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production – properties – application

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Tel: ++
387 401 831, 402 832, Fax: ++ 387 406 903

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ENVIRONMENT PROTECTION AND SUSTAINABLE DEVELOPMENT

THE INFLUENCE OF HEAT TREATMENT ON MICROSTRUCTURE AND THERMAL PROPERTIES OF C45 TOOL STEEL

Uroš Stamenković, Ivana Marković, Srba Mladenović, Dragan Manasijević, Ljubiša Balanović, Avram Kovačević, Milan Nedeljković, Jovana Božinović
University of Belgrade, Technical Faculty in Bor
Bor, Serbia

Keywords: C45 steel, Microstructure, Martensite, Thermal properties, Tempering

ABSTRACT
In this paper, C45 medium carbon tool steel was investigated after various heat treatments. The thermal properties, specifically thermal diffusivity and thermal conductivity, were measured and also the microstructure analysis was done on a light microscope. Heat treatment of the samples included: 1) the normalization heat treatment at 900°C for one hour and cooling in the air; 2) quenching the samples in water and in oil separately after reheating them at 880°C for one hour and; 3) tempering the quenched samples at 200°C-350°C for 2 hours. The results show the highest values of thermal properties for the normalized sample. Also, the lowest values were recorded for the quenched samples, and the values of thermal properties for the tempered samples are between the values of the quenched and normalized samples. Microstructure analysis shows a typical ferrite-pearlite structure after normalization. Martensite appeared in the water-quenched sample. However, the microstructure of the oil-hardened sample predominately consists of ferrite and pearlite because the critical cooling rate was not reached. Tempered samples quenched in the water had the microstructure of tempered martensite.

1. INTRODUCTION

Steels with a carbon content between 0.3-0.5% are often called medium carbon steels. These steels are used in many applications. Because of their mechanical, physical, and other properties, many of them are essentials for building parts in many industries. Those industries are automotive, naval, civil, military, electrical, etc. [1]. Medium carbon steels can exhibit different properties when subjected to various heat treatments [2]. The most common heat treatment for these steels includes quenching and tempering at high temperatures in order to achieve highly tempered martensitic microstructure which would provide the highest values of toughness and high wear resistivity [3]. In addition, medium carbon steels are considered to be a type of tool steel. For tool steels, besides good mechanical properties, several thermophysical properties are very relevant for tool design [4]. Two of those thermophysical properties are thermal diffusivity and thermal conductivity. These properties sometimes dictate the lifespan of the tool. For example, higher thermal conductivities in steels can reduce temperature gradients that appear in tools during their application [5,6]. Thermophysical properties are greatly influenced by different heat treatments, especially given the fact that a large number of these tools are used in applications at elevated temperatures. Medium carbon steel research is usually based on investigating the mechanical properties after various heat treatments. Some heat treatments have already been investigated by other researchers. In most cases, the authors dealt with how quenching in water, aqueous polymer solutions, or aqueous salt solutions as well as subsequent tempering affects the mechanical properties of C45 steel [3,7].

Groom et al. monitored the change in mechanical properties after oil quenching and tempering [8]. A. Laouissi et al. colleagues made their contribution by optimizing the heat treatment process, investigating the influence of annealing temperature as well as the influence of different types of quenching (in air, in water, and in hydrochloric acid solution) on mechanical properties [1]. Some authors examined the thermal properties of different steels after various heat treatments, including C45 steel. Wilzer et al. investigated the influence of heat treatment on the thermophysical properties of martensitic steels. They showed that tempering increases the values of thermal conductivity and thermal diffusivity, but with a decrease in hardness values [4,9].
The primary aim of this paper is the investigation of thermal properties of C45 medium carbon tool steel after normalization, and subsequently after quenching and low to medium temperature tempering (200°C-350°C). The secondary aim is to investigate the microstructures that appear after various heat treatments and see if those structures are in agreement with the obtained results for thermal properties.

2. EXPERIMENTAL PROCEDURE

Experiments were performed on C45 medium carbon tool steel with the defined chemical composition given in Table 1. Steel was received in the form of hot extruded bars with a diameter of 20 mm. The samples were firstly normalized at 900°C for one hour in an electric resistance furnace in order to normalize and eliminate the structure after the manufacturing process, and then cooled in still air. Normalized samples were then annealed at 880°C, for one hour and quenched separately in oil and in cold water. Quenched samples were tempered at different temperatures (200°C-350°C) for 2 hours. Samples were separated for further analysis after normalization, quenching, and tempering. Characterization of the samples included measuring the thermal properties and microstructural analysis on an light microscope. The 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).

