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Ljubiša Balanović
Dejan Tanikić

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PREFACE

On behalf of the Organizing Committee, it is a great honor and pleasure to welcome all esteemed participants of the 54th International October Conference on Mining and Metallurgy (IOC 2023), scheduled to take place at the picturesque Bor Lake, Serbia, from October18th to 21st 2023.

The collaborative efforts of the University of Belgrade, the Technical Faculty in Bor, and the Mining and Metallurgy Institute Bor have meticulously organized this year's IOC. Our focus remains unwavering on showcasing the latest research findings and advancements in geology, mining, metallurgy, materials science, technology, environmental protection, and other engineering disciplines. Our primary objective is to foster a dynamic environment where academics, researchers, and industry professionals can come together to share their knowledge, experiences, and innovative ideas while exploring opportunities for collaborative research endeavors.

Our conference agenda is rich and diverse, encompassing plenary sessions, engaging invited lectures, technical presentations, enlightening oral and poster sessions, informative technical tours, a diverse exhibition, and memorable social gatherings. At the heart of this event lies our strong commitment to sustainable development within the mining and metallurgy sector. We are dedicated to exploring ecologically conscious methodologies, responsible resource extraction practices, and cutting-edge technologies that reduce the industry's environmental impact and enhance the well-being of local communities.

The conference proceedings comprise 129 papers authored by individuals from universities, research institutes, and industries in 22 countries. We are proud to welcome participants from Bosnia and Herzegovina, Bulgaria, Canada, China, Croatia, Germany, Greece, India, Iran, Kazakhstan, Libya, North Macedonia, Montenegro, Morocco, Romania, Russia, Slovakia, South Africa, Spain, Turkey, United States, and, of course, Serbia.

We are excited to host the 8th International Student Conference on Technical Sciences (ISC 2023) as part of IOC 2023. This event offers students from Serbia and the wider region a unique chance to showcase their research and discuss the future of their fields with experts.

We sincerely thank the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia for their generous financial support. In addition, we express our profound gratitude to all our sponsors, exhibitors, and friends of the Conference for their contributions and unwavering support for playing a pivotal role in ensuring the success of IOC 2023.

We would like to express our heartfelt thanks to all authors, committees, reviewers, speakers, and chairpersons for their invaluable contributions in shaping IOC 2023.

We look forward to welcoming you to the 55th International October Conference on Mining and Metallurgy (IOC 2024), which will be held in October 2024.

On behalf of the 54th IOC Organizing Committee,

Prof. dr Ljubiša Balanović

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THE INFLUENCE OF QUENCHING MEDIA ON DIFFERENT PROPERTIES OF C45 CARBON STEEL

Uroš Stamenković, Ivana Marković, Srba Mladenović, Saša Marjanović, Avram Kovačević, Milijana Mitrović, Filip Basarabić

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Abstract

The subject of this paper was the investigation of the influence of different quenching media on the mechanical, thermal, and structural properties of C45 medium carbon steel. After normalization heat treatment, steel samples were austenitized at 880°C for 50 minutes. Austenitization was followed by quenching in different quenching media: pure water and different aqueous solutions (2–8%) of NaOH. After each heat treatment, hardness and thermal properties were determined, along with structural investigations using the optical microscope. After normalization, samples had the lowest hardness values, while thermal conductivity was the highest compared to the other tested samples. Metallographic analysis showed that the structure consists of fine-grained ferrite and perlite. Quenching in water and aqueous solutions, the values of hardness increased significantly, while the values of thermal properties decreased. Samples quenched in aqueous solutions exhibit extreme hardness. Metallographic analysis of the samples after quenching revealed fine needles of martensite.

