MICROSTRUCTURAL & NANOMECHANICAL PROPERTIES RESEARCH OF M300 MARAGING STEEL AFTER HEAT TREATMENT

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This article focuses on the application of ultra-low-carbon martensitic high-strength M300 maraging steel in the field of with emphasis on defence industry applications and machine gun components. Main aim of this article is analysing the effect of different heat treatment regimes, in particular solution annealing and precipitation hardening (aging), on the results of nanohardness and reduced elastic modulus of the tested material. The experimental part of the research includes the preparation of M300 steel samples The implementation of four defined thermal states using a precisely controlled dilatometric device, metallographic surface preparation and subsequent analysis using nanoindentation tests. The results demonstrating significant influence of temperature and aging time on the local mechanical properties of maraging steel and confirm the suitability of nanoindentation as a significant method of material characterization. The research contributes a better understanding of the relationship between observed microstructure, heat treatment and mechanical response of maraging steels.

KEYWORDS

M300 maraging steel, LSCM microscopy, microstructural analysis, nanoindentation technique, nanohardness, reduced Youngs elastic modulus

1 INTRODUCTION

Maraging steels generally represent a specific group of ultra-high-strength, low-carbon martensitic steels. These materials achieve their extraordinary strength not through carbon, but precisely through the precipitation of intermetallic compounds during the process of artificial aging. Their microstructure consists of low-carbon martensite, which is formed by nickel in the range of approximately 15 ÷ 25 wt. %. Due to the presence of other elements, such as cobalt, molybdenum or titanium, it ensures the formation of fine precipitates, which significantly increase strength without a significant reduction in toughness. As a result of this combination of material properties, maraging steels are among the most powerful structural materials used in industries with high demands on reliability [Ansari 2021 and Felicioni 2024] as well as in the field of weapons components and special equipment production. These types of materials are usually produced by conventional manufacturing technologies, but 3D metal printing has great potential. This concerns about the methods of the Laser Powder Bed Fusion (L-PBF / SLM) process. The authors [Dhaundiyal 2025] in their study entitled Material testing of 3D printed I-section of martensitic steel were involved in the research of such types of materials. Similarly, the authors [Omidi 2023 and Szachogluchowicz 2021] conducted research focused on SLM (Selective Laser Melting) processing of M300 Maraging steel. The authors [Pathak 2026] also focused their research on the microstructure and overall characterization of the material produced by additive technology. From the point of view of above-mentioned research based on the surface layers of the investigated M300 steel, the research of the authors [Rońda 2022] was also focused. The L-PBF (Laser Powder Bed Fusion) processing application in thin walls manufacturing also solved authors [Žaba 2026]. The chemical composition and required mechanical properties were originally defined by the American military standard MIL S 46850D. This standard specified precise ranges of the content of the main alloying elements. The subject of the authors' research is maraging M300 steel (also referred to as 1.2709). This steel is generally characterized by very high strength, good toughness and minimal deformation during heat treatment. Properties of this steel predetermine its use in the aerospace, weapons and tool industries [Mechali 2024 and Kolomy 2023]. Also based on these facts, it was necessary to approach a detailed analysis from the basic chemical composition, through surface morphology, to local and bulk nanomechanical characteristics. It is possible to formulate such a comprehensive approach that allows us to practically verify whether the individual heat treatment modes (HT480 3, HT490 6, HT460 6 and HT460 8-2x) bring the expected changes in the microstructure and whether their subsequent effect corresponds to the mechanical parameters.

Proper characterization of nanomechanical properties is essential for their effective use and understanding the influence of heat treatment. However, classical hardness and microhardness testing only provide data on macroscopic behaviour. But this fact does not allow capturing and showing local differences related to the investigated microstructure, which are subsequently crucial under extreme or cyclic loading.

Quasistatic nanoindentation as a research method represents a detailed method enabling the evaluation of local nanomechanical properties with high resolution. Based on the loading process and the penetration of the indenter of the required geometry, it is possible to determine nanohardness, reduced Young's modulus of elasticity and possibly other deformation characteristics. The nanoindentation method is particularly suitable for special high strength materials with a fine microstructure and for comparing different thermal states.

Nanoindentation is an advanced form of indentation testing. The depth of penetration of the indentation tip is monitored with nanometric-level resolution. Unlike conventional hardness and microhardness tests, where the contact area is determined by direct measurement of the resulting indentation, in quasistatic nanoindentation it is determined indirectly based on the recorded depth of penetration and the known geometry of the indenter used [Fischer-Cripps 2011]. From this perspective, quasistatic nanoindentation can be classified as a depth sensing indentation (DSI) method, also known as instrumented indentation testing (IIT). The experimental nanoindentation method used is considered quasistatic, since the load during the test increases and decreases slowly enough to neglect dynamic effects [Oliver and Pharr, 1992]. The main benefit of nanoindentation lies in the possibility of obtaining multiple mechanical characteristics of the material under investigation within a single test cycle of loading and unloading. In addition to nanohardness, it is also possible to determine the reduced Young's modulus of elasticity and other parameters describing the mechanical response of the material [Fischer-Cripps 2011]. Analysis of the indentation P-h curve of the load-displacement dependence allows one to distinguish the elastic and plastic components of deformation. Also, it is possible to evaluate the viscoelastic behaviour of the tested materials or to assess the fracture properties of brittle systems. It is the high spatial

resolution of nanoindentation that makes this research method suitable for investigating thin layers, surface treatments and local mechanical properties of heterogeneous materials. Nanoindentation tests induce a combination of elastic and plastic deformation in the material under investigation. The course of which depends on the mechanical properties of the material as well as the geometry of the indenter used. Nanohardness *H* is a measure of a material's resistance to plastic deformation caused by an external force. In nanoindentation, nanohardness is defined as the rat io of the maximum load to the projected contact area between the indenter and the sample surface. It is therefore the average contact pressure acting at the indentation point.

