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Effect of novel heat treatment on microstructure and dimensional characteristics of bearing rings after industrial processing

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ABSTRACT

The subject of the study was the evaluation of the level of deformation of bearing rings after new heat treatment with isothermal stop, as well as observation and analysis of the obtained microstructures. It is noteworthy that the material for the study consisted of parts of the reference bearing 114-1506TNG-2Z made of 100CrMnSi6-4 steel, while heat treatments were carried out on production equipment. The methodology for preparing specimens for testing the new treatment included hot forging, annealing and turning. Five variants of heat treatments consisting of austenitizing, cooling and isothermal holding in a salt solution bath were carried out as further tests. The observed reduction in strain level (cylindricity) after the isothermal process is due to a change in the mechanism of the phase transformation and the formation of a new bainitic-type microstructure. The results encourage further research into the new heat treatment and testing of products under operational conditions.

Keywords: distortion, bearing steel, isothermal hardening, nanostructurization.

INTRODUCTION

In this study, an attempt was made to produce a nanobainitic structure in the commercial bearing steel and analyze the deformation level of the bearing ring after the new heat treatment. Previous studies have shown that the use of conventional heat treatment (oil quenching and tempering) is associated with high levels of bearing ring distortion. Their presence is explained by the occurrence of structural and thermal stresses [1]. Current heat treatment leads to an excessive level of geometry changes, which is a significant problem in the context of manufacturing certain products. It is expected that the use of a salt solution as a quenching medium and quenching with an isothermal stop will help reduce distortion. To carry out the nanostructurization process, a phase transformation method was used through as being described in the literature [2]. Nanometals are mainly obtained by plastic deformation, vapor phase deposition and isothermal quenching. Many methods are known for producing nanocrystalline structures [3]. In the case of steel, a method of fragmenting the structure through phase transformations occurring during heat treatment has been developed, namely isothermal hardening (HI). Bhadeshia and Edmonds [4] were the first to introduce methods for designing steels with high mechanical properties, which are characterized by a microstructure consisting of nanometric bainitic ferrite laths and residual austenite. To obtain nanostructure bainitic, a heat treatment involving low temperature and prolonged annealing is carried out [5, 6–7]. The study was undertaken to develop parameters for conducting the above-mentioned process under production conditions using commercial 100CrMnSi6-4 bearing steel. The expected result of the research was to obtain a nanometric structure characterized by a favorable set of strength properties while maintaining high ductility.

The scope of work undertaken in the research included the development of a set of parameters for the process of nanostructurization of alloy steel, as well as analytical development (of phenomena and processes) based on the obtained experimental results. It is worth noting that the research was carried out on commercial bearing steel 100CrMnSi6-4. Usually, specially designed steels with dedicated chemical composition are used for nanostructurization processes. The test material was 100CrMnSi6-4 steel with an increased content of manganese and silicon alloying additives necessary for structure fragmentation [8]. Studies of the new heat treatment were carried out under production conditions on the equipment of the TG department of FŁT Kraśnik S.A. On the other hand, tests confirming the achievement of nanometric structure in samples (outer and inner ring of the reference bearing) treated according to the developed experimental heat treatment parameters were conducted at the Faculty of Materials Science and Engineering at Warsaw University of Technology.

MATERIALS AND METHODS

The material for the tests was bearings parts (outer and inner rings) of the reference bearing 114-1506TNG-2Z made of 100CrMnSi6-4 steel. The research began with material acceptance tests of steel bars in the delivery condition. Material acceptance tests (two bar samples with a length of 50 mm and a diameter of ø45 mm) were carried out for the 100CrMnSi6-4 material (melt 228923) delivered for testing. Parameters such as carbide network, carbide segregation, carbide banding, hardness, decarburization, and non-metallic inclusions content were evaluated. The material specification was verified by performing tests on a SPECTROLAB M12 Hybrid spectrometer using the Fe-10 chemical composition analysis method (chemical composition evaluation method for low-alloy steels). The chemical composition (wt. %) of the material tested is shown in Table 1 (ArcelorMittal supplier, melt No. 228923 of 100CrMnSi6-4 steel).

