



INVESTIGATION OF THE INFLUENCE OF THE INITIAL MICROSTRUCTURE UNDER DIFFERENT REGIMES OF HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF 42CrMo4 STEEL

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ABSTRACT

In this article, the impact of heat treatments - normalization and a combination of normalization, quenching and high-temperature tempering - on the microstructure and mechanical properties of 42CrMo4 steel specimens is investigated. Three groups of samples were studied: 1) asreceived; 2) after normalization at temperature of 860° C with holding time of 20 minutes and cooling in air; 3) after normalization (860°C/20 minutes), quenching at 850°C in oil and then tempered at 590°C, followed of cooling in air. The phase and microstructural analysis revealed the presence of retained austenite in the samples subjected to normalization. The resulting microstructure is ferrite-sorbite, containing about 10% retained austenite. The mechanical properties for the three investigated groups of samples showed the highest values for tensile strength ($R_m=1147$ MPa) and hardness (324 HBW) after normalization, and the highest elongation (12.9%) was obtained with the combination of normalization, quenching and high temperature tempering.

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1. INTRODUCTION

Steel 42CrMo4 belongs to the group of steels that undergo heat treatment before use. The classical heat treatment of these steels is quenching followed by high-temperature tempering [1, 2, 3]. After high-temperature tempering this group of steels receive most favorable combination of mechanical properties - increased strength, good plasticity and impact toughness [10]. The heat treatment is quenching to martensite and high-temperature tempering in the range of 500° to 650°C, to obtain a sorbite microstructure [12,13]. The best performance after improvement is achieved when the same structural changes occur throughout the whole cross section. Practically uniformity in properties is realized when the hardenability in the quenching process is achieved [4, 5, 10, 12].

By varying the chemical composition of the steel and the tempering temperature, it is possible to vary the mechanical properties over a wide range.

Steel 42CrMo4 is a widely used low-alloy steel containing chromium (0.9÷1.2%) and molybdenum (0.15÷0.30%), intended for work in conditions of high pressure and elevated temperature (up to 550°C) for various applications such as: automotive drive trains, bolt assemblies, forged parts, armored materials, in the energy, oil and gas industries, etc. [2,14]. The reason this combination of alloying elements to work so well is because of their complex properties. For example, Mo helps to preserve the steel's strength at higher operating temperatures and prevents secondary embrittlement after

tempering in the high-temperature range. On the other hand, chromium increases corrosion resistance and yield strength. In a compound with carbon, Cr forms carbides that increase the hardness, static strength and wear resistance, while Mo increases the hardenability and helps to maintain uniform hardness in the depth of the products [11, 12, 13].

Although the processes for heat treatment of low-alloy machinable steels are well known in practice and describe each "operation" helping to obtain the desired set of properties, the exact choice of process parameters for processing a certain grade of steel remains a complex procedure. Unfortunately, the "time-temperature" parameters of the various heat treatments are not only influenced by the chemical composition of the steel. They also depend on the history of preparation of the workpiece: metallurgical processing, state of primary microstructure, presence of plastic deformation, grain size and many other factors affecting the properties of steel [3-9].

The purpose of this article is to investigate the influence of the initial microstructure and the effect of different heat treatment regimes - normalization and high temperature tempering - on the mechanical properties of 42CrMo4 steel samples.

2. MATERIAL AND RESEARCH METHODS

2.1. Material and experimental specimens

The tests were carried out on three groups of samples with a diameter of Ø18 mm and a length of 65 mm, made

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of steel 42CrMo4 – Fig. 1.

The chemical composition of the test samples is shown in Table 1.



Fig. 1. Samples for experimental studies

Table 1 Chemical composition of investigated steel

Steel	C %	Mn %	Si %	Cr %	Mo %	P %	S %
42CrMo4	0,463	0,842	0,193	1,07	0,183	0,08	0,006

Each group contained samples made for:

- three specimens for standard one-dimensional tensile test;
- one specimen, disk type, for determination of hardness, microstructural and phase analyses.

To provide different metal matrices, different from the one in the state of delivery, the individual batches are heat treated according to the regimes presented in Table 2.

