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EFFECT OF HEAT TREATMENT ON THE MECHANICAL AND STRUCTURAL PROPERTIES OF X155CrVMo12-1 STEEL

Uroš Stamenković, Ivana Marković, Srba Mladenović, Dragan Manasijević, Petar Milanović, Milan Nedeljković

University of Belgrade, Technical Faculty in Bor, VJ 12, Bor, Serbia

Corresponding author: Uroš Stamenković, ustamenkovic@tfbor.bg.ac.rs

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ABSTRACT

This paper investigates the effects of oil quenching and tempering at various temperatures on the mechanical and structural properties of X155CrVMo12-1 tool steel. The steel specimens were austenitized at 1030 °C for half an hour, followed by quenching and tempering at different temperatures. Mechanical properties were assessed by measuring the hardness of the samples after each heat treatment. Using the conversion formula, the tensile strength values were calculated based on the measured hardness. Structural changes were analyzed using optical microscopy. The results indicate that the highest hardness values were achieved after the quenching process. However, an increase in tempering temperature led to a decrease in hardness. Optical microscopy revealed that quenching caused the appearance of martensite in the microstructure, while tempering at various temperatures caused alterations in the martensite structure.

1. INTRODUCTION

X155CrVMo12-1 steel is a cold-work tool steel characterized by high levels of carbon and chromium. It exhibits excellent dimensional stability during heat treatment, which is essential for creating precision drawing punches, stamping and extrusion dies, and other components. The chemical composition of steels used in manufacturing is regulated by standards, allowing for modifications to their structure and properties through various heat treatment methods. By optimizing these processes, different material properties can be tailored to specific applications. The typical heat treatment for X155CrVMo12-1 steel involves quenching followed by tempering. While quenching results in very high hardness, it also reduces toughness [1-5]. During the tempering process of this steel, large amounts of secondary carbides are formed due to the high carbon content and the presence of other alloying elements [6, 7]. Effective heat treatment methods are crucial for achieving a high-quality product when cold-working steels are used in the manufacturing process. Modifying the quenching parameters, along with the temperature and duration of the tempering process, directly influences carbide formation, quench stresses, and dislocation density. These factors, in turn, affect properties such as hardness, toughness, and tensile strength [8]. As a result, many researchers have examined the effect of heat treatment on different properties of X155CrVMo12-1 steel [1, 4, 5, 8-12]. V. Marušić and colleagues investigated how tempering temperature affects the hardness, toughness, and crack formation in X155CrVMo12-1 tool steel. They concluded that the optimal heat treatment involves austenitizing the steel at 1030

°C followed by quenching and tempering at around 400 °C. By applying these heat treatment conditions, the authors were able to achieve the highest toughness values of 18 J while still maintaining relatively high hardness [9]. The possibility of applying the double austenitization before quenching to obtain superior mechanical and structural properties was investigated by S. Salunkhe et al. Their findings revealed that this process resulted in greater hardness while maintaining a nearly consistent austenite grain size compared to the conventional single austenitization method. The improvements observed after double austenitization were attributed to more effective dissolution of carbides in the matrix [5].

This study seeks to enhance the understanding of how heat treatment affects the mechanical and structural properties of X155CrVMo12-1 tool steel. The heat treatment process involved annealing, quenching, and tempering at various temperatures. After each stage, the mechanical and structural properties were analyzed. Additionally, the research focused on reducing the duration of all heat treatment steps. The objective was to minimize heat treatment times while considering economic and environmental factors, as shorter processes consume less energy and are therefore more cost-effective.

2. EXPERIMENAL PROCEDURE

For this experiment, a hot extruded round bar of X155CrVMo12-1 tool steel was used, with a chemical composition that meets the requirements of standard EN ISO 4957-2:2018 [13], given in Table 1, respectively.