Preparation of specimens

The tests were conducted using a method of comparing the new heat treatment with a conventional one. Conventional quenching and tempering (HT) heat treatment were employed. Conventional heat treatment results in a tempered martensite structure and some residual austenite. Standard heat treatment in bearing production results in a high level of deformation. This affects both the course of subsequent production operations and the end product (mechanical properties). An attempt was made to carry out a new nanostructurization treatment of bearing steel under production conditions. No changes were made to the course of individual production operations.

In the first stage of the research, test specimens, i.e., bearing rings, were prepared in accordance with the technological course of bearing production. The methodology of preparing samples for testing new treatment included hot forging, annealing, and turning [Figure 1]. In both treatment variants, the starting structure for heat treatment was spheroidite [Figure 2].

Dimensional deviations were checked against the technical drawing before heat treatment. The result of these measurements is necessary to evaluate the level of distortion after the hardening treatment with isothermal stop.

In the further part of the tests, heat treatment of austenitizing in an industrial furnace, cooling and isothermal holding in a bath with salt solution and then the material was cooled to room temperature. The set of parameters for each treatment variant was developed based on available literature and patents [1, 2-7]. The samples for comparative analysis of deformation after HI/HT treatment were the outer and inner rings after turning and heat treatment.

Experimental procedure

In the next stage of the study, experimental heat treatment was carried out according to the following procedure. The same time (9 hours) and austenitization temperature (930°C) were assumed for all "HI" treatment variants. However, for the quenching process with an isothermal stop, 5 sets of processing parameters (combinations of temperature and processing time) were designed. For conventional heat treatment, the process parameters are shown below:

- HT – austenitization temperature 850°C and time 32 minutes, cooling in oil, tempering temperature 210°C and time 90 min.

Explanation of the above experimental procedure:

Figure 1. Preparation of bearing rings (from left): forging, annealing and turning

Table 1. Chemical composition of bearing steel (100CrMnSi6-4)

Elements	C	Mn	Si	Cr	Mo	Ni	Al
Wt.%	0.96	1.01	0.55	1.43	0.02	0.11	0.01

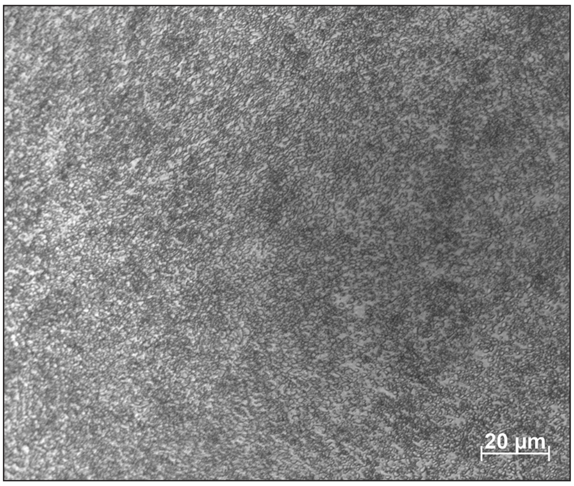

Figure 2. Material 100CrMnSi6-4 in annealed state spheroidite structure (light microscope)

- HI – isothermal quenching,
- T aust. – austenitization temperature,
- Time_9h – austenitization time,
- T1, T2, T3 – isothermal holding time,
- HI280T1 – isothermal quenching (HI) (temperature 280°C, isothermal holding time 6 hours),
- HI280T2 – isothermal quenching (HI) (temperature 280°C, isothermal holding time 10 hours),
- HI320T1 – isothermal quenching (HI) (temperature 320°C, isothermal holding time 6 hours),
- HI320T2 – isothermal quenching (HI) (temperature 320°C, isothermal holding time 10 hours),
- HI320T3 – isothermal quenching (HI) (temperature 320°C, isothermal holding time 14 hours).

The initial assumptions made for the development of HI treatment procedures were based on theoretical assumptions and analysis of previous empirical studies [9, 10–11]. A schematic of the procedure is shown in Figure 3.

