

# Effect of heat treatment on the microstructure and mechanical properties of high-manganese steel for mining grinding applications

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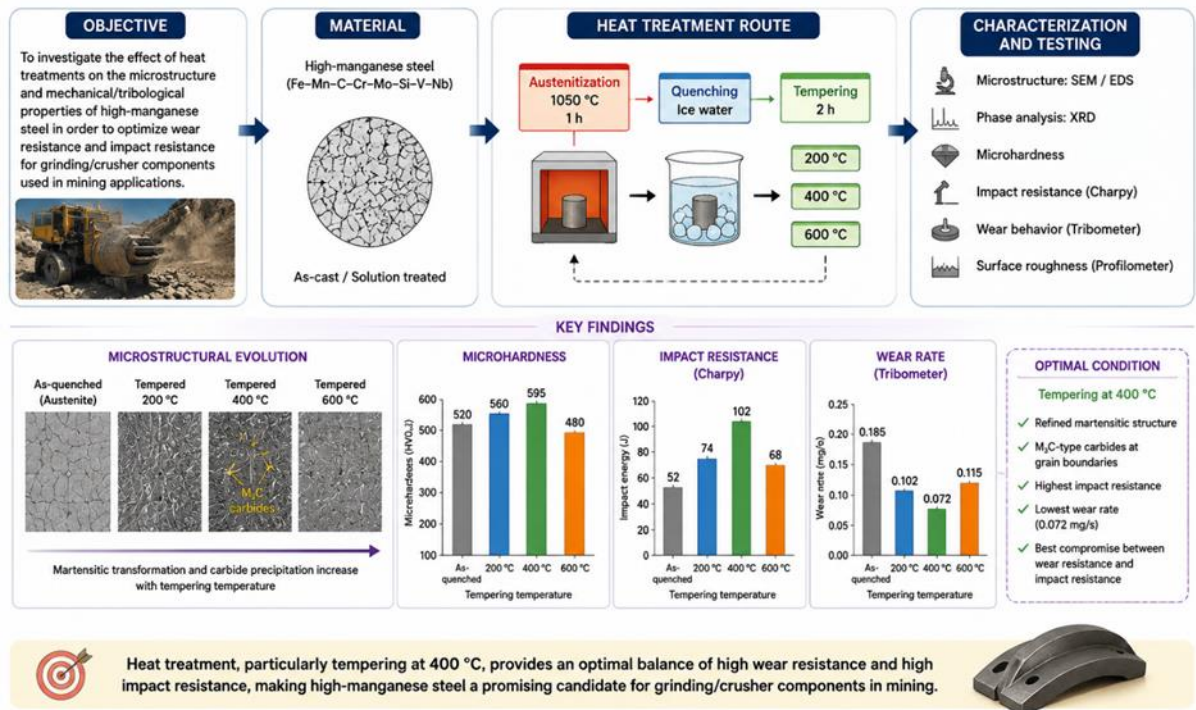
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## Graphical Abstract



## Abstract

This study investigates the effect of heat treatment on the microstructure and mechanical performance of high-manganese steel intended for mining crusher applications. The applied heat treatment consists of austenitization at 1050 °C followed by ice quenching (AQ), and subsequent tempering at 200 °C (QT200), 400 °C (QT400), and 600 °C (QT600). Microstructural characterization was performed using scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and X-ray diffraction (XRD). In addition, microhardness measurements, impact toughness tests, tribological analysis using a tribometer, and surface roughness evaluations were conducted to assess the mechanical and surface properties of the material. The results show that heat treatment significantly modifies the microstructure by promoting phase transformations and the precipitation of secondary carbides. Among the investigated conditions, QT400 leads to a refined martensitic structure with  $M_3C$ -type carbide precipitation at grain boundaries. This condition provides the best balance between wear resistance and impact toughness. The minimum wear rate recorded is 0.072 mg/s for the QT400 sample.

**Keywords:** High-manganese steel, Heat treatment, Microstructure, Wear resistance, Impact resistance.

## Highlights

- **QT400** provided the best combination of wear resistance and impact toughness in high-Mn steel.
- **QT400** refined the martensitic microstructure and promoted  $M_3C$  carbide precipitation.
- **AQ** improved microstructural stability.
- Tribological and mechanical tests confirm the optimal performance of **QT400** for crusher components.

## 1 INTRODUCTION

The Hadfield steel, also known as high-manganese steel, is a robust and durable material widely used in industrial applications that require exceptional impact resistance and long-term durability [1–3]. The addition of manganese significantly enhances the strength, ductility, and work-hardening capacity of steel by stabilizing the austenitic phase at room temperature and by affecting the stacking fault energy (SFE) of austenite [4–12, 34–35]. The SFE plays a key role in controlling deformation mechanisms such as dislocation slip, twinning, and strain-induced transformations, which directly govern the mechanical behavior of high-manganese steels. In addition, manganese and other alloying elements strongly influence austenite stability, carbide formation, and the resulting mechanical properties of high-performance steels [31–34]. The stability of austenite promoted by high manganese contents contributes to improved toughness and resistance to impact loading, making these steels particularly attractive for severe service conditions.

In the mining industry, wear-resistant materials commonly used for crusher components include high-chromium white cast irons, martensitic steels, and Hadfield steels. High-chromium cast irons exhibit excellent abrasive wear resistance due to their high carbide content but generally suffer from limited impact toughness. Martensitic steels provide high hardness and strength; however, their resistance to severe impact loading may be insufficient in demanding mining environments. In contrast, Hadfield steels offer an excellent combination of toughness, ductility, and work-hardening capability, making them particularly suitable for components exposed simultaneously to impact and abrasion. Nevertheless, their wear performance may vary depending on the operating conditions and microstructural state, highlighting the importance of optimizing heat-treatment parameters [13–18].

For this reason, high-manganese steels are extensively employed in crusher hammers, jaw crushers, mill liners, railway crossings, and other wear components operating under severe impact-abrasion conditions [4–12]. Their principal advantage lies in their ability to undergo significant strain hardening during service, whereas their main limitation is the difficulty of achieving an optimal balance between hardness, toughness, and wear resistance through microstructural control.

Heat treatment is a critical process for optimizing the mechanical performance of high-manganese steels. Rapid cooling after austenitization promotes the formation of martensite, a metastable phase known for its high strength, while subsequent tempering cycles can adjust the balance between hardness and toughness [19–22]. Achieving this balance is crucial for components that must resist both abrasive wear and impact loads [26], highlighting the importance of tailored thermal treatments. Numerous studies have investigated the microstructural and mechanical behavior of manganese steels under various heat treatment conditions [23–25,27–30]. Previous research has shown that the austenitization temperature, cooling rate, and tempering conditions strongly influence the formation of retained austenite, martensite, and carbides, thereby affecting hardness, toughness, and wear resistance.

This study aims to address these knowledge gaps by systematically investigating the effect of heat treatment on the microstructure and mechanical properties of 14% manganese steel. (AQ) followed by three tempering cycles at QT200, QT400, and QT600 is performed. Microstructural characterization is conducted using (SEM), while phase identification is achieved through (XRD). Mechanical performance is assessed through hardness, impact toughness, and wear resistance tests.