Table 1. Chemical composition of investigated steel (mass. %)

X155CrVMo12-1 steel							
C	**Si**	**Mn**	**S**	**P**	**Cr**	**V**	**Mo**
1.5-1.6	0.1-0.4	0.15-0.45	≤0.03	≤0.03	11-12	0.9-1.1	0.6-0.8

To determine the quenching temperature and further investigate phase transformations, DSC analysis of the steel under investigation was performed using the TA Instruments SDT Q600 analyzer. A 8.2 mg sample was heated from room temperature to 1100 °C at 10 °C/min in a nitrogen atmosphere. An empty alumina crucible served as the reference material.

After the DSC analysis, a piece of steel rod with a diameter of 12.7 mm was cut and placed in the furnace. In the first step of the heat treatment process, the rod was placed in the Vims Elektrik LPZ-7.5 S electric resistance furnace at 700 °C and gradually heated with the furnace to 900 °C. The piece was held at 900 °C for 20 minutes and then slowly cooled to room temperature inside the furnace. This step aimed to eliminate the original structure of the samples. The resulting annealed state served as a reference condition and was marked (AA) accordingly on all graphs.

In the second step, the rod was placed in a furnace at 1030 °C and held for 30 minutes to undergo austenitization before being oil-quenched to room temperature (marked as Q on the graphs). After quenching, the rod was cut into samples with a height of 4 mm. Each sample was then individually tempered at temperatures ranging from 50 °C to 700 °C for 20 minutes, followed by air cooling.

After each heat treatment step, the samples were extracted and analyzed using various experimental methods, including hardness testing and microstructure analysis.

After heat treatment, the samples were prepared for microscopy by grinding with waterproof silicon carbide (SiC) paper and polishing them with two alumina slurries of different particle sizes (0.3 µm and 0.05 µm). The samples were then etched with a 4% Nital solution to reveal the microstructure. Finally, the microstructures were analyzed using light optical microscopy (LOM) with a Reichert MeF2 microscope.

Vickers hardness was measured using a VEB Leipzig hardness tester with a load of 30 kg, in accordance with the EN ISO 6507-1:2023 standard [14]. Multiple measurements were taken, and the average value was calculated. Additionally, tensile strength values were estimated based on the relationship between hardness and tensile strength for steels [15]. The obtained values were converted to Brinell hardness number, then the formula for the determining the tensile strength was used:

$$\text{Tensile strength (MPa)} = 3.38 \times \text{Brinell hardness number} \quad (1)$$

3. RESULTS AND DISCUSSION

The phase transition temperatures were determined using differential scanning calorimetry (DSC) by heating the sample from 25 °C to 1100 °C at a rate of 10 °C/min. During the observation of the phase transformation, an endothermic peak was identified with a minimum at 827.38 °C (see Fig. 1). This indicates that the transformation from ferrite (or martensite) to austenite occurs within this temperature range [16].

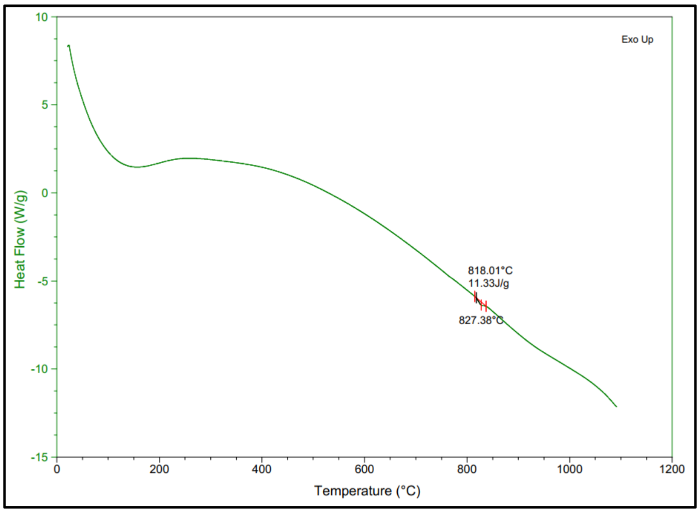


Figure 1. The DSC heating curve for the analyzed steel, highlighting the endothermic peak

