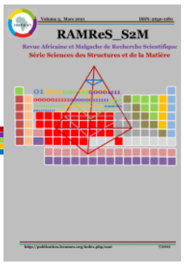
RAMReS Sciences des Structures et de la Matière Vol. 10, No. 1 (2026) 53 - 67
http://publication.lecames.org/index.php/mat *ISSN: 2630-1180*



Development of a scientific basis for heat treatment technology for high-speed steels

Belekbek Zholdoshov*, Burulai Mamatkadyrova, Seitbek Kaparov, Ayperi Kanybek Kyzy, Ulan Abdimatov

Osh Technological University named after M.M. Adyshev, Osh, Kyrgyz Republic

Received: 16 January 2026 / Received in revised form: 11 March 2026 / Accepted: 12 April 2026

***Abstract*:**

This study aims to optimize the heat treatment technology for M2 high-speed steel, enhancing its operational durability by investigating the effects of various heat treatment parameters. Experimental investigations were conducted at Osh Technological University, Kyrgyzstan, on M2 steel samples subjected to different heating rates (20 °C min^{-1}, 35 °C min^{-1}, and 50 °C min^{-1}), holding times (10 - 60 min), and quenching environments (oil, water, and nitrogen). The results demonstrated that moderate heating rates (35 °C min^{-1}) and a holding time of 30 min at 1250 °C produced an optimal balance between grain size and residual austenite content, contributing to improved hardness, wear resistance, and structural stability. Water quenching resulted in the highest hardness (860 HV30) but introduced significant residual stresses, while nitrogen quenching reduced stresses but decreased hardness. Oil quenching was identified as the most balanced method. The study highlights the importance of controlling heating rates, holding times, and tempering conditions, with tempering at 580 °C recommended for maximum wear resistance. The findings provide practical insights for industrial applications, offering an optimal heat treatment mode for high-speed steels.

***Keywords* :** Grain refinement ; Residual austenite ; Carbide distribution ; Quenching environment ; Tempering optimization ; Wear resistance.

1. Introduction

High-speed steels are widely used in machine building, tool making and metalworking due to their high hardness, wear resistance and heat resistance. However, achieving the optimum combination of these properties requires careful heat treatment, which affects the microstructure and performance characteristics of the steel. One of the key factors determining the mechanical properties of high-speed steels is the heating, holding and cooling regime. Different approaches to heat treatment can lead to changes in grain size, phase composition and carbide distribution, which directly affect the strength characteristics of the material.

One of the main problems faced by researchers is the influence of heating rate on grain structure formation. The study established that at low temperatures, moderate heating rates promote grain refinement, while excessive temperature increases lead to grain coarsening, which can

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* Corresponding author:
Email address: *zholdoshovbelekbek@gmail.com* *(B. Zholdoshov)*

https://doi.org/10.70974/mat10126053

reduce the mechanical properties of the material. Kerimkulova *et al.* [1] demonstrated that heating rates above 50 °C min^{-1} led to an increase in the residual austenite content, which in turn affects the hardness and wear resistance of steel. This phenomenon is particularly relevant for high-speed steels used under high mechanical loads and significant temperature fluctuations.

The study by Zholdoshov [2] examined the effects of annealing process parameters on the quality characteristics of tungsten high-speed steels of grades P12 and P18 of factory production melts in bars with a diameter of 18 mm. Furthermore, the annealing process modes were T = 825 and 900 °C, with different time intervals of 8, 24, and 48 h. The experimental samples were heated in steel chucks with chips to achieve protection against the effects of decarburisation and oxidation.

Another important task is the optimization of the holding time during austenitisation. Prolonged holding at high temperatures promotes carbide dissolution and grain growth, which affects the residual austenite content and mechanical properties of the material. Usubamatov *et al.* [3] found that an increase in holding time from 10 to 60 min leads to an increase in residual austenite from 7.6% to 14.5%, which can change the hardness and resistance to stress. These results indicate the need to find the optimal holding time that ensures a balance between carbide dissolution and preservation of the fine-grained structure.

The hardening method is also decisive in shaping the performance characteristics of high-speed steels (HSS). Water, oil or gas quenching has a different effect on the residual stress level and hardness of the steel. Usubamatov *et al.* [4] proved that water quenching results in the highest hardness (860 HV30) but is accompanied by significant residual stresses (570 MPa), which increases the risk of cracking in the material. At the same time, oil quenching can provide a more even distribution of stresses, which reduces the probability of defects.

One of the alternative methods of reducing residual stresses is the use of gas quenching. Fu *et al.* [5] demonstrated that nitrogen quenching reduces residual stresses (210 MPa) but leads to a decrease in hardness to 780 HV30. Thus, the choice of a hardening method requires consideration of the trade-off between strength characteristics and material structure stability. This aspect is especially relevant in the production of cutting tools, where it is critical to avoid internal defects that reduce the service life of products.

Post-quenching tempering of steel can achieve an optimum carbide distribution and reduce the level of residual austenite. Determination of the tempering temperature is important to achieve a balance between hardness and wear resistance. Xiao *et al.* [6] determined that tempering at 580 °C promotes the formation of a uniform carbide structure, providing high resistance to mechanical stress. This tempering mode minimises internal stresses, which is especially relevant when the tool is used under dynamic loads and thermal cycles.

Another important aspect is the effect of heat treatment on the wear resistance of high-speed steels. Zhang *et al.* [7] demonstrated that the best balance of properties is achieved at a moderate heating rate (35 °C min^{-1}), holding time of 30 min and oil quenching, which provides an optimal combination of hardness and wear resistance. This mode can be recommended for industrial applications, as it enables the manufacturing of high-cutting tool life without significantly reducing strength characteristics.

Additional research is being conducted on the correlation between microstructure and mechanical properties of steel. Pan *et al.* [8] determined that the formation of a fine carbide phase contributes to increased strength, but excessive carbide fragmentation can lead to a decrease in the impact strength of the material. Furthermore, the uniform distribution of carbides in the steel structure increases the service life of products, which makes this aspect relevant for optimizing heat treatment technologies.

Lastly, one of the most promising areas of research is the adaptation of heat treatment modes to increase the service life of high-speed steels in real-world operating conditions. Kuhn & Talik [9] demonstrated that optimization of heat treatment parameters can improve the stability of steel properties during long-term use, which is especially important for the tool industry. The development of new heat treatment methods based on combined heating, cooling and tempering modes can significantly improve the performance of tool materials.

Current literature on the heat treatment of high-speed steels, particularly M2 grade, lacks a comprehensive understanding of how specific parameters such as heating rates, holding times, and quenching environments interact to influence both the microstructure and mechanical properties of the steel. While previous studies have addressed the impact of individual heat treatment factors, they have often overlooked the combined effects and the optimal balance needed for enhanced performance. Furthermore, there is limited research on the precise role of moderate heating rates in achieving grain refinement and reducing residual stresses, which is critical for improving wear resistance and structural stability.