By integrating these approaches, this study provides a comprehensive understanding of how controlled heat treatments influence the performance of high-manganese steels. The results are expected to contribute to the development of optimized processing strategies for components exposed to severe mechanical and tribological conditions, particularly in the mining industry.

## **2 MATERIALS**

### **2.1 Materials**

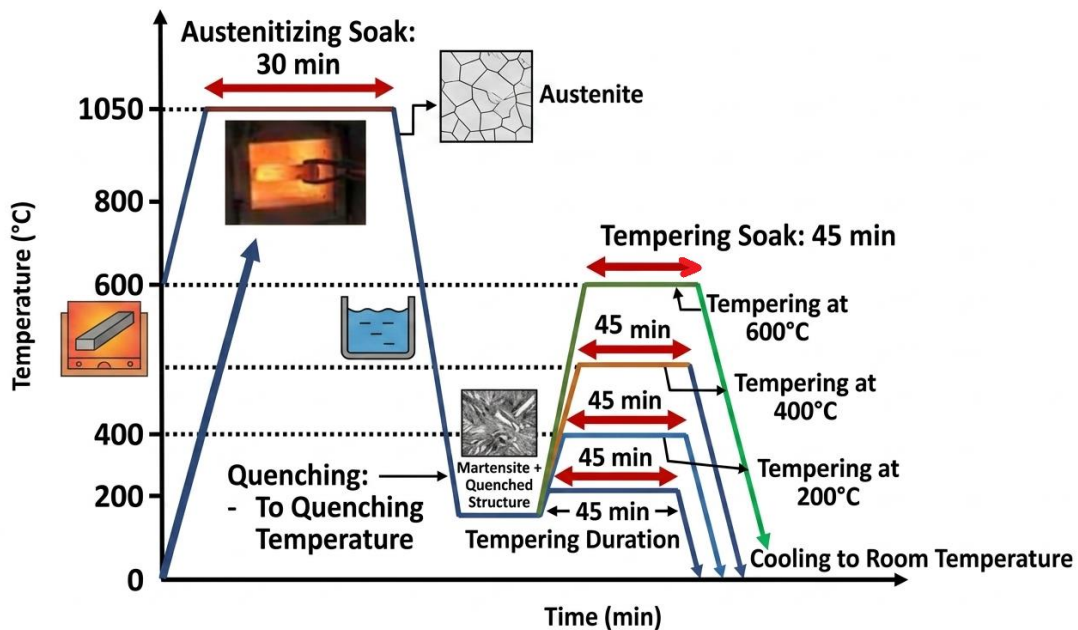
The material used is as-cast the High-manganese steel for sample fabrication. The table below (Table 1) presents the results of the chemical composition obtained using a Thermo Scientific ARL OPTIM'XTM Spectrometer.

**Table 1.** Chemical Composition of High-manganese steel (% by weight).

| %                    | C    | Si   | Mn    | Cr   | Mo    | Ni    | Cu    | Fe     |
|----------------------|------|------|-------|------|-------|-------|-------|--------|
| High-manganese steel | 1.22 | 0.25 | 14.03 | 2.16 | 0.163 | 0.239 | 0.124 | 81.814 |

A steel ingot containing High-manganese steel, initially forged, was air-cooled. Subsequently, the forged steel was cut into squares with dimensions of  $(55 \times 10 \times 10)$  mm<sup>3</sup> with V-notch. These squares were then subjected to AQ, followed by QT200, QT400, and QT600. All heat treatments were conducted in a muffle furnace.

Figure 1 depicts the schematic diagram of the heat treatment program for High-manganese steel in relation to the temperatures and durations of the heat treatment.



**Figure 1.** Schematic representation of the performed heat treatments.

## **2.2 Experimental characterization techniques**

### **2.2.1 Sample Preparation for Metallographic Observation:**

After heat treatment, the specimens were prepared for metallographic examination according to standard metallographic procedures. The samples were sectioned perpendicular to the treated surface using a precision cutting machine to avoid excessive deformation and thermal damage. The specimens were mechanically ground using successive silicon carbide (SiC) abrasive papers with different grit sizes (320, 600, 800, 1200, and 2400 grit) under continuous water lubrication. After grinding, the samples were polished using diamond suspensions of 3  $\mu\text{m}$  and 1  $\mu\text{m}$  until a mirror-like surface was obtained. The polished surfaces were cleaned with ethanol and dried before chemical etching. The microstructure was revealed using a 2% Nital solution, prepared by mixing 2 mL of nitric acid ( $\text{HNO}_3$ ) with 98 mL of ethanol ( $\text{C}_2\text{H}_5\text{OH}$ ). The samples were etched for 10 s at room temperature to reveal the different microstructural constituents. After etching, the specimens were immediately rinsed with ethanol and dried to avoid over-etching and oxidation.

### **2.2.2 X-ray Diffraction (XRD)**

X-ray diffraction analyses were performed using a PANalytical X'PERT PRO MRD diffractometer equipped with Cu  $K\alpha$  radiation. Diffraction patterns were collected over a  $2\theta$  range of  $30\text{--}120^\circ$  with a step size of  $0.04^\circ$  and a counting time of 45 s per step. Phase identification was conducted using the PDF-2 database and X'Pert HighScore Plus software, while quantitative phase analysis was carried out by Rietveld refinement using Rietica software.

### **2.2.3 Scanning Electron Microscopy (SEM)**

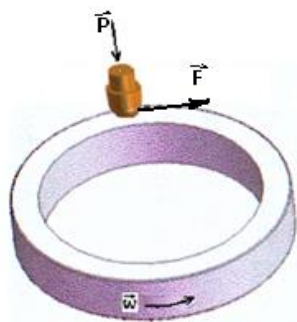
Microstructural observations were performed using a JEOL JSM-6360LV scanning electron microscope operated at an accelerating voltage of 25 kV. The chemical composition of the observed phases was determined using EDS.

### **2.2.4 Impact Toughness Testing**

Impact toughness tests were conducted using a JB-750S Charpy pendulum impact tester (TE Forcespeed Corporation). Standard V-notch specimens with dimensions of  $10 \times 10 \times 55 \text{ mm}^3$  were tested. The absorbed impact energy was recorded directly by the testing machine, and the toughness values were subsequently determined.

### **2.2.5 Tribological Testing**

Tribological behavior was evaluated using an MFT-2000 tribometer operating in a pin-on-disc configuration. Tests were performed against a Z200 steel counterface (62 HRC) under normal loads of 10, 20, 30, and 40 N at a sliding speed of 1 m/s. Sliding distances of 900 and 1800 m were investigated under ambient conditions (22–25 °C). The wear rate was determined from the mass loss measured before and after testing.



**Figure 2.** Pin-disc contact.

### 2.2.6 Surface Roughness Measurement

Surface roughness measurements were carried out using a Veeco Dektak 150 stylus profilometer. Measurements were performed with a cutoff length of 0.25 mm and a scanning speed of 0.5 mm/s over an area of  $10 \times 10 \text{ mm}^2$ . The reported values correspond to the average of two measurements for each specimen.

## 3. RESULTS AND DISCUSSION

### 3.1 X-ray diffraction structural analysis of High-manganese steel

XRD analysis was conducted to determine the phase composition of 14% manganese steel samples subjected to heat treatments. After AQ, these samples underwent successive tempering treatments QT200, QT400, and QT600, as depicted in Figure 3.