RESULTS AND DISCUSSION

After all heat treatment variants had been realized, tests were carried out to identify the

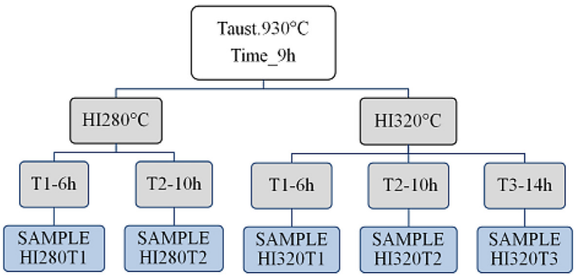

Figure 3. Procedure for conducting experimental heat treatment

structures obtained. As a first step, samples were prepared for metallographic studies (light microscopy) and hardness measurements (Vickers scale) for the bearing rings from the selected heat treatment variants (HI/HT). Electron and optical microscope observations were carried out for all HI and one HT variants. In the next stage of qualification testing, it was assumed that the analysis would be supplemented with the remaining two treatment variants HI (follow-up testing). Vickers hardness measurements were carried out for all HI treatment variants. The results are shown below [Figure 4].

Analysis of the hardness measurements showed that for all HI treatment variants, the average Vickers hardness values were 549÷560HV. The highest hardness value was found for the outer ring machined according to the parameters of the HI320T3 experiment and was 600HV. In contrast, the lowest hardness value was found for the inner ring treated to HI280T1 parameters. The lower values of the measurement result closer to the surface layer may be related to decarburization caused by the lack of a protective atmosphere during the transfer of the work pieces from the high temperature furnace to the quenching bath. After the hardness tests, the samples were prepared for tests to identify the microstructures obtained (light microscopy and scanning electron microscopy SEM). The samples

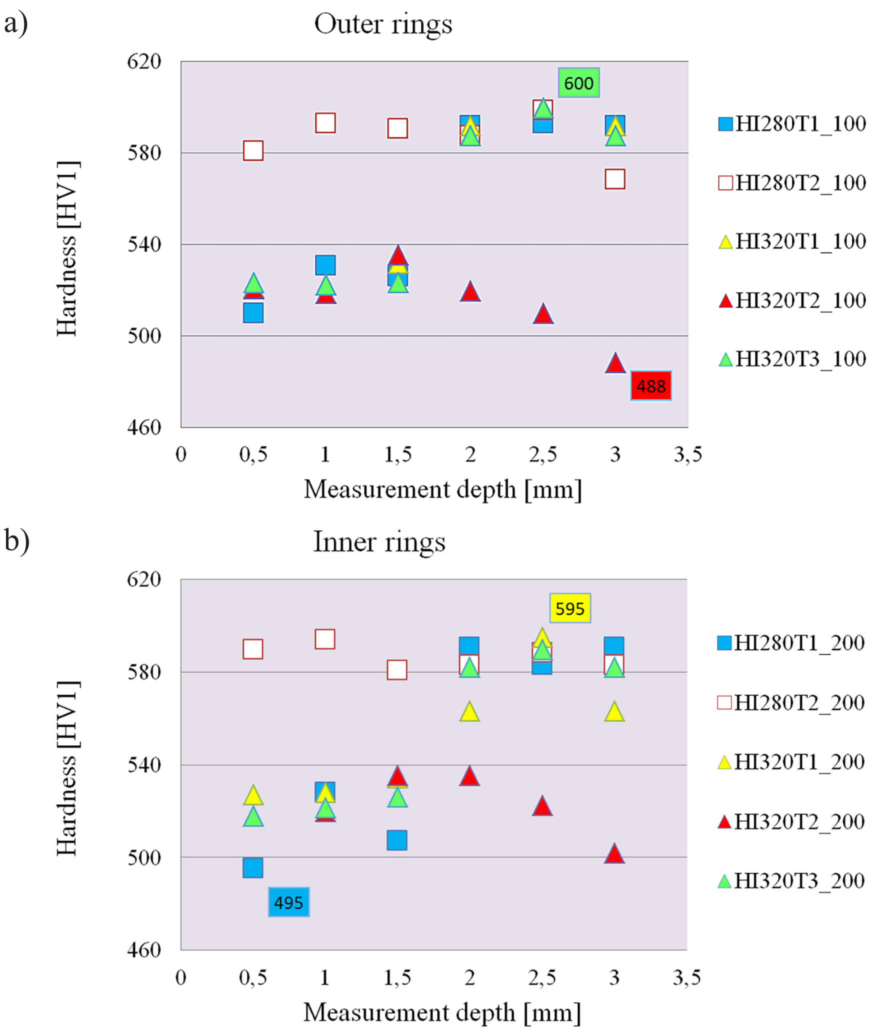

Figure 4. Hardness distributions for the outer (a) and inner bearing rings (b)

prepared for light microscopy (polishing and etching) and electron microscopy (abrasion and ion polishing) are shown below [Figure 5]. Electron channel contrast imaging (ECCI) was used to observe microstructures using the SEM technique. ECCI is a scanning electron microscopy technique that exploits the dependence of the backscattered electron (BSE) signal on the orientation of the crystal lattice planes relative to the incident electron beam (electron channeling mechanism) [12, 13].