The heating time depends on the maximum temperature to which the steel is heated, its chemical composition, the cross-section of the samples and the type of heating device. The time of heat treatment is a sum of the time for heating to the given temperature and the holding time, for the necessary phase and structural transformations to take place, and the homogenization of the austenite regarding to carbon and alloying elements. Usually, the holding time is assumed to be 15-20% of the heating time [12, 13].

Table 2 Regimes of heat treatment of the studied samples from steel 42CrMo4

Group	Type of heat treatment	Regimes		
		Temperature of heating, °C	Holding time, min	Cooling environment
I	As received	-	-	-
II	Normalization	860	20	In air
III	Normalization	860	20	In air
	Quenching	850	15	In oil
	Tempering	590	45	In air

2.2. Microstructural analysis

Metallographic cross-sections shown in Fig. 2 were used to examine the microstructure in the as received state and after heat treatment. The metallographic cross-sections

were made with two-component electroconductive resin Technovit 5000 on a copper base, intended for examination by means of a scanning electron microscope (SEM).

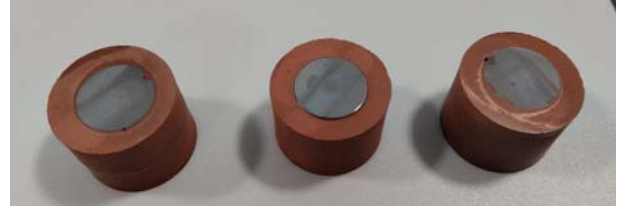


Fig. 2. Samples for metallographic investigations

The studies were carried out with the help of a scanning electron microscope - Zeiss Evo 10 on the metallographic cross-sections previously ground, polished and developed with the help of a 5% solution of HNO₃ in ethyl alcohol.

Metallographic analyzes were performed with an accelerating voltage of 20 kV at a magnification of ×1000 times.

2.3. Investigation of mechanical properties

Tensile strength, yield strength and elongation are determined according to the classical methodology of tensile tests, at room temperature. The tests were carried out using a testing machine - Zwick/Roell Vibrophore 100, with a deformation rate of 10⁻³ s⁻¹. The dimensions of the samples are in accordance with ISO 6892-1:2019 and are shown in Fig. 3. The experiments are carried out with three groups of samples according to Table 2, each of which contains three specimens. The result for each group was determined using the arithmetic mean value obtained from three samples.

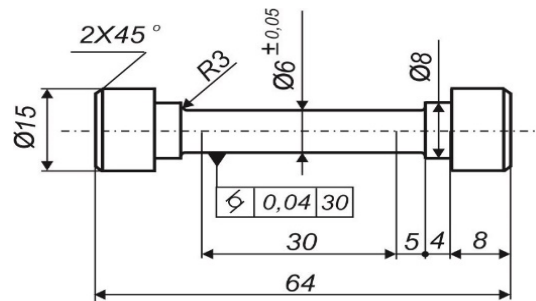


Fig. 3. Tensile test specimen (dimensions are in mm)

The HBW hardness was measured according to EN ISO 6506 using a combined Brinell/Vickers hardness tester, for the Brinell hardness test, was used an indenter with diameter D = 2.5 mm and load of F = 62.5 kg and was held for time of 15 s. One specimen from each group was tested, using the test specimens from the metallographic analysis. The result for each group is the arithmetic mean of five measurements.

2.4. Phase analysis

Phase analysis was determined using a “Bruker D8 Advance” X-ray diffractometer. The analysis was carried out by the “Coupled Two Theta” method, using chromium K α radiation, with a wave length of 2.2897 Å and a focusing orientation at a point with a hole diameter of 1 mm. The survey range is from 60° to 160°. The magnitude of the current of the X-ray generator is 40 mA, and the applied voltage of the X-ray tube is 30 kV. The scan mode

has a 2θ angle increment step size of 0.1° and a dwell time of each scan step of 0.5 s.

3. EXPERIMENTAL RESULTS AND COMMENTS

The results of the mechanical tests are summarized in Table 3.

Table 3 Results of mechanical tests

Group	$Rp_{0.2}$ MPa	Rm , MPa	A , %	HBW , kgf/mm ²
I	708	747	10,9	234
II	939	1147	8,8	324
III	966	1044	12,9	307

The conducted research makes it possible to evaluate the effect of heat treatment of 42CrMo4 steel, relative to the initial microstructure, of the material in as received state. Figures 4 to 6 show the obtained microstructures for the three studied groups of samples.