This study aimed to fill these gaps by systematically optimizing heat treatment parameters, and introduced a novel approach by exploring the effects of heating rate, holding time, and quenching medium in a more integrated manner than previous optimization efforts, providing a more practical and comprehensive framework for industrial applications. To achieve this goal, tasks that included analysing the effect of different austenitising, quenching and tempering regimes on the mechanical properties of steel, as well as assessing their impact on residual stresses and microstructure of the material, were formulated.

2. Materials and methods

2.1. Material and sample preparation

The study was conducted at Osh Technological University named after M.M. Adyshev, in Osh, Kyrgyzstan, from January to February 2025. The object of the study was high-speed steels used in mechanical engineering. In this study, 5 samples per condition were used for each heat treatment parameter. The tested samples were bars of high-speed steel grade M2 [10] with a diameter of 12 mm and a length of 100 mm. Additionally, 20×20×5 mm plates were used for metallographic analysis. The specimens were machined and then ground to ensure the accuracy of the geometric parameters. Before heat treatment, all samples underwent standard preparation, including cleaning in an ultrasonic bath using isopropyl alcohol for 15 min to remove contaminants and oxide films. Then they were subjected to a comprehensive heat treatment, including heating to an austenitising temperature in the range of 1180–1250 °C at different heating rates (20, 35 and 50 °C min^{-1}), holding for 10–60 min and subsequent quenching in various media – oil, water and gas (nitrogen). The selected heating rates (20, 35, and 50 °C min^{-1}) and temperatures (1180–1250 °C) are based on modern industrial and laboratory standards. Lower heating rates (20 °C min^{-1}) allow for grain refinement, improving toughness but are slower, making them less suitable for high-throughput industries. The medium rate (35 °C min^{-1}) offers a balance between efficiency and quality, while the higher rate (50 °C min^{-1}) simulates rapid industrial heating processes, though it risks grain coarsening at higher temperatures. The temperature range of 1180–1250 °C is standard for austenitising high-speed steels, optimizing carbide dissolution and austenite formation for maximum hardness, wear resistance, and structural stability. This combination reflects both industrial practices and laboratory precision. The effect of holding time was assessed by changes in the phase composition and grain size of austenite. After heat treatment, the samples were subjected to a detailed analysis of structure, mechanical properties and residual stresses. After quenching, the samples were tempered at temperatures of 540–600 °C in 20 °C increments and for a duration of 1 to 4 h. Additionally, the effect of step cooling on the formation of secondary carbides and their uniform distribution in the steel structure was studied. These heat treatment parameters were chosen to optimize the strength and wear characteristics of the material.

2.2. Heat treatment protocols

The heat treatment was performed using a Carbolite Gero STF 15/450 muffle furnace (UK) with a temperature programmable up to 1300 °C and a heating rate of up to 50 °C min^{-1}. The temperature was controlled using a type S thermocouple and a Eurotherm 3504 digital controller (UK).

The quenching was conducted in an oil medium (Houghton Quench K) and a nitrogen stream at a cooling rate of 25 °C/s.

Tempering was carried out in a Memmert UF110 drying furnace (Germany) at temperatures of 540–600 °C with a holding time of 1 to 3 h. To study the effect of different cooling modes, cooling in an aqueous medium and controlled cooling in an oven with a gradual temperature decrease were additionally used.

2.3. Microstructural and phase characterisation

Microstructural analysis was performed using a Zeiss Axio Observer optical microscope (Germany) after standard metallographic preparation, including grinding, polishing and etching with a 3% nitric acid solution in ethanol. The phase composition was studied by X-ray diffractometry using a Bruker D8 Advance diffractometer (Germany) with CuK_α radiation ($\lambda = 1.5406$ Å), a scanning step of 0.02° and a range of 2θ angles from 20° to 90°. Additionally, the distribution of carbide inclusions was analysed by scanning electron microscopy using a Tescan Vega 3 (Czech Republic).

2.4. Mechanical and tribological testing

The mechanical properties were assessed by the results of Vickers hardness tests using a Zwick/Roell ZHV30 device (Germany) at a load of 30 kgf and a holding time of 10 s. The impact strength was measured on an Instron Dynatup 9250HV pendulum tester (USA) using U-notched specimens. Friction and wear were determined using the ball-on-disc method on an Anton Paar TRB3 (Austria) at a load of 10 N and a sliding speed of 5 cm/s. Additionally, cyclic fatigue testing was performed using an Instron 8801 electromechanical testing machine (USA) with a load amplitude of 5 to 50 kN and a frequency of 20 Hz. The wear tests were conducted using a WC-Co ball as the counterbody material, which is commonly employed in wear testing due to its high hardness and wear resistance. The sliding distance for each test was set at 1000 m to ensure a significant wear track and to simulate typical operational conditions under which the M2 high-speed steel is used. The tests were carried out in a dry environment, without lubrication, to mimic general wear conditions in industrial applications.

2.5. Residual stress analysis

Structural changes were analysed by differential scanning calorimetry (Netzsch DSC 214 Polyma, Germany) with a temperature range from 20 to 1300 °C. DSC was used to investigate the thermal properties and phase transformations of M2 high-speed steel during heating and cooling. The primary purpose of the DSC analysis was to quantify the phase transitions, particularly the austenite-to-martensite transformation and other microstructural changes that occurred during heat treatment. The DSC measured latent heat associated with these phase transformations, providing insights into the energy required for the dissolution of carbides and the subsequent transformation of the steel's microstructure. Additionally, the DSC helped determine the thermal stability of the austenitic phase, which was crucial for understanding how heat treatment parameters affected the final mechanical properties of the steel. Residual stress measurements were conducted using the $\sin^2\psi$ method via X-ray diffraction (XRD) to accurately assess the stress distribution in M2 high-speed steel samples. The measurement covered a range of ψ angles from −45° to +45°, with 5° increments between each angle. This selection ensured a detailed and comprehensive evaluation of residual stresses at various depths within the material. A total of at least 5 different ψ angles were employed to obtain a reliable depth profile of the residual stresses. To calculate the residual stresses, elastic constants specific to M2 high-speed steel were used: Young's modulus ($E = 210\,\mathrm{GPa}$) and Poisson's ratio ($\nu = 0.3$).

2.6. Data processing and statistical analysis

Statistical data processing was performed using IBM SPSS Statistics [11] (USA). The reliability of the differences was assessed using analysis of variance (ANOVA) and Student's t-test at a significance level of $p < 0.05$. All experiments were performed more than three times, and the experimental results are presented as mean values with standard deviations.

3. Results and discussion

The study of M2 steel samples after heating in the temperature range of 1180–1250 °C at different rates (20, 35 and 50 °C min^{-1}) revealed the effect of this parameter on the phase composition and grain size of austenite. The data are presented in figures 1 and 2. As the heating rate increased, a decrease in grain size was observed at lower temperatures, but upon reaching 1250 °C, the grain became coarse-grained regardless of the heating rate. An increase in residual austenite content was also observed at higher heating rates. These results determined the optimal temperature regime for heat treatment of high-speed steel.

