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The influence of hardening medium in the vacuum carburizing process on the distortion of machine elements used in the automotive industry

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ABSTRACT

Purpose: As part of this study, the influence of the hardening medium on distortions of FineCarb® carburized rollers used in the automotive industry as elements of fuel pumps has been examined. The analysis was carried out for the process of quenching in gas at different pressure of cooling gas and quenching in oil at variable delay time of oil mixers.

Design/methodology/approach: The research was carried out on real elements used in the automotive industry as elements of fuel pumps. FineCarb® vacuum carburizing technology was used in order to obtain optimal parameters of the surface layers. During quenching a variable related to the parameters of the quenching medium was introduced. For quenching in gas it was the pressure at which nitrogen was introduced into the cooling chamber, while for quenching in oil it was the time of mixers delay. The sample batch was laid out in accordance with the PPAP (Production Part Approval Process) requirements for the automotive industry. Microhardness and radial runout measurements were carried out on the samples and subjected to statistical analysis.

Findings: The analysis of each hardening processes has showed that depending on the cooling medium used, different distortion values are obtained. The distortion value is significantly influenced by the parameters of the hardening process – gas pressure/oil mixers delay. With the proposed quenching parameters, there is no relationship between the location of the sample in the furnace chamber and the distortion value. The smallest hardening distortions were obtained as a result of the hardening process in gas at a gas pressure of 3 bar. Hardening in gas was characterized by the smallest scatter values of obtained results of radial runout.

Research limitations/implications: Basing on the studies and analyses carried out in this work, it can be concluded that the introduction of gas quenching technology instead of oil quenching technology is justified qualitatively and economically alike. Hardening in gas was also characterized by the smallest scatter values of obtained results of radial runout. This is an extremely important technological and economic aspect, due to the cost of grinding processing.

Practical implications: The automotive and aviation industries are putting ever greater demands on the quality of manufactured components while reducing costs.

It requires optimization of technological processes from co-operators. In the case of hardening plants, the most important aspect is obtaining repeatable, precisely planned parameters of the carburized layer, as well as minimizing the negative phenomena that cause dimensional changes after hardening of elements. The tests allowed to determine the most effective hardening conditions in terms of obtained distortions and costs of eliminating distortions. However, the selection of the optimal parameters depends on whether the core hardness requirements are also determined.

Originality/value: The conducted tests allowed to determine the most effective hardening conditions in terms of obtained distortions, costs of levelling distortions and a complete technological process for the automotive industry.

Keywords: Distortion, Gas quenching, Oil quenching, Thermo-chemical treatment, Vacuum carburizing

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MANUFACTURING AND PROCESSING

1. Introduction

Heat and thermo-chemical treatment is one of the main ways to give elements the appropriate mechanical properties such as hardness, strength and plasticity [1-6]. Carburizing with subsequent hardening is the most commonly used surface treatment in the automotive industry used to increase strength properties.

Low-pressure carburizing [7,8] exceeds conventional carburizing [9,10] in terms of efficiency and has a number of advantages, such as: no internal oxidation, greater uniformity of layers, energy efficiency and environmental friendliness. At the same time, the requirements for minimizing negative phenomena causing dimensional changes after hardening are still rising. [11-13].

The goal of modern hardening technology is to obtain high-quality automotive components with minimized distortion levels, which are, however, directly correlated with heat treatment. As a result of the uneven cooling of each detail in various fragments of the charge volume, which is the result of a heterogeneous and unrepeatable flow of the coolant into the chamber volume, the unfavourable distortions of elements occur [14-17]. In most cases, the hardening distortions are corrected by appropriate methods of metal machining (e.g. grinding) or straightening [18-23]. Correction of hardening distortions is one of the most expensive technological processes. In order to limit the occurrence of distortions, advanced cooling systems are being developed and gas (mainly nitrogen, less helium) is increasingly used instead of oil [24-29].