Keywords*: quenching, aqueous salt solutions, hardness, thermal conductivity*

1. INTRODUCTION

Carbon steels with carbon content between 0.3-0.5% are often called medium-carbon steels. These steels play an important role in the industry settings such as transportation industries, military and civil [1]. The C45 steels belong in this category as well. Machine parts made out of these steels sometimes require extremely high values of hardness and tensile strength due to the high demand for wear-resistant materials. Generally, these are steels that have martensitic structures, and often their hardness exceeds 800 HV, with tensile strength over 2500 MPa [2,3]. In order to improve properties of steels, heat treatment must be applied. Overall, most used heat treatments of steel include: normalizing heat treatment in order to obtain fine pearlite, and quenching for obtaining martensite [4,5]. Quenching heat treatment is one of the most important processes that often improves the performance and applicability of steels through martensite formation. During quenching, the metallic sample is rapidly cooled in a quenching medium (quenching solution) from the austenitization temperature, in the range of 845–900°C (for carbon steels) [6]. The two important phenomena that occur during quenching and influence the final structure and properties of steels are heat transfer and wetting [7]. The commonly used quenchants are water, oil, brine (aqueous salt solution), and synthetic solutions. All of these quenching media have their positive and negative sides. Water has low cost and is highly available, but provides high quenching rates that can lead to cracks; oils are expensive but provide slower cooling than water which is sometimes necessary, and are excellent quenchant for alloyed steels; polymer solutions provide quenching speed between water and oil, but those solutions are expensive and have varying concentrations throughout the quenching process. Brine solutions are used in cases where higher quenching severity is required [8]. During the quenching in liquid quenchants, three stages are usually observed: *vapor blanket*, *nucleate boiling*, and *convective cooling*. The second stage (nucleate boiling) is the most important stage in the quenching process. The faster the second stage starts, the faster the cooling rate will be. In order for the second stage to start, the first one has to be shortened, i.e., the vapor blanket should be eliminated [9]. One way to eliminate a vapor blanket and obtain more uniform cooling is to add various types of salts to the water in different concentrations, creating aqueous salt solutions. It is important to note that since high cooling rates are obtained by quenching in brine, the propensity for cracking and distortion is also increased, so brine solutions are often used for the quenching of low-hardenability steels [10,11]. Some authors investigated the influence of quenching in different salt solutions. Lozano et al. gave a great deal of information on quenching in differently concentrated aqueous salt solutions. Among the investigated quenching solutions, the results of the quenching rate of aqueous solutions of NaOH at different concentrations were also given. Lozano et al. concluded that with an increase in the concentration of NaOH in the solution, the quenching rate increases [10]. The quenching power of aqueous salt solutions was investigated by L.H. Zordao et al. The authors investigated the properties of the C45 steel after quenching in differently concentrated aqueous salt solutions (NaCl, $NaNO_2$, Na_2SO_4, $NaHCO_3$). They showed that quenching in aqueous salt solutions breaks up the vapor blanket and leads to better heat dissipation during cooling. Also, in almost all tested solutions, an increase in salt concentration led to an increase in the cooling rate during quenching [9]. Sitorus et al. investigated the effect of quenching in NaOH solution on the properties of medium-carbon steel. The authors showed that an increase in the concentration of the NaOH solution leads first to an increase and then to a decrease in the tensile strength of the tested steel. The authors obtained the maximum values of mechanical properties after quenching in a 20% NaOH solution [12].

By reviewing the literature, no data were found on how quenching in aqueous salt solutions affects the change in thermal properties. Considering that items made of C45 steel are used at high temperatures after quenching, it is of great importance to know the change in thermal properties after obtaining extremely high hardness values by quenching in aqueous salt solutions. The goal of this paper was to obtain the extremely high values of hardness by quenching the samples made from C45 in the NaOH aqueous salt solution. After that, determine the influence of high quenching rate on thermal and structural properties.

2. EXPERIMENTAL

The experiments were performed on medium-carbon (C45) steel. Steel was obtained in the form of a round bar with a diameter of 20 mm. The chemical composition of the investigated steel is given in Table 1.

Table 1 - Chemical compositions of investigated steel (mass. %)

C45 medium-carbon steel				
Fe	**C**	**Mn**	**S**	**P**
98.51-98.98	0.42-0.5	0.6-0.9	≤0.05	≤0.04

In the first place, all the samples were normalized at 900°C for 1 hour in an electric resistance furnace, Vims elektrik LPŽ-7,5 S in order to remove the as-received structure, and then cooled in air. After normalization, samples were heated to austenitization temperature at 880°C for 50 minutes and then quenched separately in water and in 2%, 4%, 6%, and 8% NaOH solutions. After each heat treatment, samples were separated and investigated. The heat treatment process can be seen in Figure 1.