Light microscopy was used for the investigation of the microstructure. Preparation of the samples included wet grinding on a series of SiC papers, and polishing with alumina suspension with two different granulations of Al_2O_3: particle sizes of 0.3 µm and 0.05 µm. 4% Nital solution was used for the etching of the samples by immersion to reveal the microstructure. The microstructures were examined on two light microscopes CarlZeiss Jena Epytip 2 and Reichert MeF2. Also, the equipment used and various steps in the heat treatment process can be seen in Figure 1a-d.

Table 1. Chemical composition 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

Figure 1. Equipment and different steps in the heat treatment process: a) electric resistance furnace; b) sample heating; c) and d) samples after tempering for 2 hours at different temperatures

3. RESULTS AND DISCUSSION

3.1. The properties of investigated samples after normalizing

After normalization heat treatment, the fabricated structure was removed and the structure of investigated samples was normalized. Obtained results show relatively high values of thermal diffusivity and thermal conductivity, 16.97 mm^2/s, and 60.9 W/m*K, respectively. The relatively high values for thermal properties were obtained due to the normalization heat treatment which involved high-temperature heating and slow cooling leading to an equilibrium state at room temperature. The equilibrium state caused by slow cooling has a low density of dislocation and vacancies, so the movement of electrons (as thermal energy carriers) is facilitated. In this state, samples had a microstructure that consisted of a fine mixture of ferrite and pearlite, shown in Figure 2a-b. Duka et al. stated that the microstructure of C45 steel is composed of 66% pearlite and 34% ferrite [10].

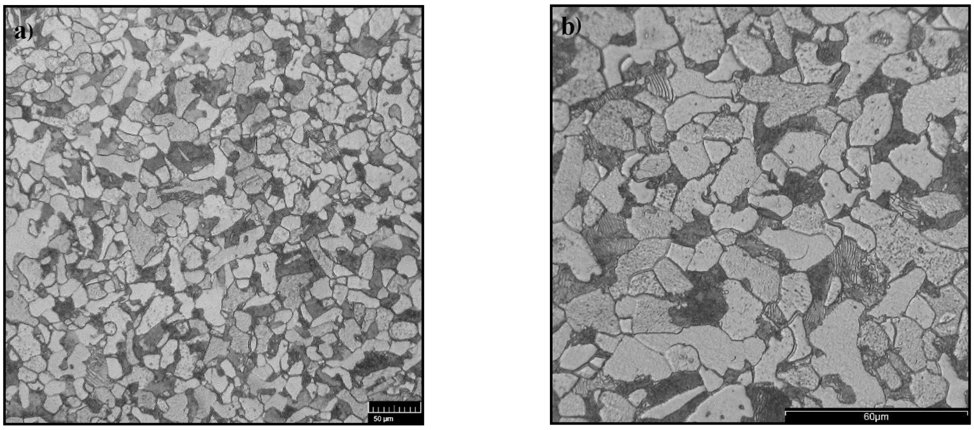

Figure 2. Microstructure of the investigated C45 steel after the normalization heat treatment; a) magnification is x500; b) magnification is x1000

3.2. The properties of investigated samples after quenching

After the normalizing heat treatment, samples were austenitized and quenched to room temperature using two different quenchants. Table 2 shows the results after quenching separately in oil and in water.

Table 2. Thermal properties of the investigated steel after quenching

Type of quenchant	Thermal diffusivity (mm^2/s)	Thermal conductivity (W/m*K)
Water	11.41	43.76
Oil	11.88	46.49

The values of thermal diffusivity and thermal conductivity decreased after quenching in water and oil when compared to the values obtained after normalization. The absolute decrease in thermal diffusivity and thermal conductivity after quenching in water is 5.56 mm^2/s and 17.14 W/m*K, respectively. After quenching in oil, the results are somewhat different and an absolute decrease of 5.09 mm^2/s and 14.41 W/m*K was recorded for thermal diffusivity and thermal conductivity, respectively. After quenching in water, the formation of martensite led to the formation of a supersaturated solid solution of carbon in the iron matrix. According to Wilzner, all other elements that enter into the composition of steel are trapped in addition to carbon during tempering. In this regard, martensite is characterized by high supersaturation as well as a high density of dislocations and vacancies. This type of structure hinders the movement of electrons, as carriers of thermal energy, lowering the values of thermal properties [4,9].

These characterizations are less pronounced in the samples that were quenched in oil, because, due to the insufficient cooling rate, a mixed microstructure is expected. This can be concluded by comparing the results obtained after quenching in water with those obtained after quenching in oil. The comparison of those results shows that higher values of thermal properties are obtained after quenching in oil.

