Investigation of the thermal properties of X155CrVMo12-1 steel after quenching and tempering

Uroš Stamenković, Ivana Marković, Srba Mladenović, Dragan Manasijević, Milan Nedeljković, Petar Milanović
University of Belgrade, Technical faculty in Bor, Bor, Serbia
ustamenkovic@tfbor.bg.ac.rs

***Abstract**: This paper investigates the effects of oil quenching and tempering at various temperatures on the mechanical and thermal properties of X155CrVMo12-1 tool steel. The steel specimens were austenitized at 1030 °C for half an hour, followed by quenching in oil and tempering at temperatures ranging from 50 °C to 700 °C. Mechanical properties were assessed by measuring the microhardness of the samples after each heat treatment. Thermal properties were investigated using the Xenon flash method (DXF analysis) to measure thermal diffusivity, thermal conductivity, and specific heat. The results show that the highest microhardness values were achieved after quenching, while the lowest values were observed for thermal diffusivity and thermal conductivity. Following quenching, the microhardness values gradually decreased with an increase in tempering temperature, whereas the values of thermal diffusivity and thermal conductivity increased. Even after tempering at 500 °C, the microhardness values remained quite high, with only a 23.41% decrease from the quenched state. Furthermore, there was a significant improvement in thermal properties, with thermal diffusivity increasing by 38.34% and thermal conductivity improving by 23.99%.*

***Keywords**: THERMAL DIFFUSIVITY, THERMAL CONDUCTIVITY, MICROHARDNESS, HEAT TREATMENT, X155CrVMo12-1*

1. Introduction

Tool steels can be used in a variety of applications. X155CrVMo12-1 (AISI D2) tool steel is often used for manufacturing high-precision tool dies, drawing punches, stamping dies, etc. The chemical compositions of steels utilized in production are governed by standards; therefore, alterations of their properties are possible only through different heat treatment techniques. By fine-tuning these processes, various material properties can be customized for particular uses. Many tool steels, X155CrVMo12-1 included, are often used in a state of tempered martensite (they are tempered after quenching) [1-4]. In tool manufacturing, high wear resistance and high hardness are achieved through quenching. However, this process also results in brittleness and low impact toughness. To overcome these issues, tools typically need to be tempered to reduce brittleness and increase toughness. Proper heat treatment techniques are essential for producing high-quality products when working with cold-working steels during manufacturing. Adjusting the quenching conditions, in addition to the temperature and duration of the tempering stage, has a direct impact on carbide development, quench stresses, and dislocation density. These elements, consequently, influence characteristics like hardness, toughness, tensile strength, but also some thermophysical properties like thermal diffusivity, thermal conductivity and specific heat [5].

Thermal diffusivity and thermal conductivity are essential properties to consider when evaluating tool steels. These characteristics affect how heat is transferred throughout the manufactured component. Understanding the changes in thermal properties, particularly with variations in temperature, is crucial for assessing the productivity, quality, and durability of tools and dies. X155CrVMo12-1 tool steel is commonly used for producing injection dies that form complex shapes, with materials being injected under high pressure and elevated temperatures, often reaching up to 500 °C. The cyclical heating and cooling of the die during production impact its productivity cycle and overall lifespan. Therefore, it is vital to understand how thermal properties change, especially at operational temperatures. Some authors focused on determining the ideal heat treatment parameters in order to improve mechanical properties. The effects of tempering temperature on hardness, toughness, and crack development of AISI D2 steel were investigated by V. Marušić et al. [6]. Authors determined that the ideal heat treatment consists of austenitizing the steel at 1030 °C, followed by quenching and tempering at approximately 400 °C. After the recommended heat treatment parameters, the authors reported achieving high values of toughness while preserving relatively high hardness levels [6].

This research aims to improve the comprehension of how heat treatment influences the mechanical and thermal characteristics of X155CrVMo12-1 tool steel. The heat treatment procedure included annealing, quenching, and tempering at different temperatures. Various properties were assessed after each phase. The goal was to reduce heat treatment times while taking into account economic and environmental considerations, as shorter processes require less energy and are thus more cost-efficient.