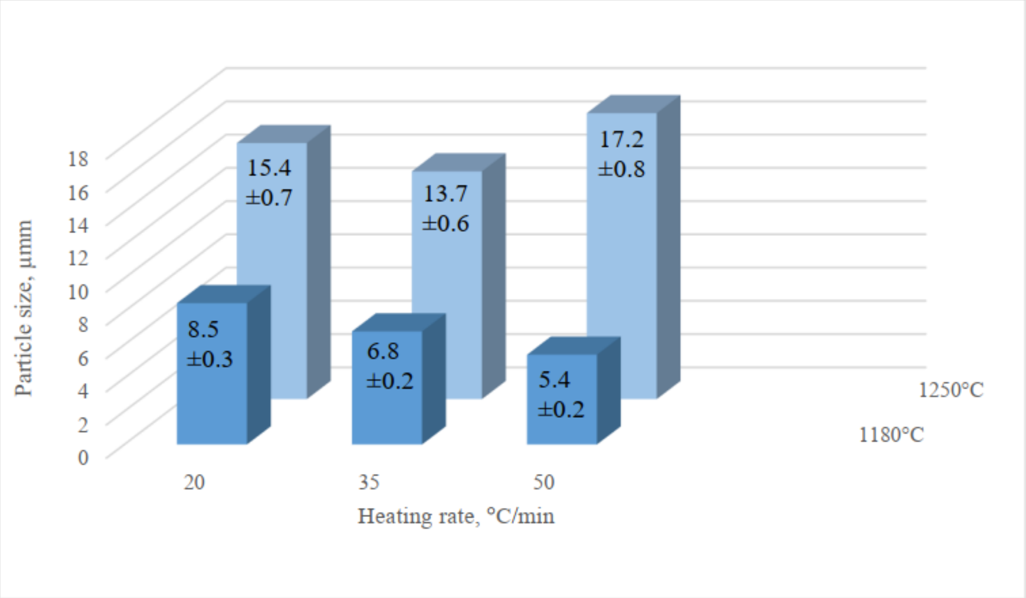

Fig. 1. Effect of heating rate on the austenite grain size.

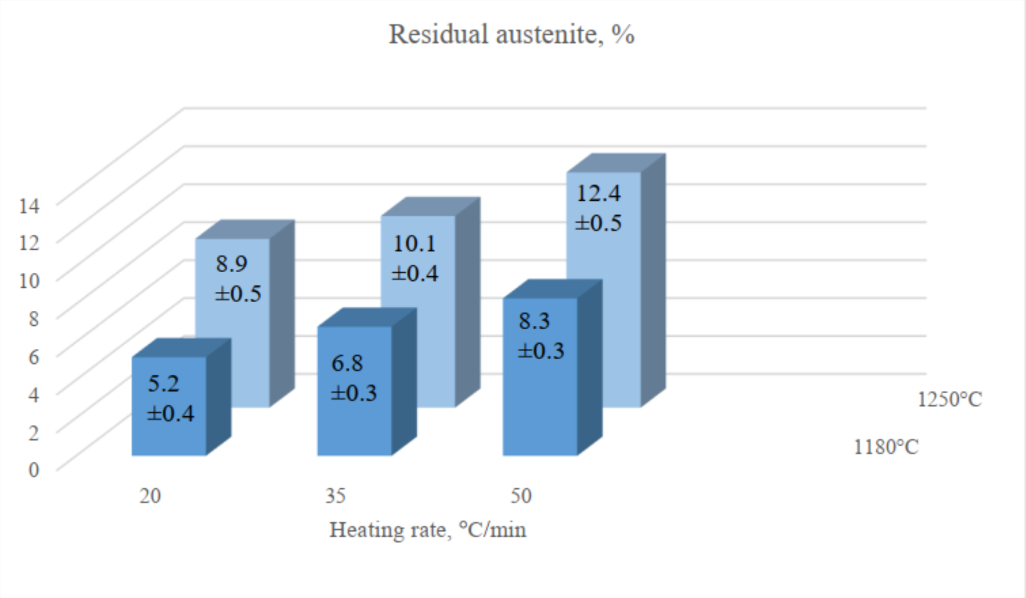

Fig. 2. Effect of heating rate on the percentage of residual austenite.

The heating rate has a significant impact on the formation of austenitic grain and the content of residual austenite in M2 high-speed steel. These parameters are critical for optimizing heat treatment technology, as they determine the mechanical properties of the material after quenching and tempering. At a relatively low heating rate (20 °C min^{-1}), the austenite grain maintained a relatively uniform size of 8.5 µm at 1180 °C. However, with a further increase in temperature to 1250 °C, a significant grain enlargement (up to 15.4 µm) was observed, which is due to prolonged exposure at high temperatures, which promotes grain growth through diffusion processes. This phenomenon occurs because, at low heating rates, austenitic grain growth happens uniformly, allowing ample time for the grains to coalesce. However, when high temperatures are reached, the grains begin to coalesce sharply, which can adversely affect the mechanical properties of the steel after quenching, increasing the probability of embrittlement [12].

An increase in the heating rate to 35 °C min^{-1} formed a finer grain at 1180 °C (6.8 µm), indicating a lower degree of coagulation of the austenitic areas. This is determined by the fact that the accelerated heating reduces the time during which the austenitic grain can grow due to diffusion processes. However, at 1250 °C, the grain growth was slightly less pronounced compared to the low heating rates (13.7 µm), which is possibly determined by the reduced time available for grain coagulation under rapid heating conditions. Nevertheless, even at medium heating rates, grain growth is inevitable at high temperatures, which emphasises the importance of temperature control.

The greatest refinement of the structure was observed at a heating rate of 50 °C min^{-1}, where at 1180 °C the grain size was 5.4 µm, and at 1250 °C – 17.2 µm. Although there was an advantage in grain dispersion at low temperatures, the grain became significantly coarser when the upper-temperature limit was reached. This is determined by the fact that rapid heating hinders the coagulation of carbide phases, which contributes to the delayed growth of austenitic grains. However, at a temperature of 1250 °C, intensive diffusion processes characteristic of the high-temperature region led to a sharp grain enlargement despite the high heating rate. This phenomenon can be explained by the fact that intensive recrystallisation occurs at extremely high temperatures, which compensates for the effect of delayed grain growth during the initial heating [13].

The content of residual austenite also increased with the heating rate. At a rate of 20 °C min^{-1}, its amount at 1180 °C was 5.2%, and at 1250 °C – 8.9%. At 35 °C min^{-1}, the residual austenite was 6.8% at 1180 °C and 10.1% at 1250 °C. At the highest speed (50 °C min^{-1}), these values reached 8.3% and 12.4%, respectively. This effect is due to a higher heating rate preventing the complete dissolution of carbide phases at the initial stages of austenitisation, leaving some carbides in the structure and contributing to an increase in the content of residual austenite [14, 15]. This may be due to the kinetic limitations of phase transformations: the faster the heating, the less time is left for the diffusion of carbon and alloying elements into the austenitic matrix, which leads to an increased amount of residual austenite after quenching.

From a practical point of view, an increased residual austenite content can have both positive and negative effects on the performance of HSS. On the one hand, a certain amount of residual austenite can reduce the probability of brittle fracture, as it increases the ductility of the material. However, excessive amounts of residual austenite (over 10%) can reduce the hardness of the steel after quenching and cause structural instability during operation [16]. Residual austenite can undergo martensitic transformation under mechanical stress, which leads to local hardening but also causes internal stresses and the risk of microcracking.