2 MATERIALS AND METHODS

2.1 Characteristics of maraging steel

Maraging steel M300 (also known as 1.2709) is generally characterized by very high strength, good toughness and minimal deformation during heat treatment. All of these abovementioned properties make M300 steel suitable for use in the aerospace, weapons and tool industries. Maraging steel M300 is alloyed mainly with nickel Ni, cobalt Co, molybdenum Mo and titanium Ti, while the carbon content is very low (C < 0.03%). In terms of the chemical composition of M300 steel, the low carbon content ensures high toughness, good weldability and minimizes the formation of carbides. The main contribution to the strength properties is made by the formation of precipitates of Ni, Co and Mo in martensitic matrix during ageing. This is a key to achieving ultra-high strength, while silicon and manganese are present only in trace amounts for technological reasons in production. The chemical composition and required mechanical properties were originally defined by the American military standard MIL S 46850D. This standard specified the exact ranges of the content of the main alloying elements in steel. It is precisely the low carbon content that ensures very good weldability of M300 steel and prevents the formation of carbides. This fact negatively affects the overall toughness of the material. In the solution annealing state, the M300 maraging steel has a fine-grained martensitic microstructure with a low dislocation content. The described structure provides M300 steel with a suitable basis for subsequent precipitation strengthening. The main strengthening mechanism of M300 maraging steel is precipitation hardening by intermetallic phases. These are mainly Ni_3Ti and Ni_3Mo components. The hardening process of the steel takes place at temperatures approximately in the range of 460 ÷ 500 °C for several hours. During the abovementioned process, a significant increase in strength occurs while maintaining relatively good toughness. Typical values of the mechanical properties of the M300 steel after hardening include a tensile strength of over 2000 MPa. A range of hardness is approximately 54 ÷ 56 HRC and a modulus of elasticity of around 190 ÷ 200 GPa. The mechanical properties of M300 steel are hardness, strength, modulus of elasticity, fracture toughness and resistance to plastic deformation. All of these properties directly affect the behaviour of the material under load and its long-term operational reliability. Their mutual combination allows us to assess the ability of the steel to withstand mechanical stress, wear and fatigue phenomena in real operating conditions. This is especially crucial in applications with high demands on accuracy, safety and durability of structural elements. In terms of surface treatment, the material is also suitable for nitriding. It can improve its wear resistance. The M300 steel is produced using the modern metallurgical process VIM + VAR (vacuum induction furnace + vacuum remelting), which ensures high purity, homogeneity and a very low level of inclusions. All of these are the key properties for applications with high demands on strength and toughness.

2.2 Heat treatment of Maraging M300 steel

Heat treatment is a key technological step in shaping the microstructure and mechanical properties. In the case of maraging steels, it plays a decisive role in achieving their characteristic properties, such as very high strength, hardness and good toughness. The basic heat treatment of M300 consists of three main steps: solution annealing, rapid cooling and hardening (aging). A significant advantage is the minimal dimensional change during heat treatment, while there is no need to ensure against surface decarburization. The M300 steel allows uniform hardening even for large cross-sections and retains good machinability by chipping even in the hardened state. The heat treatment of the experimental M300 steel was carried out on a TA Instruments DIL 805A/D dilatometer. This device allows precise control of heating and cooling regimes. A total of four thermal states (HT480-3, HT490-6, HT460-6, HT460-8-2x) were prepared in the process of the experiments. The states represented different degrees of precipitation, strengthening and microstructural stability. All regimes were based on a single solution annealing step (820 °C / 1 h / AC). The aim of which was to dissolve precipitates and homogenize the solid solution. Subsequently, different precipitation hardening regimes were applied, leading to specific microstructural states. Each temperature cycle was prepared using a programmable dilatometer control, which allows precise adjustment of heating and cooling rates, dwell times in individual phases, atmospheric conditions compatible with surface protection, and continuous recording of sample dilation. Based on the four defined precipitation curing modes, the following conditions were prepared.

1st state: HT480-3 maximum hardening (significant hardening, good homogeneity).

2nd state: HT490-6 stabilized state (most balanced state, good hardness, stability).

3rd state: HT460-6 tempered at low temperature (high hardness and higher variability).

4th state: HT460-8-2x two-stage aging (homogeneous and stable state with balanced properties).

The first state represents a regime or mode characterizing optimal aging in which the concentration and distribution of precipitates (especially MC and M_2C carbides) provide the highest level of strengthening.

The second state is suitable as a basis for stress-sensitive technological applications. Higher temperature and longer time lead to partial growth of precipitates, which reduces extreme hardness, increases thermal stability, improves surface behaviour in high-temperature processes (e.g. Physical vapour Deposition PVD/ Chemical Vapour Deposition CVD coatings).

The third state is characterized by a lower hardening temperature and promotes a finer precipitation structure. This results in higher toughness, less brittleness compared to the maximum strengthening state, a potentially advantageous interface for coatings with high residual stresses.

The fourth state represents a two-stage regime allowing precipitation processes in the first step, a subsequent reorganization and homogenization of precipitates during the second step, creating a stable and uniform microstructure. This state is particularly suitable for applications requiring thermomechanical stability and uniform mechanical responses. The above heat-treated states differ mainly in the volume and distribution of precipitates, the level of dispersion strengthening, the microstructural stability at elevated temperatures, the resulting hardness, strength and toughness.

All these differences have a fundamental impact on the course of nanoindentation curves, thus local hardness and elastic modulus, as well as on fatigue resistance. Therefore, the creation of four states was crucial for a comprehensive analysis of the experimental material like maraging steel M300.