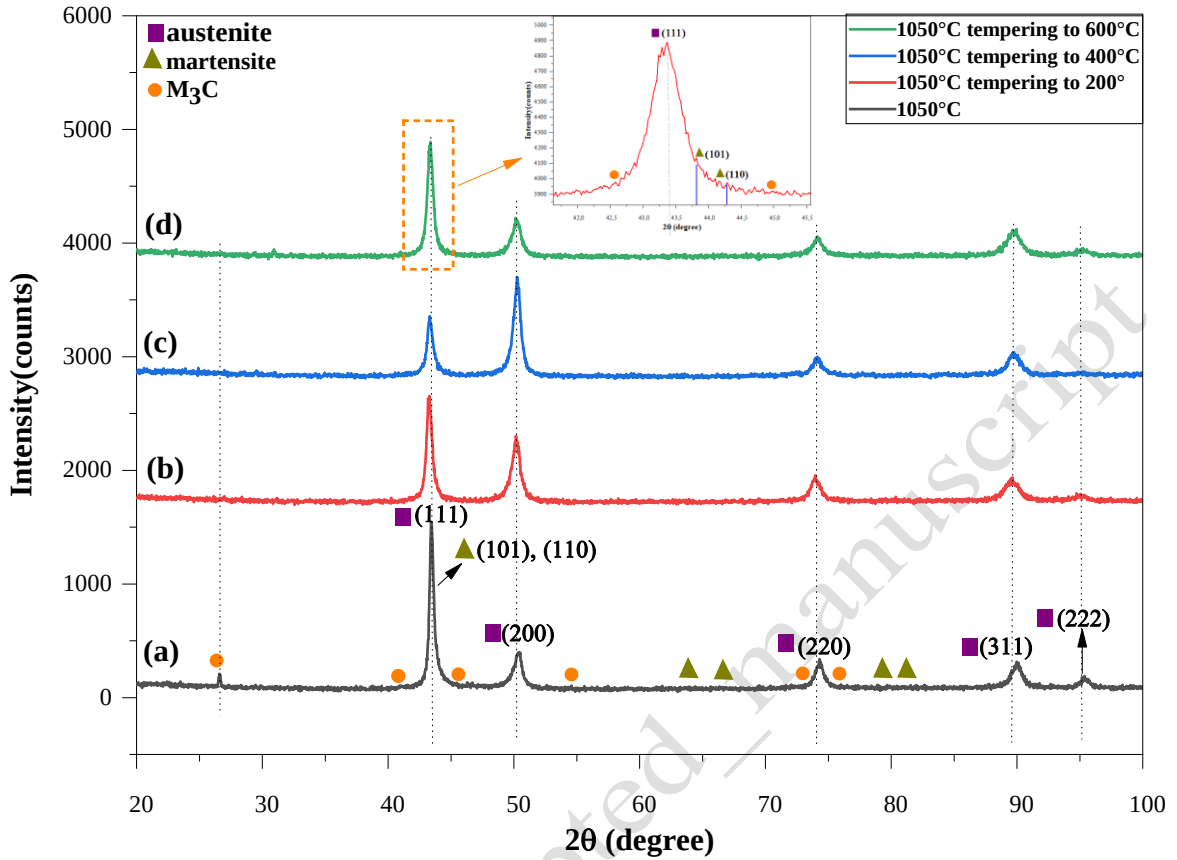


Figure 3. XRD patterns of high-manganese steel across various heat-treatment states: (a) AQ, (b) QT200, (c) QT400, and (d) QT600.

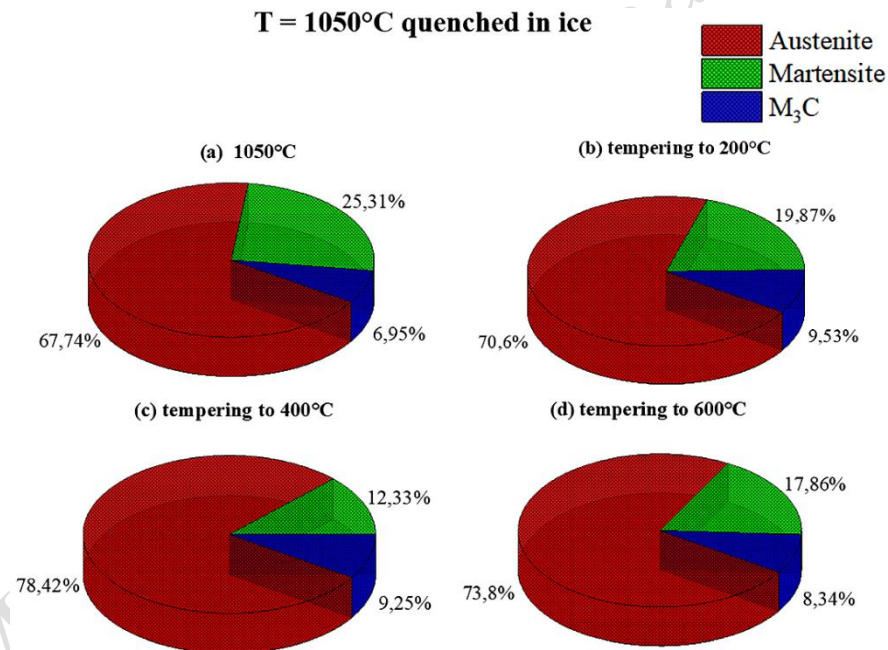
The XRD patterns revealed that all heat-treated samples were mainly composed of austenite, martensite, and  $M_3C$  carbides. The diffraction peaks corresponding to the austenitic phase (FCC structure, JCPDS No. 052-0512), martensite (tetragonal structure, JCPDS No. 044-1292), and  $M_3C$  carbides confirmed the coexistence of these phases after the different heat treatments. Rietveld refinement further enabled the determination of the crystallographic parameters and quantitative phase fractions.

The presence of retained austenite in all conditions indicates that the high manganese content effectively stabilizes the austenitic phase during cooling. However, the occurrence of as-quenched martensite in the AQ condition demonstrates that part of the austenite transformed during quenching due to local variations in chemical composition and phase stability. After tempering (QT200, QT400, and QT600), this martensite was transformed into tempered martensite. The tempering process promotes carbon diffusion from the supersaturated martensitic lattice and carbide precipitation, thereby reducing the tetragonality and internal stresses of the martensite. The detection of  $M_3C$  carbides further

confirms carbide precipitation during tempering, which contributes to strengthening through precipitation hardening.

A notable feature is the higher intensity of the austenite peak at approximately  $50^\circ$  for the QT400 sample. This behavior suggests a greater stability or volume fraction of retained austenite compared with the AQ, QT200, and QT600 conditions. The enhanced retention of austenite at QT400 may result from the balance between carbide precipitation and phase transformation kinetics during tempering. Similar observations have been reported in high-manganese steels, where intermediate tempering temperatures promote the stabilization of retained austenite and influence the martensite–austenite equilibrium.

The phase evolution observed in the present study is consistent with previous investigations on high-manganese steels, which reported that quenching produces a mixed microstructure of retained austenite and martensite, while subsequent tempering modifies the relative phase fractions through carbide precipitation and phase redistribution. These microstructural changes are expected to significantly influence the hardness, toughness, and wear resistance of the investigated steel.