The microstructure of steel 42CrMo4 in the as received state (group I) is ferrite-pearlite, which is typical for sub-eutectoid steels Fig. 4. The resulting lighter areas in the metallographic photograph are phases of cementite, which is a component of the structural constituent pearlite, while the darker areas are ferrite.

A significant difference in the microstructure and mechanical properties is observed in the samples examined

after normalization - Fig. 5. The resulting structure is ferrite-sorbite, in which the presence of about 10% retained austenite was found. To determine its quantity, specialized software DIFFRAC.DQuant V1.5 was used. The phase distribution was determined as the ratio between the areas of the diffraction maxima of lines (200) and (220) of γ -Fe, to the areas of the corresponding maxima of α -Fe, for lines (200) and (211).

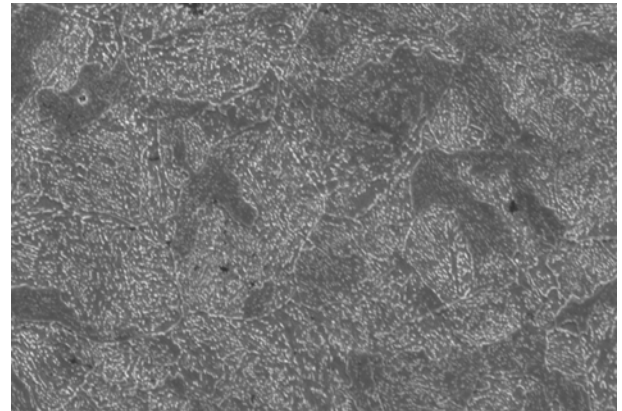


Fig. 4. Microstructure of steel 42CrMo4 in the as received state $\times 1000$

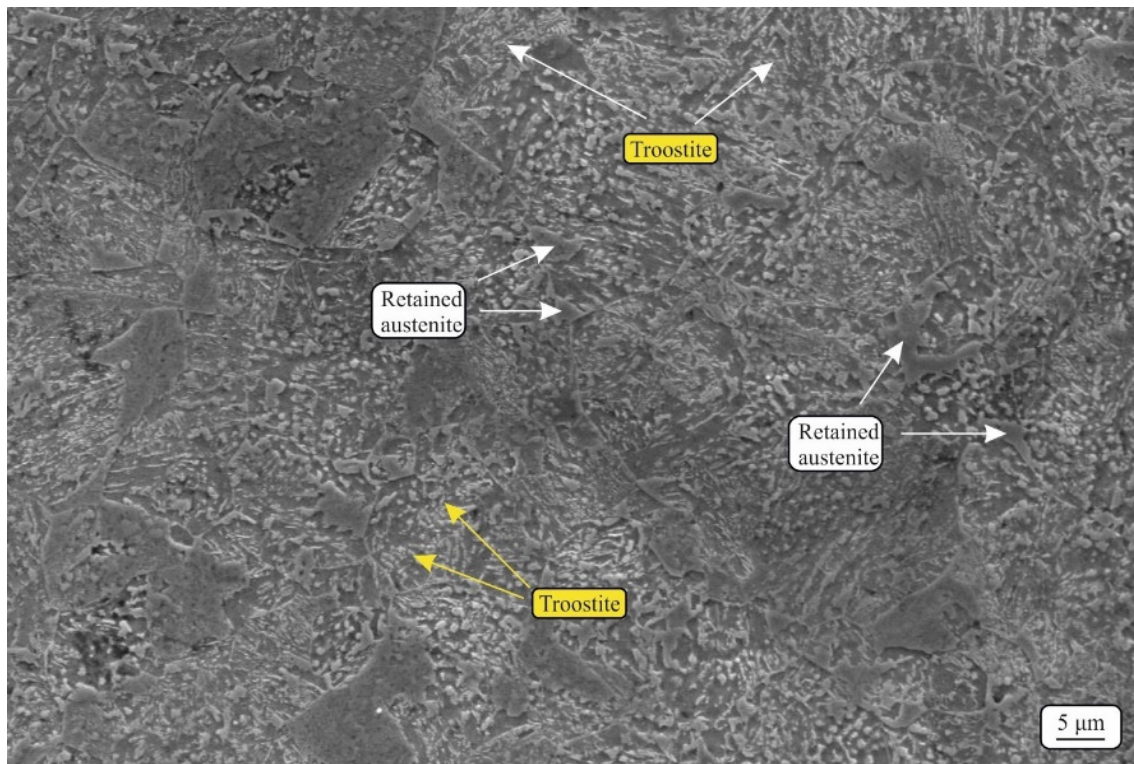


Fig. 5. Microstructure of 42CrMo4 steel after normalization $\times 1000$

The relative intensity of the individual diffraction maxima was also taken into account when calculating the percentage ratio between the two phases. The accuracy of the phase distribution measurement depends on the accuracy of the obtained diffraction pattern and increases as the scanning time increases and the step of increasing the angle 2θ is smaller. For greater accuracy of the background of the diffraction pattern and the obtained peaks, the

measurement is repeated in the "automatic repeat" mode until a "smoothed" diffraction pattern is obtained.

The increased cooling rate in the normalization process leads to the comminution of the structural constituents during the breakdown of austenite. This microstructure refinement is a physical basis for a significant increase in the tensile strength and hardness of the studied steel - Table 3 and Fig. 5. The tensile strength Rm , after normalization, increases by about 65% and reaches 1147 MPa, compared

to that in the as received state - 747 MPa. The resulting hardness is the highest - 324 HBW, while in as received state it is the lowest - 234 HBW. These results are largely correlated with the results from the mechanical tests.