Increasing requirements in the automotive and aviation industries concerning heat treated details, force sub-contractors to optimize the machining so as to lead to cost reduction while maintaining high mechanical properties of the layer and core, still maintaining the lowest level of distortion. The level of distortion is a component that is influenced by several factors occurring at different stages of production. As the research presented in [30-39] shows, 50-60% of distortions are caused by incorrect material selection and geometry. The remaining 40-50% are the result of heat treatment: type of furnace, distribution of details in the chamber, cooling method and cooling medium. The selection of the latter is crucial in shaping the structure during heat treatment.

The article presents the analysis of hardening distortions using high pressure gas and oil as a hardening medium for the part of machines used in the automotive industry after the carburizing process.

2. Materials and heat treatments

2.1. Research element

The elements intended for analysis were 60 rollers (Fig. 1) made of 16MnCr5 steel used in the automotive industry as elements of fuel pumps. The tests were carried out on real elements, according to the recipient's requirements. These elements require a hardened surface layer to a hardness of about 58-62 HRC and a thickness of about 0.4 mm (for criterion = 550 HV) and a maximum radial runout of 0.07 mm.

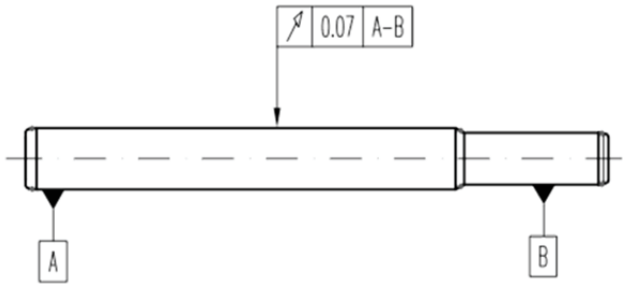

Fig. 1. An overview drawing of the sample together with the radial runout measurement location

2.2. Thermo-chemical treatment

FineCarb® vacuum carburizing technology was used in order to obtain optimal parameters of the surface layers, and thus to prevent the formation of internal oxidation and uncontrolled, unfavourable precipitation. According to the proposed technology, before the start of the carburizing segments, the charges were held at 920°C for 120 min, which contributed to the stabilization of the temperature throughout the entire cross-section of the element. Then, multi-segment carburizing was carried out at 920°C. The times of each saturation/diffusion stages to obtain the assumed carbon concentration profile were selected on the basis of a simulation performed in the SimVaCPlus® program, which should meet the assumed requirements for the carburized surface layer. After carburizing, quenching from 870°C was applied. The formula of the carburizing process was identical for all the processes, while during quenching there has been introduced a variable related to the parameters of the quenching medium. For quenching in gas it was the pressure at which nitrogen was admitted to the cooling chamber, while for quenching in oil it was the mixer delay time (Tab. 1).

Table 1.
Parameters of the executed cooling method processes

Process No.	Gas hardening	Oil hardening
	Cooling gas pressure, bar	Mixer delay time, s
I (1-9, 55 samples)	16	-
II (10-18, 56 samples)	8	-
III (19-27, 57 samples)	3	-
IV (28-36, 58 samples)	-	10
V (37-45, 59 samples)	-	5
VI (46-54, 60 samples)	-	1

All thermo-chemical treatment processes were carried out at Hart-Tech Ltd. in a multi-purpose, intelligent modular centre (furnace chamber dimensions: 800 mm x 600 mm x 620 mm), enabling the FineCarb® vacuum carburizing process and hardening in both gas and oil (Fig. 2) realization.

