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SYSTEM SAFETY: HUMAN - TECHNICAL FACILITY – ENVIRONMENT
7(1), 2025, pp. 364-374

COMPARISON OF THE INFLUENCE OF AUSTENITIZATION AND QUENCHING CONDITIONS ON THE MICROSTRUCTURE OF HSLA 38MNVS6 STEEL

DOI: 10.2478/czoto-2025-0034
Received: 11/11/2025
Accepted: 09/12/2025

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Abstract:
The study investigates the effect of various heat treatment conditions on HSLA steel 38MnVS6, aiming to expand its potential applications in the automotive industry. The study focuses on optimizing the parameters of austenitizing, quenching, and low-temperature tempering. The objective was to achieve a predominantly martensitic microstructure and ensure a minimum hardness of 50 HRC throughout the cross-section of the material. Three heat treatment regimes were applied to the samples at an austenitizing temperature of 870°C. In the first two regimes, quenching was performed in oil at 120°C and 70°C, while in the third regime, a different quenching oil was used at the same temperature of 70°C. For each sample, surface and core hardness were measured using the Rockwell method, followed by detailed microstructural analysis. The results showed that increasing the carbon potential in the furnace reduced the ferrite fraction at the surface and positively affected surface hardness. A key finding was that the use of low-viscosity quenching oil enables the achievement of the critical cooling rate required for the desired hardness. Moreover, lowering the oil temperature effectively suppressed the formation of undesirable fine lamellar pearlite (troostite). The results indicate the potential of the experimental material for applications subjected to high dynamic loading. Therefore, further research should include fatigue strength and tribological testing to further validate the material performance.

Keywords: HSLA steels, 38MnVS6, austenitization, quenching

1. INTRODUCTION

High-strength low-alloy steels (HSLA) constitute an important group of structural materials that have received increasing attention due to their favorable balance of strength, toughness, and weldability. Their mechanical properties are achieved through

microalloying with elements such as vanadium, niobium, and titanium, which promote precipitation strengthening and grain refinement. Compared to conventional carbon steels, HSLA steels exhibit higher yield strength at lower carbon contents, resulting in improved formability and increased resistance to brittle fracture.
The microstructure and performance of HSLA steels are strongly influenced by thermomechanical processing and subsequent heat treatments. Processes such as austenitization, quenching, and tempering are critical for controlling transformation behavior and phase distributions among ferrite, bainite, and martensite. The appropriate selection of these parameters enables the optimization of hardness, strength, and ductility, which are essential for components subjected to dynamic loading.
Among all HSLA grades, 38MnVS6 steel is particularly attractive for automotive applications that require high fatigue resistance and surface hardness. Therefore, understanding the influence of austenitization and quenching conditions on its microstructure is essential for improving process performance and reliability. The experimental results of this study are intended to support the practical implementation of optimized heat treatment regimes for industrial applications (Zhao et al., 2019, https://www.textronsteelalloys.com/38mnvs6-round-bars-1-1303).

2. METHODOLOGY OF RESEARCH

The experimental material used in this study was high-strength low-alloy (HSLA) steel 38MnVS6, standardized according to EN 10267: 1998 "Ferritic-pearlitic steels for precipitation hardening from hot-working temperatures" (EN 10267: 1998).
This steel is classified as a medium-carbon, low-alloy, high-strength grade that contains manganese and vanadium as the principal alloying elements, along with a controlled sulfur content to enhance machinability. The specific combination of these elements contributes to its favorable balance of strength, toughness, and processing characteristics.
Due to these properties, 38MnVS6 is predominantly used in the precipitation-hardened condition for manufacturing mechanically stressed components in the automotive and mechanical engineering industries. Typical applications include crankshafts, rotary bearings, axle pins, hubs, piston heads, and gear wheels. Thus, its widespread use can be attributed to its high strength, reliable performance under cyclic loading, and good machinability (Skočovský et al., 2024; Material specification sheet, 2025).
The material was supplied in the form of machined Cylindrical samples with a diameter of 16 mm and a length of 50 mm. For each heat treatment condition, five samples were prepared to ensure reproducibility of the results. The chemical composition of the 38MnVS6 steel, verified using a SPEKTROMAXx emission spectrometer, is presented in Table 1.