The microstructural analysis confirmed the statements above to some extent. After quenching in water, finely distributed martensite needles can be observed in the microstructure. For the oil-quenched sample, the critical cooling rate was not reached, therefore no martensite was formed. The microstructure of the oil-hardened sample is of a mixed type, which predominately consists of ferrite and pearlite. Microstructures can be seen in Figure 3a-d.

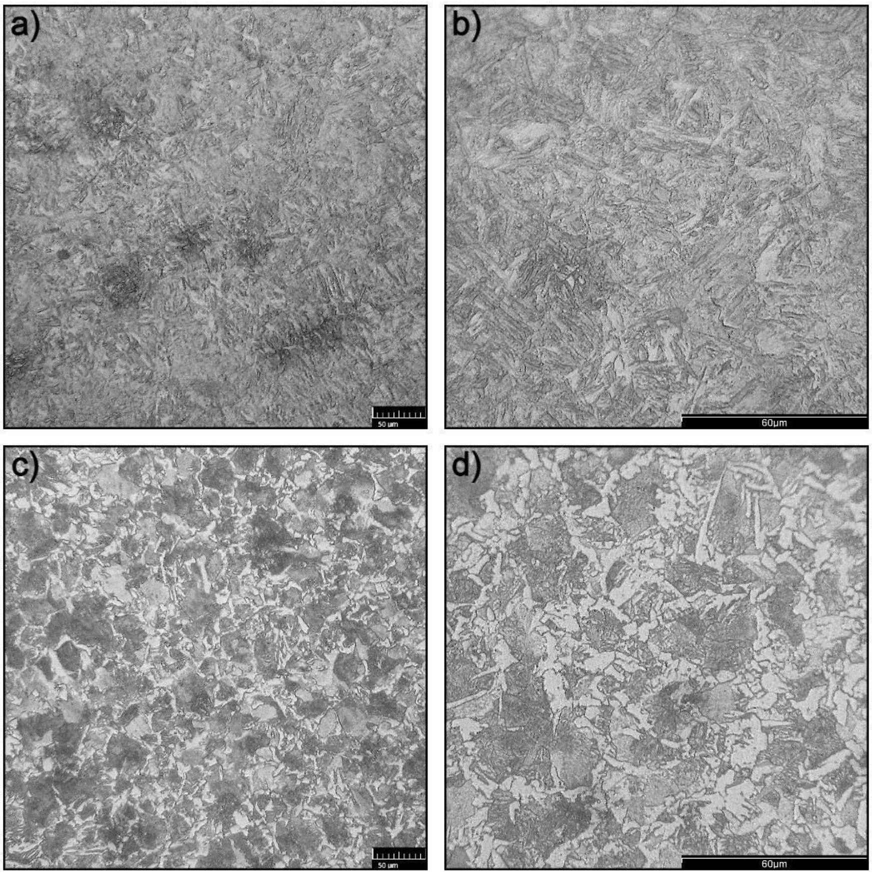

Figure 3. Microstructure of the investigated C45 steel after quenching;
a) in water, magnification is x500; b) in water, magnification is x1000; c) in oil, magnification is x500; d) in oil, magnification is x1000

3.3. The properties of investigated samples after tempering

After quenching in water and oil separately, samples were subjected to tempering at different temperatures for 2 hours. During tempering, changes in the thermal properties were observed and investigated. Figure 4 shows the obtained values for thermal diffusivity and thermal conductivity after tempering at 200°C-350°C for 2 hours. Analysis of the obtained results shows that the values of thermal diffusivity and thermal conductivity gradually increase with the increase of tempering temperature.

The reason for the increase in values of thermal properties lies in the tempering of hardened samples. Winczek et al. stated that steels with a carbon content > 0.2 wt.% starts tempering even at room temperature [11]. During tempering, there is a reduction in stress and the transformation of martensite that was formed by quenching into tempered martensite. After tempering in this temperature range there are a couple of processes that occur simultaneously: the diffusion of carbon atoms; the loss of tetragonality of martensite; the formation of cubic ferrite; the formation of cementite; the decomposition of residual austenite; whereby lower hardness values are recorded [4,7,8,11].