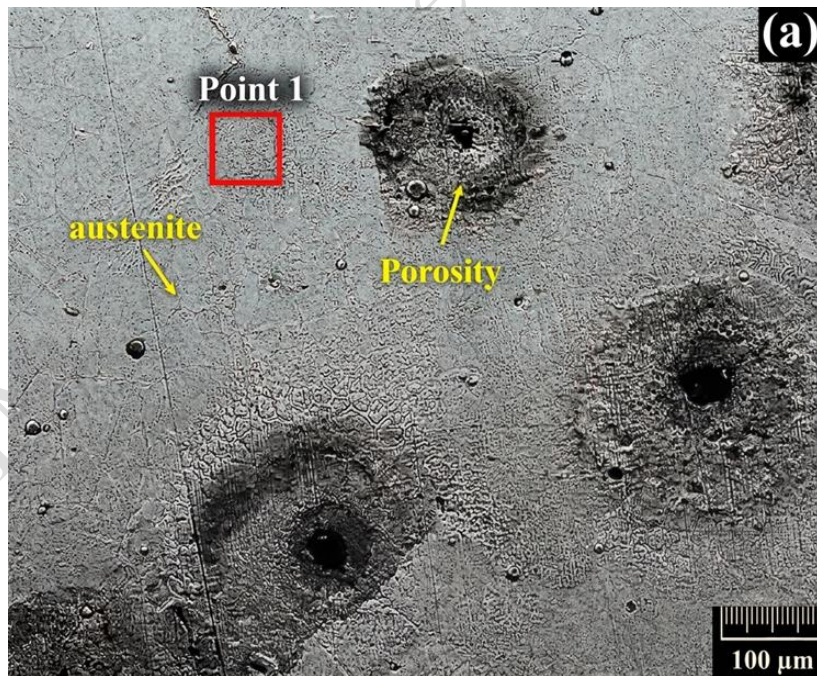
**Figure 4.** Phase quantification for (a) AQ and tempered (b) QT200, (c) QT400, (d) QT600: high-manganese steel samples.

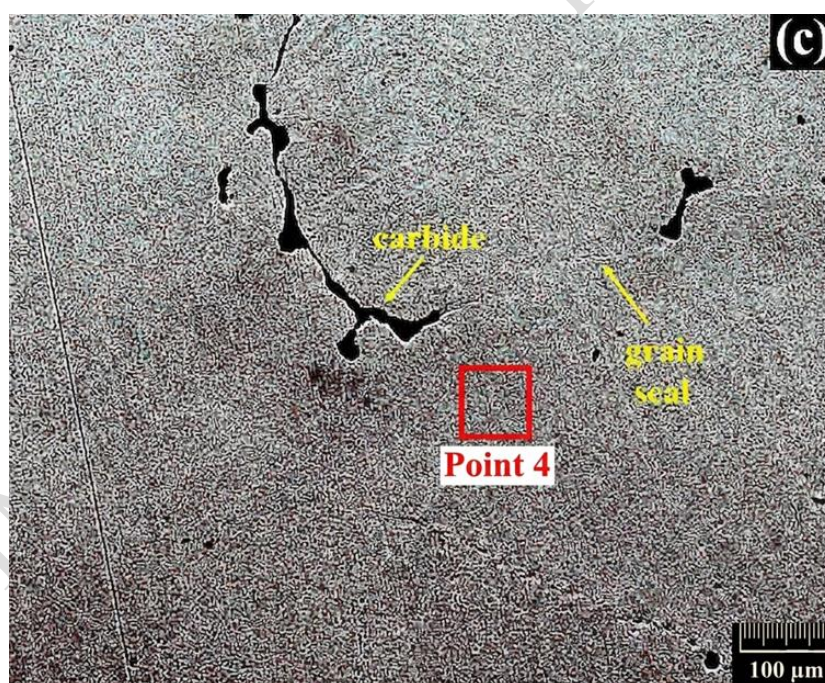
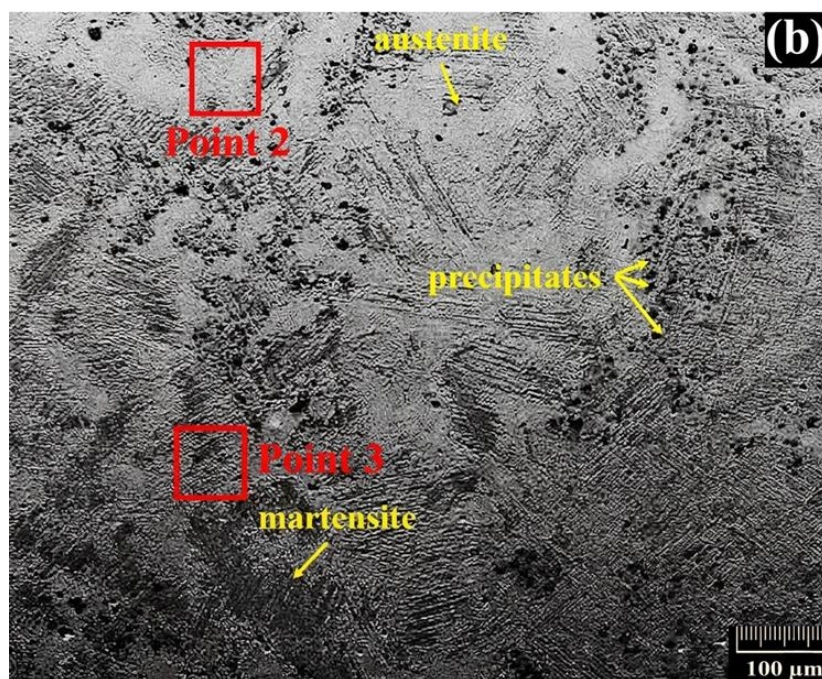
The quantitative phase analysis obtained from the Rietveld refinement of the XRD patterns presented in Figure 4 revealed that the highest retained austenite fraction (78.42%) was achieved in the QT400 sample. This result indicates that tempering at an intermediate temperature promotes the stabilization of retained austenite through carbon redistribution within the microstructure. Carbon diffusion during tempering enriches the austenitic regions, thereby increasing their stability and reducing their tendency to