2. Experimental part

Experimental investigation was performed on X155CrVMo12-1 tool steel. Investigated steel was received in the form of rounded bar and machined to the diameter of 12.7 mm. The Table 1 represents the chemical composition of the investigated steel which is in accordance with standard EN ISO 4957-2:2018 [7].

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

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

The heat treatment procedure was carried out in several stages. A steel rod with a diameter of 12.7 mm was cut and placed inside the furnace. In the first stage, the rod was inserted into the Vims Elektrik LPZ-7.5 electric resistance furnace at 700 °C and progressively heated to 900 °C. It was held at 900 °C for 20 minutes before being gradually cooled to room temperature within the furnace. This phase in the heat treatment process aimed to eliminate the steel's original structure by annealing it. In the second stage, the rod was placed in the furnace at 1030 °C and kept at that temperature for 30 minutes to undergo austenitization, followed by oil quenching to room temperature (denoted as Q on the graphs). After the quenching process, the rod was cut into samples that were 4 mm thick. Each sample was then tempered individually at temperatures ranging from 50 °C to 700 °C for 20 minutes, followed by air cooling. Following each heat treatment phase, the samples were extracted and examined using several experimental techniques.

The Vickers method was employed to assess microhardness according to ASTM E384 standard [8]. The measurements were carried out using the PMT-3 Vickers microhardness tester. The surfaces of the investigated samples were ground and polished. A load of 1.47 N was applied for a duration of 15 seconds. Several measurements were taken, and the average value was determined.

Thermal properties were determined by the Xenon flash method (DXF analysis) and measured in two ways: 1. The quenched sample was continuously heated in a protective atmosphere from room temperature (25 °C) to 400 °C, with measurements taken at various elevated temperatures (25, 50, 100, 200, 300, and 400 °C). 2. Thermal properties were also measured at room temperature (25 °C) after the samples underwent different heat treatment processes and were allowed to cool to room temperature before measurement.

3. Results and discussion

3.1. Results after annealing and quenching

After annealing, the as-fabricated structure was removed. The obtained microhardness was found to be 248 $HV_{0.15}$. This microhardness value is expected to be low due to the applied heat treatment. Other authors have reported somewhat similar values [9, 10]. The thermal diffusivity and thermal conductivity values measured in this experiment were the highest recorded for this steel, 8.37 mm^2/s and 31.31 W/m×K, respectively. According to Nykiel et al., the annealed state achieved through slow cooling results in a structure that consists of a ferritic matrix with dispersed primary and secondary carbides [9]. Due to this near-equilibrium state, the matrix is relaxed, making it easier for electrons to flow as heat carriers, which is why the thermal properties are at their highest.

After annealing, samples were austenitized at 1030 °C for 30 minutes and quenched in oil. In Figure 1, the change in hardness of the investigated steels during different heat treatments can be seen. The obtained microhardness values after quenching was 1052 $HV_{0.15}$, which is more then four times in comparison to the annealed state. Consequently, the thermal diffusivity and thermal conductivity values were lowest recorded for this steel in this experiment, 4.33 mm^2/s and 18.83 W/m×K, respectively. The high values of microhardness with the low values obtained for thermal properties indicate the high hardenability of this steel and that the oil quenching caused the martensite formation. The formation of martensite causes the increment of number of dislocations and twins while reducing the number of slip systems. All of this blocks the movement of dislocations causing the strengthening [11]. Similarly, martensite also represents the super saturated solid solution of carbon and alloying elements in the iron matrix. After quenching, the alloying elements are trapped in the matrix causing the dispersion of the electrons. As electrons carry the thermal energy, their dispersion causes the values of thermal properties to decrease [12, 13].

Samples were examined using the Xenon flash method to investigate the effects of heat treatment. The quenched sample was gradually heated at a rate of 10 °C per minute, from 25 °C to 400 °C, as illustrated in Figure 1. The objective was to assess any changes in the sample's thermal properties after exposure to these temperatures following the quenching process. During the cold-forming process, tools are typically heated up to 400 °C, making it crucial to understand how thermal properties behave within this temperature range.