Table 1
Chemical composition of experimental samples

Steel	Concentration of chemical elements [Wt%]							
	C	Si	Mn	P	S	Cr	V	N
38MnVS6	0.390	0.100	1.480	0.010	0.021	0.090	0.100	0.013

2.1 Heat treatment

Heat treatment (HT) was performed in a multi-purpose chamber furnace Aichelin VKES 4/1 under a protective atmosphere based on endothermic gas (so-called endogas). This atmosphere, composed primarily of CO, H_2, and N_2, prevents oxidation and decarburization during the heat treatment process (Multi-Purpose Chamber Furnace Plant, 2025).

The specific heat treatment Modes applied in this study are described in detail in Chapter 3 . Mode 1 was designed according to theoretical principles, while Modes 2 and 3 were subsequently optimized based on the results obtained from the preceding Mode.

Two different quenching oils were employed. Oil 1 is a hot-bath quenching oil specifically developed for isothermal quenching processes and is suitable for use in the temperature range of 50 – 160°C. Oil 2 is a high-performance, fast-quenching oil designed for conventional low-temperature hardening, typically used within the 50 – 80°C range. It is characterized by low to medium viscosity and a high cooling rate (Liščić et al., 2010, Kaliace-Media, 2025).

2.2 Metallographic analysis

Samples for microstructural analysis were prepared both before heat treatment and after each heat treatment Mode. Samples were cut perpendicularly from the cylindrical bars, mounted, and subsequently ground and polished using a Struers TegraPol-15 device. The polished surfaces were etched with 3% Nital for 5 seconds to reveal the microstructure and examined using a Leica Dmi8 inverted light microscope.

2.3 Hardness tests

Hardness tests were performed on all samples after each Mode. These were measured using the Rockwell method, in accordance with STN EN ISO 6508-1, and were performed on a Struers DuraVision-30 hardness tester. A diamond indenter with a conical tip, a vertex angle of 120°, and a radius of curvature of 0.2 mm (STN EN ISO 6508-1) was used for this test. The measurement was performed at a temperature of 20°C ± 3°C. The required hardness of the material after heat treatment was set at 49 – 54 HRC. Three hardness measurements were performed on each sample on the surface of the sample, where correction factors for curved surfaces specified in STN EN ISO 6508-1, Annex C, were applied. Furthermore, four indentations were made to measure the hardness in the core (in the perpendicular cross-section) of the sample (Dowling, 2013, Hardness Test Theory, 2025).

3. RESULTS AND DISCUSSION

The microstructure of the sample was analyzed before heat treatment using an optical microscope (Figure 1). Based on observation, the microstructure was evaluated as pearlitic-ferritic, which corresponds to the classification specified in EN 10267: 1998. The presence of non-metallic inclusions, mainly manganese sulfide (MnS), was also identified in the structure, which had an elongated shape oriented in the direction of previous forming.

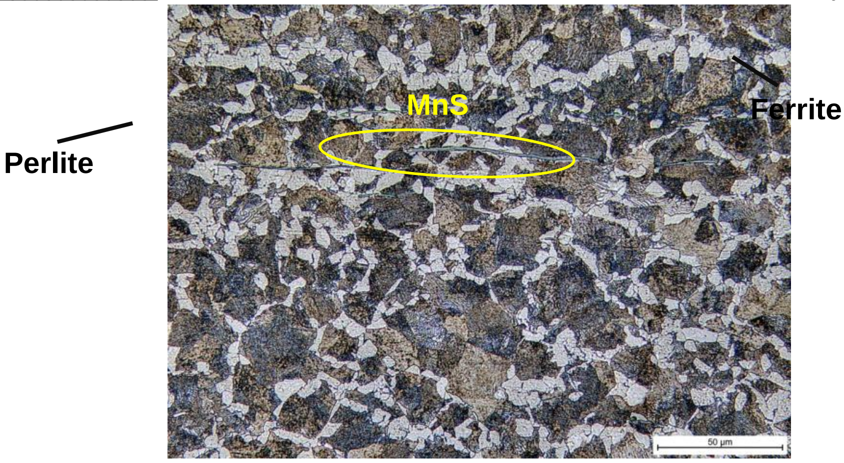

Fig. 1. Detail of the microstructure of the sample in its initial state, etched with 3% Nital

