



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

Vladimir Todorov\*, Vladimir Dunchev

Technical University of Gabrovo, 5300 Gabrovo, Bulgaria

### ARTICLE INFO

#### Article history:

Received 9 December 2021

Accepted 15 March 2022

#### Keywords:

35CrMnSi steel, microstructure, mechanical properties; hardness; microhardness; phase analysis

### 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 600°C with a heating time of 90 min and furnace cooling; annealing at a temperature of 880°C with a heating time of 90 min and furnace cooling; normalization at a temperature of 880°C 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.*

© 2022 Journal of the Technical University of Gabrovo. All rights reserved.

### 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 separately, 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.

\* Corresponding author. E-mail: v\_p\_todorov@abv.bg

## 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;

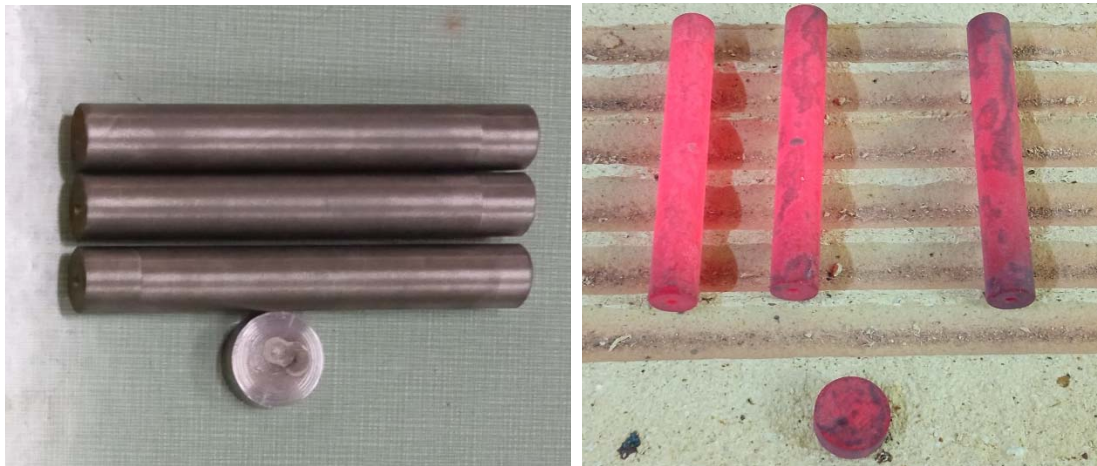
- one specimen type disk to determine the hardness, microhardness, microstructural and phase analysis.

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, °C	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  $\times 500$ . 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 (ZHV $\mu$ 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  $1.78897 \text{ \AA}$  and a focus orientation at a point with a hole diameter of  $1 \text{ mm}$  was used. The test range is from  $30^\circ$  to  $156^\circ$ , the magnitude of the current of the X-ray generator is  $40 \text{ mA}$ , and the applied voltage of the X-ray tube is  $35 \text{ kV}$ . The scanning mode has an incremental step size of  $2\theta - 0.1^\circ$  and a retention time of each step of the study -  $0,5 \text{ s}$ .

## 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  $600^{\circ}\text{C}$  (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  $600^{\circ}\text{C}$  (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  $R_m$  is approximately twice as high ( $R_m=1467\text{ MPa}$ ) as in the delivered state ( $R_m=777\text{ MPa}$ ).

In the fourth group samples (annealing at  $880^{\circ}\text{C}$ ), 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 ( $R_{p\ 0.2}=423\text{ MPa}$ ;  $R_m=814\text{ MPa}$ ).

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  $600^{\circ}\text{C}$ . These results are largely correlated with the results of mechanical tests (see Table 3).

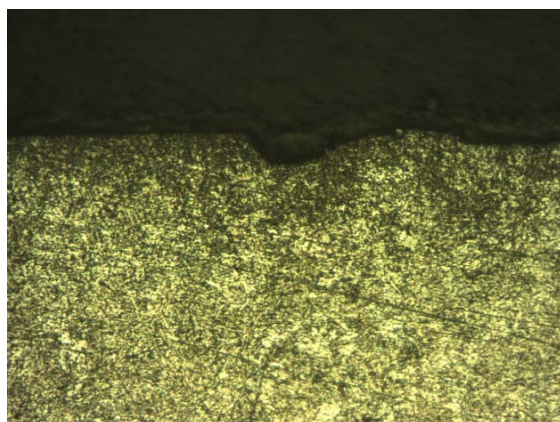


Fig. 2. Specimens for metallographic research:

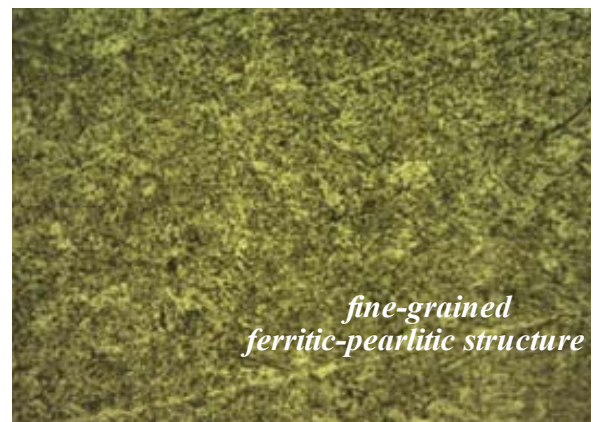
1 - as received; 2 - annealing at  $600^{\circ}\text{C}$ ; 3 - normalizing; 4- annealing at  $880^{\circ}\text{C}$

Table 3 The mechanical test results

Group	$R_{p\ 0.2}$ , MPa	$R_m$ , MPa	$A$ , %	$Z$ , %	HBW, kgf/mm <sup>2</sup>
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”  $\times 500$   
a) in the surface layer; b) in the core.



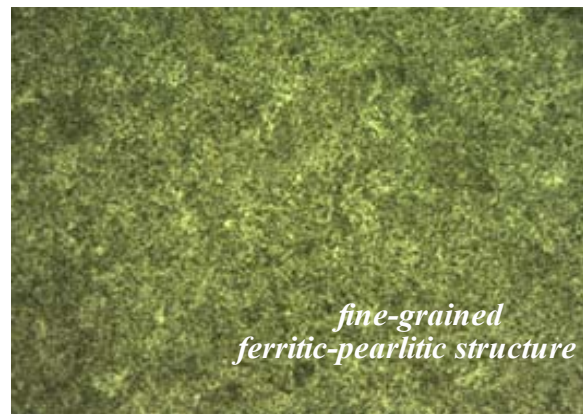
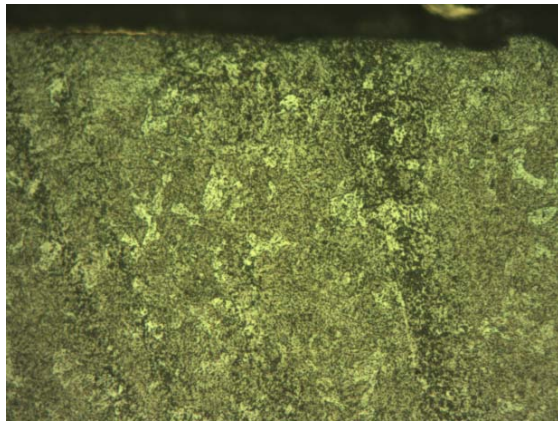


Fig. 4. Microstructure of 35CrMnSi steel after annealing at 600°C x 500  
a) in the surface layer; b) in the core.

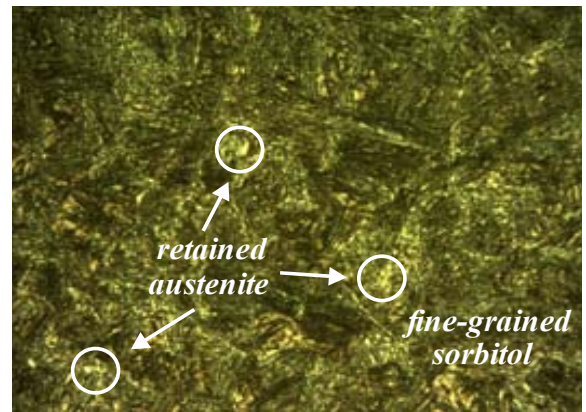
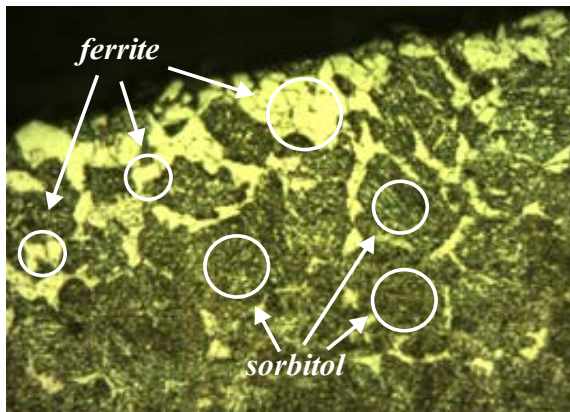


Fig. 5. Microstructure of 35CrMnSi steel after normalizing x 500  
a) in the surface layer; b) in the core.