2.3 *Experimental methods*

As mentioned earlier, a comprehensive assessment of the properties of the M300 steel requires a multi-level analytical approach that allows linking the chemical composition, surface morphology, microstructure and mechanical response of the investigated material at the nanoscale. The chemical composition was verified by optical emission spectrometry (SpectroMaxx). The surface morphology was evaluated by a confocal microscope OLYMPUS LEXT OLS 5100. Local nanomechanical properties were experimentally determined by nanoindentation (Hysitron TI 950 device). The experimental research and individual evaluation methods, as well as their analysis themselves, were designed to provide an integrated view of the behaviour of the tested M300 steel in different thermal states. Their goal was to create a comprehensive view of the heat treatment influence on the microstructure and nanomechanical properties of the investigated M300 steel.

3 RESULTS & DISCUSSION

3.1 *Chemical composition analysiss*

The chemical composition of the M300 steel significantly affects the microstructure, hardness, and precipitate stability. The results of the chemical analysis provided the basis for a correct and reproducible evaluation of other experimental methods. The chemical analysis was performed as the first step in the evaluation of the M300 steel to confirm the declared composition of the investigated samples and to verify its chemical homogeneity before the heat treatment. The measurement was performed on only for one sample in the as-received condition, with five separate repeated measurements being performed to eliminate measurement error and to verify the stability of the results. Heat treatment can potentially cause surface changes (oxidation, diffusion losses of light elements), the chemical analysis was intentionally performed before any heat treatment to establish a reliable reference chemical basis for all subsequent experiments.

M300	C	Si	Mn	Mo	Ni	Co	Ti	Al	Fe
Mean (n=5)	0.015	0,019	0,024	5.37	17.82	9.36	0.688	0.053	65.3
SD	0.0025	0.0006	0.0002	0.107	0.0443	0.028	0.005	0.0008	0.098
Stand. X2NiCoMo 18-9-5	<=0,03	max. 0.1	max. 0.1	4,5-5,5	18-19	8-10	0.5 - 0,8	0,05-015	65,1 - 68,4

TABLE 1. CHEMICAL COMPOSITION (WT.%) OF M300 STEEL IN THE CONDITION SUPPLIED BY THE MANUFACTURER

The results contained in Tab. 1 correlate with the expected values for the M300 steel. The carbon (C) is a higher than the standard value. The standard also states 0.005% of C, while the average value is 0.015%, which is higher. It is also significant that values below 0.03% are still typical for M300 steels. The obtained results also confirm a fact, that it does not contain non-standard deviations, and therefore can serve as a reference state for comparison with heat-treated samples (HT480-3, HT490-6, HT460-6, HT460-8-2x).

3.2 *Microstructure analysis*

Microscopic analysis represents a key step in the process of the experiments carried out in assessing the surface quality of the investigated experimental samples before carrying out detailed nanomechanical tests. Given the high sensitivity of nanoindentation as an evaluation method to surface defects, it was necessary to verify whether the process of cutting, grinding, polishing and heat treatment of the experimental samples did not accidentally affect the surface integrity of the investigated material. The above-mentioned analysis was performed on all samples of the investigated M300 steel, namely on one reference sample in the condition supplied by the manufacturer and four samples after different precipitation hardening regimes. The microstructural analysis was performed using the Olympus LEXT OLS 5100 laser scanning confocal microscope, and microstructures were evaluated in 2D mode. The performed microstructural analysis forms an important visual and morphological basis for subsequent experiments focused on quasistatic nanoindentation, nanohardness and a comprehensive comparison of nanomechanical properties. The first sample examined in the as-received condition and represents the reference condition of the M300 steel. It serves as a starting point for comparison with samples after individual precipitation hardening regimes. The following confocal microscope image shows a heterogeneous microstructure (Fig. 1) typical for maraging steel in the condition before heat treatment. As can be seen, the microstructure consists of lath martensite arranged in martensite blocks and some secondary phase particles based on alloying element (Mo, Ti). This structure is relatively soft as typical for annealed state of the experimental steel what allows easy machining of the material before final hardening.

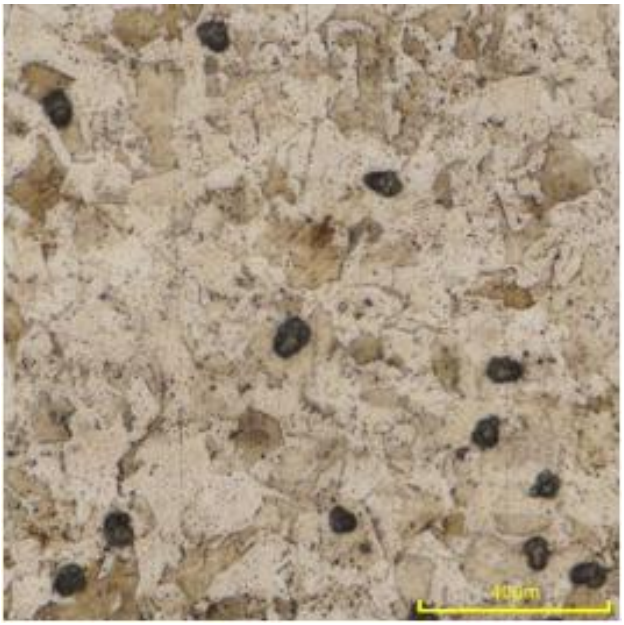


Figure 1. View of the LSCM image of the M300 microstructure in the as-received state at 100x magnification

The Fig. 2 presents a LSCM image of the investigated microstructure of the M300 steel in the state after the heat treatment HT480 3. This is the peak-aged state, achieved by precipitation hardening at 480°C for 3 hours. This is the thermal regime at which the steel under study achieves the highest strengthening according to the steel manufacturer, due to the increase in fine precipitates. The microstructure shown in Figure 2 consists of clearly visible martensitic blocks. The investigated structure contains of dark bands caused by the uneven

distribution of alloying elements (Ni, Co, Mo) during the solidification of the ingot. This is subsequently lengthened in the rolling direction. However, during a longer hardening times, these elements are redistributed by diffusion, as a result of which of these bands completely disappear in subsequent heat treatment regimes.