As a result of microscopic and electron-microscopic observations of the microstructures obtained after HI treatment, a significant fragmentation of the structure was observed for all the samples analyzed. For the samples treated according to conventional heat treatment parameters (quenching and tempering), a tempered martensite structure was observed. For the HI280T1, HI320T1, H320T3 treatment variants, the observed microstructures consisted of bainitic ferrite (BF) with carbides (carbides characterized by the same direction) and retained austenite (RA) [14]. Examples of the microstructures obtained are shown in the images below [Figure 6, 7–9].

In the next stage of the work, metrology measurements and strain level analysis were performed after HI and HT heat treatments. The phenomena leading to deformation are complex and involve various aspects of materials engineering and metrology. Therefore, it is first necessary to

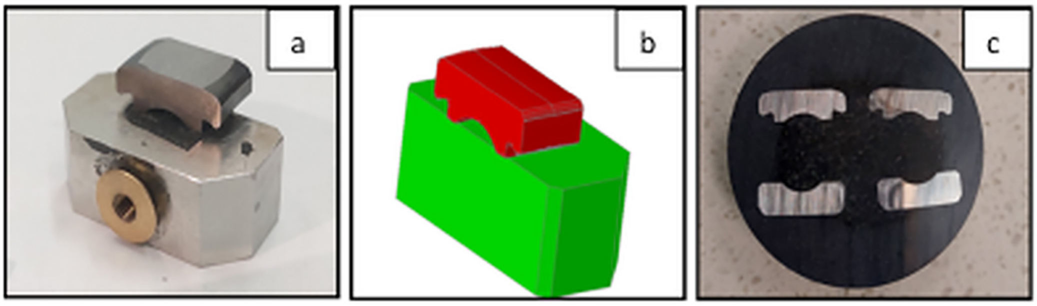

Figure 5. Samples for study by SEM technique (a, b) and light microscopy (c)