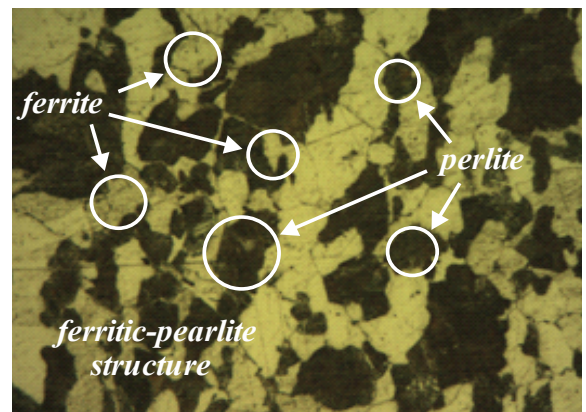
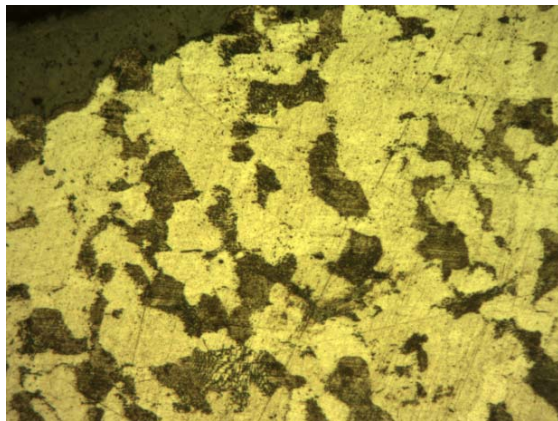


Fig. 6. Microstructure of 35CrMnSi steel after annealing at 880°C x 500  
a) in the surface layer; b) in the core.

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  $\alpha Fe$ , diffraction maxima - (111) and (200) of  $\gamma Fe$  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.

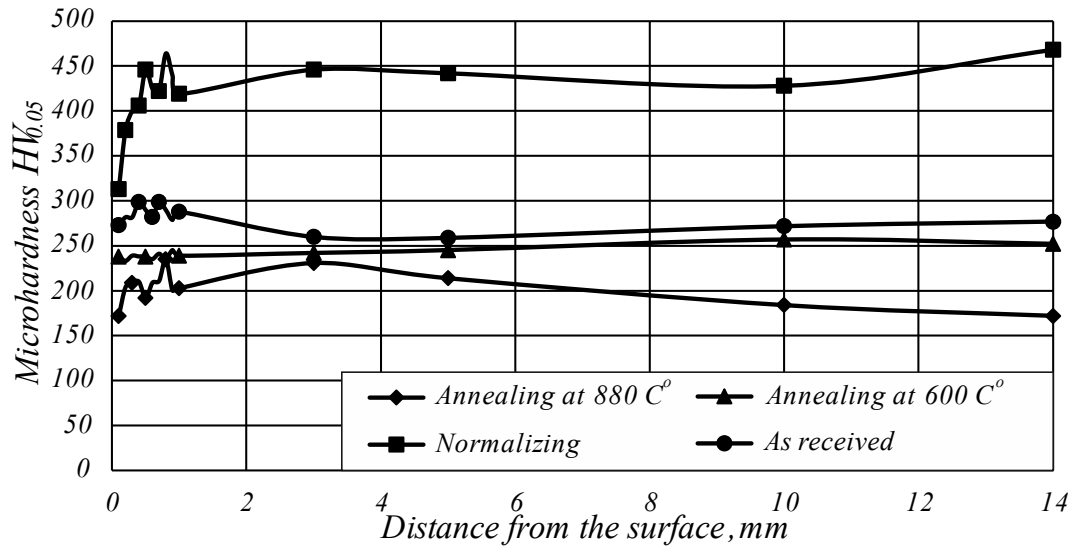


Fig. 7. Microhardness  $HV_{0.05}$  of the tested specimens in “as received state” and after heat treatment