Hardness was measured on the VEB Leipzig Vickers hardness tester using a 30 kg load and a 15 s dwelling time.

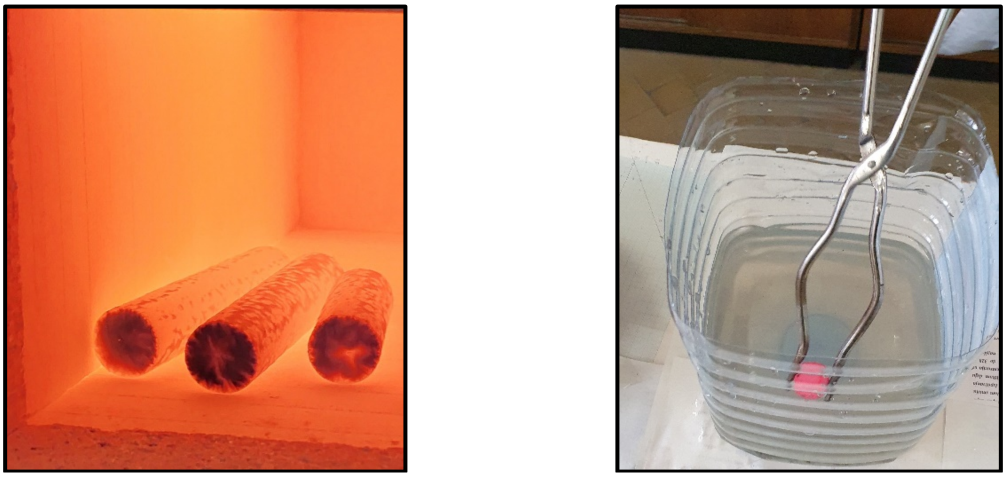

Figure 1 - Heat treatment of steel samples in an electric resistance furnace, followed by quenching

Xenon flash method was applied to determine the thermal diffusivity of the investigated samples after different heat treatments by irradiating the disc-shaped specimens with a diameter of 12.7 mm with the xenon lamp in a nitrogen atmosphere. The thermal conductivity as a function of temperature was calculated according to the equation:

$$\lambda(T) = \rho(T) \times c_p(T) \times \alpha(T) \quad (1)$$

where, λ - thermal conductivity; (W/m*K), ρ – density; (kg/m^3), c_p – specific heat capacity; (J/kg*K), α - thermal diffusivity; (cm^2/s), T – temperature; (°C).

A Reichert MeF2 optical microscope was used for the investigation of the microstructures. The preparation of the samples for optical examinations included wet grinding on a series of SiC papers; polishing with alumina suspension; and etching in a 4% Nital solution.

3. RESULTS AND DISCUSSION

In figures 2 and 3, the change in hardness and thermal conductivity of the samples can be seen as a function of the applied heat treatment: normalization, quenching in water, and quenching in differently concentrated aqueous NaOH solutions, respectively.

