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INVESTIGATION OF THE INFLUENCE OF THE INITIAL MICROSTRUCTURE UNDER DIFFERENT MODES OF HEAT TREATMENT ON THE MECHANICAL PROPERTIES OF 35CrMnSi STEEL

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ABSTRACT

The influence of the initial microstructure on the mechanical properties of 35CrMnSi steel samples is investigated in the article. The main goal of the research is to obtain an initial microstructure, providing a favorable basis for subsequent processing by surface plastic deformation. Four groups of samples are made and subjected to heat treatment in different modes. The first group was examined in the state as-received, the other three processed by: annealing at a temperature of 600ºC with a heating time of 90 min and furnace cooling; annealing at a temperature of 880ºC with a heating time of 90 min and furnace cooling; normalization at a temperature of 880ºC with a heating time of 30 min and air cooling.

By phase and microstructural analysis, it was found that phase conversion is present only after normalization, and the resulting structure is a combination of sorbite-like perlite and residual austenite. The samples subjected to normalization show the highest values for tensile strength, hardness, and microhardness compared to the other groups of heat treatment modes.

1. INTRODUCTION

It is known that the joint alloying with chromium, manganese and silicon significantly increases the technological and mechanical properties of the improved steels. A representative of this group of steels is 35CrMnSi alloyed constructional steel, which is used for applications requiring high static and dynamic strength and impact toughness [1-3].

Examined separetly, the alloying of these alloys is not enough to achieve optimal mechanical properties. The main role in increasing the working capacity of structural elements is the modification of their surface layers. The creation of compressive residual stresses and the production of fine-grained structures are a favorable basis for increasing the service life of various components in the aerospace, maritime and railway transport.

The burnishing methods are the main approach to obtain fine-grained microstructure [4-7]. The refinement degree of the microstructure after burnishing largely depends on the type and condition of the initial microstructure. The initial microstructure depends on a number of factors characterizing the production process for producing the workpiece: type of heat treatment (heating temperature, retention time, cooling rate), the presence of plastic deformation and a number of other factors determining the state of the metal matrix [4-7].

It is known that when the steel is heated until the recrystallization temperature reaches, i.e. approximately 40% of the melting temperature, a process of primary recrystallization begins [8,9]. The size of the newly formed crystals depends on the temperature reached, the retention time at this temperature and the degree of preliminary plastic deformation. The higher the temperature and retention time, the greater the recrystallization and coagulation processes. On the other hand, the plastic strain rate has a significant effect on the preliminary fragmentation and crystallographic reorientation, and anisotropy in the properties of the polycrystalline structure.

It is a known fact that burnishing is an effective approach to improve the complex state of the surface layers (Surface Integrity), and hence to increase the operation performance of metal components [10-17]. Under the same conditions of the deformation process, the obtained strength and structural characteristics are correlated with the initial structure state. Therefore, in order to multiply the effect of the static burnishing, it is necessary to provide a suitable initial structure that allows optimization of the desired strength complex.

The aim of this article is to evaluate the influence of the initial microstructure in different modes of heat treatment on the mechanical properties of 35CrMnSi steel specimens.

The results obtained from the study are the basis for evaluating the effectiveness of subsequent static burnishing in correlation with the initial microstructure.

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2. MATERIAL AND METHODS

2.1. Material and experimental specimens

The study was performed on four groups of samples with a diameter of Ø24 mm and a length of 120 mm, made of 35CrMnSi steel.

The chemical composition and type of test specimens are shown in Table 1 and Fig. 1.

A series containing the following specimens was made for each group (Fig. 1):

● three standard specimens for one-dimensional tensile testing;

● one specimen type disk to determine the hardness, microhardness, microstructural and phase analysis.

To ensure different metal matrices that differ from the "as received", the individual series are thermally treated with the modes listed 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 specimens and the type of heating device. The heat treatment time is the sum of the heating time to the given temperature and the retention time (austenitization) at this temperature. The retention time is usually assumed to be 15-20% of the heating time [18, 19].