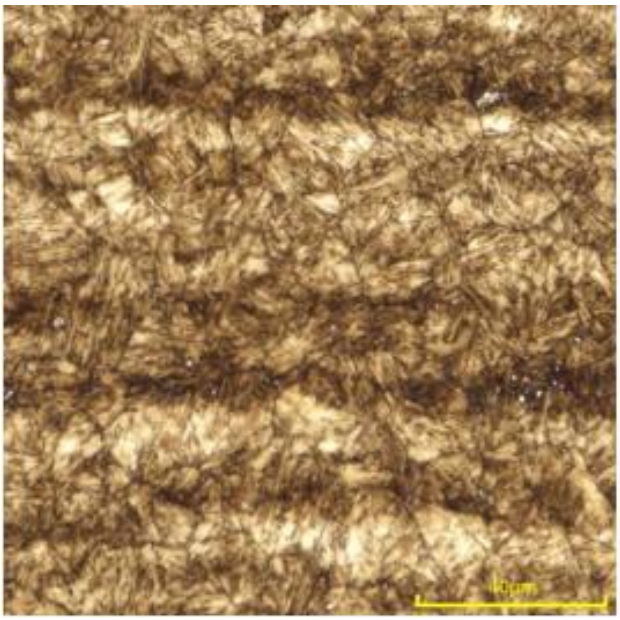


Figure 2. LSCM view of the microstructure of M300 in the state after heat treatment of HT 480-3 at 100x magnification

The Fig. 3 describes the microstructure of the M300 steel in the HT490-6 condition, which represents a stabilized state achieved by precipitation hardening at 490°C for 6 hours. The heat treatment regime mentioned above leads to partial coarsening and enlargement of precipitates.

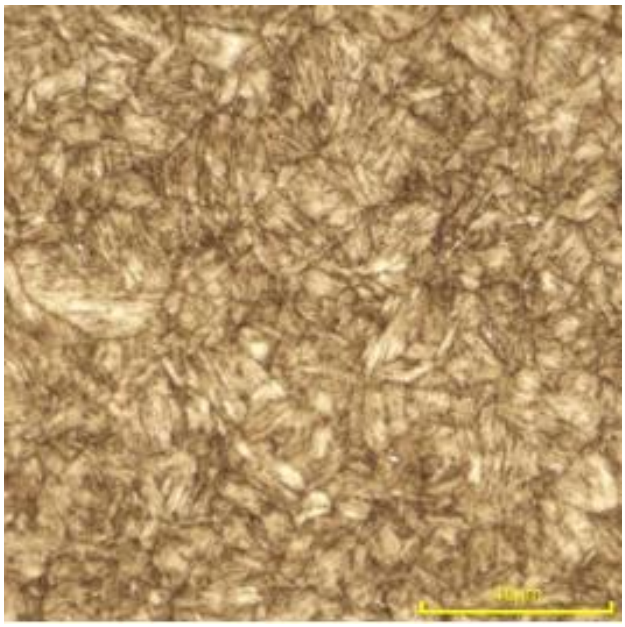


Figure 3. View of LSCM image of M300 maraging steel microstructure in the HT490-6 heat treated state representing the stabilized state at 100x magnification

The expected result is a microstructure (see Fig. 3), that is less extremely strengthened than in the peak-aged condition state (HT480-3). However it exhibits higher temperature stability, more uniform surface appearance and finer microrelief. The examined microstructure is also finer-grained and visually more homogeneous. It is due to the longer hardening time, and consists of martensitic blocks. No coarse phases or bands that were present in the HT 480-3 condition are visible in the microstructure. Compared to previous conditions, the HT490-6 heat treatment is one of the most stable surface conditions in terms of morphology, which makes it suitable for highly reliable micromechanical measurements. The above-mentioned condition generally represents a compromise between the hardness, homogeneity and microstructural stability.

The Figure 4 corresponds to the microstructure of the investigated M300 steel in the HT460-6 state, which corresponds to the low temperature aged process. This is a precipitation hardening process at 460°C for 6 hours. This regime is characterized by the formation of fine, but thermodynamically stable precipitates, which promote an increase in toughness and reduce the brittleness of the material. The investigated microstructure shows less pronounced martensitic blocks compared to the HT480-3 and HT490-6 states. This is a consequence of the lower diffusion intensity at 460°C. For the same reason of insufficient diffusion, there was no complete redistribution of alloying elements, so the band (line) texture still remains visible in the structure. The surface morphology also confirms that low temperature aging leads to a stable but less sharp structure, which is ready for precise mechanical testing.