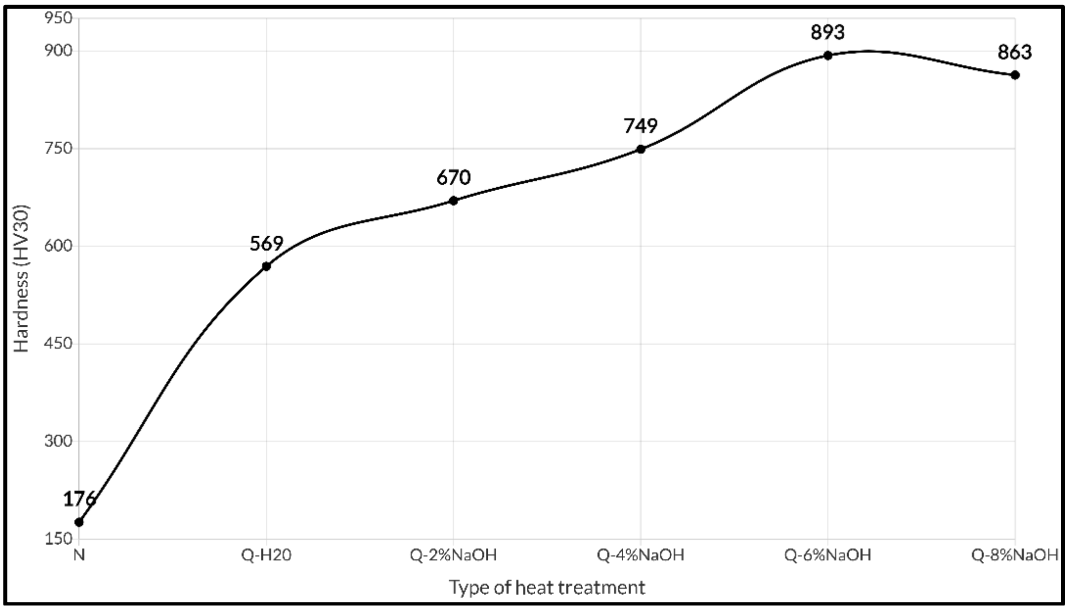

Figure 2 – Change in hardness as a function of the type of heat treatment; N- Normalized; Q-H20- quenched in water; Q-2-8%NaOH- quenched in NaOH solutions

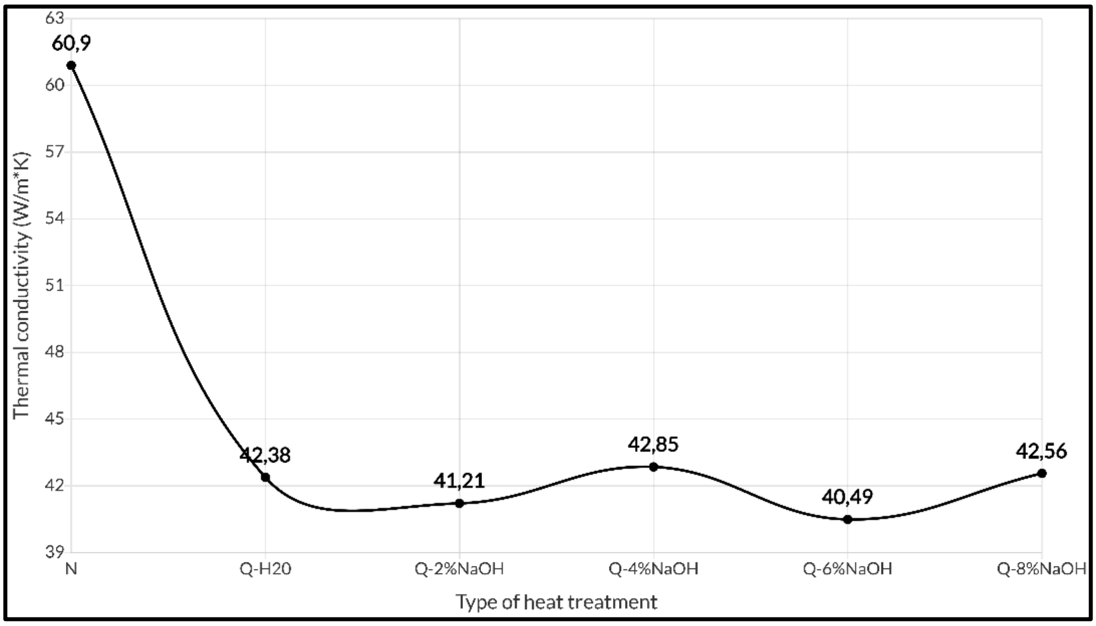

Figure 3 – Change in thermal conductivity as a function of the type of heat treatment; N-Normalized; Q-H20- quenched in water; Q-2-8%NaOH- quenched in NaOH solutions

On analysis of the graph given in Fig. 2, it can be concluded that the hardness values increased very rapidly after quenching in water and aqueous NaOH solutions. The absolute increase in hardness of the water-quenched sample compared to the normalized one is 393 HV30. By quenching in the NaOH solutions, extremely high hardness was obtained, higher than the samples quenched in water. Quenching in a 2% NaOH solution caused an increase in hardness by 101 HV30 in comparison to the hardness of the water-quenched sample. Also, an increase in the concentration of NaOH led to an increase in the hardness after quenching. The maximum hardness of 893 HV30 was obtained after quenching in a 6% NaOH solution. A further increase in NaOH concentration (8%) led to a slight decrease in hardness.