Table 1 *Chemical composition of 35CrMnSi steel*

Steel grade	***C, %***	***Mn, %***	***Si, %***	***P, %***	***S, %***	***Cr, %***	***Ni, %***
35CrMnSi	*0,32-0,39*	*0,8-1,1*	*1,1-1,4*	*≤ 0,025*	*≤ 0,025*	*1,1-1,4*	*≤ 0,3*

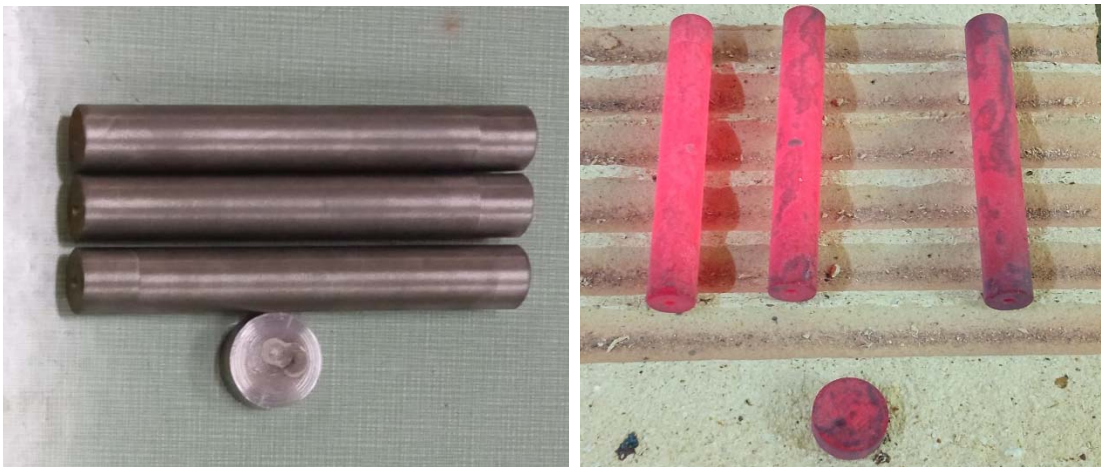


Fig. 1. Workpieces for experimental study specimens

Table 2 *Heat treatment modes of the studied specimen groups*

Group	***Type of heat tretment***	***Mode***		
		Heating temperature, ºC	***Heating time, min***	***Cooling environment***
I	*As received*	-	-	-
II	*Annealing*	*600*	*90*	*With the furnace*
III	*Normalizing*	*880*	*30*	*On air*
IV	*Annealing*	*880*	*30*	*With the furnace*

2.2. Microstructural analysis

Metallographic sections were prepared (Fig. 2) for the microstructure study in a "as received" state and after different heat treatments.

The metal base type is determined after etching at a magnification × 500. A 5% solution of nitric acid in ethyl alcohol was used to survey the structure.

2.3. Mechanical properties investigation

Five-fold test specimens were used to determine the mechanical characteristics tensile strength R_m, yield strength $R_{p0.2}$, elongation A, and transverse contraction Z. The experimental test were performed on a Zwick / Roell Vibrophore 100 test machine according to DIN EN ISO 6892-1.

HBW hardness and microhardness were determined by the Brinell and Vickers method (ZHVμ□S – Zwick/Roell), respectively, using test specimens from metallographic analysis.

2.4. Phase analysis

The phase analysis was performed using Bruker D8 Advance X-ray diffractometer. The “Coupled Two Theta” method was used for the analysis. Cobalt $K\alpha$ radiation with a wavelength of *1.78897 Å* and a focus orientation at a point with a hole diameter of *1 mm* was used. The test range is from $30°$ to $156°$, the magnitude of the current of the X-ray generator is *40 mA*, and the applied voltage of the X-ray tube is *35 kV*. The scanning mode has an incremental step size of $2\theta - 0.1°$ and a retention time of each step of the study - *0,5 s*.

3. EXPERIMENTAL RESULTS AND COMMENTS

The mechanical test results are summarized in Table 3.

The conducted microstructural and strength studies make it possible to assess the impact of the initial microstructure in terms of subsequent treatments by static burnishing. The obtained microstructures in the surface layers and in a core of the specimens for the four studied modes of heat treatment (see Table 2) are shown in Fig. 3 – Fig. 6.

The microstructural studies show that the structure of the specimen after annealing at *600°C* (Fig. 4) is fine-grained than that of the "as received state" material (Fig. 3). A probable reason for this is the presence of deformation texture and hardening effect, obtained during the process of making the initial rolling and the subsequent recrystallization processes during heating. This is confirmed by the results obtained for the mechanical properties and the lower hardness of HBW of the specimen after annealing at *600°C* (Table 3).