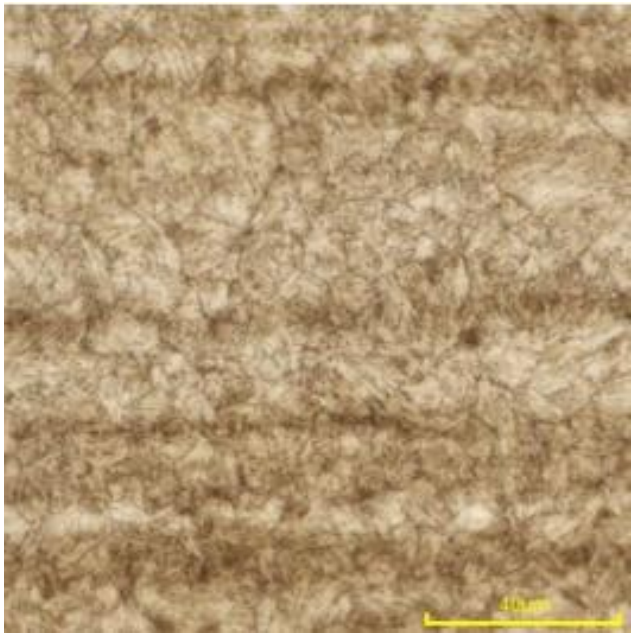


Figure 4. View of LSCM image of M300 microstructure in HT460-6 heat treated condition representing low temperature aged process at 100x magnification

The Figure 5 shows the M300 microstructure of the HT460-8-2x sample, which is a double-ageing treatment. This is a heat treatment regime consisting of two consecutive aging cycles at 460°C, each lasting 8 hours with intercooling. This regime promotes further homogenization and reorganization of the precipitates, resulting in a very stable and microscopically uniform structure (see Figure 5). From the Fig. 5, it is clear that the investigated microstructure shows the homogeneous martensitic blocks with clearly visible boundaries. This is due to the low temperature but very long hardening time. The presumed reason for this condition is the reorganization and coherence of precipitates during double aging. Furthermore, it shows the highest microstructural homogeneity of all investigated conditions. The two-stage aging allowed for a gradual reorganization of precipitates, which led to a very stable martensitic microstructure with minimal surface roughness.

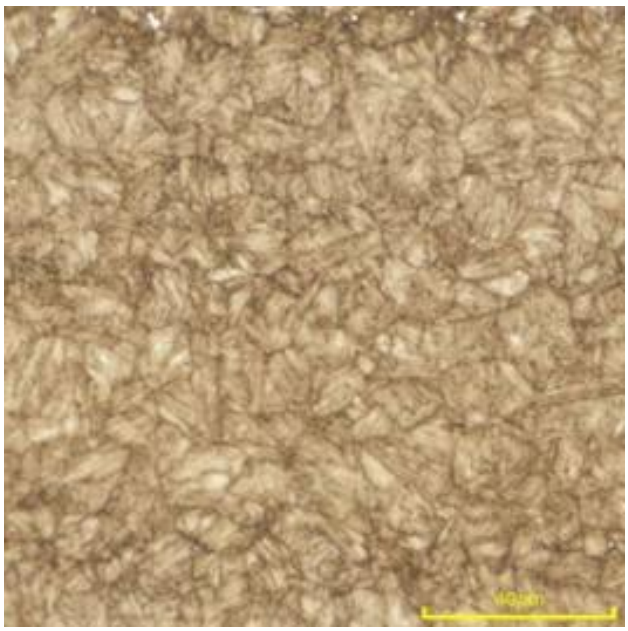


Figure 5. View of LSCM image of M300 microstructure in the HT460 8-2x heat treated state representing the double aging process at 100x magnification

3.3 Nanomechanical properties analysis & results

As part of the performed quasistatic nanoindentation experiments, measurements consisting of a total of six individual indentations were localized at selected points of the microstructure of the analysed area (boundary). Each evaluated area as an SPM (Scanning probe Microscopy) scan had defined dimensions of the 20 × 20 µm. These dimensions were maintained for all examined samples. A standard trapezoidal curve with a maximum loading force of F = 10,000 µN and a holding time of t = 2 s was used as the loading profile for all measurements. All the nanoindentation measurements were performed using an experimental device of the Hysitron Triboindenter TI950 type. The device allows for precise determination of local mechanical properties at the nanometric level. The measured positions of individual indents are shown on the so-called SPM (Scanning Probe Microscopy) scan of the evaluated area of the examined samples. The resulting measured numerical values of the nanoindentation hardness H [GPa] and the reduced Young's modulus of elasticity Er [GPa] in individual positions as well as the estimated phases of the microstructure are given in the relevant tables (see Tab. 2.1 to Tab. 6.1) From the individual indentations performed directly at selected positions in the SPM scans, the corresponding P-h curves in the graphical dependences of loading and unloading were subsequently produced (as can be seen in Fig. 11 to 15). After each nanoindentation measurement, a final statistical evaluation was also performed, including the minimum, maximum, range, average, standard deviation (SD) and variance values (also seen in Tab. 2.1 to Tab. 6.1). The SPM scans of individual evaluated areas of size 20 × 20 µm for the examined samples containing the positions of individual indentations are shown in Fig. 6 to Fig. 10.

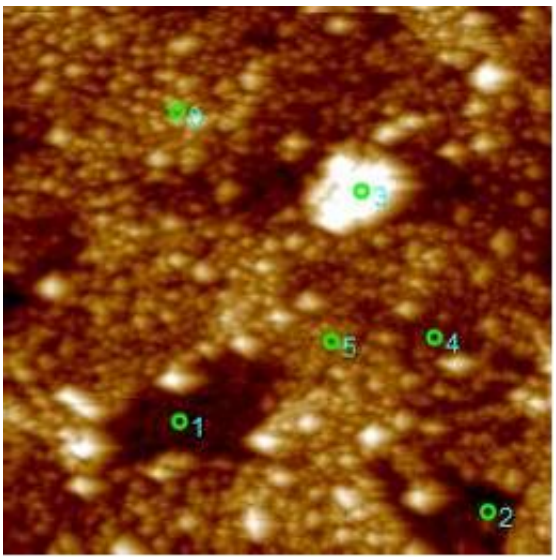


Figure 6. View of SPM scan with indentation positions of sample M300 in as received condition