The first thing to notice in Fig. 3 is that, in general, with quenching, the thermal conductivity values decrease. Immediately after quenching in water, the thermal conductivity decreased by 18.52 W/m*K compared to the normalized state. Thermal conductivity values fluctuate after quenching in differently concentrated NaOH solutions. During quenching in a 4% NaOH solution, slightly higher thermal conductivity values were obtained than those obtained after quenching in pure water. Similarly to the obtained hardness values, the thermal conductivity was the lowest after quenching in a 6% NaOH solution. Also, somewhat higher values of thermal conductivity were obtained after quenching in an 8% NaOH solution.

The reason for obtaining very high hardness values after quenching in differently concentrated aqueous NaOH solutions lies in the achievement of extremely high cooling rates. By adding various inorganic salts to the water, the vapor blanket is broken during quenching. After immersing the austenitized piece in an aqueous solution (in our case, a NaOH solution), salt crystals are deposited at the boundary between the red-hot piece and the coolant. At the boundary of the hot piece, due to the very high temperature and supersaturation, microexplosions occur that break the vapor blanket [8,9,13,14]. By breaking the vapor blanket, it is possible to obtain extremely high cooling rates, even up to 2-3 times higher than the cooling rate in water [15]. When such extremely high cooling rates are achieved, it is possible that a larger amount of martensite is obtained in the structure, i.e., that the hardenability suddenly rises, and with that, higher hardness values are expected. This was also shown by Zordao et al. in their work by quenching in aqueous solutions of Na_2SO_4 and NaCl [9]. Sitorus et al. also obtained similar results, where with increasing concentrations of NaOH in quenching solutions, hardness values gradually increased [12].

On the other hand, this type of structure hinders the movement of electrons (carriers of thermal energy), lowering the values of thermal conductivity [16,17]. Quenching in NaOH solutions caused extreme saturation of the iron matrix due to high cooling rates. Quenched-in carbon, certain other elements present in steel, and quenched-in vacancies serve as electron scattering centers. This is also the reason for the general drastic reduction of thermal properties after quenching in NaOH solutions compared to the normalized state, and later also compared to the state after quenching in water. The fluctuation of thermal conductivity after quenching in NaOH solution is explained by the fact that, by quenching in aqueous solutions, it is impossible to predict what saturation will be in the lattice after quenching and what the morphology of martensite will be. In this regard, there is a possibility that, regardless of the high values of hardness obtained with a higher proportion of martensite due to high cooling rates, the flow of electrons in such a lattice will be somewhat more pronounced. This can be seen with the sample that was quenched in an 8% NaOH solution, where a slightly lower hardness was obtained compared to the maximum (6% NaOH), but there is a significantly higher thermal conductivity.