3.1 Heat treatment Mode 1

The first heat treatment regime was designed based on theoretical considerations, with the primary objective of achieving complete transformation of the initial pearlitic–ferritic microstructure into homogeneous austenite while minimizing the risk of excessive austenitic grain growth. The austenitization temperature was therefore set at 870°C, corresponding to the critical temperature AC_3. For 38MnVS6 steel with a carbon content of 0.39%, the value of AC_3=783.3°C, as determined from the continuous cooling transformation (CCT) diagram. A holding time of 80 minutes was applied to ensure sufficient carbon diffusion throughout the material volume, promoting both chemical and structural homogenization. Furthermore, he carbon potential of the furnace atmosphere was maintained at 0.39 to establish equilibrium carbon conditions at the sample surface and to prevent undesired surface decarburization or enrichment (Erçayhan and Saklakoğlu, 2021, (Material data sheet, 2025).

Isothermal quenching oil was selected for the quenching process, which allows rapid cooling from the austenite region to an isothermal temperature of 120°C. In this temperature range, pearlitic and bainitic transformation is suppressed, while immediate martensitic transformation does not yet occur. Maintaining the samples at this temperature allows for a controlled martensitic transformation, reducing internal stresses and minimizing the risk of deformation, cracking, or twisting.

Further low-temperature tempering at 200°C for 70 minutes serves to eliminate the brittleness of the newly formed martensite and, at the same time, to stabilize the resulting microstructure without significant loss of hardness. This step contributes to the reduction of residual stresses and increases the dimensional stability of the samples, which is important in terms of their long-term operational reliability. The selected parameters for heat treatment Mode 1 are summarized in Table 2.

The averages of the hardness test results, measured on the surface and in the core of five samples, are recorded in Table 3.

The microstructure after the first experimental heat treatment regime is shown in Figures 2 – 3 and consists of a martensitic-bainitic-pearlitic structure. The martensitic structure (M) is typically formed by needle-like formations and is shown in brown in the Figures, depending on the orientation of the lamellae and the degree of tempering, which is typical for Nital etching.

Table 2
Technological procedure for heat treatment Mode 1

Austenitization			Hardening		Tempering	
Temperature [°C]	Time [min]	Cp	Hardening medium	Temperature [°C]	Temperature [°C]	Time [min]
870	80	0.39	Oil 1	120	200	70

Table 3
Results of hardness tests for Mode 1

Measurement location	Method	Sample				
		1	2	3	4	5
Surface	HRC	46.7	48.1	47.5	47.8	45.9
Core	HRC	47.8	49.5	48.8	48.6	46.4

The presence of the bainitic phase is a result of the lower cooling rate in an oil bath at a temperature of 120°C, which was not sufficient for the complete martensitic transformation of all austenite, and is represented in the microstructure in a minimal to imperceptible amount. The present pearlite, precipitated in the form of very fine lamellae (troostite), appears white-blue in the images and, as can be seen in Figure 2, represents approximately 40% of the microstructure volume, which has a significant effect on the reduced hardness of the material.
Figure 3 illustrates the oxidation of the surface layer of the material, which occurred as a result of the loss of alloying elements. This area is characterized by the presence of a ferritic microstructure (F), located mainly along the boundaries of the original austenitic grains.