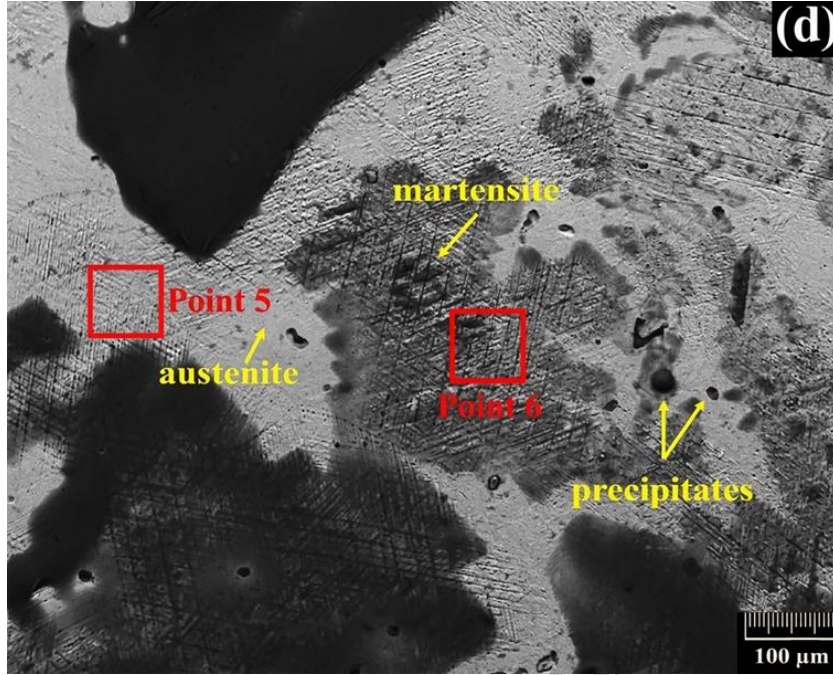
transform into martensite upon cooling. In contrast, the AQ sample exhibited a lower austenite fraction (67.74%) due to the partial transformation of austenite into martensite during rapid cooling in ice water. The high cooling rate suppresses diffusion-controlled transformations and favors the formation of martensite, a metastable phase known for its high hardness and wear resistance. The increase in martensite content is therefore expected to improve the mechanical strength and tribological performance of the steel. The higher retained austenite fraction observed after QT400 suggests that this treatment provides a favorable balance between austenite stabilization and carbide precipitation. Similar behavior has been reported in high-manganese steels, where intermediate tempering temperatures enhance the stability of retained austenite through carbon partitioning while preserving adequate mechanical properties. Conversely, excessive martensite formation in the **AQ** condition may increase hardness but can also generate residual stresses and reduce toughness, as reported in previous studies [31].

### 3.2 SEM microstructural characterization of high-manganese steel

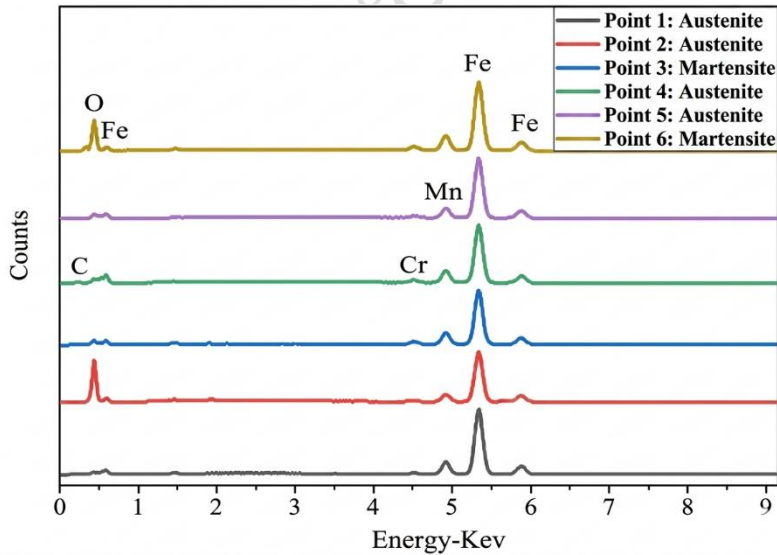
The microstructural characteristics of the samples treated under AQ, QT200, QT400, and QT600 conditions were studied using SEM coupled with EDS microanalysis. This method enables the detection and identification of the chemical composition of the various structural components of the High-manganese steel, as illustrated in Figure 5 and Figure 6.







**Figure 5.** Microstructural evolution of the steel under different heat-treatment conditions.



**Figure 6.** EDS elemental microanalysis of the high-manganese steel matrix.

Figure 5a presents the microstructure of the high-manganese steel under the AQ condition. The microstructure is predominantly composed of retained austenite, in agreement with the XRD results. Some porosities are also observed within the matrix. These defects are most likely associated with the casting process and may act as stress

concentration sites, thereby facilitating crack initiation and reducing the overall mechanical integrity of the material [32].

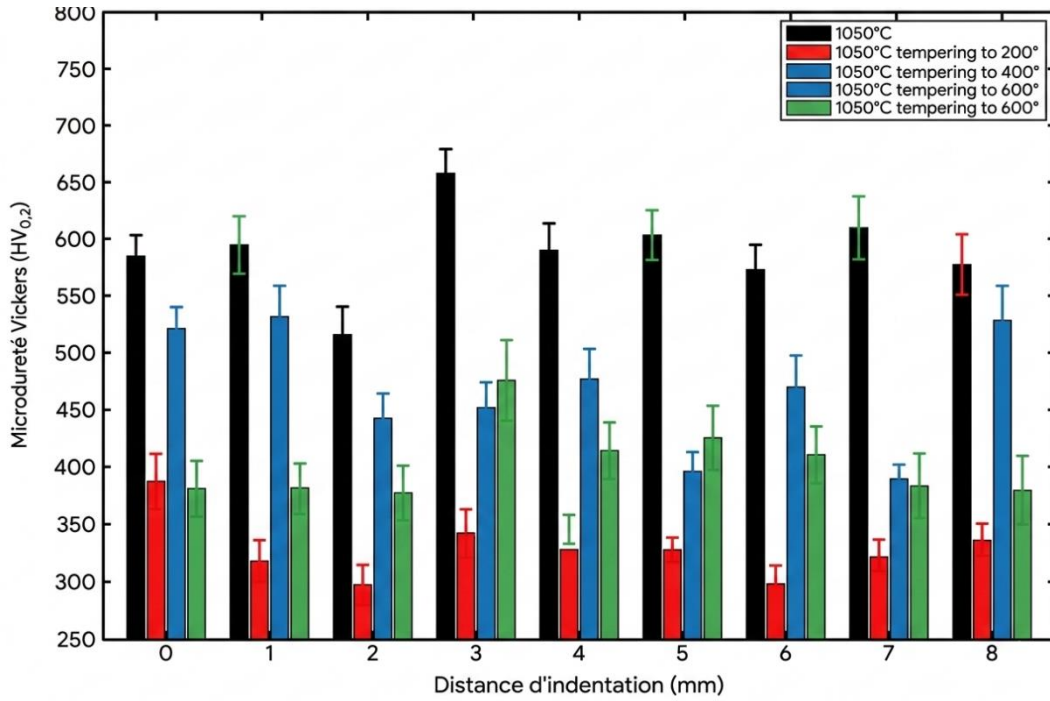
Following QT200 (Figure 5b), the microstructure exhibits the coexistence of retained austenite, tempered martensite, and carbide precipitates. The formation of  $M_3C$  carbides along the grain boundaries indicates that tempering promotes carbon redistribution from the supersaturated martensitic matrix and carbide precipitation. As a result, the as-quenched martensite formed during quenching is transformed into tempered martensite, accompanied by a reduction in lattice tetragonality and internal residual stresses. These carbide precipitates contribute to strengthening the material by hindering dislocation motion and increasing resistance to plastic deformation.

As shown in Figure 5c, QT400 exhibits retained austenite, tempered martensite, and a finer, more homogeneous distribution of  $M_3C$  carbides throughout the microstructure. This observation is consistent with the XRD results, which revealed the highest retained austenite fraction for this condition. The improved carbide dispersion can be attributed to enhanced carbon diffusion during tempering, resulting in a more uniform redistribution of carbon and alloying elements. In addition, the high manganese content contributes to austenite stabilization and influences the precipitation behavior of carbides.