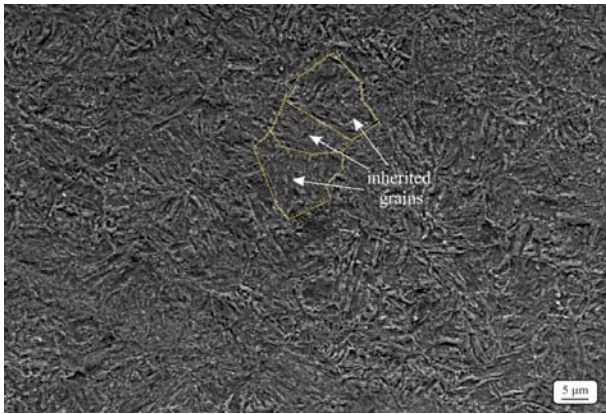


Fig. 6. Microstructure of 42CrMo4 steel after quenching and high temperature tempering $\times 1000$

The samples of group III were subjected to a "combined" thermal impact, including sequentially the processes: normalization from a temperature of 860°C; quenching at 850°C and subsequent high-temperature tempering at 590°C, with a holding time of 45 min.

The resulting martensitic structure, after quenching, undergoes changes in the tempering process - Fig. 6. The presence of chromium and molybdenum greatly complicates the breakdown of martensite, lowering the rate of diffusion processes and shifting the temperature for the onset of breakdown to the higher temperature range. This process is further complicated by the need to form M_3C carbides in the structure. These are complex carbides of molybdenum and chromium with cementite, of the $FeCrMo_3C$ type. The newly formed carbides have an elongated plate-like shape. At this reversion temperature, the acicular shape of the starting phase is preserved. The ongoing structural changes associated with the breakdown

of martensite leads to the elimination of deformations in the crystal lattice, the disappearance of third-order microstresses and the lowering of residual internal stresses. The newly obtained structural state has a lower free energy and a more stable structural state, providing higher plasticity with relative elongation of 12.9%. The increased elongation is at the expense of lower yield strength and tensile strength.

Figure 7 shows the diffractograms of the investigated samples.

The presence of retained austenite in the structure of the normalized sample is also confirmed by the conducted phase analysis - Fig. 7. Besides the standard diffraction maxima of lines (110), (211) and (220) of α -Fe, diffraction maxima - (111), (200) and (220) of γ -Fe also appear on the diffractogram. It can be assumed that the reason for the presence of retained austenite is the relatively high cooling rate in combination with the action of chromium, molybdenum and manganese. Each of these alloying elements slows down the γ -Fe \rightarrow α -Fe phase transformation, shifting it to lower temperatures and hindering the diffusive redistribution of carbon [1, 12, 13].