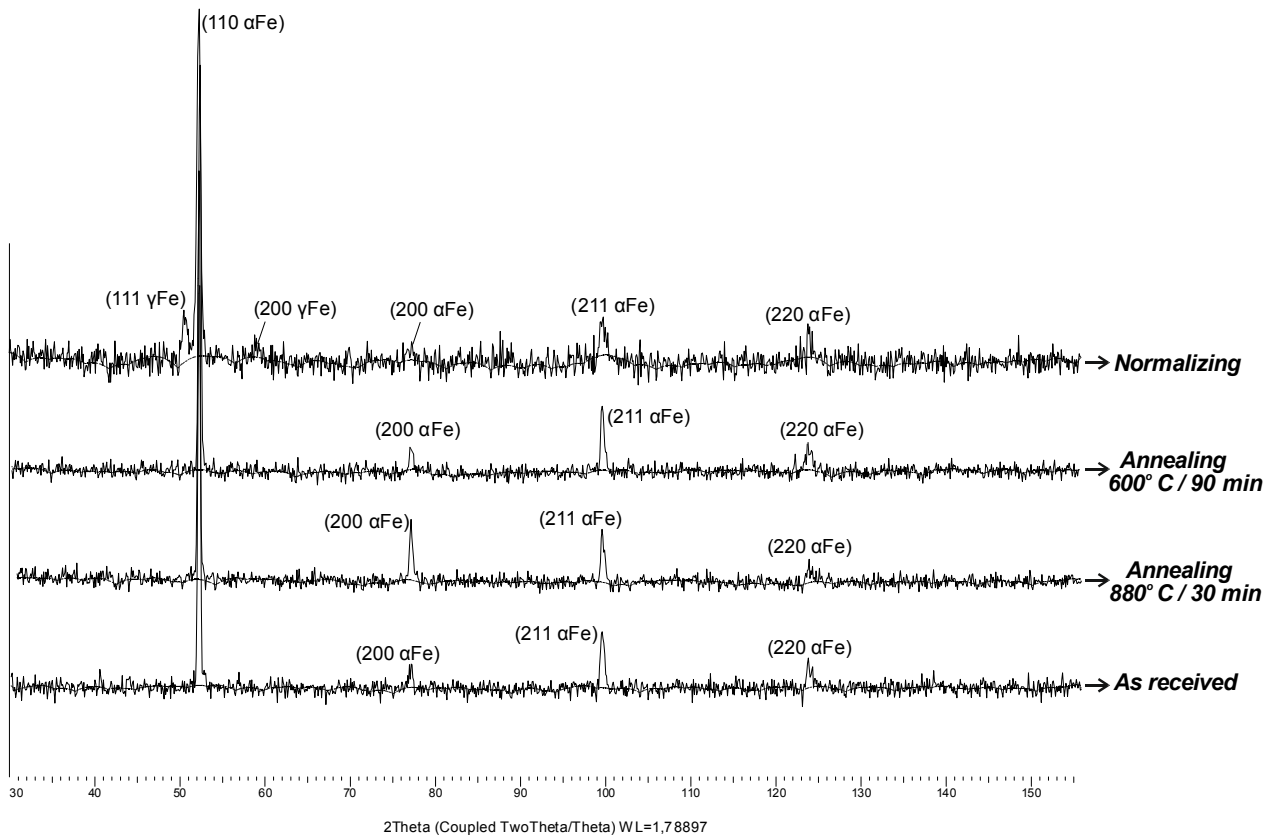


Fig. 8. X-ray diffraction patterns of the tested specimens

#### 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 ( $R_m=1467 \text{ MPa}$ ) 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  $880^\circ\text{C}$  leads to a pronounced ferritic-pearlite structure with relatively the largest grains. This coarse-grained structure is the reason for lowering the yield strength ( $R_{0.2}=423 \text{ MPa}$ ) 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  $600^\circ\text{C}$ , no significant change was found in both the microstructure and the mechanical characteristics compared to those in the “as received state”.