For the tempered samples (QT200, QT400, and QT600), the microstructure consists of retained austenite, tempered martensite, and carbide precipitates. SEM observations indicate that these carbide precipitates appear relatively homogeneously distributed within the observed regions, without significant carbide clustering at the analyzed scale. Such a distribution may contribute to strengthening, as finely dispersed carbides can act as barriers to dislocation motion and crack propagation. Similar observations have been reported in high-manganese steels, where well-dispersed carbides contribute to improved hardness, wear resistance, and microstructural stability. Consequently, the microstructural evolution induced by tempering is expected to contribute to the improvement of the mechanical and tribological properties of the investigated steel.

### **3.3 Microhardness measurements**

The Figure 7 depicts the evolution of Vickers microhardness for various samples (sample surface) subjected to AQ, QT200, QT400, and QT600 conditions for high-manganese steel.



**Figure 7.** Vickers microhardness of various samples processed from High-manganese steel.

The analysis of Figure 7 shows that the Vickers microhardness varies significantly depending on the applied heat treatment. The AQ sample, quenched in ice water, exhibits the highest microhardness value ( $656 \pm 21.32$  HV0.2). This increase is mainly attributed to the formation of a high fraction of as-quenched martensite, which is characterized by a supersaturated body-centered tetragonal (BCT) structure and is therefore known for its high hardness.

The rapid cooling rate promotes the formation of as-quenched martensite, which markedly enhances the resistance to plastic deformation. Similar trends have been reported in the literature, where rapid quenching of high-manganese steels leads to increased hardness through the formation of as-quenched martensite [33]. However, this sample also shows the highest standard deviation ( $\pm 21.32$  HV0.2), indicating greater scatter in the measurements. This variability can be attributed to microstructural heterogeneity and residual stresses induced during rapid quenching, which may lead to local variations in hardness across the material.

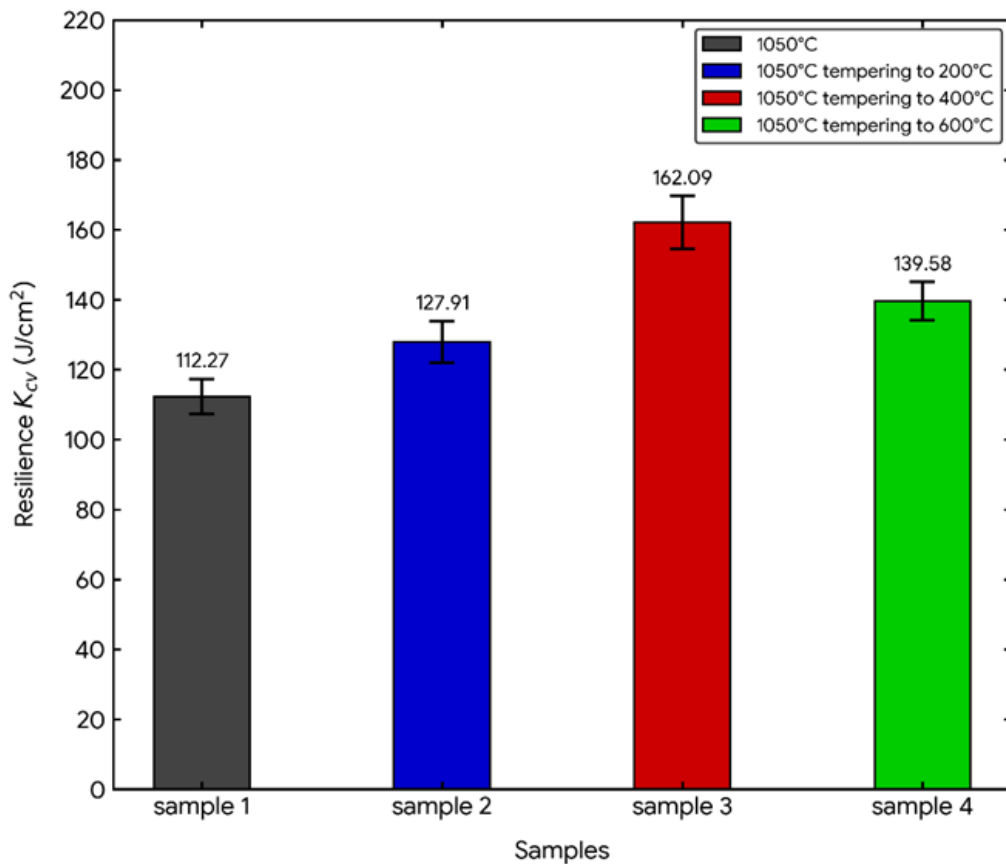
In contrast, the QT400 sample exhibits a lower microhardness value ( $523 \pm 20.14$  HV0.2) but a lower dispersion of the measured values. This reduction in hardness is attributed to the tempering of the as-quenched martensite into tempered martensite, accompanied by carbon redistribution and carbide precipitation, which relieve internal residual stresses.

Consequently, the QT400 sample exhibits a more stable and homogeneous microstructure after tempering while maintaining a relatively high hardness.

Microstructural observations revealed a more homogeneous distribution of  $M_3C$  carbides and a higher fraction of retained austenite in this condition, contributing to a more uniform mechanical response. Furthermore, the reduced variation in microhardness observed in the tempered samples indicates that the heat treatment helps relieve residual stresses introduced during quenching. Tempering promotes carbon redistribution and microstructural stabilization, leading to improved uniformity of mechanical properties. Overall, the results demonstrate that hardness is strongly governed by the balance between martensite formation, retained austenite stability, and carbide distribution within the microstructure.

### 3.4 Resilience test results

Figure 8 depicts the results of resilience tests conducted on a series of high-manganese steel samples. These samples were subjected to different heat-treatment conditions: AQ, QT200, QT400, and QT600.



**Figure 8.** Impact of heat treatment on impact resistance.

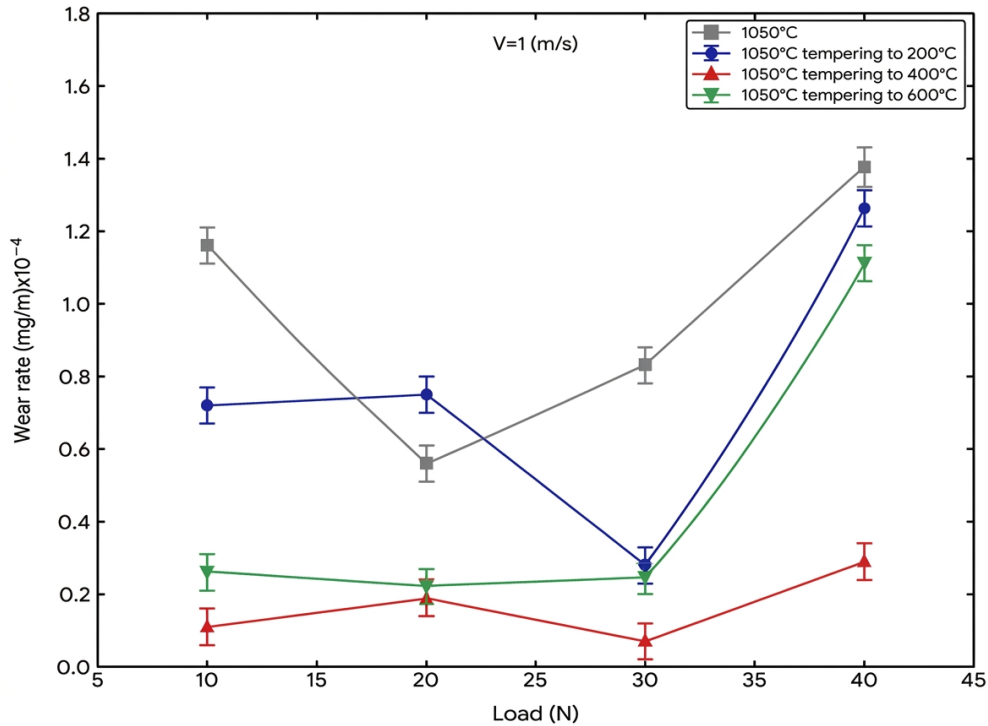
The results presented in Figure 8 show that the QT400 sample exhibits the highest impact resistance, reaching 162.09 J/cm<sup>2</sup>. This improvement is mainly associated with the combined effect of microstructural refinement and phase balance induced by tempering. In particular, the increase in retained austenite fraction in QT400 enhances energy absorption capacity, as austenite can accommodate plastic deformation through its ductile nature. In addition, the formation of finely dispersed M<sub>3</sub>C carbides contributes to strengthening without severely reducing toughness by acting as obstacles to dislocation motion while maintaining structural continuity.