Significant differences in the microstructure and mechanical properties are observed in the specimen subjected to normalizing (Fig. 5). The resulting structure is sorbitol-like perlite, in which a small amount of retained austenite was found. The increased cooling rate leads to refinement of the structure during the decomposition of austenite. This refined microstructure is the physical basis for a significant increase in tensile strength and hardness of the tested steel (see Table 3 and Fig. 7). The tensile strength *Rm* is approximately twice as high (*Rm=1467 MPa*) as in the delivered state (*Rm=777 MPa*).

In the fourth group samples (annealing at *880°C*), the microstructure is ferritic-pearlitic, typical of structures obtained after complete annealing (Fig. 6). A maximum equilibrium structural state is obtained, providing high ductility (*A=19,8 %*) and relatively low values for the tensile strength and tensile strength ($Rp_{0.2}$*=423 MPa; Rm=814 MPa*).

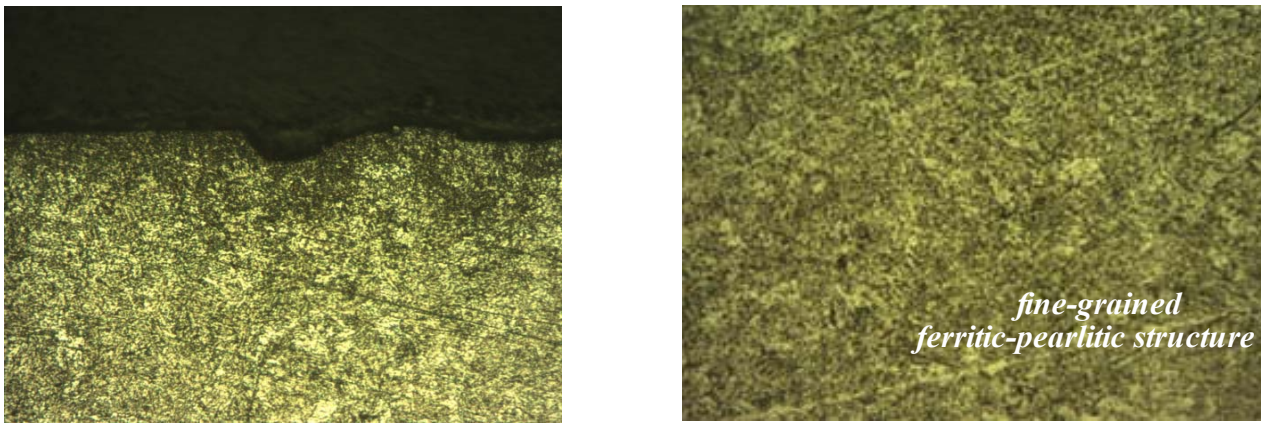
Graphs showing the change in the microhardness $HV_{0.05}$ in a depth from the surface are shown in Fig. 7. The highest microhardness is shown by the specimen subjected to normalizing, and the lowest - the specimen annealed at *600°C*. These results are largely correlated with the results of mechanical tests (see Table 3).

Fig. 2. Specimens for metallographic research:

1 - as received; 2 - annealing at 600°C; 3 - normalizing; 4- annealing at 880°C

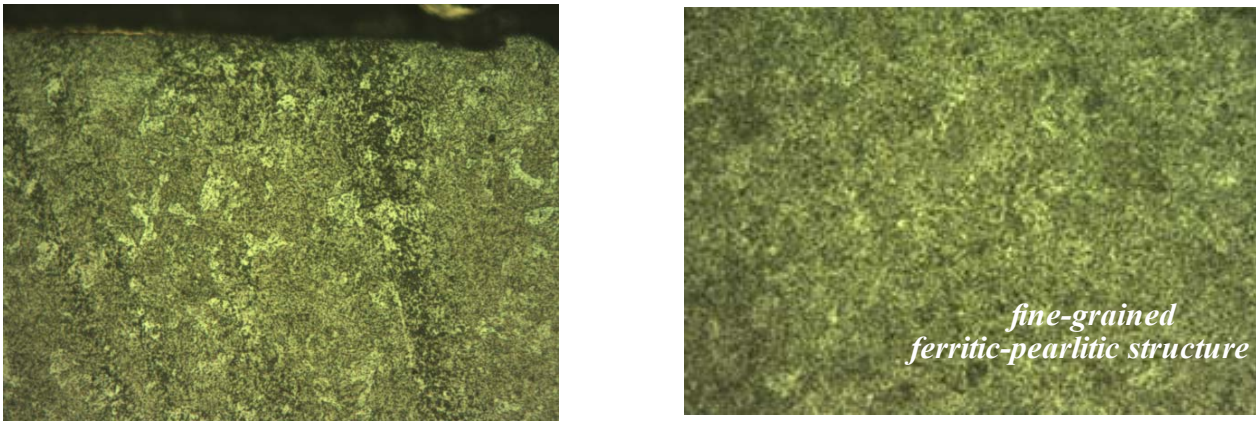
Table 3 *The mechanical test results*

Group	***$Rp_{0.2}$, MPa***	***Rm, MPa***	***A, %***	***Z, %***	***HBW, kgf/mm²***
I	*546*	*777*	*18,5*	*35*	*222*
II	*530*	*757*	*19,7*	*56,4*	*198*
III	*871*	*1467*	*5,6*	*29,7*	*265*
IV	*423*	*814*	*19,8*	*37,4*	*167*



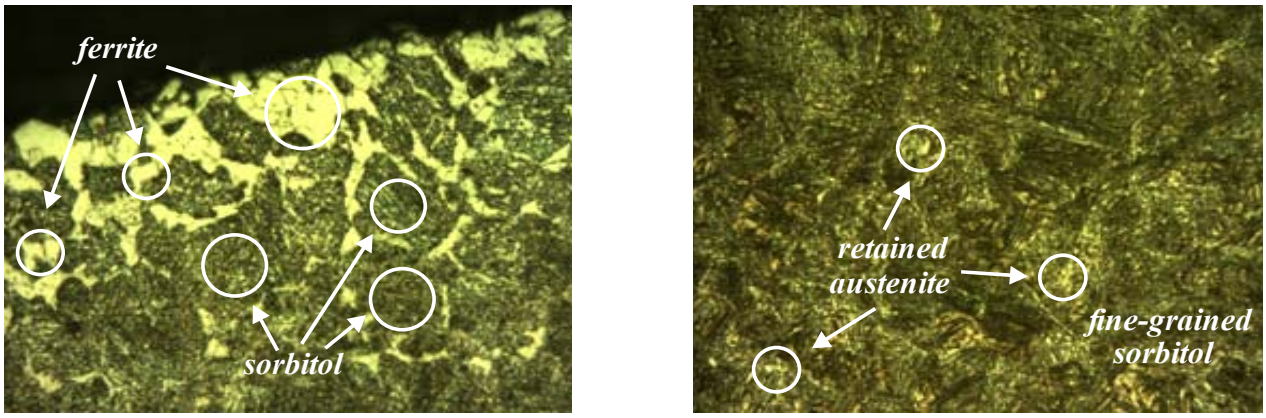
a) *b)*

Fig. 3. Microstructure of 35CrMnSi steel in "as received state" × 500
a) in the surface layer; b) in the core.