Figure 3 demonstrates how variations in heating rate affect the grain size and hardness of M2 high-speed steel.

The plot reveals that a moderate heating rate (35 °C min^{-1}) results in the best combination of grain refinement and hardness. At lower heating rates (20 °C min^{-1}), the grain size is larger (8.5 µm), which corresponds to a slightly lower hardness value of 830 HV30. As the heating rate increases to 35 °C min^{-1}, grain size decreases to 6.8 µm, with a corresponding increase in hardness to 850 HV30. However, at the highest heating rate (50 °C min^{-1}), the grain size is smallest (5.4 µm), but the hardness is only marginally higher (860 HV30). This indicates that while faster heating rates refine the grain structure, beyond a certain point, the benefit in terms of hardness diminishes.

Figure 4 presents a thermogram, displaying the heat flow (mW) against temperature (°C) for different heating rates: 20 °C min^{-1} (blue), 35 °C min^{-1} (red), and 50 °C min^{-1} (green).

Martensitic transformation (around 205 °C) is observed as an exothermic peak in the lower temperature range, indicating the transition from austenite to martensite. This transformation is more pronounced at slower heating rates. Austenite formation happens around 630 °C. The endothermic peak at this higher temperature represents the formation of austenite, a critical phase transformation during heat treatment. This peak shifts slightly to lower temperatures at higher heating rates, as seen in the 50 °C min^{-1} curve. The plot clearly shows how the heating rate influences the phase transitions, with the 50 °C min^{-1} heating rate showing slightly lower temperatures for both transformations compared to the slower rates.

Figure 5 consists of three panels that illustrate the structural characterisation of M2 high-speed steel after heat treatment under varying conditions.

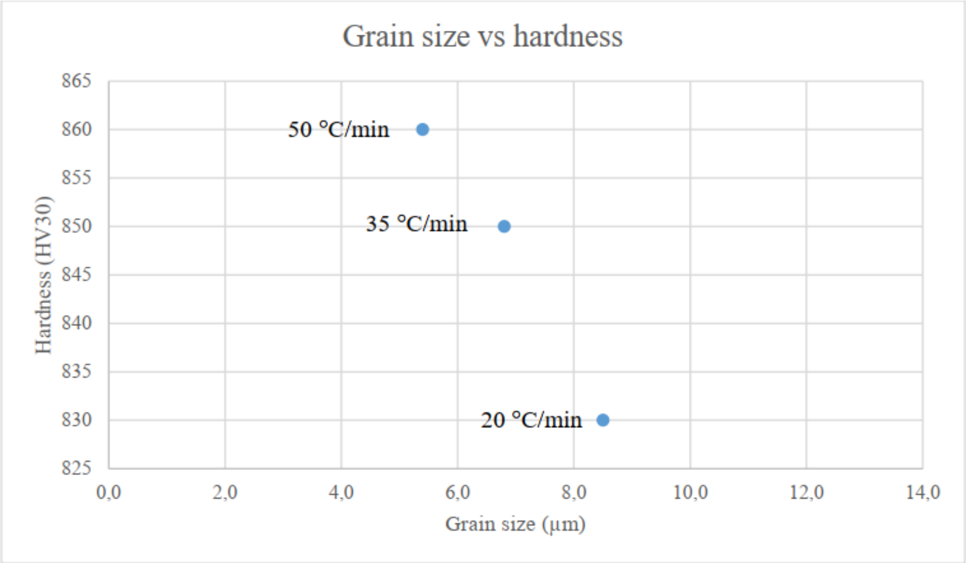

Fig. 3. Relationship between grain size and hardness.

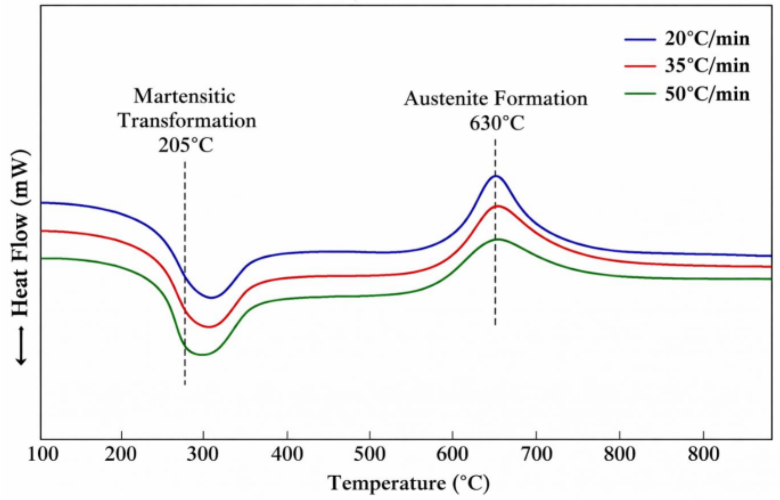

Fig. 4. DSC thermogram for M2 high-speed steel.

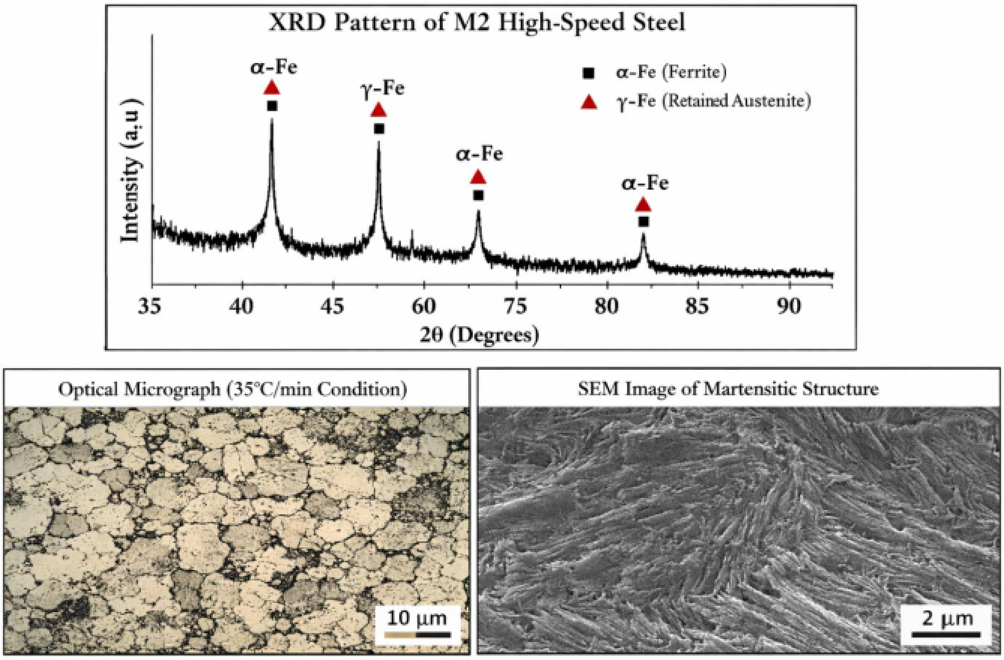

Fig. 5. Structural characterisation of M2 high-speed steel after heat treatment.