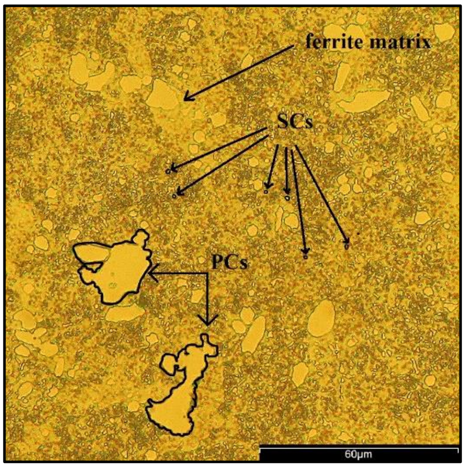


Figure 2. Investigated steel after annealing, magnification x1000

According to DSC analysis and recommendations from other authors [9], the quenching temperature was set to 1030 °C, which is well above the transformation temperature.

After annealing, the hardness of the samples is relatively low, around 250 HV. This result is expected due to the very slow cooling process in the furnace. The structure consists of fine eutectic and secondary carbides within a ferritic matrix [10]. Microstructure analysis of the annealed sample (see Figure 2) supports this observation. Primary carbides (PCs) appear as large white areas, while secondary carbides (SCs) are visible as very fine particles that are difficult to distinguish at this magnification.

Following the annealing heat treatment, all the samples were austenitized at 1030 °C for 30 minutes and then quenched. The graphs in Figures 3 and 4 show how hardness and tensile strength change with tempering temperature after the quenching process. The graph lines appear similar because tensile strength values are directly derived from hardness values. One key observation is the effect of quenching, illustrated by the differences in the dotted lines. When comparing the hardness of the annealed sample to that of the quenched sample, it is clear that the hardness nearly increases fourfold. This demonstrates this steel's high hardenability and indicates that martensite forms after quenching. The formation of martensite results in an increased number of dislocations and twins while reducing the number of slip systems. Consequently, the obstruction of dislocations leads to significant strengthening of the material [17].

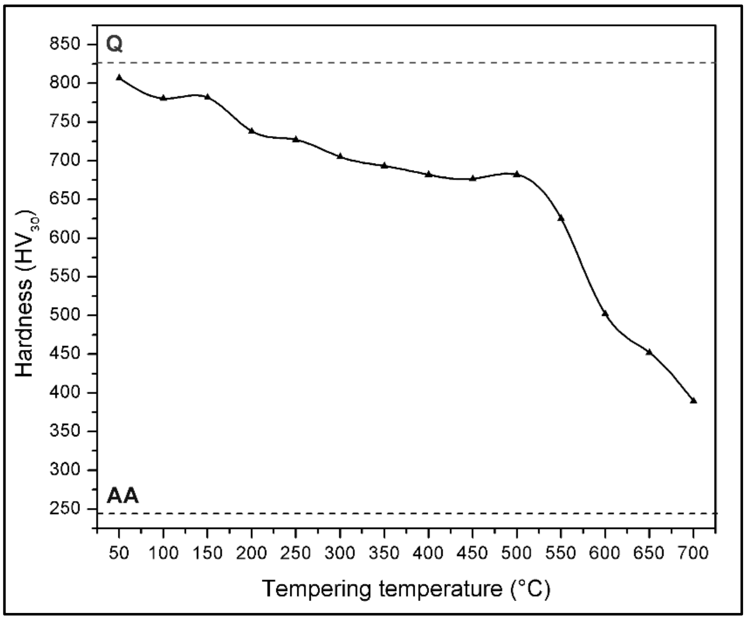


Figure 3. Change in hardness values after tempering quenched samples at different temperatures for 20 minutes; ***Q- after quenching; AA – after annealing***