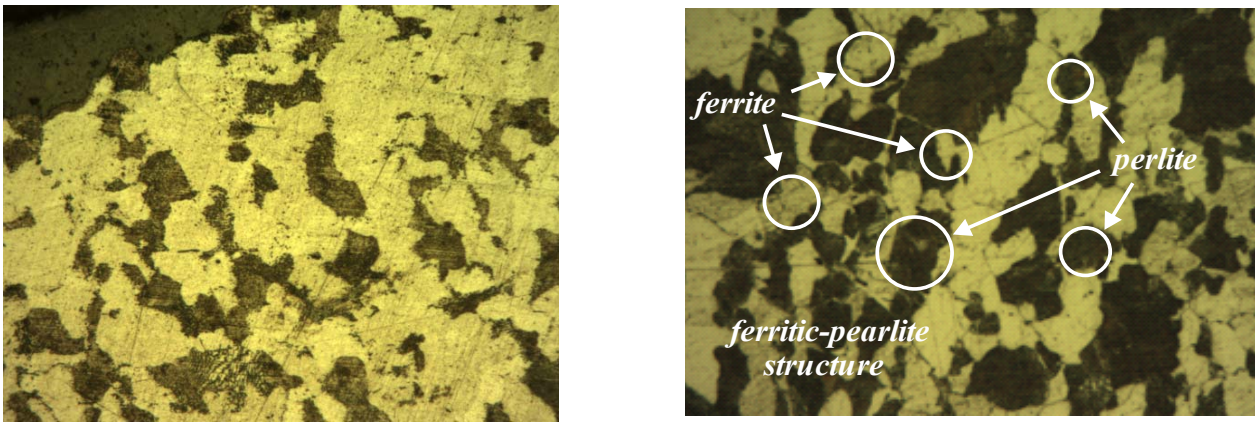
a) *b)*

Fig. 4. Microstructure of 35CrMnSi steel after annealing at 600°C × 500
a) in the surface layer; b) in the core.



a) *b)*

Fig. 5. Microstructure of 35CrMnSi steel after normalizing × 500
a) in the surface layer; b) in the core.



a) *b)*

Fig. 6. Microstructure of 35CrMnSi steel after annealing at 880°C × 500
a) in the surface layer; b) in the core.

Fig. 8 shows the diffractograms of the tested samples.

The presence of retained austenite in the structure of the normalized specimen is also confirmed by the conducted phase analysis (Fig. 8). In addition to the standard diffraction maxima of lines (110), (210) and (220) of αFe, diffraction maxima - (111) and (200) of γFe also appear on the diffraction pattern. 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 Mn as an alloying element, which slows down the phase conversion $\gamma Fe \rightarrow \alpha Fe$. In the ferrite grain nucleation zones, carbon is expelled so that small zones with relatively higher carbon and manganese contents are formed, which interfere with the conversion $\gamma Fe \rightarrow \alpha Fe$ at a relatively high cooling rate.

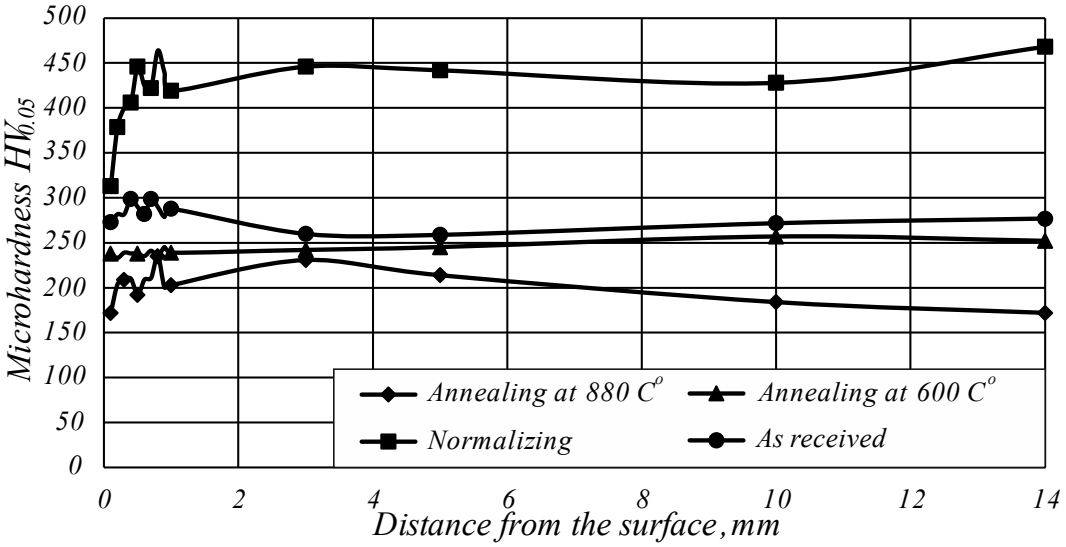


Fig. 7. Microhardness $HV_{0.05}$ of the tested specimens in "as received state" and after heat treatment