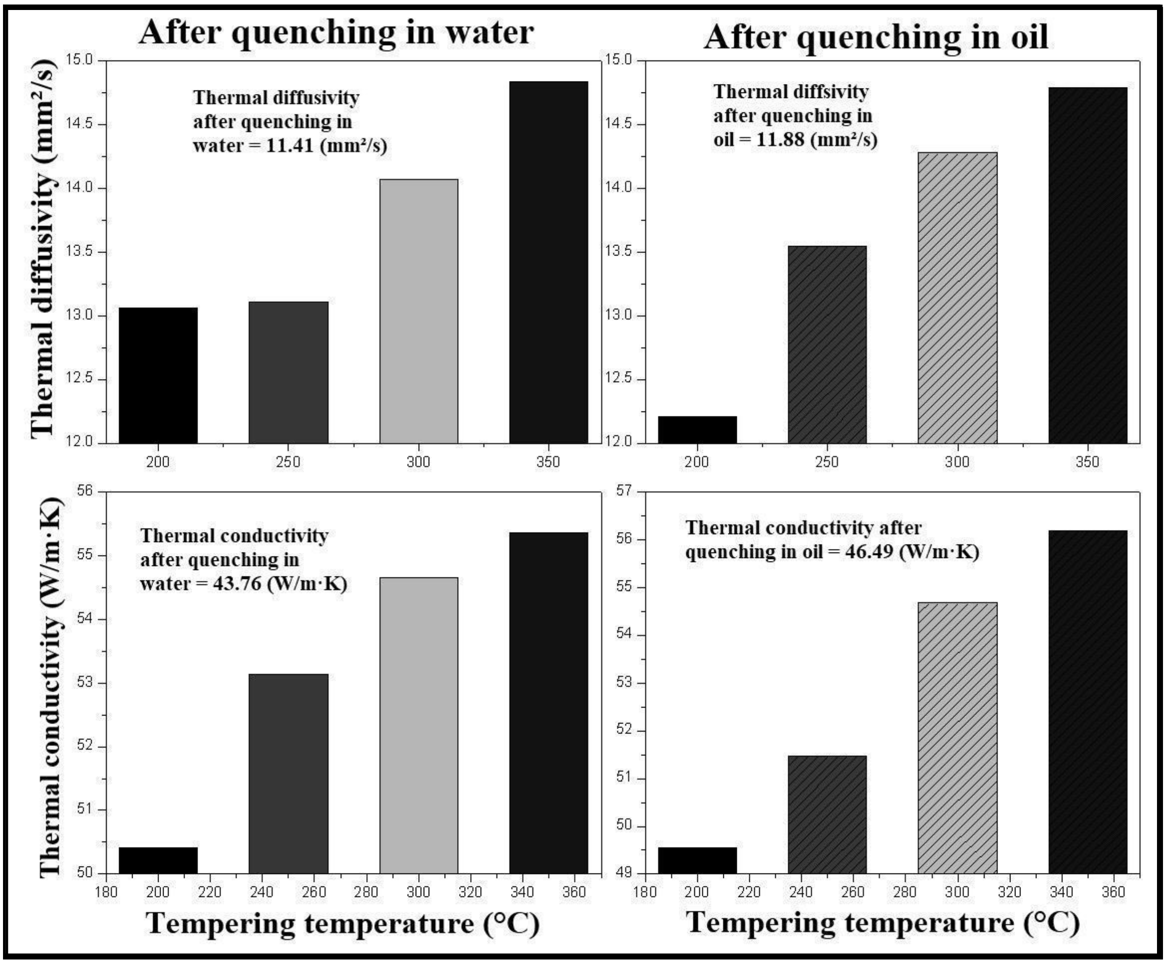

Figure 4. Change in thermal properties after tempering quenched samples at different temperatures for 2 hours

During tempering, with the increase in tempering temperature, a slight rearrangement in the structure occurs. Change in thermal properties depends on two mutual processes, namely: 1) thermal vibrations in the lattice caused by the increase in temperature and 2) precipitation of carbon atoms from the supersaturated martensitic lattice. Consequently, these two processes are at odds. So essentially, one process (1) hinders the movement of

electrons and causes the values of thermal properties to decrease and one process (2) facilitated the movement of electrons and causes the increase of values for investigated thermal properties. Depending on which of the processes is more active at a given moment, values of thermal properties will be defined accordingly. Given that, the measurements of the thermal properties in this part of the experiment were made at room temperature, the thermal vibrations were significantly reduced, so in this case, the process of precipitation from the supersaturated martensite prevailed [4,9,12].
As for the samples that were tempered after quenching in oil, obtained values for those samples show a similar trend to the water-quenched samples, which is interesting considering that no martensitic microstructure was obtained in these samples. It can be assumed that due to the heating of those samples, the acceleration of diffusion and the removal of possible residual stresses occurred causing the values of thermal properties to increase in comparison to the quenched sample.