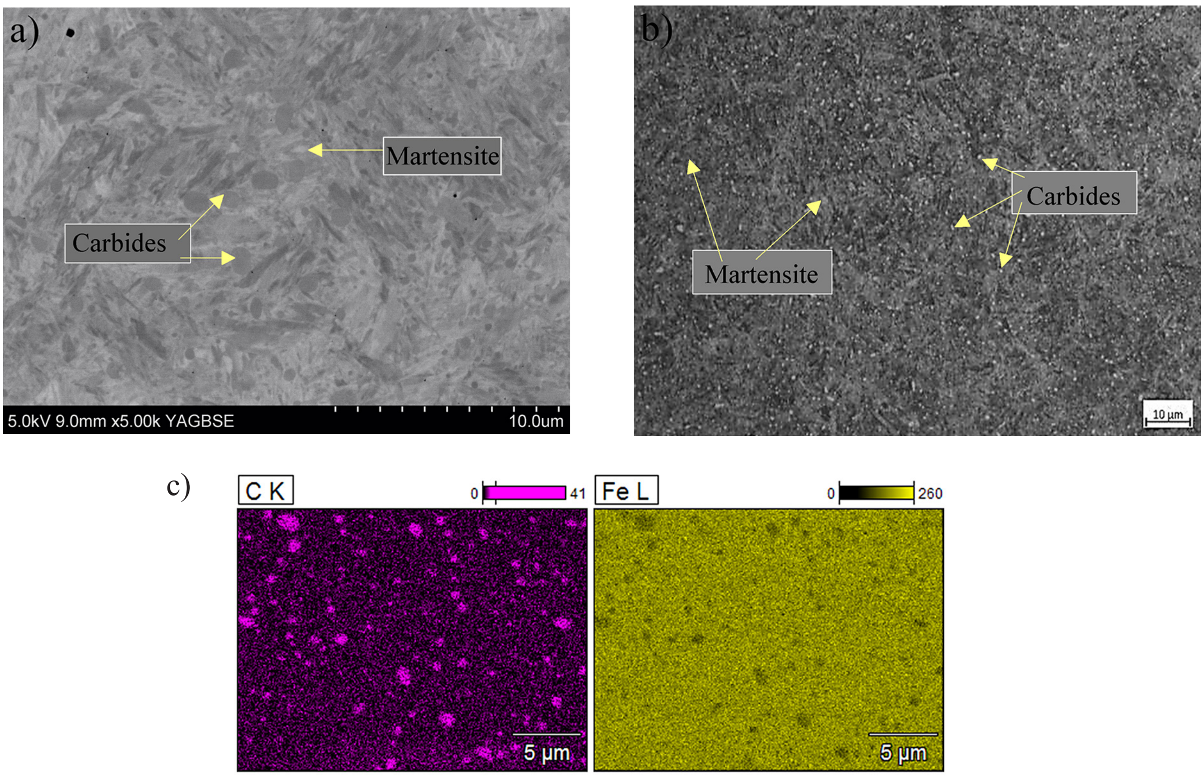

Figure 6. Microstructures – HT variant (a) SEM (Hitachi SU70), (b) light microscopy, (c) EDS analysis

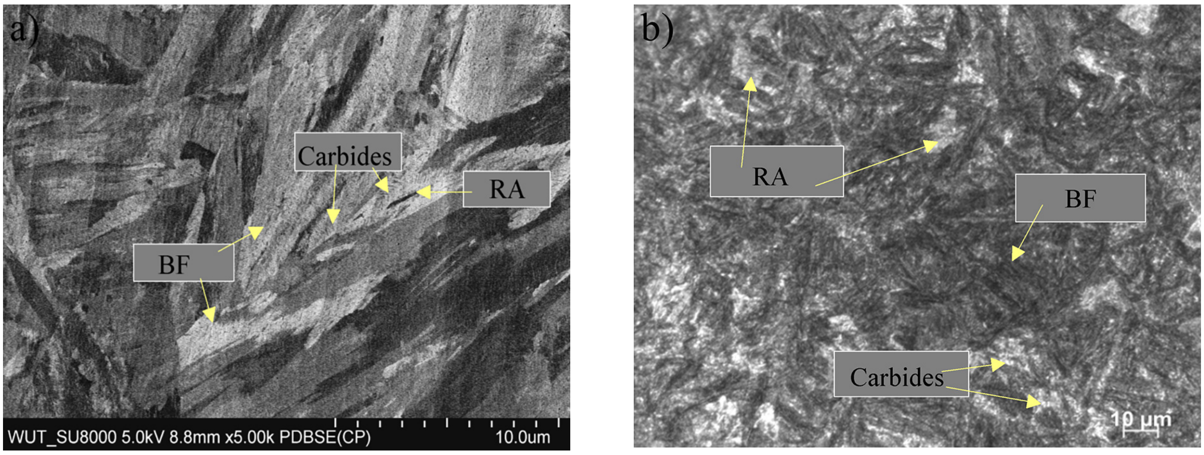

Figure 7. Microstructures – HI280T1 variant (a) SEM (Hitachi SU8000), (b) light microscopy