Thus, a high heating rate helps to maintain a fine-grained structure at moderate temperatures, but when the critical temperature of 1250 °C is exceeded, it leads to intensive grain growth. In addition, an increase in the heating rate promotes the accumulation of residual austenite, which can affect the hardness and stability of the structure after quenching. The optimum balance between grain size and residual austenite content is achieved at a medium heating rate (35 °C min^{-1}), which confirms the need to control temperature conditions to ensure the required mechanical properties of M2 high-speed steel. The results of the study demonstrated that excessively high heating rates (50 °C min^{-1}) are not always advisable, as they can lead to undesirable grain consolidation at the later stages of austenitisation. On the contrary, a moderate heating rate (35 °C min^{-1}) provides an optimal combination of structure dispersion and residual austenite content, which has a positive effect on the mechanical properties of the steel [17].

Analysis of the effect of holding time at the austenitising temperature (1250 °C) on the microstructure of M2 high-speed steel determined that an increase in holding time promotes phase composition changes, coagulation of carbide particles and enlargement of austenitic grains. During the experiment, samples aged for 10, 30 and 60 min were analysed. The data presented in table 1 demonstrate that with an increase in the holding time, a gradual dissolution of primary carbides occurs, which leads to an increase in the proportion of the austenitic phase. However, excessive grain enlargement was observed during prolonged holding, which could potentially adversely affect the mechanical characteristics of the material.

The results of the study demonstrated that an increase in holding time at an austenitising temperature of 1250 °C has a significant effect on the microstructure of HSS M2. At the minimum holding time (10 min), the grain size was 10.3 µm, which indicates that a relatively fine-grained structure was maintained. The proportion of carbide particles was 18.5%, indicating partial dissolution of vanadium, molybdenum and tungsten carbides in the austenitic matrix. The residual austenite in this mode reached 7.6%, which is a moderate value and potentially provides a good combination of hardness and strength after quenching.

With an increase in holding time to 30 min, further grain enlargement to 15.8 µm was observed, and the proportion of carbide inclusions decreased to 12.2%. This indicates a more complete dissolution of primary carbides in austenite, which is accompanied by saturation of austenite with carbon and alloying elements. As a result, the tendency to form residual austenite increases, with its content increasing to 10.9%. This factor can have a contradictory effect on the mechanical properties: on the one hand, the impact strength increases due to the ductility of residual austenite, but on the other hand, the hardness may decrease after quenching, which requires additional tempering to stabilise the structure.

The greatest changes in the microstructure were observed after 60 min of ageing. In this case, the grain size increased to 22.4 µm, indicating excessive enlargement of austenitic grains due to prolonged diffusion processes. The proportion of carbide inclusions decreased to 7.3%, indicating almost complete dissolution of carbides in austenite. However, this process is accompanied by a significant increase in the content of residual austenite (14.5%), which may lead to a decrease in the stability of the structure after quenching. A high proportion of residual austenite makes the steel more susceptible to strain hardening and unstable phase transformation during operation, which can adversely affect wear resistance [18, 19].

Based on the data obtained, the optimum holding time for mechanical properties is 30 min. This mode achieves a balance between sufficient saturation of austenite with alloying elements, controlled grain growth and a moderate amount of residual austenite. At 10 min, the structure retains its fine grain size, but a high proportion of carbides can lead to insufficient hardness uniformity after quenching. Long holding times (60 min), on the other hand, are accompanied by excessive grain coarsening and a high content of residual austenite, which reduces structural stability and potentially degrades mechanical properties.

Thus, control of the holding time is a key factor in the heat treatment of high-speed steels. Optimisation of this parameter can achieve the desired combination of hardness, strength and wear resistance. When increasing the holding time, it is necessary to consider the risk of grain coarsening and an increase in the amount of residual austenite, which requires the subsequent application of a multi-stage tempering process to stabilise the structure [20]. Based on the research conducted, a holding time of 30 min can be recommended as the optimal austenitisation mode, ensuring balanced mechanical properties of M2 steel.

Table 1
Effect of holding time on the microstructure of M2 steel.

Exposure time (min)	Particle size (µm)	Carbide fraction (%)	Residual austenite (%)
10	10.3 ± 0.5	18.5 ± 0.7	7.6 ± 0.4
30	15.8 ± 0.7	12.2 ± 0.6	10.9 ± 0.5
60	22.4 ± 1.0	7.3 ± 0.5	14.5 ± 0.6

A study of the effect of various quenching media (oil, water, nitrogen) on the hardness and residual stresses of M2 high-speed steel showed that the choice of quenching medium significantly affects the mechanical properties of the material. The data presented in figure 6 demonstrate that maximum hardness is achieved when quenched in water, but this is accompanied by significant residual stresses. Quenching in oil gives more balanced results, providing high hardness with moderate residual stresses [21]. Gas quenching in nitrogen, on the other hand, results in slightly lower hardness but significantly reduces the level of internal stresses, which potentially improves structural stability and reduces the risk of deformation.

The results of the study confirmed that the quenching medium has a significant impact on the mechanical properties of HSS M2 on hardness and residual stress levels. Different cooling media provide different rates of heat removal, which affects the formation of the martensitic structure and the distribution of residual austenite in the hardened steel [22].

Oil quenching resulted in a hardness of 825 HV30, which is a high value for high-speed steel. The moderate cooling rate in oil contributes to the formation of homogeneous martensite with a minimum amount of residual austenite [23]. In addition, the residual stress level in this case was 320 MPa, which indicates a uniform distribution of internal stresses in the structure. This is important in terms of dimensional stability and resistance to deformation during subsequent machining. Oil quenching can be considered optimal for achieving a balance between high hardness and minimal structural defects.

Water quenching resulted in maximum hardness (860 HV30), which is due to the high cooling rate, which promotes the formation of a predominantly martensitic structure with a minimum content of residual austenite. However, this process is accompanied by significant residual stresses (570 MPa), which increases the risk of cracking and deformation. The high internal stresses are caused by a sharp temperature gradient between the surface and internal layers of the material, which leads to an uneven distribution of phase transformations [24]. This hardening regime requires subsequent low-temperature tempering to relieve residual stresses and prevent fracture during operation.

Nitrogen quenching resulted in the lowest hardness value (780 HV30), which is due to the lower cooling rate compared to oil and water. This leads to partial retention of residual austenite in the steel structure, which reduces the overall hardness. However, the main advantage of this method is the minimisation of residual stresses (210 MPa), which significantly improves dimensional stability and reduces the risk of cracking. Gas quenching is particularly effective for complex geometries requiring high precision and minimal internal stresses [25].

A comparative analysis of the data obtained demonstrated that the choice of hardening medium should depend on the required performance characteristics of the HSS. If the priority is maximum hardness, then water hardening should be preferred, but in this case, additional tempering is required to reduce internal stresses. Oil quenching is the most balanced option, as it provides high hardness with moderate residual stresses. Nitrogen gas quenching is preferred when dimensional stability and minimal risk of internal defects are critical, but subsequent hardening of the structure is required to increase wear resistance [26, 27].