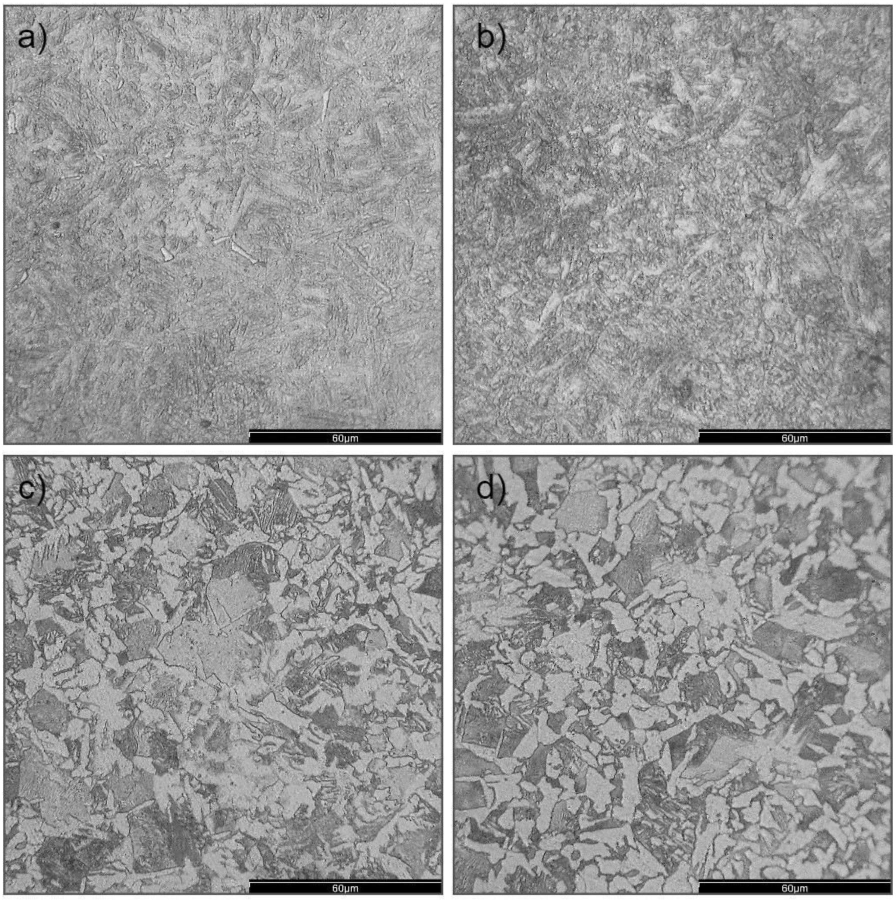

Figure 5. Microstructures after: a) quenching in water and tempering at 200°C, 2h; b) quenching in water and tempering at 350°C, 2h; c) quenching in oil and tempering at 200°C, 2h; d) quenching in oil and tempering at 350°C, 2h;

Analysis of the microstructures after tempering is in agreement with the given statements about the influence of tempering on thermal properties. Figure 5a-d shows the microstructures after quenching and tempering at 200°C and 350°C for 2 hours. After quenching in water and tempering, microstructures are well homogenized and they consist of tempered martensite where martensitic needles are less pronounced. Due to the low tempering temperatures, microstructures do not differ as much as those obtained after quenching. As for the microstructures obtained after quenching in oil and tempering, considering that the critical cooling rate was not achieved by quenching in oil, and that martensite was not formed, concrete changes in the microstructure cannot be expected. The grains are somewhat larger due to exposure to slightly higher temperatures.

4. CONCLUSIONS

The influence of different heat treatments on the microstructure and thermal properties of C45 medium carbon tool steel was investigated. Some conclusions can be outlined:

- After normalization heat treatment, values of thermal properties are the highest of all investigated states. Microstructure consists of a fine mixture of ferrite and pearlite.
- Quenching in water caused the formation of martensite in the structure. The values of thermal diffusivity and thermal conductivity decreased in comparison to the values obtained for the normalized sample. The relative decrease in values of thermal diffusivity and thermal conductivity were, 33% and 28%, respectively.
- The critical cooling rate was not achieved by quenching in oil, so martensite was not present in the microstructure. Nevertheless, the values of thermal diffusivity and thermal conductivity decreased in comparison to the values obtained for the normalized sample. The relative decrease in values of thermal diffusivity and thermal conductivity were, 30% and 24%, respectively.
- After tempering the quenched samples, the values of the thermal properties gradually increase with the increase of the tempering temperature. The values of thermal diffusivity and thermal conductivity had the lowest increase at the tempering temperature of 200°C and the highest increase at the tempering temperature of 350°C. The relative increase in values of thermal properties was in the range of 20-30%.
- Microstructural analysis after quenching in water and tempering showed typical microstructure of tempered martensite.

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