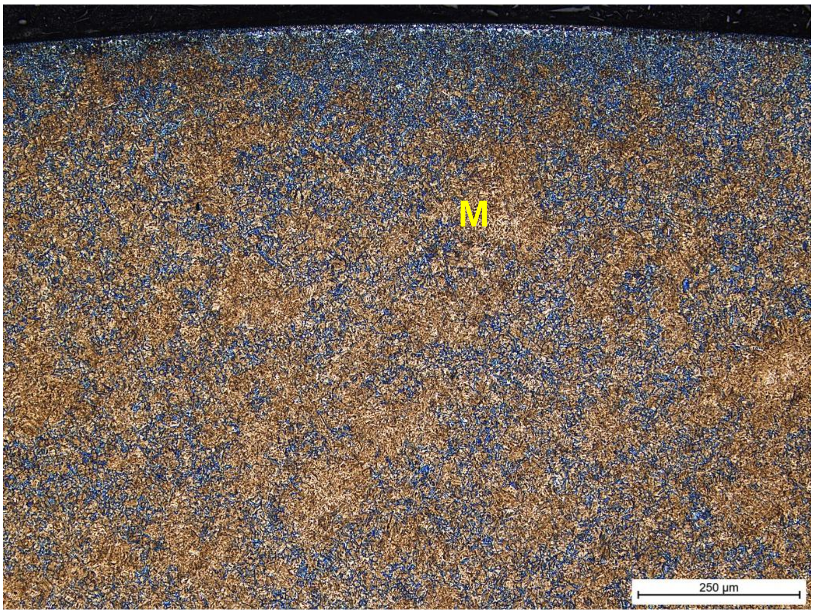

Fig. 2. Microstructure of the surface of a 38MnVS6 steel sample, Mode 1, etched with 3% Nital

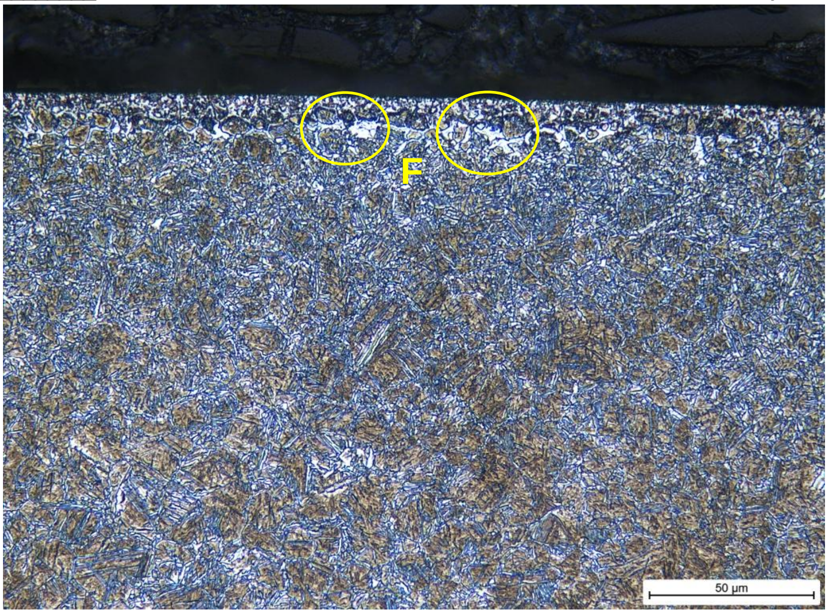

Fig. 3. Detail of the microstructure of the surface of a 38MnVS6 steel sample, Mode 1, etched with 3% Nital

3.2 Heat Treatment Mode 2

Based on the results obtained from the first heat treatment Mode, the process parameters were subsequently optimized. The austenitization conditions, specifically a temperature of 890°C and a holding time of 75 minutes, were found to be satisfactory and were therefore retained for the following Modes. The tempering parameters were also verified and maintained. To minimize surface decarburization, the carbon potential of the furnace atmosphere was slightly increased to Cp = 0.42. During quenching, a more intensive cooling effect was required; therefore, a lower oil bath temperature of 80°C was selected to promote the formation of a harder martensitic structure. This adjustment also ensured a controlled transformation process, allowing for the development of internal stresses within acceptable limits and reducing the risk of cracking or deformation. The selected heat treatment parameters for Mode 2 are summarized in Table 4, where changes from the previous Mode are highlighted in blue.

Table 4
Technological procedure for heat treatment Mode 2

Austenitization			Hardening		Tempering	
Temperature [°C]	Time [min]	Cp	Hardening medium	Temperature [°C]	Temperature [°C]	Time [min]
870	80	**0.42**	Oil 1	**70**	200	70

The averages of the hardness test results measured on the surface and in the core of five samples are recorded in Table 5.

Similar to the first Mode, the microstructure is evaluated as a martensitic-bainitic-pearlitic structure. However, compared to the previous Mode, it is finer, more homogeneous, and has a significantly lower proportion of fine lamellar pearlite (Figures 4 – 5). This is a result of the reduction in the temperature of the quenching oil, which promoted the formation of a martensitic structure.