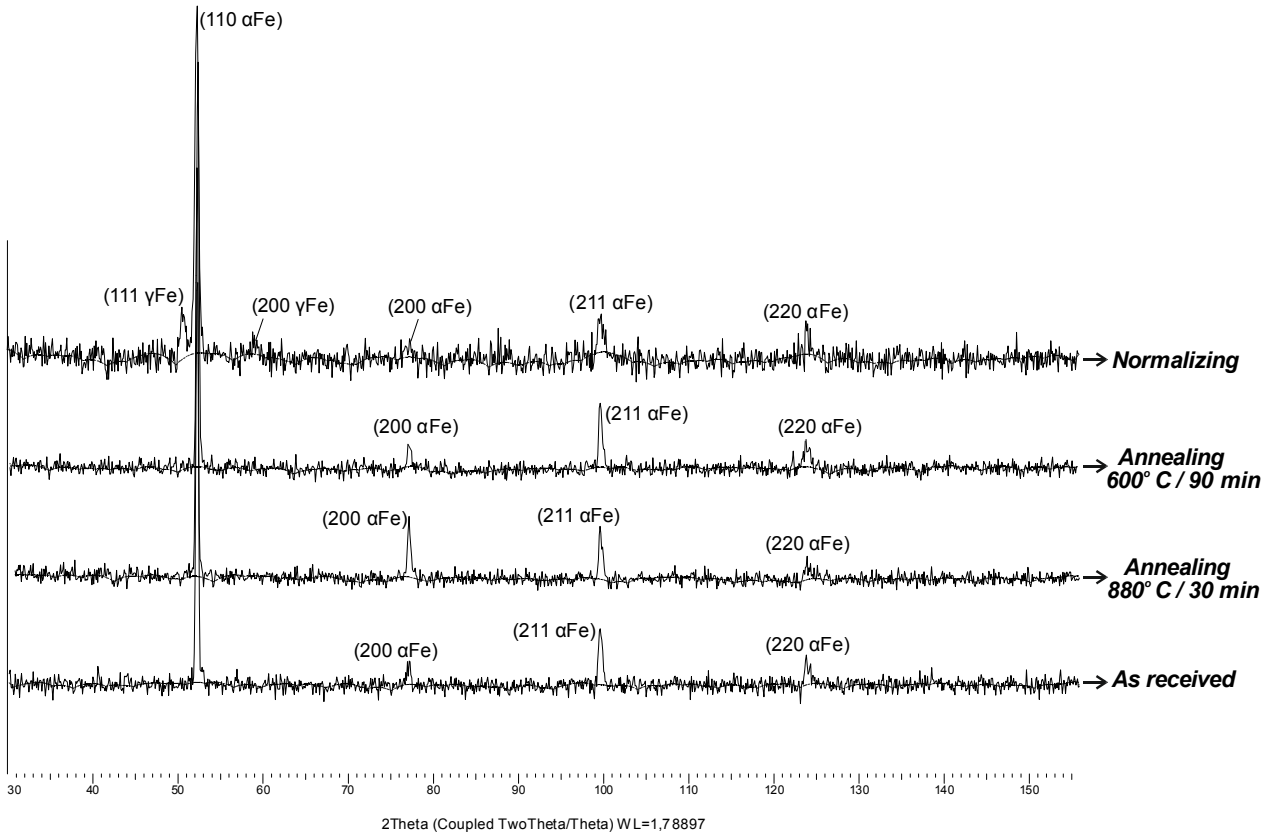


Fig. 8. X-ray diffraction patterns of the tested specimens

4. CONCLUSIONS

The effect of the heat treatment type and "as received state" on the microstructure and mechanical characteristics of structural alloy steel 35CrMnSi was studied. The results obtained can be summarized as follows:

- The heat treatment type and "as received state" lead to noticeable differences, both in the structural conditions and mechanical characteristics;
- The specimens subjected to normalizing were found to have the highest tensile strength (R_m=*1467 MPa*) and hardness. The physical basis for these mechanical characteristics, as well as the highest measured hardness and micro-hardness, is the obtained fine-grained sorbitol structure;
- The annealing at *880°C* leads to a pronounced ferritic-pearlite structure with relatively the largest grains. This coarse-grained structure is the reason for lowering the yield strength ($R_{0.2}$=*423 MPa*) relative to the "as received state", as well as the lowest values for hardness (*HBW=167*) and microhardness $HV_{0.05}$ on the surface and in depth;
- After annealing at 600 ° C, no significant change was found in both the microstructure and the mechanical characteristics compared to those in the "as received state".

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