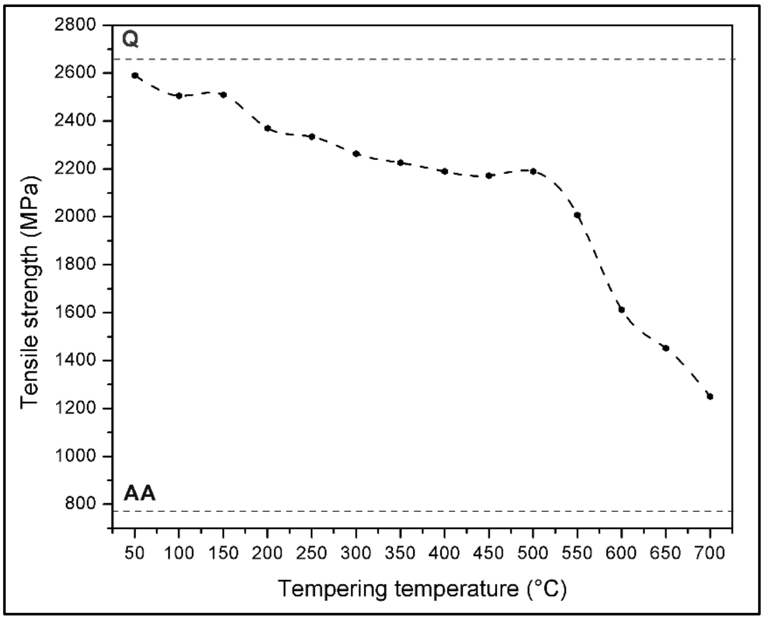
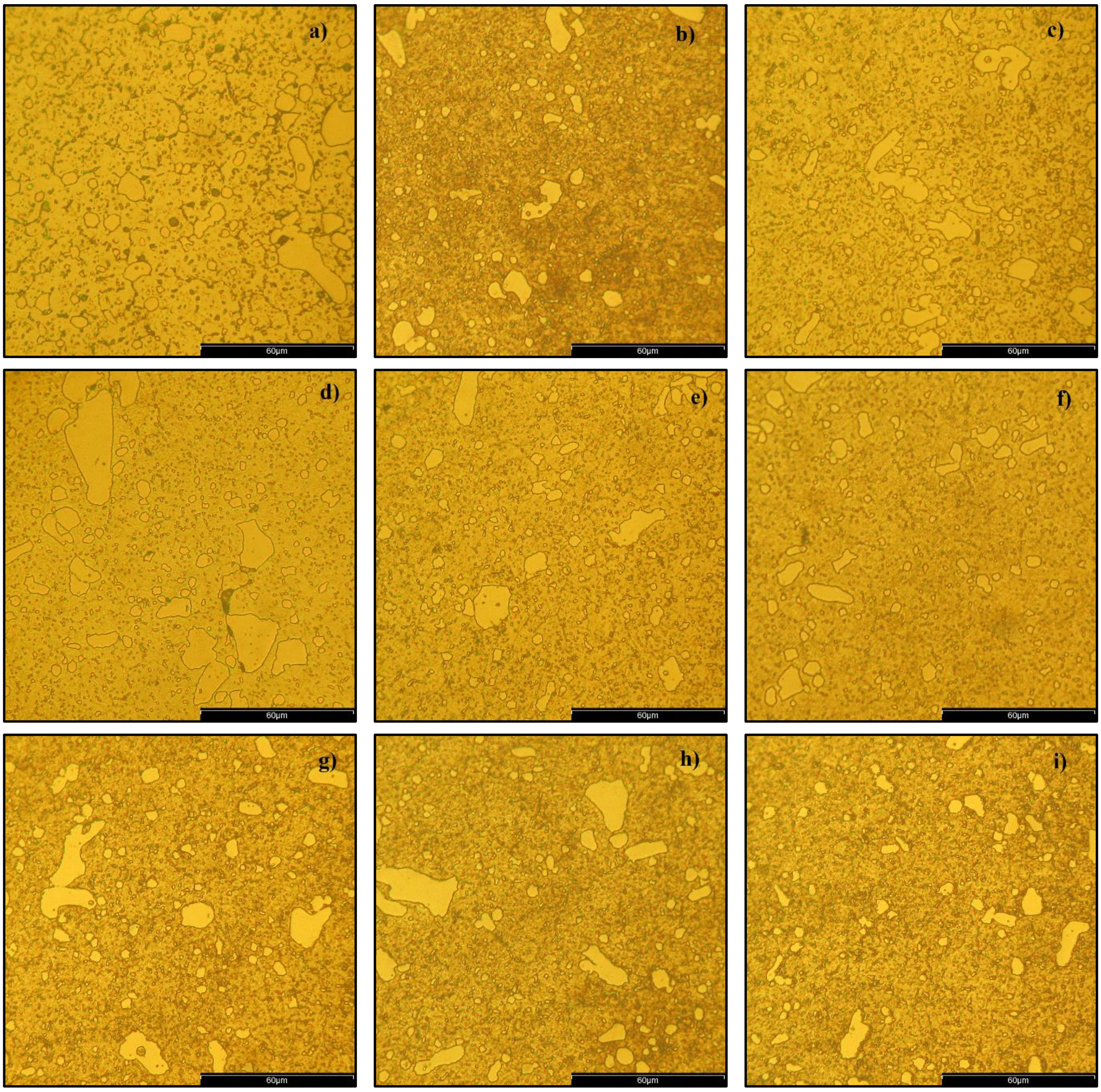