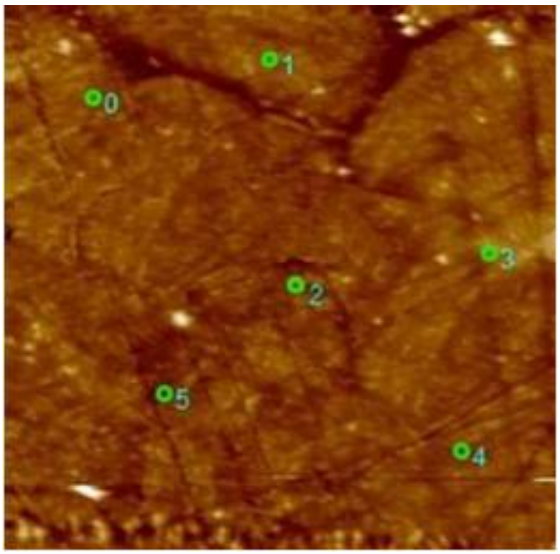


Figure 7. View of SPM scan with indentation positions of M300 sample in HT480-3 (peak aged) condition

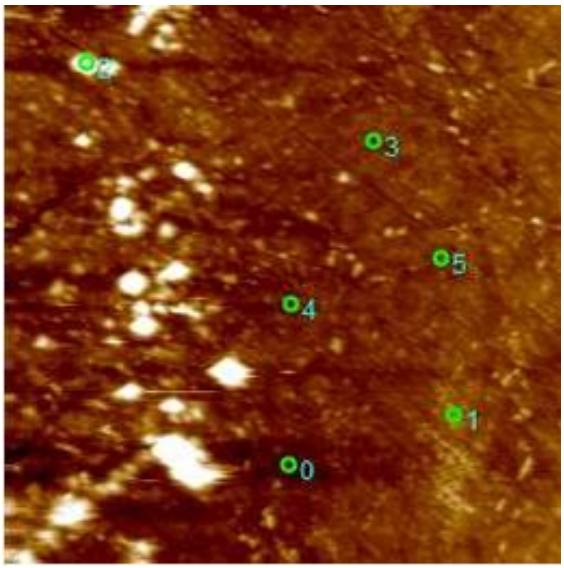


Figure 8. View of SPM scan with indentation positions of M300 sample in stabilized state HT490-6

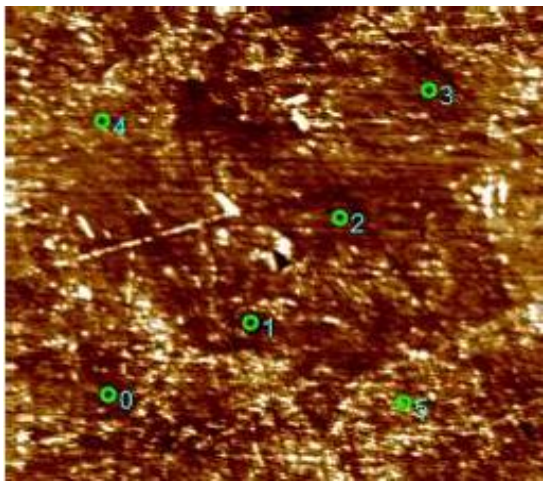


Figure 9. View of SPM scan with indentation positions of M300 sample in HT460-6 (low temperature aged) condition

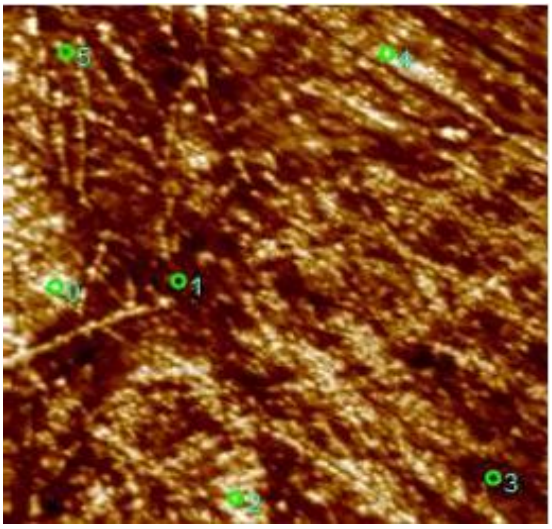


Figure 10. View of SPM scan with indentation positions of sample M300 in HT460-8-2x condition (double aging)

Indent	H (GPa)	E_r (GPa)	Phase
0	3.41	172.1	Intermetallic
1	3.98	180.1	Intermetallic
2	3.74	193.9	Intermetallic
3	3.62	189.4	Intermetallic
4	4.52	202.4	Martensite
5	4.41	201.1	Martensite
Average	3.95	189.8	-
SD	0.40	10.88	-

TABLE 2.1. MEASURED VALUES AND STATISTICAL PARAMETERS OF H AND ER FOR THE MEASURED SAMPLE (AS RECEIVED)

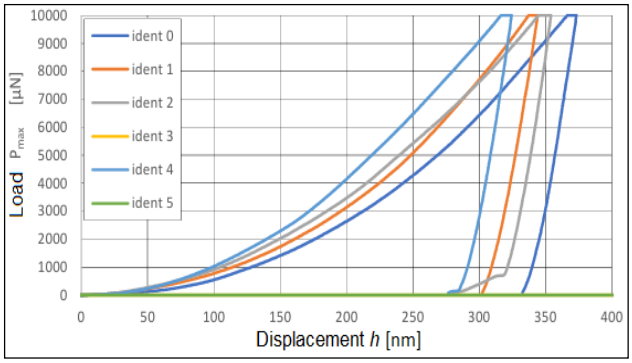


Figure 11. Shape of P-h curves from indentations of sample M300 in the as received condition