This action of theirs is multiplied by the joint influence in the process of austenite decay. In the transformation zones, the carbon is pushed ahead of the front of the growing ferrite crystal so that small regions of austenite with a relatively high carbon content are formed. This austenite stabilizes, its M_s point decreases in the negative temperature range, and it cannot undergo a diffusion less $\gamma \rightarrow \alpha$ transformation of the crystal lattice. On the other hand, the presence of chromium and molybdenum hinders the diffusion of carbon from these enriched austenite zones and some of it is retained, in the form of retained austenite. This effect is further enhanced by the increased cooling rate and the need for diffusive redistribution of Mo and Cr, differently soluble in ferrite and cementite, in the conditions of difficult diffusion.

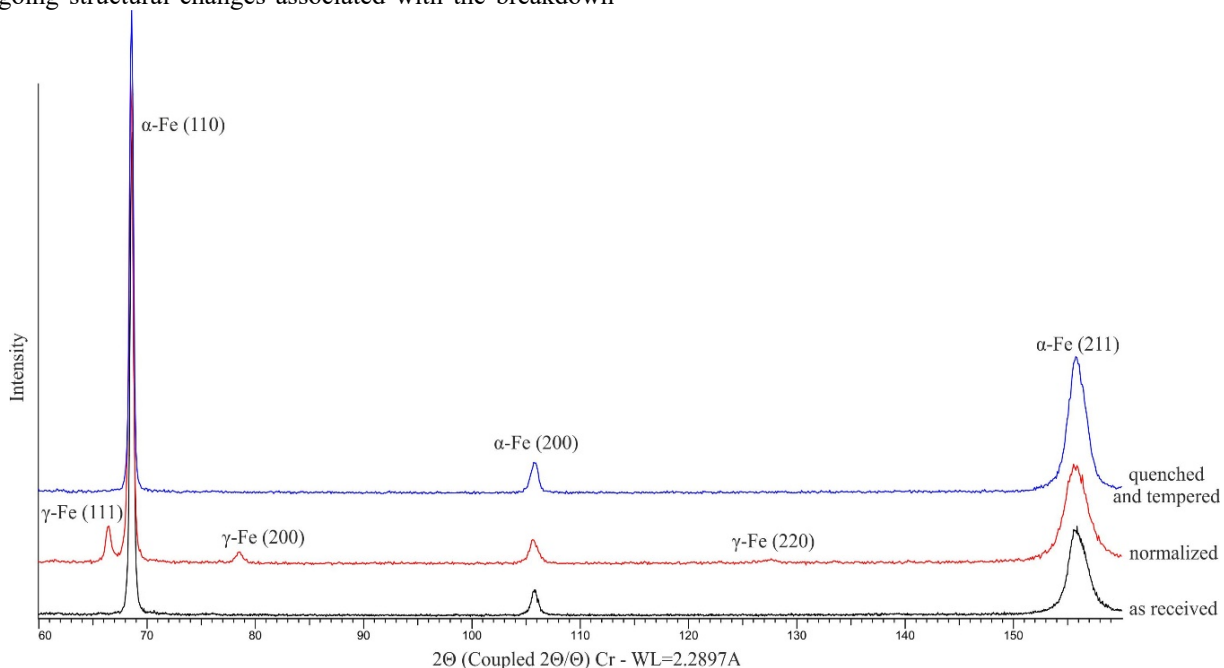


Fig. 7. X-ray diffractograms of the studied samples

4. CONCLUSIONS

The influence of the type of heat treatment and the as received state on the microstructure and mechanical characteristics of low alloyed steel 42CrMo4 was investigated. The results obtained can be summarized as follows:

- The type of heat treatment and the as received state lead to noticeable differences, both in the microstructure and in the mechanical characteristics;

- The samples subjected to normalization were found to have the highest tensile strength, $R_m=1147$ MPa and hardness. A physical basis for these mechanical characteristics, as well as the highest hardness measured, is the resulting fine-grained sorbitol structure;

- The combination of heat treatments normalization, quenching and high temperature tempering results in the highest elongation values of 12.9% for the three investigated groups.

With the heat treatment regimes selected in this way, partially inherited grains from the original as received structure are preserved.

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