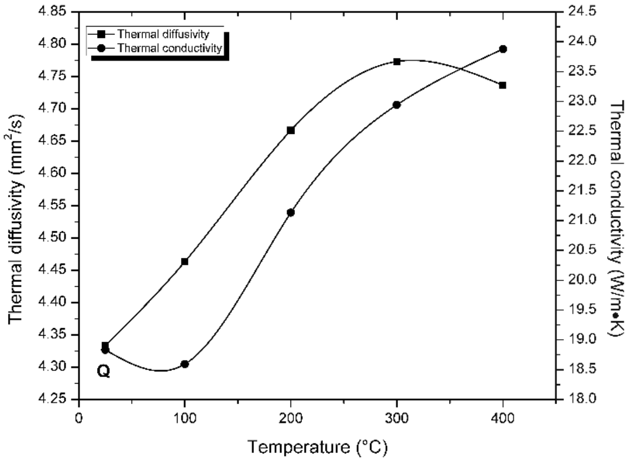

***Fig. 1** The influence of temperature on thermal properties after quenching; Q – represents the quenching state*

From the Figure 1, it can be seen that thermal diffusivity and thermal conductivity values increase with the temperature after quenching. As the temperature of the sample rises during testing, carbon atoms and alloying elements begin to precipitate out of the saturated matrix. This process results in the martensite lattice becoming more desaturated. In a desaturated lattice, electrons can move more freely, which increases their movement and leads to higher values of thermal diffusivity and thermal conductivity [1, 14]. Similar findings regarding the thermal conductivity of quenched AISI D2 steel were reported by N.A. Guru et al. [5].

3.2. Results after tempering

Figure 2 represents the influence of tempering temperature on the mechanical and thermal properties of the investigated steel. After quenching, samples were subjected to tempering at different temperatures for 20 minutes, after which they were cooled in still air to room temperature and investigated.

Tempering has been shown to progressively lower hardness as the temperature increases, mainly due to changes in the structure. H. Torkamani et al. [15] highlighted two significant effects of tempering on the structure. Initially, the reduction in hardness at elevated tempering temperatures is attributed to recovery processes that decrease dislocation density and relieve stresses from quenching. Additionally, tempering facilitates the conversion of residual austenite into martensite and the creation of secondary carbides (SCs). These SCs impede dislocation movement, thereby enhancing hardness [15-19]. Figure 2 illustrates that hardness remains elevated even at higher tempering temperatures (up to 500 °C), after which a noticeable drop occurs. Similar results have been observed by other researchers [4, 6, 10, 15, 20, 21]. The sustained high hardness is associated with the uneven distribution of coarse SCs within the matrix, which blocks dislocation movement. However, when tempering temperatures exceed 500 °C, SCs precipitate more efficiently from the martensite matrix, resulting in a more uniform distribution due to improved diffusion. Consequently, dislocation movement becomes less restricted, leading to a reduction in hardness.