Indent	H (GPa)	E_r (GPa)	Phase
0	6.86	194.9	Martensitic matrix with precipitates
1	6.75	195.2	Martensitic matrix with precipitates
2	5.84	196.8	Martensitic matrix with precipitates
3	6.58	204.8	Martensitic matrix with precipitates
4	6.21	185.7	Martensitic matrix with precipitates
5	6.24	175.9	Martensitic matrix with precipitates
Average	6.42	192.5	-
SD	0.39	10.26	-

TABLE 3.1. MEASURED VALUES AND STATISTICAL PARAMETERS OF H AND ER FOR THE SAMPLE (PEAK-AGED)

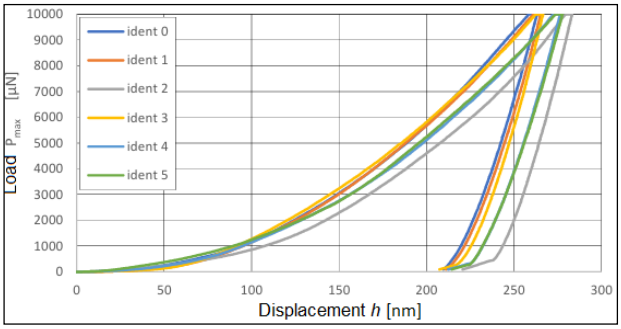


Figure 12. Shape of P-h curves from indentations of sample M300 in the (peak-aged) state

Indent	H (GPa)	E_r (GPa)	Phase
0	7.44	198.5	Martensitic matrix with precipitates
1	7.46	199.9	Martensitic matrix with precipitates
2	4.88	161.4	Reverse austenite
3	7.21	196.4	Martensitic matrix with precipitates
4	7.36	200.1	Martensitic matrix with precipitates
5	6.85	201.9	Martensitic matrix with precipitates
Average	7.27	199.4	-
SD	0.25	2.02	-

TABLE 4.1. MEASURED VALUES AND STATISTICAL PARAMETERS OF *H* AND E_R FOR THE SAMPLE IN THE STABILIZED STATE

Based on the achieved results of all the measured values of nanohardness *H* and the values of reduced Young's modulus *Er* and their evaluation for all investigated heat treatment states of the investigated material maraging steel M300, as well as its basic state after delivery, it can be said that nanoindentation provided comprehensive data on the nanomechanical

properties of all five states of the experimental samples, including the achieved shapes of the P-h curves.

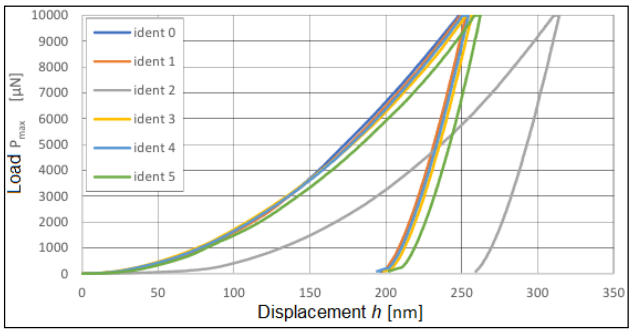


Figure 13. Shape of P-h curves from indentations of sample M300 in stabilized state HT490-6

Indent	H (GPa)	E_r (GPa)	Phase
0	7.42	210.4	Martensitic matrix with precipitates
1	7.79	202.2	Martensitic matrix with precipitates
2	7.35	186.4	Martensitic matrix with precipitates
3	7.42	197.7	Martensitic matrix with precipitates
4	6.98	210.3	Martensitic matrix with precipitates
5	7.04	194.5	Martensitic matrix with precipitates
Average	7.33	200.31	-
SD	0.30	9.56	-

TABLE 5.1. MEASURED VALUES AND STATISTICAL PARAMETERS OF H AND ER VALUES FOR THE SAMPLE (LOW TEMPERATURE AGED)

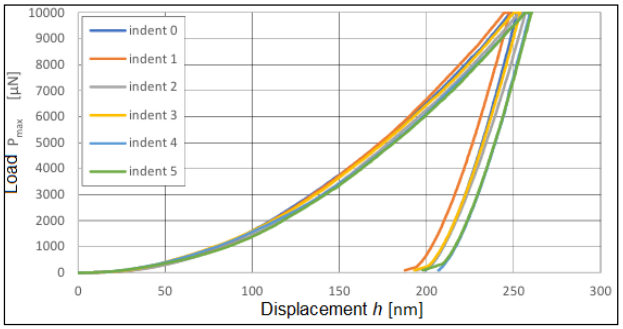


Figure 14. Shape of P-h curves from indentations of sample M300 in the low temperature aged state

Indent	H (GPa)	E_r (GPa)	Phase
0	7.12	197.7	Martensitic matrix with precipitates
1	7.61	201.1	Martensitic matrix with precipitates
2	6.76	203.9	Martensitic matrix with precipitates
3	6.83	200.3	Martensitic matrix with precipitates
4	6.93	179.1	Martensitic matrix with precipitates
5	7.19	202.1	Martensitic matrix with precipitates
Average	7.11	197.4	-
SD	0.3	9.39	-

TABLE 6.1. MEASURED VALUES AND STATISTICAL PARAMETERS OF H AND ER VALUES FOR THE SAMPLE (DOUBLE AGING)

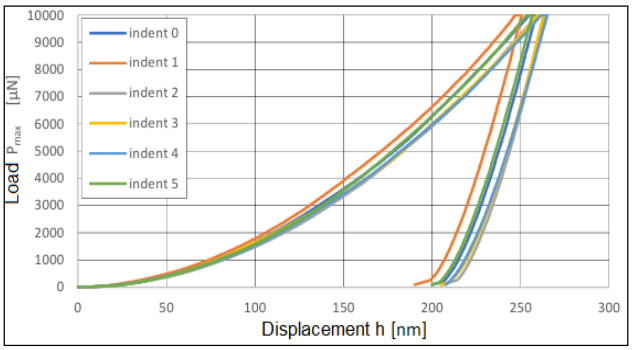


Figure 15. Shape of P-h curves from indentations of sample M300 in condition (double aging)