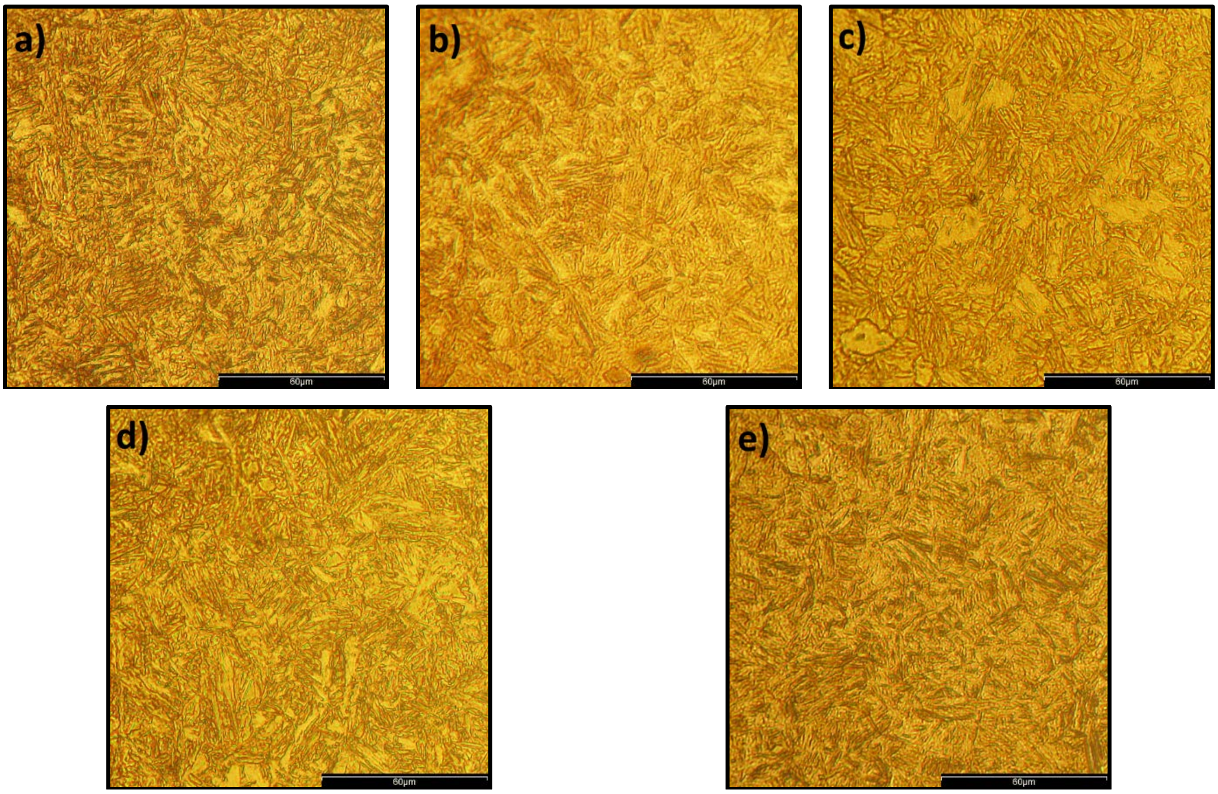

Figure 4 – Microstructure of the C45 after quenching in: a) water; b) 2%NaOH; c) 4%NaOH; d) 6%NaOH; e) 8%NaOH

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he microstructure of the quenched samples can be seen in Figure 4. An analysis of the microstructures can confirm, to some extent, what was stated before. In all samples, the critical cooling rate was reached, so martensite was obtained. No major differences can be observed in the microstructures after quenching in water and aqueous NaOH solutions.

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4. CONCLUSIONS

Based on the obtained results, the following conclusions can be drawn:

- After quenching in water, the hardness increased compared to the normalized sample.
- Extremely high cooling rates were achieved by quenching in aqueous NaOH solutions. This condition resulted in extremely high values of mechanical properties but also relatively low values of thermal properties.
- A 407% increase in hardness (the maximum) was achieved after quenching in a 6% NaOH solution in comparison to the normalized sample, and a 57% increase in comparison to the sample quenched in water.
- By quenching in aqueous NaOH solutions, the thermal conductivity was significantly lower in comparison to the normalized sample and, in some cases, lower in comparison to the sample quenched in water.
- The value of thermal conductivity was the lowest after quenching in a 6% NaOH solution.

Based on the conducted experiments, it can be concluded that water and NaOH aqueous solutions are adequate for quenching C45 steel. After quenching, no distortion, cracks, or other damages were observed on the samples. The obtained hardness values are extremely high for this type of steel.

An increase in the concentration of NaOH in the quench bath led to an increase in the hardness values. With an increase in NaOH concentration, hardness increased, reaching maximum values after quenching in a 6% solution. After that, the hardness decreased slightly after quenching in an 8% solution. It is interesting that after quenching in an 8% NaOH solution, the hardness had a relative decrease of 3.3% in relation to the maximum obtained hardness value after quenching in a 6% NaOH solution. On the other hand, by quenching in an 8% NaOH solution, the thermal conductivity had a relative increase of 5.11% compared to the sample quenched in a 6% NaOH solution and even a relative increase of 0.42% compared to the sample that was water quenched.

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