Table 5
Hardness test results for Mode 2

Measurement location	Method	Sample				
		1	2	3	4	5
Surface	HRC	49.5	50.2	49.7	51.1	50.6
Core	HRC	46.2	47.4	46.8	48.6	48.0

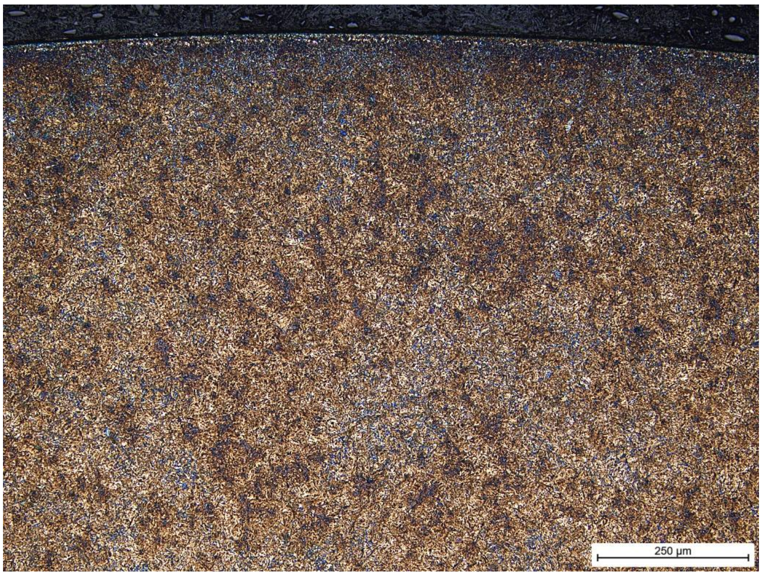

Fig. 4. Microstructure of the surface of a 38MnVS6 steel sample, Mode 2, etched with 3% Nital

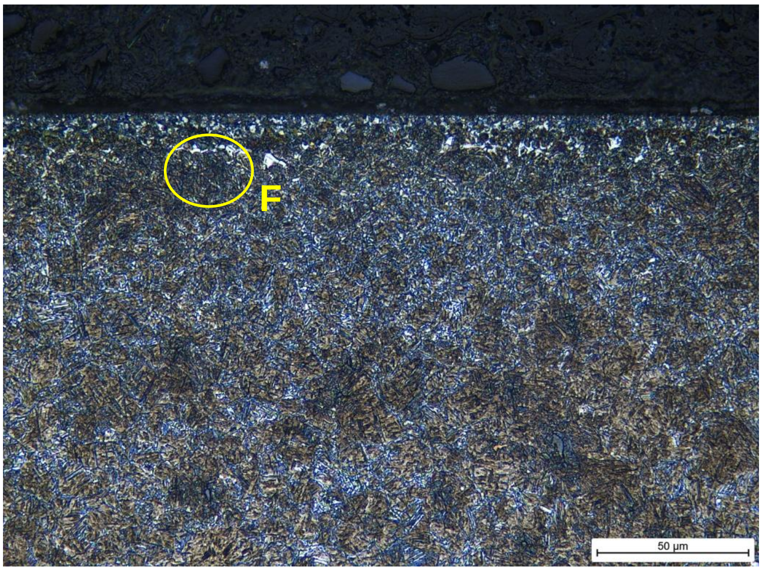

Fig. 5. Detail of the microstructure of the surface of a 38MnVS6 steel sample Mode 2, etched with 3% Nital

The increase in the carbon potential of the furnace atmosphere was reflected in the resulting microstructure (Figure 5) by a significant reduction in the proportion of ferrite (F) in the surface layer. Although this adjustment led to an improvement in surface hardness, no significant enhancement was observed in the core hardness. The modification of the quenching oil temperature likewise did not produce a noticeable effect on hardness, which is consistent with theoretical findings indicating that the cooling capacity of oil is governed primarily by its viscosity rather than its temperature. Therefore, in the subsequent heat treatment Mode, the quenching medium was replaced with an oil of higher cooling capacity to promote more effective formation of a martensitic structure.