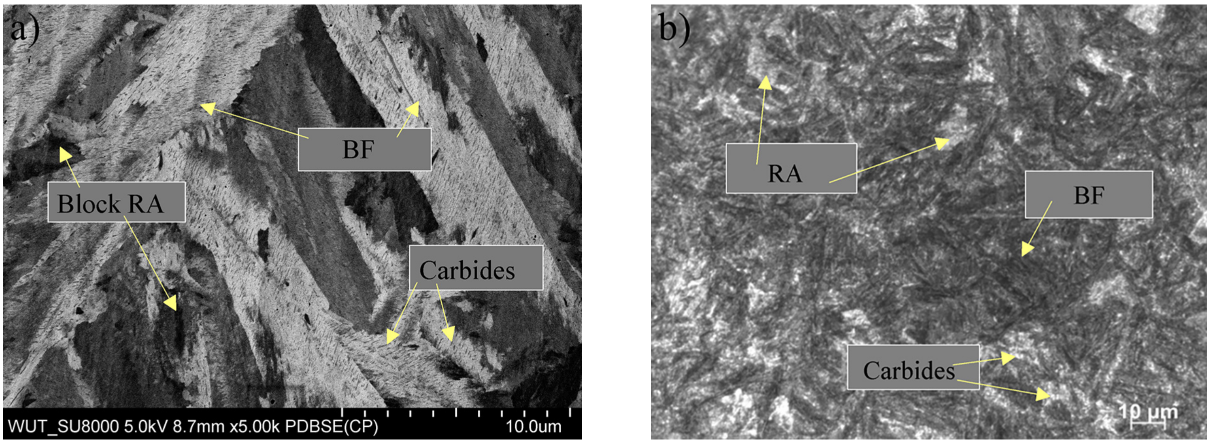

Figure 8. Microstructures – HI320T1 variant (a) SEM (Hitachi SU8000), (b) light microscopy

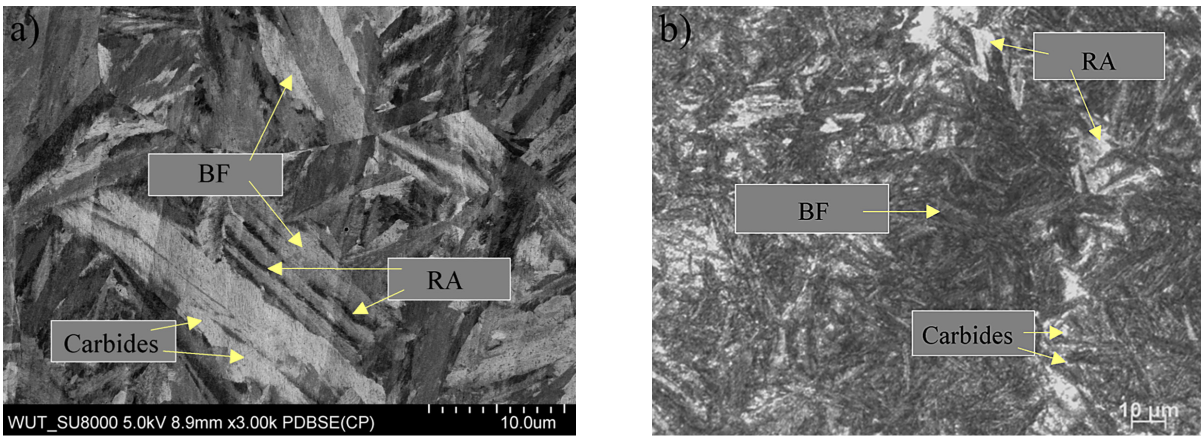

Figure 9. Microstructures – HI320T3 variant (a) SEM (Hitachi SU8000), (b) light microscopy

define deformation as any unplanned change in the dimension or shape of a component as a result of a heat treatment operation. The next step was to consider two categories of deformation: dimensional changes such as out-of-roundness and dimensional changes in the growth or shrinkage of the component [15, 16-17]. The latter are attributed to phase transformations occurring during heat treatment. In addition, the term dimensional stability is used to refer to changes occurring during the operation of the finished product that are caused by microstructural changes.

Statistical control of dimensional changes was carried out for six pieces of permanently marked work pieces and for the two sides of the outer and inner ring. On the other hand, the level of deformation (cylindricity, ovality) of the test pieces was assessed for each ring and each HI heat treatment variant. Analyses of dimensional changes and distortion levels were carried out for the outer diameter of the bearing rings (inner and outer ring), as shown in the following figures [Figure 10, 11].

The dimensional changes and the level of deformation after heat treatment (HT/HI) were analyzed for the characteristic diameters according to the standard geometry of the bearing components. Measurements of the characteristic diameters of the bearing rings were taken on both sides of the rings, i.e. side “1” and side “2” in the analyses below.