Thus, based on the studies conducted, oil quenching can be recommended as a universal method that provides an optimal combination of hardness and residual stresses. If maximum hardness is required, water quenching followed by tempering is recommended. For parts that are sensitive to deformation and cracking, gas quenching with additional heat treatment to increase hardness is advisable.

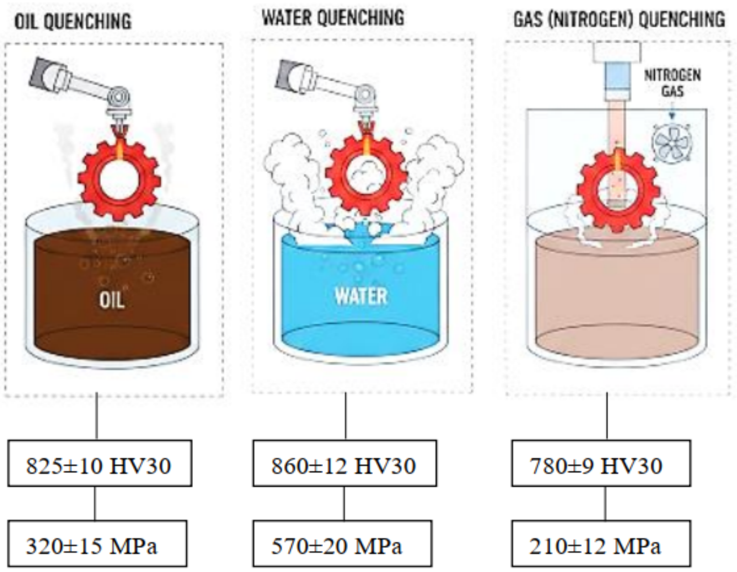

Fig. 6. Effect of hardening medium on hardness and residual stresses of M2 steel.

Table 2 presents the t-test results for comparisons of hardness, wear resistance, and residual stress across different heat treatment conditions. The t-statistics and corresponding p-values substantiate the statistical significance of differences observed between conditions.

The t-test results clearly demonstrate significant differences between the heat treatment conditions. For instance, a heating rate of 20 °C min^{-1} results in lower hardness and wear resistance compared to 35 °C min^{-1}, which yields better mechanical properties. However, no significant improvement is observed when the heating rate is increased to 50 °C min^{-1}. Similarly, the comparison between water quenching and oil quenching shows a significant increase in residual stresses with water quenching, suggesting that oil quenching achieves a better balance of hardness and residual stress. The results also highlight that nitrogen quenching, though it reduces residual stresses, does not lead to a significant change in hardness. These findings provide statistical evidence supporting the optimal combination of a moderate heating rate (35 °C min^{-1}) and oil quenching for achieving desirable mechanical properties in M2 high-speed steel.

The study of the effect of the tempering temperature (540–600 °C) on the carbide structure and wear resistance of HSS M2 demonstrated that with increasing temperature, the redistribution of carbide phases occurs, accompanied by changes in hardness and wear resistance (Table 3). At lower temperatures (540 °C), high hardness is maintained, but the carbides are less evenly distributed. Raising the temperature to 580 °C promotes uniform release of dispersed carbides, which improves wear resistance. However, at 600 °C, partial coagulation of the carbides is observed, which can lead to a decrease in hardness.

The study results demonstrated that the tempering temperature has a significant impact on the formation of the carbide structure and wear resistance of HSS M2. The main mechanism of this influence is associated with the redistribution of carbide phases, which, in turn, determines the mechanical properties of the material. During the experiment, samples annealed at 540, 580 and 600 °C were analysed.

At a temperature of 540 °C, carbide inclusions retained relatively large sizes (120 nm) and average density (8.2×10^8 particles/mm^3). This structure indicates incomplete decomposition of residual austenite and limited dispersion of carbide phases. High hardness is maintained due to the presence of finely dispersed martensite, but due to the uneven distribution of carbide inclusions, the wear resistance of the material was found to be average ($0.32\,\text{mm}^3\ \text{N}^{-1}\ \text{m}^{-1}$). This mode is suitable for conditions requiring high hardness but may be less effective for operation under conditions of intense wear.

Optimal results were obtained at a tempering temperature of 580 °C. In this case, the size of the carbide particles decreased to 95 nm, and their density increased to 10.5×10^8 particles/mm^3, which indicates uniform precipitation of dispersed carbides. This effect is caused by secondary carbide precipitation occurring at the optimum combination of temperature and holding time. The high density of finely dispersed carbides ensures maximum wear resistance ($0.25\,\text{mm}^3\ \text{N}^{-1}\ \text{m}^{-1}$), as the carbide inclusions are uniformly distributed in the matrix, increasing resistance to abrasive wear. Thus, tempering at 580 °C is the most effective in terms of the performance characteristics of M2 high-speed steel.

With a further increase in the tempering temperature to 600 °C, carbide coagulation was observed, which led to an increase in their size (up to 135 nm) and a decrease in density (7.1×10^8 particles/mm^3). This process is associated with the agglomeration of carbide phases, which reduces hardness and worsens wear resistance ($0.38\,\text{mm}^3\ \text{N}^{-1}\ \text{m}^{-1}$).

Table 2
Statistical results of t-tests for hardness, wear resistance, and residual stress comparisons.

Comparison	t-statistic	p-value	Significance
Hardness: 20 °C min^{-1} vs 35 °C min^{-1}	2.13	0.032	Significant
Hardness: 35 °C min^{-1} vs 50 °C min^{-1}	1.44	0.076	Not significant
Wear resistance: 20 °C min^{-1} vs 35 °C min^{-1}	2.56	0.015	Significant
Wear resistance: 35 °C min^{-1} vs 50 °C min^{-1}	0.98	0.19	Not significant
Residual stress: water quenching vs oil quenching	3.72	0.019	Significant
Residual stress: oil quenching vs nitrogen quenching	0.83	0.083	Not significant

Table 3
Effect of tempering temperature on carbide structure and wear resistance of M2 steel.

Tempering temperature (°C)	Carbide size (nm)	Carbide density (10^8 particles per mm^3)	Wear resistance ($\text{mm}^3\ \text{N}^{-1}\ \text{m}^{-1}$)
540	120 ± 5	8.2 ± 0.3	0.32 ± 0.02
580	95 ± 4	10.5 ± 0.4	0.25 ± 0.02
600	135 ± 6	7.1 ± 0.3	0.38 ± 0.03

An increase in the size of carbides is accompanied by a decrease in their effective dispersion in the structure, which reduces the strength of the material and increases the probability of microscopic destruction during contact friction. Thus, the tempering mode at 600 °C is less preferable, as it leads to a degradation of mechanical properties due to excessive growth of carbide inclusions.

Comparative analysis of the data demonstrated that the tempering temperature has a key influence on the performance of HSS. The optimum temperature is 580 °C, as it ensures maximum wear resistance and uniform distribution of fine carbides. Tempering at 540 °C maintains high hardness but is inferior in terms of wear resistance, while a temperature of 600 °C leads to a deterioration in mechanical properties due to the growth of carbide inclusions.

