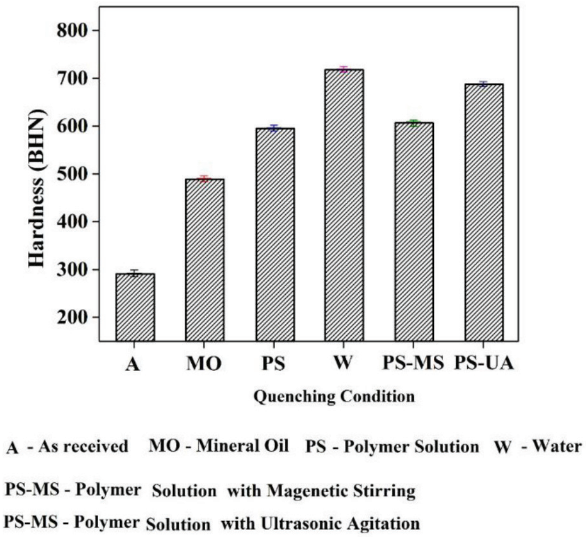

Figure 5. Brinell hardness values of 42CrMo4 alloy steel samples quenched in different quenchants.

martensite whereas lower hardness values were observed with mineral oil and polymer quenching. Agitation of polymer solution resulted in higher hardness value due to increased cooling rate. Ultrasonic agitation of polymer solution resulted in higher hardness value than magnetic stirring and without agitation due to formation of strong carbide network.

4.0 Conclusions

Quench hardening of 42CrMo4 alloy steel was carried out with different quenchants mineral oil, polymer solution and water. The hardening was also carried out with agitated condition of polymer solution. Based on the results and discussion, the following conclusion were drawn.

1. Cooling conditions during the quenching hardening of 42CrMo4 alloy steel have significant effect on phase transformation.
2. Microstructures of sample quenched in mineral oil and polymer solution show martensite with low volume fraction of bainite.
3. Microstructure of sample quenched in water shows martensite with more amount of needle-like/acicular bainitic ferrite.
4. The presence of chromium and molybdenum were expected to promote the bainite formation during quenching.

5. Ultrasonic agitation during quenching enhances the carbon diffusion and form carbide network during quenching.

5.0 Acknowledgment

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