Figure 4. Change in tensile strength values calculated from the hardness values; ***Q- after quenching; AA – after annealing***

Tempering has been observed to progressively lower hardness values as the temperature increases due to structural changes. H. Torkamani et al. [1] identified two main effects of tempering on material structure. First, hardness decreases with higher tempering temperatures because recovery occurs, which reduces dislocation density and relieves quenching stresses. Second, tempering facilitates the transformation of residual austenite into martensite and the formation of secondary carbides (SCs). These SCs block dislocations and enhance hardness [1, 18-21]. The graph (Fig. 1) illustrates that high hardness values are maintained even at relatively high tempering temperatures (up to 500 °C), after which a sharp decline occurs. Similar results have been reported by other researchers [1, 5, 9, 11, 12, 22]. The retention of high hardness is attributed to the uneven distribution of coarse SCs within the matrix, which obstructs the movement of dislocations. As the tempering temperature increases (above 500 °C), secondary carbides (SCs) precipitate more effectively from the saturated martensite matrix, resulting in a more uniform distribution due to enhanced diffusion. Consequently, dislocation movement becomes easier, leading to a decrease in hardness values.



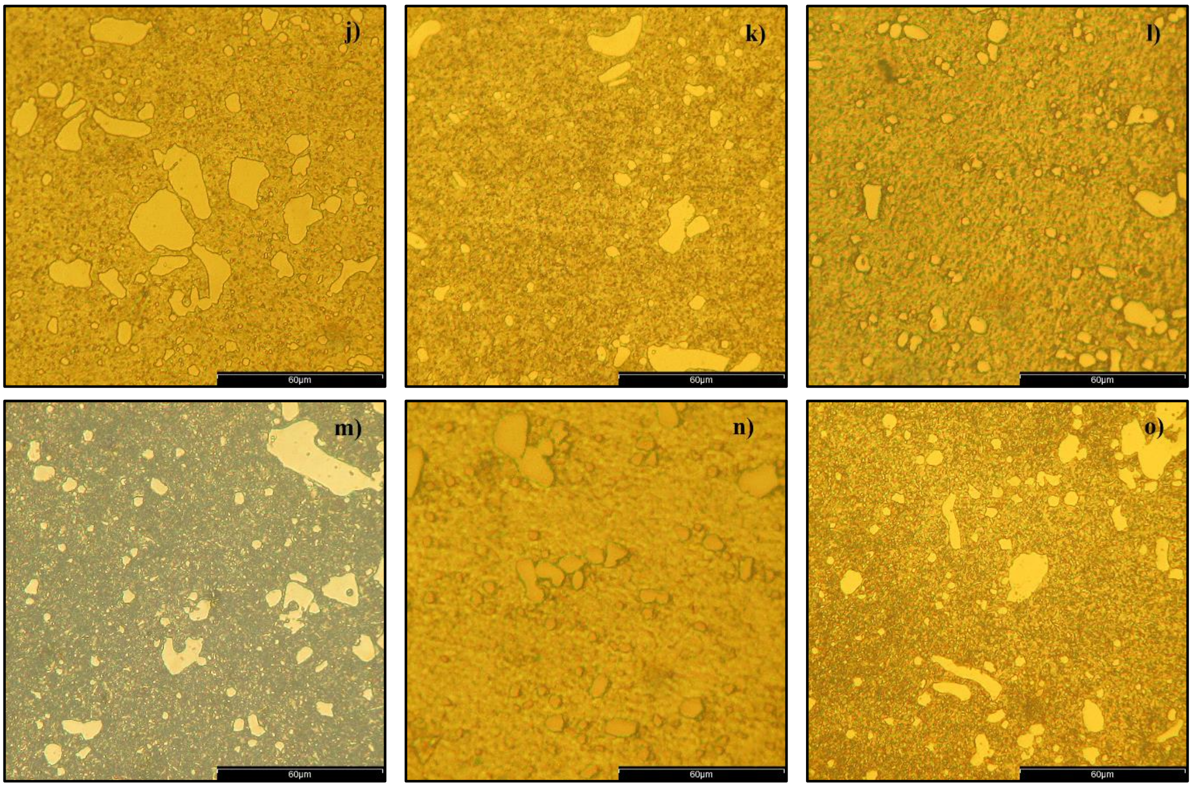


Figure 5. Microphotographs of the samples after: a) quenching; and after tempering at: b) 50 °C; c) 100 °C, d) 150 °C, e) 200 °C, f) 250 °C, g) 300 °C, h) 350 °C, i) 400 °C, j) 450 °C, k) 500 °C, l) 550 °C, m) 600 °C, n) 650 °C, o) 700 °C; magnification x1000

The microstructural analysis presented in Figs. 5a–o shows a variation in the microstructures of the samples examined, further supporting the earlier observation that tempering affects mechanical properties. The structure of the quenched sample (Fig. 5a) consists of martensite with dispersed carbides. The primary eutectic carbides are still visible in all of the microstructures because the austenitization temperature and time were not sufficient enough for