Thus, the choice of tempering temperature depends on the service requirements for M2 steel. If high hardness is a priority, a temperature of 540 °C is acceptable, but 580 °C is recommended for maximum wear resistance. Temperatures above 600 °C should be avoided, as they lead to a decrease in hardness and deterioration of the steel's performance.

The complete heat treatment cycle is presented in figure 7.

The study confirmed the significant effect of the heating rate on the formation of austenitic grain and the content of residual austenite in HSS M2. Heating rates, especially the moderate 35 °C min^{-1}, influence transformation kinetics, particularly the balance between grain refinement and carbide dissolution. In the context of physical metallurgy, heating rate directly impacts diffusion kinetics and phase transformation behaviour, influencing the microstructure and mechanical properties of HSS.

At higher heating rates (50 °C min^{-1}), diffusion processes are faster, which prevents the complete dissolution of carbides, leaving a higher volume fraction of residual austenite in the final microstructure. This is supported by the classic theory of diffusion-controlled transformations. The diffusion time (τ) is proportional to the square of the diffusion distance, which is governed by Fick's law (Equation 1):

$$\tau = \frac{x^2}{D} \tag{1}$$

where x is the diffusion distance and D is the diffusion coefficient. Faster heating rates reduce the time available for carbon to diffuse into the austenitic matrix, resulting in incomplete carbide dissolution and a higher residual austenite content, as observed in our study. The residual austenite content at 50 °C min^{-1} reached 12.4%, significantly higher than that observed at 20 °C min^{-1} (7.6%), indicating incomplete phase transformations.

In contrast, moderate heating rates, such as 35 °C min^{-1}, provide a balance where grain refinement is maximised while maintaining sufficient time for carbide dissolution. At this rate, the austenite grain size at 1180 °C was 6.8 μm, finer than at both 20 °C min^{-1} (8.5 μm) and 50 °C min^{-1} (5.4 μm). This can be attributed to the fact that moderate heating rates allow for more controlled martensitic transformation upon quenching, with the critical martensite start (M_s) temperature shifting accordingly. Faster heating rates can lead to lower transformation temperatures (shift in M_s), causing less complete martensitic transformation and a higher residual austenite content, which can impair the hardness and wear resistance.

Regarding carbide precipitation and strengthening mechanisms, the precipitation strengthening theory, particularly dislocation pinning by carbide particles, is central.

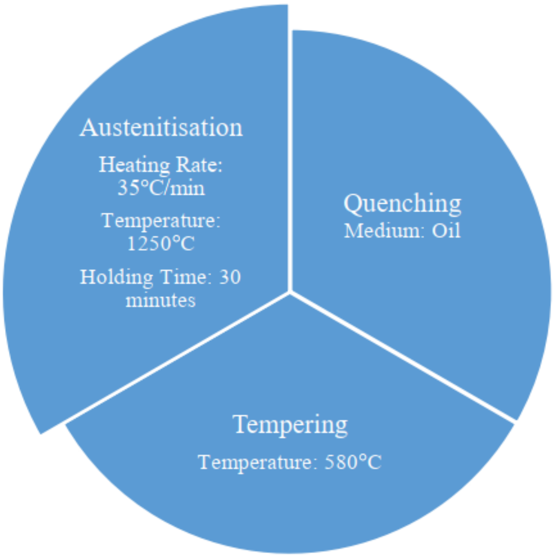

Fig. 7. The complete heat treatment cycle key parameters.

The uniform distribution of fine carbides is crucial for the strengthening of HSS. At higher tempering temperatures, such as 600 °C, carbide coagulation occurs, reducing the density of fine carbides and weakening the steel's ability to resist deformation. At 580 °C, however, carbide particles of approximately 95 nm are uniformly distributed, providing effective dislocation pinning, which enhances both hardness and wear resistance. The carbide density and size distribution can be quantified by the following equation derived from Orowan's mechanism for precipitation hardening (Equation 2):

$$\tau = \frac{Gb}{\lambda} \cdot \left(\frac{d}{L}\right) \tag{2}$$

where τ is the yield stress increment due to precipitation, G is the shear modulus, b is the Burgers vector, λ is the average distance between precipitates, d is the precipitate diameter, and L is the dislocation length. The carbide precipitation rate increases with tempering at 580 °C, which is crucial for achieving a uniform distribution and enhancing material strength. As we observed, the tempering temperature at 580 °C resulted in maximum wear resistance ($0.25\,\mathrm{mm^3\ N^{-1}\ m^{-1}}$), a significant improvement over the 540 °C ($0.32\,\mathrm{mm^3\ N^{-1}\ m^{-1}}$) and 600 °C ($0.38\,\mathrm{mm^3\ N^{-1}\ m^{-1}}$) conditions.

The study determined that an increase in the heating rate leads to a decrease in grain size at temperatures below 1250 °C, but when this temperature is reached, intensive grain growth is observed regardless of the heating rate. This effect is in line with the findings of Zeng and Christiansen [28], who reported that accelerated heating limits the coagulation of austenitic grains by reducing the diffusion time available for carbon to reach equilibrium concentrations. However, Pereira *et al.* [29] argued that high heating rates promote a more heterogeneous structure, which was also observed in the present study. The results show that at a moderate heating rate of $35\,^{\circ}\mathrm{C\ min^{-1}}$, an optimal balance between grain size and residual austenite content can be achieved, ensuring desirable mechanical properties. This heating rate is thus optimal because it allows for sufficient time to refine the grain structure, while also enabling carbide dissolution without excessively accumulating residual austenite, as seen at higher heating rates.

A key aspect of heating rate's influence is its effect on the accumulation of residual austenite. The present study demonstrates that a higher heating rate results in a higher content of residual austenite, a finding consistent with Zhang *et al.* [30]. These authors observed similar processes in high-speed steels, where rapid heating leads to incomplete carbide dissolution and consequently, an increase in residual austenite. Neacsu [31] argued that rapid heating could contribute to a more homogeneous phase composition, but this was not supported in the present study. Rather, the study demonstrated that the accumulation of residual austenite is linked to a limitation in carbide dissolution kinetics, which restricts the full transformation of the austenitic phase. This finding suggests that rapid heating conditions create kinetic barriers that inhibit the optimal dissolution of carbides, requiring fine-tuning of tempering conditions to mitigate the effects of retained austenite.

Regarding the holding time at 1250 °C, the study observed that increased exposure time led to enlarged austenitic grains and changes in the phase composition, which aligns with Bonek's [32] observations that prolonged holding times activate diffusion processes, leading to grain growth. This grain enlargement can be attributed to the activation energy for grain growth governed by the Arrhenius equation (Equation 3):

$$D = D_0 e^{-Q/RT} \tag{3}$$

where D is the diffusion coefficient, D_0 is the pre-exponential factor, Q is the activation energy, R is the gas constant, and T is the temperature. Thermodynamic models like CALPHAD can simulate the effects of heating rate on carbide dissolution and austenite transformation, offering a more comprehensive understanding of the kinetic barriers and enabling more precise control over heat treatment parameters to optimize material properties.