The synergistic combination of retained austenite and finely distributed carbides promotes crack blunting and delays crack propagation, which explains the superior impact performance in this condition. Similar behavior has been reported in high-manganese steels, where intermediate tempering improves toughness by optimizing the balance between hard and ductile phases.

In contrast, the lowest impact resistance (112.27 J/cm<sup>2</sup>) is observed in the AQ condition. This behavior is mainly attributed to the high fraction of martensite formed during rapid cooling. Martensite, due to its high hardness and low ability to undergo plastic deformation, reduces the capacity of the material to absorb impact energy, leading to brittle-like behavior under dynamic loading. Moreover, the presence of porosities observed in SEM micrographs further deteriorates impact resistance by acting as stress concentration sites that facilitate crack initiation and propagation. The combined effect of martensitic transformation and microstructural defects therefore explains the reduced toughness of the AQ sample. Overall, these results highlight that QT400 provides an optimal balance between strength and toughness by promoting a more stable and damage-tolerant microstructure.

### **3.5 Tribological test results**

Dry wear tests were performed under varying loads of 10, 20, 30, and 40 N, with a sliding speed of 1 m/s for 25 minutes. The results of these wear tests for the four samples are presented in Figure 9.



**Figure 9.** Wear rate of samples at different tempering conditions as a function of applied load.

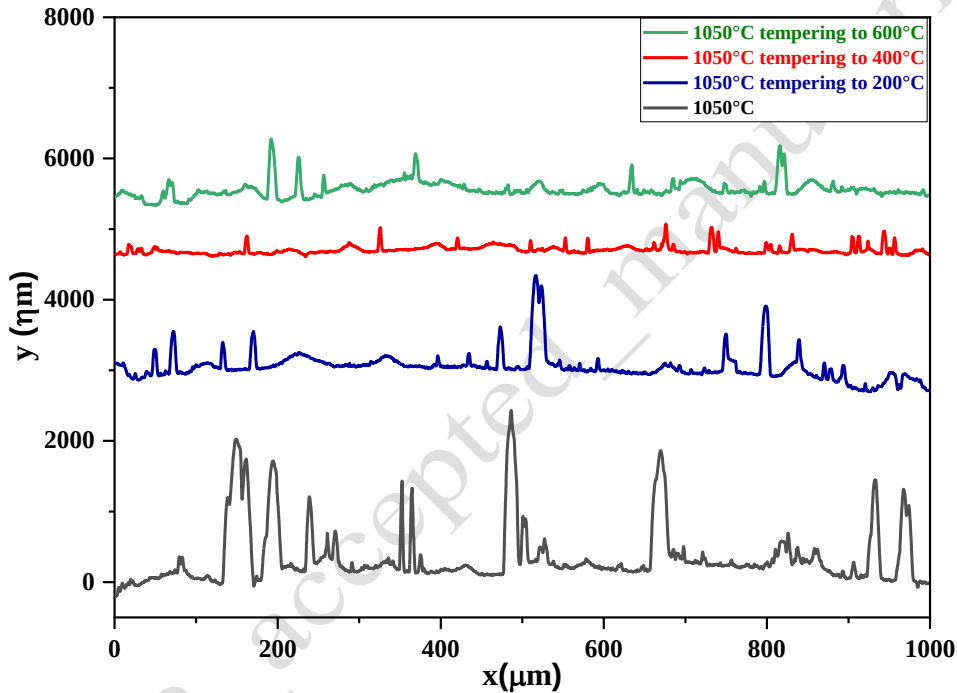
The tribological results show that the QT400 sample exhibits a stable wear rate under all applied loads (10, 20, 30, and 40 N) at a sliding speed of 1 m/s (Figure 9). This stability reflects an improved resistance to wear under varying mechanical conditions. The low wear rate ( $0.072 \times 10^{-4}$  mg/m) is attributed to the homogeneous microstructure obtained after tempering, characterized by a fine and uniform distribution of  $M_3C$  carbides. These carbides strengthen the matrix by acting as effective barriers to dislocation motion and by reducing plastic deformation at the contact surface during sliding. In addition, the presence of a significant fraction of retained austenite further contributes to the improved tribological performance. Under applied stress, retained austenite may undergo strain-induced transformation, which enhances energy absorption and delays surface damage. The synergistic effect between stabilized austenite and finely dispersed carbides therefore explains the superior wear resistance and stability of the QT400 condition.

In contrast, the AQ sample exhibits a much higher wear rate, reaching approximately  $1.38 \times 10^{-4}$  mg/m under the same sliding conditions. This deterioration in wear resistance is associated with a microstructure dominated by hard martensite and the presence of porosities observed by SEM. These defects act as stress concentration sites, promoting crack initiation and material removal through delamination and asperity fracture mechanisms. Moreover, the less uniform distribution and possible coarsening of carbides in the AQ condition further intensify abrasive wear at the surface. The combined effect of martensitic brittleness, microstructural defects, and heterogeneous carbide distribution

leads to increased material loss and reduced wear resistance. Overall, these results demonstrate that QT400 optimizes the tribological behavior of the investigated steel by promoting a balanced microstructure composed of stabilized austenite and finely dispersed carbides, resulting in significantly improved wear resistance.