Fig. 2. Modular centre located in HART-TECH Ltd

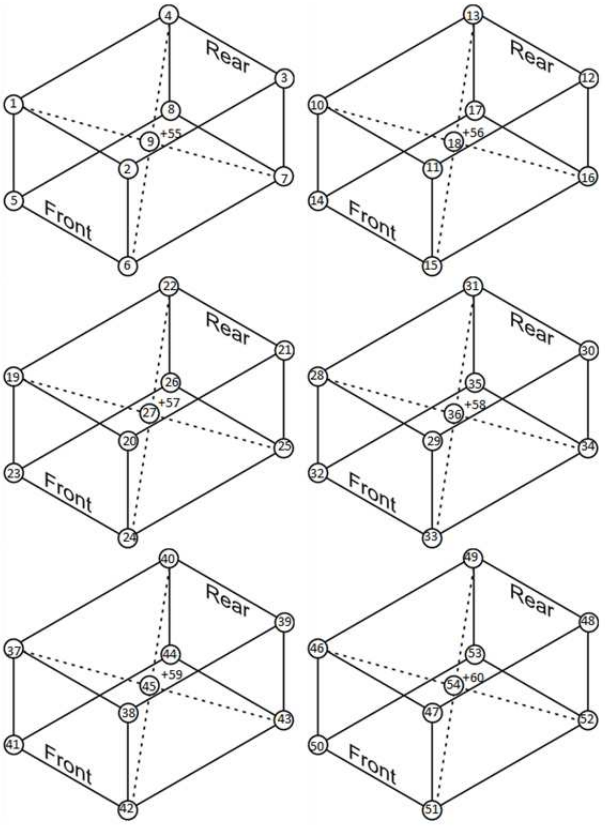

Fig. 3. Layout of control samples in the batch for thermo-chemical treatment processes (see Tab. 1)

Each furnace charge contained 60 samples, including 10 electroplated (Fig. 3), which were checked for surface hardness and radial runout. The batch with samples was arranged in accordance with the PPAP (Production Part Approval Process) requirements for the automotive industry [40]. PPAP is the process of approving the production part in accordance with the specification of customer requirements – this applies to new products that have not yet been delivered to the contractor or have been modified. Different location of the samples is given due to temperature and gas flow tests in the furnace chamber and verification of invariance of other process parameters in the marked places of the batch.

3. Results

3.1. Hardness and microhardness measurements

Surface and core hardness was measured using the Rockwell C scale method (INNOVA-TEST hardness tester, type 600A) on each sample (Fig. 4) from six processes in order to verify the technological conditions required by the customer. Compliance with the assumed conditions and a relatively larger difference between surface and core hardness for gas-hardened samples was found for all samples (Tab. 2).

Table 2.
Measurement of surface hardness and core

	Gas hardening			Oil hardening		
	Process No.					
Hardness, HRC	I	II	III	IV	V	VI
Surface	61.3	59.4	59.2	60.3	61.5	62.1
Core	36.5	35.1	25.4	38.1	40.2	41.3

Microhardness tests were carried out using the Vickers method (INNOVATEST Nexus 4305 hardness tester). Each measurement was made every 100 µm from the sample surface (Fig. 4). Hardness tests were made in accordance with standard PN-ISO 2639: 2005, at load 10 N (HV1).

The measured microhardness distributions are generally comparable between the analysed processes, and the differences are caused by the change in the method of sample cooling. According to the PN-EN ISO 2639_2005 standard, it is assumed that the limit value of the effective carburizing layer measured perpendicularly to the outer surface is 550 HV. Hardness above 550 HV1 was obtained for all processes at a depth of 0.4 mm, thus the requirement for carburized layer thickness has been met.