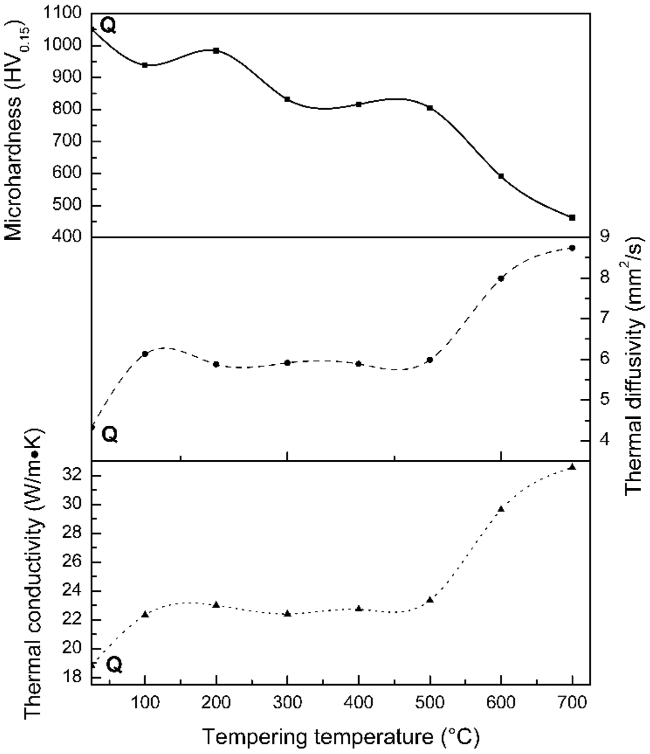

***Fig. 2** The influence of different heat treatments on the tensile strength of investigated steels*

The changes in thermal diffusivity and thermal conductivity with respect to tempering temperature are also illustrated in Figure 2. The findings indicate that thermal diffusivity and conductivity exhibit a similar pattern. The graphs show that the lowest thermal diffusivity and conductivity values are recorded after the quenching process. Compared to the quenched sample, both thermal diffusivity and conductivity gradually increase as the tempering temperature rises. The samples that were tempered at the highest temperature (700 °C) had the highest values for thermal diffusivity and conductivity. Fundamentally, the same mechanisms that cause a decrease in hardness also contribute to an increase in thermal diffusivity and conductivity. The reduction of the supersaturated matrix due to tempering minimizes scattering and enhances electron mobility, thereby improving thermal properties [22]. J. Wilzer et al. [1] also validated that tempering increases the thermal conductivity of both carbon and alloy steels.

From the analyzed results given in Figure 2, it should be noted that while tempering to about 500 °C may result in a slight decrease in hardness, the improvement in thermal properties outweighs this. As a result, a component will maintain its mechanical properties, such as microhardness and resistance to wear, while benefiting from enhanced heat dissipation due to an increase in thermal diffusivity and conductivity.

4. Conclusions

The influence of different heat treatments on microhardness, thermal diffusivity and thermal conductivity was investigated. Some conclusions can be outlined:

- X155CrVMo12-1 tool steel demonstrates a high sensitivity to changes in mechanical and thermal properties due to heat treatment.
- The quenching process significantly affects the structure, mechanical properties, and thermal properties of the investigated steel. When the sample was quenched in an oil bath, its hardness increased more than fourfold compared to the annealed sample, rising from 248 to 1051 $HV_{0.15}$. However, this process resulted in a decrease in thermal diffusivity and thermal conductivity, which decreased from 8.37 mm²/sec and 31.31 W/m×K (after annealing) to 4.33 mm²/sec and 18.83 W/m×K (after quenching), respectively, due to the formation of martensite.
- The ongoing heating of the oil-quenched sample, as shown by the DXF analysis, suggests that further tempering within the temperature range of 25 to 400 °C would be beneficial. The thermal diffusivity and conductivity values observed were higher than those recorded for the quenched sample.
- The mechanical and thermal properties were affected by the tempering process. Microhardness values progressively decreased with rising tempering temperatures. The maximum microhardness was recorded after quenching, followed by a gradual decline from 1051 to 462 $HV_{0.15}$ after tempering at 700 °C.
- With the increase in tempering temperature, both thermal diffusivity and thermal conductivity also showed a gradual rise. The minimum values for thermal diffusivity and conductivity were achieved after quenching. Tempering led to an increase in thermal diffusivity and conductivity values from 4.33 mm²/sec and 18.83 W/m×K after quenching to 8.74 mm²/sec and 32.6 W/m×K after tempering at 700 °C, respectively.

This heat treatment method produced excellent results. Quenching the steel samples resulted in high microhardness values. Even after tempering at 500 °C, the microhardness values remained quite high, with only a 23.41% decrease from the quenched state. Furthermore, there was a significant improvement in thermal properties, with thermal diffusivity increasing by 38.34% and thermal conductivity improving by 23.99%. These enhancements will facilitate better heat dissipation during tool usage, potentially extending the tool's lifespan and increasing productivity. Energy requirements are also decreased by shortening the length of all heat treatment procedures, which increases the process's cost-effectiveness.

Acknowledgment

The research presented in this paper was done with the financial support of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, with the funding of the scientific research work at the University of Belgrade, Technical Faculty in Bor, according to the contract with registration number 451-03-137/2025-03/200131.