### 3.6 Profile-based characterization of roughness

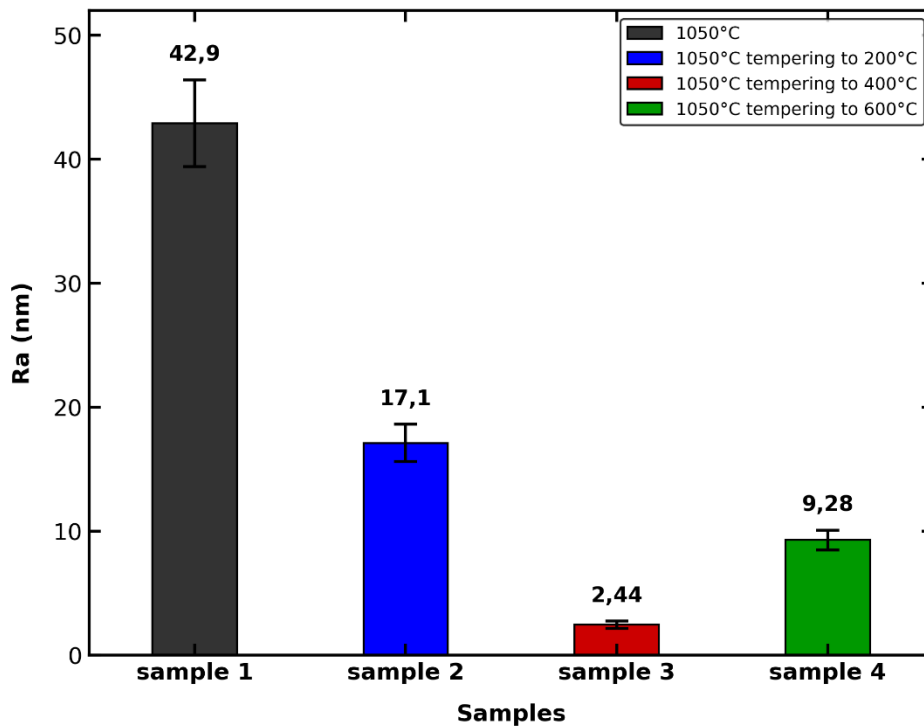
Surface roughness of the samples treated and quenched in ice was characterized using profile-based analysis of Ra. The results are presented in Figure 10. The X-axis represents displacement in microns, while the Y-axis corresponds to surface height in micrometers.



**Figure 10.** Roughness profile.

The analysis of Figure 10 shows that the maximum roughness height reaches approximately 2670 nm for the AQ sample. This high surface roughness indicates pronounced asperity formation and severe surface damage, which is consistent with a dominant material removal mechanism involving adhesive wear and micro-tearing, as also evidenced by the higher wear rate observed in tribological tests. In contrast, the QT400 sample exhibits a significantly lower maximum asperity height of approximately 500 nm. This reduction in surface roughness suggests a transition towards a more stable wear regime, characterized by mild abrasion and localized plastic deformation (ploughing) rather than severe material pull-out. This behavior can be attributed to the presence of hard  $M_3C$  carbides, which enhance surface load-bearing capacity and reduce severe surface damage during sliding. The tribological results are consistent with these observations, confirming improved wear stability under different loading conditions for

the tempered sample. In addition, minor surface undulations may be associated with the formation of a third-body layer at the interface, which can act as a transient load-carrying medium and contribute to the stabilization of the frictional contact. Overall, the surface of the QT400 sample exhibits a more uniform and stable morphology, with fewer deep pits and surface irregularities. This improvement is related to the combined effect of a stabilized austenitic matrix and a fine, homogeneous distribution of carbides, which together enhance resistance to surface degradation during sliding. Figure 11 presents the Ra roughness values obtained after wear tests on samples treated at AQ, followed by tempering at QT200, QT400, and QT600.



**Figure 11.** Roughness Ra of the different samples after wear tests.

Analysis of the results (Figure 11) shows a decrease in surface roughness from 42.9 nm to 2.44 nm for the AQ sample compared to the QT400 sample. The QT400 sample exhibits the lowest roughness among all tested samples, indicating that the tempering process significantly influences the microstructure, phase composition, and formation of new phases. This improvement in surface quality can be attributed to several factors. Tempering modifies the microstructure and relieves residual stresses generated during the initial heat treatment, thereby reducing surface irregularities and enhancing texture uniformity. These combined effects result in decreased roughness and improved tribological performance. Other factors, such as applied load and sliding speed during wear tests, may also affect surface roughness.

## CONCLUSION

This study investigated the effect of heat treatment on the microstructure and mechanical properties of the high-manganese steel used in mining crushing applications. The main objective was to identify the optimal processing conditions to achieve a balanced combination of hardness, toughness, and wear resistance.

The results show that quenching followed by tempering leads to a significant microstructural evolution, characterized by an austenitic matrix containing secondary phases such as martensite and  $M_3C$ -type carbides. This microstructural modification plays a key role in determining the mechanical behavior of the material. Among the investigated conditions, QT400 provides the best overall performance. This condition promotes a homogeneous microstructure with a stable austenitic matrix reinforced by a fine and uniform distribution of carbides, resulting in improved impact resistance and wear resistance. Therefore, QT400 can be considered the optimal condition for the high-manganese steel intended for severe service conditions in mining and wear-intensive industrial applications.

## Designation of heat-treated specimens

| Sample designation | Heat treatment                                           |
|--------------------|----------------------------------------------------------|
| AQ                 | Austenitized at 1050 °C for 30 min + ice-water quenching |
| QT200              | (As Quenched)AQ + tempering at 200 °C for 45 min         |
| QT400              | (As Quenched)AQ + tempering at 400 °C for 45 min         |
| QT600              | (As Quenched)AQ + tempering at 600 °C for 45 min         |

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## Data Availability

The data supporting the findings of this study are included within the article and/or its supplementary materials.

## Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

## Author Contributions

Khima Salim was responsible for the conceptualization of the study, methodology, investigation, data collection, data curation, and original draft writing. Younes Rassim supervised the entire project, validated the results, participated in manuscript review and editing, and managed project administration. Sadeddine Abdelhamid contributed to formal data analysis, visualization, and data curation. Bradai Mohand Amokrane provided resources and participated in investigation, particularly in microstructural characterization using SEM and XRD. Haitham M. Hadidi contributed to software development, validation of results, and manuscript revision. All authors have read and approved the final version of the manuscript.

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## FIGURE CAPTIONS

**Figure 1.** Quenching and tempering heat treatment program used for 14 % Mn steel.

**Figure 2.** Pin-disc contact.

**Figure 3.** Diffractograms of 14% Mn steel treated at (a) 1050°C quenched in ice, (b) 1050°C quenched in ice followed by tempering at 200°C, (c) 1050°C quenched in ice followed by tempering at 400°C, (d) 1050°C quenched in ice followed by tempering at 600°C.

**Figure 4.** Quantification of the phases of 14% Mn steel treated at (a) 1050°C quenched in ice, (b) 1050°C quenched in ice followed by tempering at 200°C, (c) 1050°C quenched in ice followed by tempering at 400°C, (d) 1050°C quenched in ice followed by tempering at 600°C.

**Figure 5.** Analysis of microstructure of samples treated at (a) 1050°C quenched in ice, (b) 1050°C quenched in ice followed by tempering at 200°C, (c) 1050°C quenched in ice followed by tempering at 400°C, (d) 1050°C quenched in ice followed by tempering at 600°C.

**Figure 6.** EDS microanalysis of 14% Mn steel.

**Figure 7.** Vickers microhardness of various samples processed from 14% manganese steel.

**Figure 8.** Impact of heat treatment on impact resistance.

**Figure 9.** Wear rate of samples at different tempering conditions as a function of applied load.

**Figure 10.** Roughness profile.

**Figure 11.** Roughness Ra of the different samples after wear tests.

## TABLES

**Table 1.** Chemical Composition of 14% Mn Steel (% by weight).

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