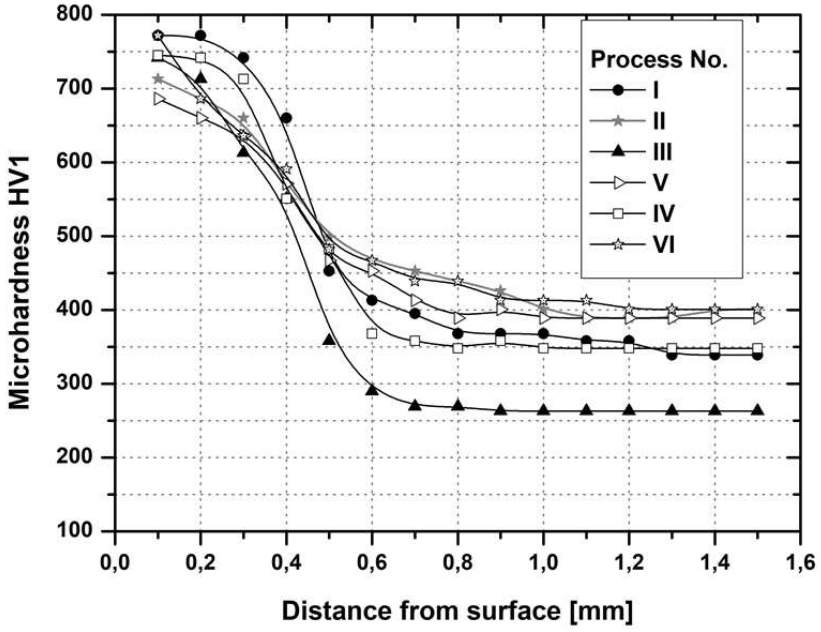

Fig. 4. Microhardness distribution in the surface layer of 16MnCr5 steel samples after vacuum hardening and oil hardening (see Tab. 1)

3.2. Radial runout measurements

Radial runout tests were carried out both before (r) and after the thermochemical treatment (r_{HT}). Runout measurement was performed on a bench tester for shaft runout measurement equipped with a Preisser digital sensor made in accordance with DIN 878 and a reading accuracy of 0.001 mm. The measurement of radial runout was subjected to statistical analysis with determination of median, first quartile and third quartile. By default, the box is determined by the 25th and 75th percentiles. The 50th percentile is known as the median. The limits are the minimum and maximum values.

Figures 5-10 shows the obtained results of the runout measurement in the samples before the process and after the carburizing and hardening process in various parameters of the cooling medium.