References

[1] Wilzer J., Ludke F., Weber S., Theisen W., The influence of heat treatment and resulting microstructures on the thermophysical properties of martensitic steels, Journal of Materials Science, Volume 48 (2013), pp. 8483–8492.

[2] Firrao D., Matteis P., Russo Spena P., Gerosa R., Influence of the microstructure on fatigue and fracture toughness properties of large heat-treated mold steels, Materials Science and Engineering: A, Volume 559 (2013), pp. 371-383.

[3] Surberg C.H., Stratton P., Lingenhole K., The effect of some heat treatment parameters on the dimensional stability of AISI D2, Cryogenics, Volume 48 (2008), pp. 42–47.

[4] Salunkhe S., Fabijanic D., Nayak J., Hodgson P., Effect of single and double austenitization treatments on the microstructure and hardness of AISI D2 tool steel, Materials Today: Proceedings, Volume 2 (2015), pp. 1901–1906.

[5] Guru N.A., Swaminathan G., Prasanna Venkatesh P.R., Aravind P., Experimental investigation on hardness and thermal conductivity of D2 steel alloyed with copper, Materials Today: Proceedings, Volume 5 (2018), pp. 27673–27679.

[6] Marušic V., Milinović A., Opačak I., Putnik I., Research into possibilities of reducing the X155CrVMo12-1 tool steel fragility, Metalurgija, Volume 57 (2018), pp. 330–332.

[7] EN ISO 4957:2018. Tool steels. - https://www.iso.org/standard/70646.html

[8] ASTM E384-22. Standard Test Method for Microindentation Hardness of Materials. - https://www.astm.org/e0384-22.html

[9] Nykiel T., Hryniewicz T., Effect of high-temperature heating on chemical changes in M_7C_3 carbides of AISI D2 tool steel, International Letters of Chemistry, Physics and Astronomy, Volume 36 (2014), pp. 258–271.

[10] Conci M.D., Centeno D.M.A., Goldenstein H., Farina P.F.S., Study of short times tempering for AISI D2 cold work tool steel, Materials Research, Volume 26 (2023), e20230059.

[11] Lakhtin Y., Engineering, Physical Metallurgy and Heat-treatment – English translation from the Russian by Nicolas Weinstein, Second printing. Mir Publishers, Moscow, 1983.

[12] Reed R.P., Clark A.F., Materials at Low Temperatures, ASM International, Ohio, 1983.

[13] Wenzl H., Welter J. M., Electrical transport properties of pure metals and their influence by trace contamination, International Journal of Materials Research, Volume 65 (1974), pp. 205–214.

[14] Tritt T.M., Thermal Conductivity: Theory, Properties and Applications, Plenum Publisher, New York, 2004.

[15] Torkamani H., Raygan Sh., Rassizadehghani J., Comparing microstructure and mechanical properties of AISI D2 steel after bright hardening and oil quenching, Material Design, Volume 54 (2014), pp. 1049–1055.

[16] Liscic B., Tensi H.M., Canale L.C.F., Totten G.E., Quenching Theory and Technology – 2nd edition, CRC Press, Taylor and Francis Group, 2010.

[17] Totten G.E., Steel Heat Treatment, Taylor & Francis, 2006.

[18] Unterweiser P.M., Heat Treater's Guide: Standard Practices and Procedures for Steel, ASM International, 1995.

[19] Avner S.H., Introduction to Physical Metallurgy – 2nd edition, McGraw-Hill, 1974.

[20] Mochtar M.A., Putra W.N., Abram M., Effect of tempering temperature and subzero treatment on microstructures, retained austenite, and hardness of AISI D2 tool steel, Materials Research Express, Volume 10 (2023), 056511.

[21] Tiziani A., Molimari A., Improvement of AISI D2 steel properties by unconventional vacuum heat treatments, Materials Science and Engineering: A, Volume 101 (1988), pp. 125–133.

[22] Hafenstein S., Werner E., Wilzer J., Theisen W., Weber S., Sunderkotter C., Bachmann M., Influence of temperature and tempering conditions on thermal conductivity of hot work tool steels for hot stamping applications, Steel Research International, Volume 82 (2015), pp. 1628–1635.