## REFERENCES

- [1] Rashkov N., Heat treatment of special steels and alloys, Sofia, 1993, ISBN 954-8465-05-1 (in Bulgarian)
- [2] Bain E.C., Paxton H.W. Alloying Elements in Steel, American Society for Metals, Metals Park, OH, 1961
- [3] Xu Yongjie, Wang Zhijun, Pan Shouli, Li Shuo. Research on Failure Behavior of 35CrMnSi based on Ballistic Experiment. International Conference on Materials Engineering and Information Technology Applications MEITA (2015) 519-525
- [4] Tariq F., Baloch R.A. Formation of multiphase microstructure in steel 35CrMnSi by intercritical annealing – quenching – partitioning heat treatment. Metal Science and Heat Treatment, 58 (2017) (Russian Original - 2016) 562-567
- [5] Li Yang, Xiao GuiYong, Chen LuBin & Lu YuPeng. Microstructural evolution in 35CrMnSi steel during multi-cyclic quenching and partitioning heat treatment. SCIENCE CHINA Technological Sciences October 2013 56 (10) (2013) 2581–2585 doi: 10.1007/s11431-013-5341-z
- [6] Congcong Jiang, Xiuzhi Zhang, Dan Wang, Lina Zhang, Xin Cheng. Phosphate conversion coatings on 35CrMnSi steels subjected to different heat treatments. Electrochemistry Communications 110 (2020) 106636
- [7] Dunchev V., Capek J., Atanasov M., Effect of ion nitriding on fatigue behavior of steel 35HGS, Journal of the Technical University of Gabrovo, 58 (2019) 20-25
- [8] Alaneme K.K., Okotete E.A. Recrystallization mechanisms and microstructure development in emerging metallic materials: A review. Journal of Science: Advanced Materials and Devices 4 (2019) 19-33
- [9] Zhongwang Wu, Zili Jin, Huiping Ren, Ruixiang Liu, Tao Li, Xin Zhang. Investigation on the primary and secondary recrystallization textures of rare earth micro-alloyed grain-oriented silicon steel. IOP Conf. Series: Journal of Physics: Conf. Series 1270 (2019) 012003 IOP Publishing doi:10.1088/1742-6596/1270/1/012003
- [10] Maximov J., Duncheva G., Anchev A., Ganey N., Amudjev I., Dunchev V., Effect of slide burnishing method on the surface integrity of AISI 316Ti chromium-nickel steel, Journal of the Brazilian Society of Mechanical Sciences and Engineering, (2018) 40:194
- [11] Maximov J., Duncheva G., Anchev A., Ganey N., Dunchev V., Effect of cyclic hardening on fatigue performance of slide burnished components made of low-alloy medium carbon steel, Fatigue&Fracture of Engineering Materials&Structures 42 (6) (2019) 1414-1425
- [12] Maximov J., Duncheva G., Anchev A., Dunchev V., Ichkova M., Improvement in fatigue strength of 41Cr4 steel through slide diamond burnishing, Journal of the Brazilian Society of Mechanical Sciences and Engineering 42 (4) (2020) 1-20
- [13] Rao D.S., Hebbar H.S., Komaraiah M., Kempaiah U.N., Burnishing parameters on surface hardness and wear resistance of HSLA dual-phase steels. Mater Manuf Process 23(3) (2008) 295-302
- [14] Saldana-Robles A., Plascencia-Mora H., Aguilera-Gomez E., Marquez-Herrera A., Diosdado-De la Pena J.A., Influence of ball-burnishing on roughness, hardness and corrosion resistance of AISI 1045 steel. Surf Coat Technol 339 (2018) 191–198
- [15] Maximov J., Duncheva G., Anchev A., Ichkova M., Slide burnishing—review and prospects. International Journal of Advanced Manufacturing Technology. 104 (2019) 785-801
- [16] Maximov J., Duncheva G., Anchev A., Dunchev V., Smoothing, deep, or mixed diamond burnishing of low-alloy steel components – optimization procedures. International Journal of Advanced Manufacturing Technology 106 (2019) 1917-1929
- [17] Maximov J., Anchev A., Duncheva G., Ganey N., Selimov K. Influence of the process parameters on the surface roughness, micro-hardness, and residual stresses in slide burnishing of high-strength aluminum alloys, J Braz. Soc. Mech. Sci. Eng. 39(8) (2017) 3067-3078
- [18] Rashkov N., Heat treatment of steels, Technic, Sofia (1977) (in Bulgarian)
- [19] Firger J., Handbook of heat treatment, Technic, Sofia (1985) (in Bulgarian)