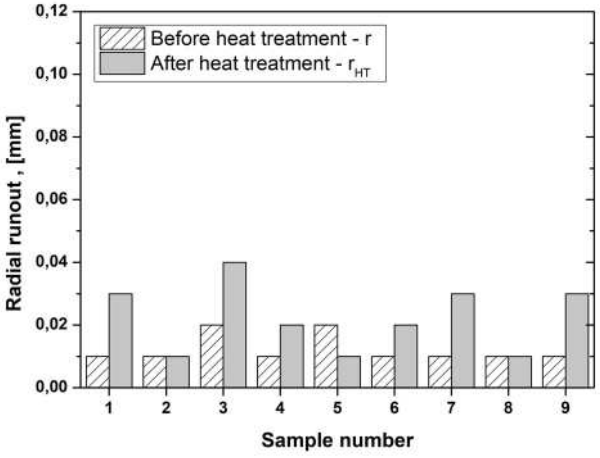

Fig. 5. Radial runout – gas-hardened samples, pressure 16 bar

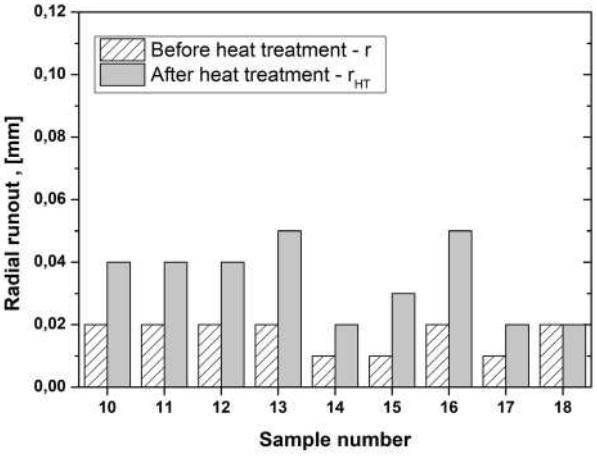

Fig. 6. Radial runout – gas-hardened samples, pressure 8 bar

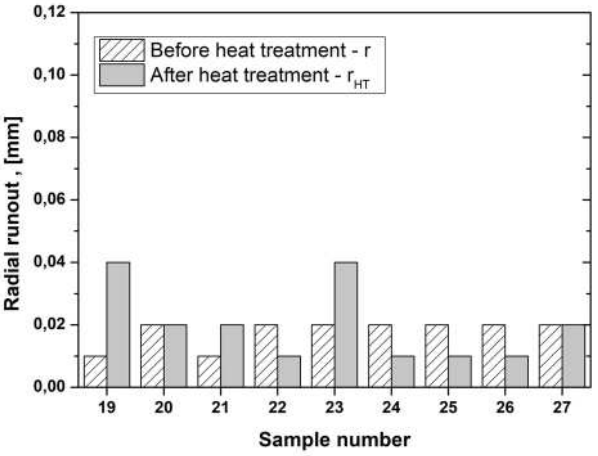

Fig. 7. Radial runout – gas-hardened samples, pressure 3 bar

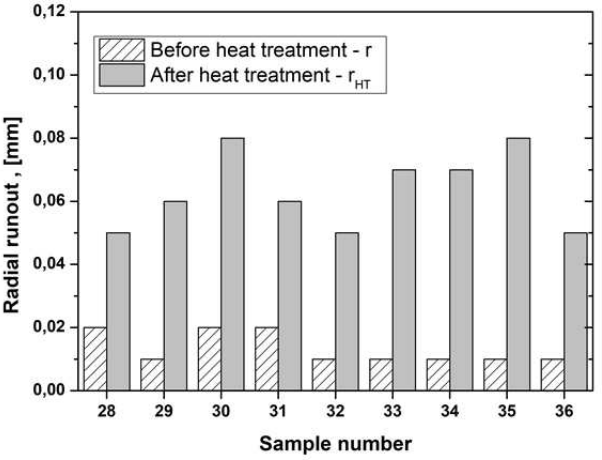

Fig. 8. Radial runout – oil-hardened samples, mixer delay 10s

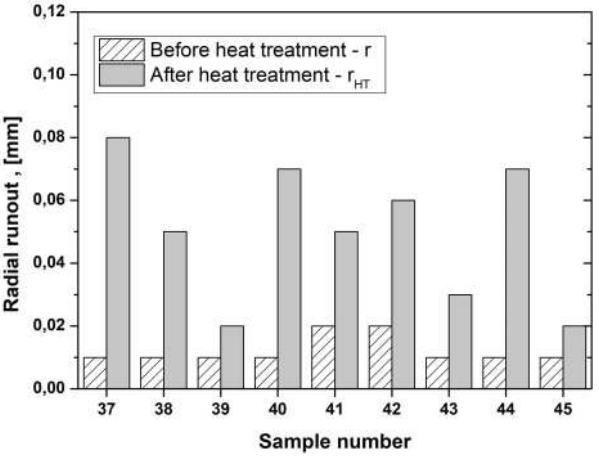

Fig. 9. Radial runout – oil-hardened samples, mixer delay 6s

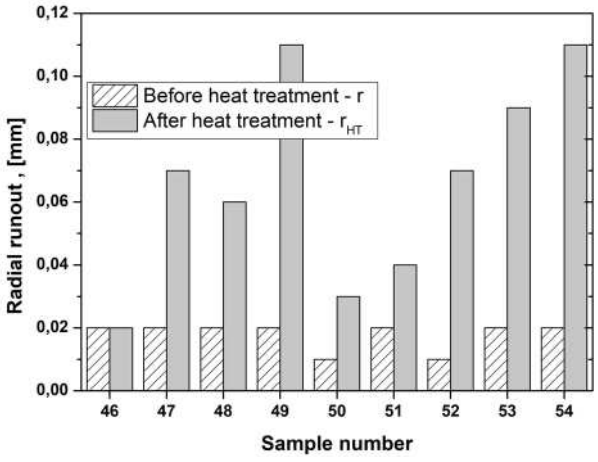

Fig. 10. Radial runout – oil-hardened samples, mixers delay 1s

Figures 11-12 show statistically developed results of radial runout measurement obtained for individual quenching processes compared to the initial values.