Analysis of dimensional changes and distortions levels for all variants of experimental heat treatment was carried out for all characteristic diameters. Due to the reproducibility of the nature of the changes for these diameters, the paper presents two geometry parameters and the associated

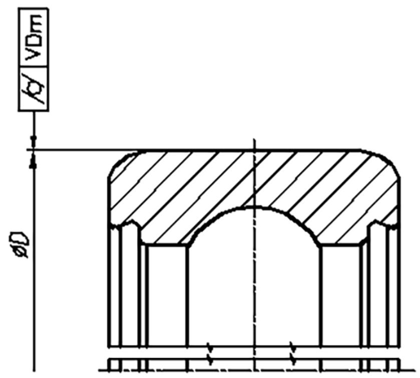

Figure 10. Outer bearing ring – characteristic diameter – D

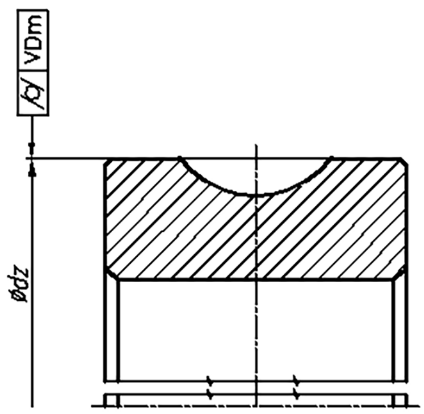

Figure 11. Inner bearing ring – characteristic diameter – dz

nature of the dimensional changes. Geometric analysis was presented for the outer diameter of the bearing ring (for outer ring ϕD, for inner ring ϕdz). Two parameters were analyzed, as defined below: ZW – dimensional changes_(averages of deviations) after heat treatment for outer and inner rings (side 1 and side 2) and VDm – out of cylindrical (taper), according to the following formulas:

$$ZW = \underbrace{((D_{max} + D_{min})/2}_{\text{heat treatment}\uparrow} - \underbrace{(D_{max} + D_{min})/2)}_{\uparrow\text{ turning}} \quad (1)$$

$$VD_m = \left| D_{side1} - D_{side2} \right| \quad (2)$$

where: D_{side1} – average value of max and min deviations from nominal outside diameter dimension (top of the ring), D_{side2} – average value of max and min deviations from nominal outside diameter dimension (bottom of the ring).

According to internally developed calculation formulas, the outer diameter spreads, i.e., the maximum and minimum values for the nominal diameters of the control parameters were determined. The terminology of measurements according to the standard is explained below:
- nominal diameter – the theoretical diameter from which deviations are measured;
- deviation of the single outside diameter – difference of the single outside diameter and the nominal outside diameter.

The deviations were read on measuring instruments based on the differential measurement method according to the requirements of geometric specifications [18, 19-23]. These metrological analyses are very important when designing new products regardless of bearing type. Each new product must meet the design requirements related to the conditions of future operation. In the area of rolling bearing production, more and more modern metrological tests are appearing, hence the extension of geometric analyses should be taken into account in the next stage of research work [20].

The same direction of dimensional change after heat treatment was observed for the outer and inner ring (side 1 and side 2) for all variants of quenching with isothermal retention. Deviations from the nominal dimension were characterized by negative values, indicating material shrinkage. As an example, the direction of change in the dimensions of the outer diameter ϕdz of the inner ring is shown below (Figures 12, 13). In the case

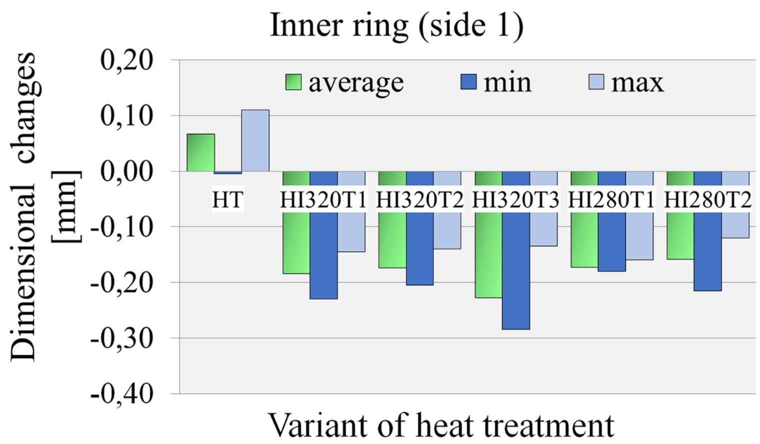

Figure 12. Dimensional changes for the outer diameter (dz) of the inner ring (side 1)