3.3 Heat Treatment Mode 3

In Mode 3, only the type of quenching oil was changed to a high-performance, fast-quenching oil with lower viscosity. The other parameters remained unchanged and are recorded in Table 6, where the change from the previous Mode is highlighted in blue.

Table 6
Technological procedure for heat treatment in Mode 3

Austenitization			Hardening		Tempering	
Temperature [°C]	**Time [min]**	**Cp**	**Hardening medium**	**Temperature [°C]**	**Temperature [°C]**	**Time [min]**
870	80	0.42	**Oil 2**	70	200	70

The averages of the hardness test results measured on the surface and in the core of five samples are recorded in Table 7.

Table 7
Hardness test results for Mode 3

Measurement location	Method	Sample				
		1	**2**	**3**	**4**	**5**
Surface	HRC	53.1	52.9	53.0	53.5	52.7
Core	HRC	50.9	50.2	50.6	51.0	50.2

The change to a higher viscosity quenching oil was demonstrated in the microstructure by the achievement of a predominantly martensitic structure with a smaller proportion of bainite and unevenly distributed islands of fine lamellar pearlite structure (troostite), indicated by the yellow arrows in Figure 6. A more detailed view of the small occurrence of fine lamellar pearlite (T) is shown in Figure 7, as well as the decarburization of the surface layer manifested by the exclusion of the ferritic structure (F) along the grain boundaries.

The hardness measurements of all samples processed in Mode 3 reached values within the required range of 49 – 54 HRC. A marked increase in both surface and core hardness was achieved after switching to a quenching oil with lower viscosity. These results confirm that the parameters of the applied heat treatment were correctly optimized.

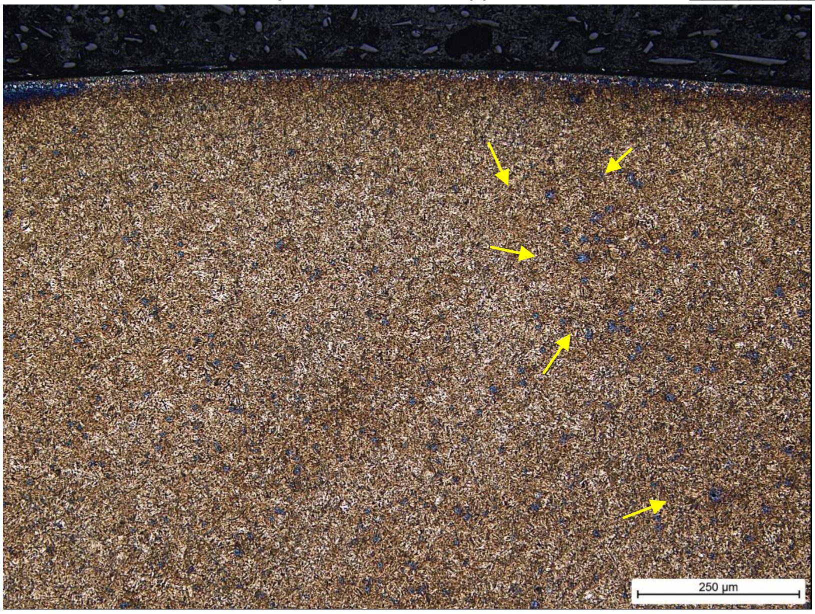

Fig. 6. Microstructure of the surface of a 38MnVS6 steel sample, Mode 3, etched with 3% Nital