Thermal condition	H (GPa)	Characteristics
As received	3.87	Martensite without precipitates
HT480-3	6.42	Maximum reinforcement
HT490-6	7.28	Stabilized uniform reinforcement
HT460-6	7.33	High hardness and higher dispersion
HT460-8x2	7.07	The most homogeneous low-temperature state

TABLE 7.1. SUMMARY COMPARISON OF H VALUES (GPA) FOR ALL STATES OF THE INVESTIGATED M300 MATERIAL SAMPLES

Based on a summary comparison of the achieved H values (see Tab.7.1), it can be stated that the highest hardness is achieved by the HT460-6 (7.325 GPa), followed by the HT490-6 and the HT460-8×2. The HT480-3 shows high, but not maximum, strengthening. The reference state has the lowest hardness, which corresponds to the absence of precipitates. The highest and most stable Er value is shown by the HT490-6 (see Tab. 7.2). The HT460-8×2 state has a similar stiffness with lower dispersion than the HT460-6 state. The reference state shows the lowest *Er* modulus.

Thermal condition	E_r (GPa)	Phase
As received	186.8	without solidifying precipitates
HT480-3	192.5	increase due to fine precipitates
HT490-6	199.5	highest stability and consistency
HT460-6	200.2	higher variance due to heterogeneity
HT460-8x2	197.42	uniform stiffness across the surface

TABLE 7.2. SUMMARY COMPARISON OF E_R VALUES (GPA) FOR ALL STATES OF THE INVESTIGATED M300 MATERIAL SAMPLES

Likewise, from the point of view of evaluating the values of the dispersion within the statistical values of the measured

quantities, it can be summarized that its highest value was recorded in the states after delivery and the heat treatment state marked HT-460-6. Its average value was found in the state of HT480-3 and the lowest values occurred in the states marked of HT490 6 and the HT460 8×2. The experimentally obtained values were processed using the TriboScan evaluation software and compared with external sources, such as the work of [Huang et al. 2016]. At the same time, the fact that the dispersion in the individual measurements reflects the degree of microstructural homogeneity is valid. From the point of view of the overall evaluation of the individual thermal phenomena studied, it can be summarized that the sample in the state after delivery has the lowest hardness and stability and, on the contrary, high dispersion. In the state of HT480-3, a significant strengthening, a sharp response and a good homogeneity prevail. The state after the heat treatment of HT490-6 can be characterized as the most balanced, characterized by good hardness, stability and heterogeneity. The HT460-6 (low temperature aged) condition also has high hardness, but higher variability. The last monitored condition, HT460-8×2 (double aging), can be characterized as a very homogeneous and stable condition with balanced properties.

4 CONCLUSIONS

One of the main objectives of the above-mentioned research by the authors was to compare experimental maraging steel M300 in the as-delivered state and its individual heat treatment regimes. Also, within the framework of the set objectives of the research, an overall evaluation of the degree of their mutual agreement was carried out. The main experimental methods used in the process of performed experiments in this article were the microstructural analysis (using the LSCM method) and experimental analysis of nanomechanical properties (using the nanoindentation method). The achieved research results showed that both methods used provide consistent trends in all analysed thermal states. From a quantitative and a qualitative point of view, a quasistatic nanoindentation is much more sensitive to local microstructural differences than classical methods of determining hardness or microhardness. This is due to the fact that it measures the response of the material within individual martensitic blocks and between precipitates. From the point of view of individual states after heat treatment, the state labeled of HT490-6 shows the best combination of hardness, stiffness and low dispersion. It indicates optimal stabilization of precipitates. The condition marked of HT460-8×2 achieves comparable hardness, but with higher homogeneity and a more uniform response. It is the result of a two-stage aging process. The condition marked of HT480 3 is characterized by the most pronounced local strengthening, but with slightly higher variability. On the contrary, the condition of HT460-6 shows a greater dispersion of values, which is related to a less homogeneous distribution of precipitates at a lower aging temperature. A comparison of the dispersion of individual measurements undoubtedly confirms the fact that quasistatic nanoindentation is much more suitable for identifying local differences in the investigated microstructure. While, for example, the classical evaluation of the HV1 hardness provides more stable average values. The lowest dispersion was recorded for the heat treatment conditions with the designations of HT490-6 and HT460-8×2. This corresponds to their high microstructural homogeneity. The trend of increasing nanohardness and elastic modulus was in the condition supplied by the manufacturer, and in the condition of HT480-3 indicating maximum strengthening, and also in the HT490-6 indicating stabilized condition. The HT460-6 was tempered at low temperature and the HT460-8-2x at two-stage aging. In terms of individual heat treatment conditions, the HT490-6 shows the best combination of hardness, stiffness and low dispersion, which indicates optimal stabilization of precipitates. Quasistatic nanoindentation has thus proven to be a significant alternative to the generally used classical microhardness tests, especially in the evaluation of local properties and thin surface layers. Based on the achieved results of this research of the microstructure and nanomechanical properties of the investigated samples of the maraging steel M300 after heat treatment, it can be stated that both research methods complement each other and provide a consistent view of the material and nanomechanical properties of the investigated material. It is the combination of these performed research methods that represents a detailed approach for a comprehensive evaluation of the influence of heat treatment on the M300 maraging steel. Appropriate application of the thermal regime will allow for targeted optimization of the properties of the investigated material for specific technical applications. The knowledge obtained will subsequently serve as a basis for further research in the field of quasistatic nanoindentation, optimization of heat treatment of maraging steels also produced by additive technologies, while the most suitable heat treatment modes will be sought.

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