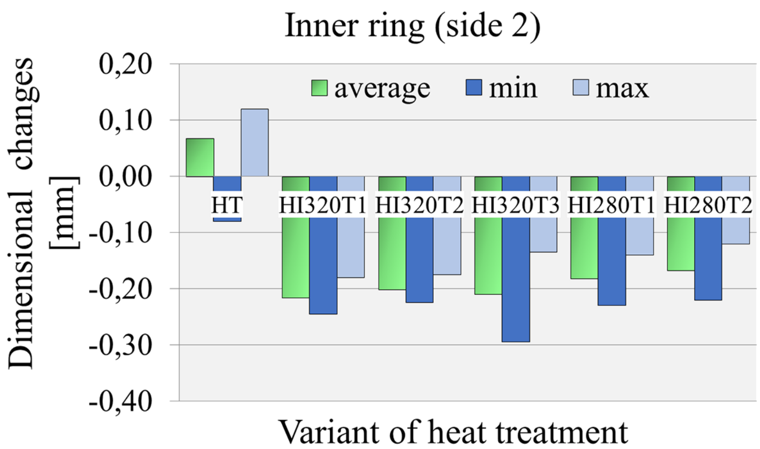

Figure 13. Dimensional changes for the inner diameter (dz) of the inner ring (side 2)

of the cylindricity parameter (taper), similar values were observed for all variants of the isothermal hardening treatment of the reference rings. Compared to conventional HT machining, lower average VDm values were observed for the machining variants: HI280T1 (inner ring dz diameter) and HI280T1, HI280T2, HI320T1, HI320T2, HI320T3 (outer ring D diameter). To illustrate the results of the measurements, a comparative analysis of the HI/HT treatment for an example HI treatment variant, namely HI280T1 (for the diameter ϕdz of the inner ring), is shown below [Figure 14].

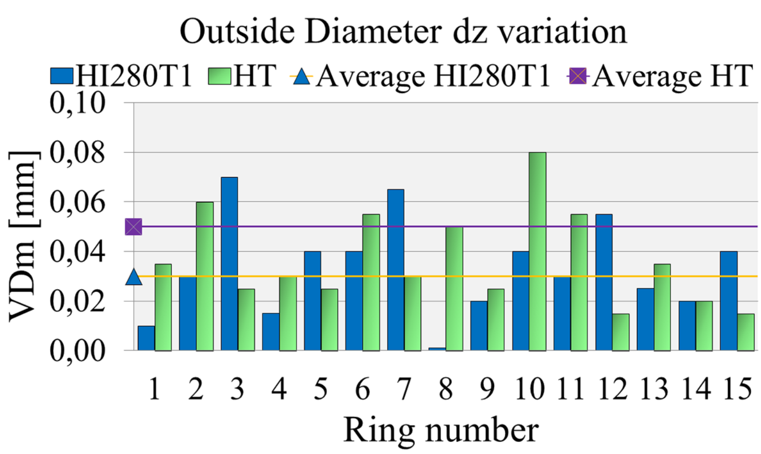

Figure 14. Deformation analysis (VDm) for the inner ring HT/HI280T1

CONCLUSIONS

Analyses of dimensional changes and observed microstructures obtained after HI heat treatment led to the following conclusions: the use of salt solution as a quenching medium and isothermal quenching contributed to the reduction of ring deformation (VDm). The observed reduction in the level of deformation after the isothermal process is due to a change in the mechanism of phase transformation and the formation of a new bainitic-type microstructure (observed fragmentation of the structure). The microstructures obtained after the new heat treatment direct further research into extended analysis using advanced testing techniques. A reduction in the level of distortion on the reference details in the cylindricity (VDm) of the bearing rings was observed.

Deviations from the nominal dimension showed the same direction of change, i.e. negative values for all "HI" treatment variants and the analyzed characteristic outer diameters of bearing rings. It was found that the repeatability of dimensional changes for all analyzed characteristic diameters after HI treatment (five treatment variants). After isothermal retention hardening treatments, a new character of geometry changes was observed. This will positively affect further manufacturing operations (grinding, machining and assembly).

Values in the range 549÷560HV for all HI treatment variants were obtained from hardness measurements of bearing components. It was confirmed that it is possible to achieve a fragmented bainitic-type structure in conventional bearing steel throughout the finished product and on conventional production equipment.

Therefore, the results obtained are of great importance for designing the course of production operations related to the implementation of the new product, which will be the 114-1506TNG-2Z bearing made according to the newly developed nanostructurization technology.

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