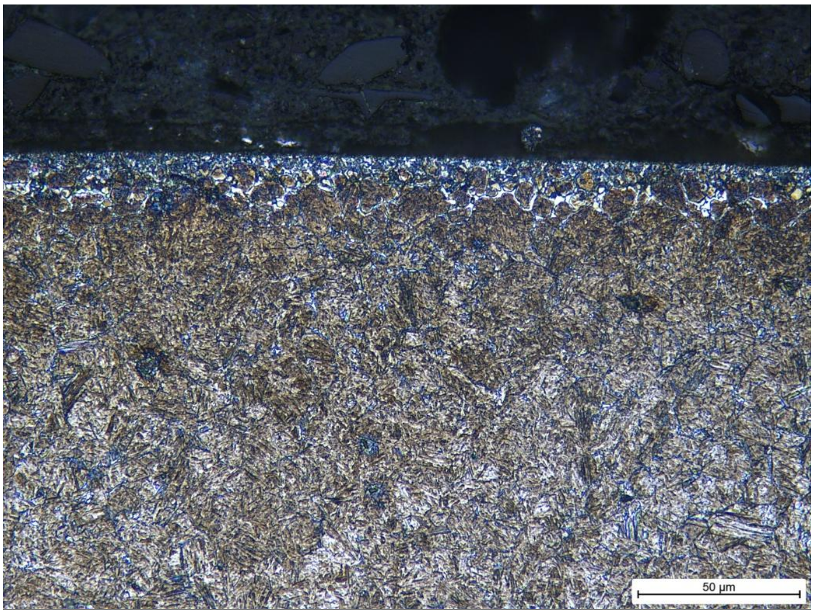

Fig. 7. Detail of the microstructure of the surface of a 38MnVS6 steel sample, Mode 3, etched with 3% Nital

Based on available literature, no study has been published to date that systematically evaluates the optimization of quenching and low-temperature tempering of 38MnVS6 steel with the objective of obtaining a predominantly martensitic microstructure and a hardness level of 49 – 54 HRC. Although several publications discuss heat treatment parameters for this steel grade, none of them report achieving the required hardness values.

According to published data, 38MnVS6 steel typically reaches hardness levels of 20 – 32 HRC in its standard processing condition (after precipitation hardening), depending on the specific treatment and the resulting microstructure (Material data sheet, 2025; Berns and Theisen, 2008).

For comparison, a previous study (Tsai et al., 2022) reported maximum hardness values of approximately 34 HRC. This was obtained after quenching from an austenitizing temperature of 1150°C for 30 minutes, followed by two-stage cooling—rapid cooling in a salt bath at 600–650°C for 30 minutes, and subsequent slow cooling in water. Meanwhile, another study (Siwiec et al., 2020) investigated the application of normalization in a PP-300 continuous furnace at 910 °C, followed by cooling under a fan operating at 5200 rpm. This process yielded a surface hardness of 24 HRC.

In this context, the results presented in this study expand current knowledge on the processing of HSLA steels of this category and support the broader use of 38MnVS6 steel in automotive applications. For industrial implementation, or when designing components with larger cross-sections, it is advisable to extend the austenitization holding time to improve austenite homogenization and thus further reduce the presence of fine lamellar pearlite in the final microstructure after quenching.

4. CONCLUSION

The work deals with the optimization of conditions for austenitization, hardening, and low-temperature tempering of 38MnVS6 steel. The aim was to achieve a predominantly martensitic structure and hardness on the surface and in the core of the samples in the range of 49 – 54 HRC. The following conclusions can be drawn from the results of experimental tests of three different heat treatment regimes, which included parameter optimization, surface and core hardness measurements of the analyzed samples, and microstructure analysis:

1. In all heat treatment Modes, the resulting microstructure was characterized as martensitic-bainitic, with a minimum to approximately 40% share of fine lamellar pearlite (troostite) and a negligible amount of residual austenite.
2. The change in the temperature of the quenching medium did not show a significant effect on the resulting hardness values. However, the viscosity of the oil used was the decisive factor. The application of high-performance quenching oil with lower viscosity, despite its higher cooling effect, did not lead to the formation of deformations and cracks on the quenched samples, and at the same time ensured the achievement of a predominantly martensitic structure.
3. The heat treatment conditions of Mode 3 achieved satisfactory hardness values on the surface and in the core of the samples. Of the five samples, the minimum hardness value measured on the surface was 52.7 HRC and in the core 50.2 HRC. The hardness requirement was in the range of 49 – 54 HRC.
4. Based on the experimental research conducted, it can be concluded that HSLA steel 38MnVS6 is a suitable alternative to commonly used carbon structural steels in the automotive and engineering industries, especially for hardening in chamber furnaces.

ACKNOWLEDGEMENTS

The Ministry of Education, Research, Development and Youth of the Slovak Republic supported the research by projects KEGA no. 009ŽU-4/2023 and KEGA no. 004ŽU-4/2023.

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