them to be dissolved. In contrast, the microstructures of the tempered samples (Figs. 5b–j) don't show any particular change in comparison to the microstructure obtained after quenching [12]. Optical microscopy analysis indicates that tempering within this temperature range leads to only minor structural changes. However, tempering above 500 °C results in more significant alterations in the structure (Figs. 5k–o). At this higher temperature, there is an increased presence of small, finely dispersed secondary carbides (SCs) within a finer martensite matrix. This is consistent with the anticipated effects of tempering in this range, which facilitates the formation of SCs and the transformation of coarse martensite into a finer structure [11, 12]. At even higher tempering temperatures (>600 °C) it is expected for the matrix to shift from martensite to ferrite.

4. CONCLUSIONS

The effects of various heat treatments on mechanical and structural properties were studied. Some conclusions were drawn from the investigation:

a) X155CrVMo12-1 steel undergoes significant changes in its mechanical and structural properties due to heat treatment.
b) The annealed sample exhibited the lowest hardness values. Quenching significantly affected the mechanical properties of the material, leading to notable structural changes.

The hardness dramatically increased from 241 HV_{30} for the annealed sample to 821 HV_{30} following the quenching process, representing a 241% rise.

c) Tempering had an impact on both the mechanical and structural properties of the material. As the tempering temperature increased, the hardness values gradually decreased. A more significant decrease in hardness values was detected after tempering at temperatures above 500 °C. For instance, when the quenched sample was tempered at 700 °C, it experienced the lowest hardness value, falling from 821 HV_{30} to 389 HV_{30}, which represents a decrease of 52.62%.

d) After tempering, the microstructure analysis revealed tempered martensite, as well as eutectic and secondary carbides that were distributed throughout the structure.

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