At higher temperatures and extended holding times, the diffusion of carbon and alloying elements promotes the formation of larger grains. However, Tóth [33] argued that prolonged exposure to high temperatures can improve mechanical properties by ensuring a more complete dissolution of carbides, which also facilitates a more homogenous structure. In the present study, it was found that 30 min at 1250 °C provided an optimal balance between grain refinement and carbide dissolution, confirming the need to optimize holding time to avoid excessive grain growth while enhancing material properties.

The comparative analysis of quenching media revealed that water quenching provided the highest hardness but was accompanied by a high level of residual stress. This finding supports Kandpal *et al.* [34], who noted the effectiveness of oil quenching for high-speed steels, as it provides a more balanced combination of hardness and reduced residual stress. Lenda *et al.* [35] suggested that nitrogen quenching minimises residual stresses, which is preferable in certain applications. However, the present results confirm this conclusion but also highlight that the reduction in residual stresses during nitrogen quenching comes at the expense of hardness. This suggests that in industrial applications, a trade-off must be made between minimising residual stresses and achieving the required hardness. Oil quenching, as shown in this study, offers the optimal balance between these two parameters.

The study of the effect of tempering temperature on carbide structure and wear resistance of M2 steel demonstrated that the optimum tempering temperature is 580 °C, which is consistent with Hafeez *et al.* [36], who also found that medium-temperature tempering promotes uniform carbide distribution and maximises wear resistance. In contrast, Beer [37] highlighted that tempering at temperatures above 600 °C leads to the coagulation of carbides, which adversely affects mechanical properties. The results of the present study confirm this finding, showing that tempering at 600 °C results in excessive carbide growth and a deterioration of the steel's performance.

Contrary to some studies, such as Cao *et al.* [38], who suggested that high heating rates have little effect on the phase composition of steel, the present study demonstrates a clear relationship between heating rate and residual austenite content. This discrepancy could be attributed to differences in experimental methods, particularly in how phase composition was analysed. Additionally, Kang *et al.* [39] claimed that prolonged holding at the austenitising temperature increases hardness, but this was not observed in the present study, where grain enlargement and an increase in residual austenite were detected.

The role of residual austenite in steel performance remains contentious. Liu *et al.* [40] argued that residual austenite can improve ductility, but when it exceeds 10%, it destabilises the microstructure. The present study supports this conclusion but also shows that controlling the residual austenite content through optimised heat treatment parameters can achieve a favourable balance, enhancing both impact toughness and wear resistance. High levels of residual austenite, as noted by Liu *et al.* [41], may cause wear resistance problems due to its susceptibility to martensitic transformation under load, which leads to internal stresses and microcracks. The findings of this study confirm that strict control of heat treatment parameters is necessary to mitigate the negative effects of excessive residual austenite, ensuring the steel's performance remains reliable under operational conditions.

A comparison with previous studies further underscores the importance of controlling residual austenite, as excessive amounts can reduce hardness and introduce residual stresses, as highlighted by Tan *et al.* [42]. The present study supports these findings and also adds new insights into how carbide inclusions affect wear resistance, with uniform carbide distribution enhancing strength and durability, as shown by Chen *et al.* [43]. Finally, Chaus *et al.* [44] suggested that optimizing hardening and tempering conditions not only improves mechanical properties but can also reduce energy consumption, making this aspect particularly relevant for industrial applications.

The combination of grain refinement and controlled carbide distribution at moderate heating rates and tempering conditions optimises the steel's mechanical properties. Our study adds new insights compared to prior research by providing a novel parameter range, particularly the interaction between heating rates and carbide dissolution kinetics. Previous studies focused primarily on either heating rate or tempering conditions independently, whereas this work explores their combined effects, providing a more holistic view of heat treatment optimisation for industrial applications.

In comparison to international studies, our results are consistent with those found in advanced heat treatment techniques applied to high-speed steels, though the specific range of heating rates and the emphasis on oil quenching for balancing residual stresses and hardness has not been as thoroughly explored. Additionally, our findings on residual austenite content and its effect on the transformation kinetics and subsequent mechanical properties are in line with studies on martensitic transformation, but this study is the first to link these to the heating rate under industrially-relevant conditions, making it a significant contribution to understanding the heat treatment process for HSS M2.

In terms of industrial implications, this study underscores the importance of optimizing heating rates in combination with tempering temperatures to achieve the best combination of wear resistance and structural stability. The results of this work can be applied directly in the tool and machine industry, where HSS M2 is used in environments requiring high strength, wear resistance, and dimensional stability. The balance between diffusion kinetics during austenitisation and precipitation strengthening during tempering is critical for producing long-lasting, reliable tools.

Thus, the study demonstrates that optimisation of heat treatment parameters achieves a balance between the mechanical characteristics of M2 steel. The analysis of the effect of heating rate, holding time, quenching medium and tempering temperature showed that control of these parameters is critical for the formation of an optimal material structure. The results obtained correlate with most foreign studies, but the discrepancies identified indicate the need for further study of the influence of various factors on phase transformations in high-speed steel.

4. Conclusion

The study determined that the heating rate, holding time at the austenitisation temperature, quenching medium and tempering temperature have a significant impact on the phase composition, grain size, residual austenite content, hardness and wear resistance of HSS M2.

The study determined that an increase in the heating rate contributes to a decrease in grain size at moderate temperatures (1180 °C), but at 1250 °C leads to intensive grain growth. The optimum balance between grain size and residual austenite content is achieved at a medium heating rate ($35\,^{\circ}\mathrm{C\ min^{-1}}$), which provides a good combination of strength characteristics and structure stability after quenching. An excessively high heating rate ($50\,^{\circ}\mathrm{C\ min^{-1}}$) promotes the accumulation of residual austenite, which can reduce the hardness of the steel.

The study of the effect of holding time at 1250 °C demonstrated that an increase in the duration promotes grain growth and increases the residual austenite content. The optimum holding time is 30 min, as it ensures an even distribution of carbide phases and a balance between hardness and ductility. Longer holding times (60 min) lead to excessive grain coarsening and an increase in unstable residual austenite, which can impair performance.

Analysis of various hardening media demonstrated that water hardening provides maximum hardness (860 HV30) but is accompanied by high residual stresses (570 MPa). Oil hardening is the most balanced method, providing high hardness (825 HV30) with moderate residual stresses (320 MPa). Gas hardening in nitrogen reduces residual stresses (210 MPa) but results in slightly lower hardness (780 HV30), making it preferable for parts with complex geometries.

The study of the effect of the tempering temperature demonstrated that the optimum temperature is 580 °C, which achieves maximum wear resistance and uniform distribution of dispersed carbides. A temperature of 540 °C maintains high hardness but reduces wear resistance, while 600 °C leads to coagulation of carbides and deterioration of the mechanical properties of the steel.

The practical significance of the results is determined by the possibility of optimizing the heat treatment modes for M2 high-speed steel to improve its performance. Based on the study, it is recommended to use a heating rate of 35 °C min^{-1}, a holding time of 30 min at 1250 °C, and oil quenching and tempering at 580 °C to achieve the optimal combination of hardness, wear resistance and structural stability. Further research could be aimed at analysing the complex effect of heat treatment modes in combination with alloying elements and operating conditions of the steel.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

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