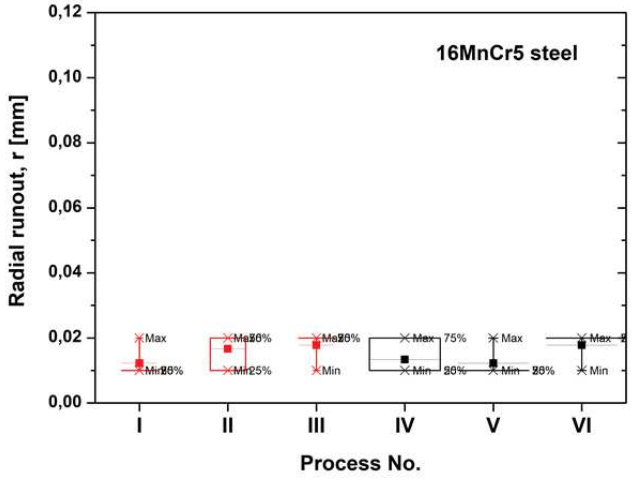

Fig. 11. Box plot for the values of radial runout before the subsequent stages of quench process

Figure 13 presents the differences ($\Delta r=r_{HT}-r$) in measurements of radial runout of rollers for various hardening processes (see Tab. 1).

Analysing the obtained results (Figs. 5-10), it can be seen that there is no relationship between the location of the sample in the furnace load and the distortion value, because in each of the processes the samples showing the largest distortion difference were in a different place.

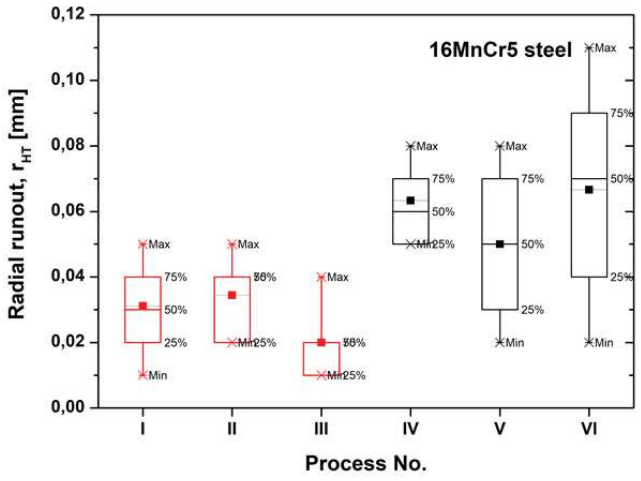

Fig. 12. Box plot for the values of radial runout after the subsequent stages of quench process

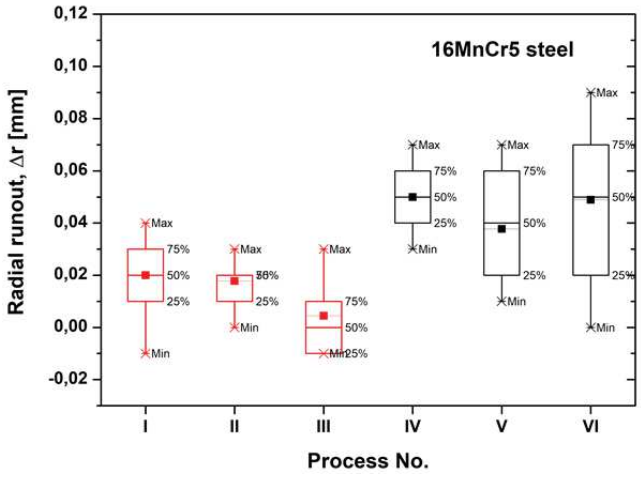

Fig. 13. Box plot for the values of differences between the radial runout after and before the subsequent stage of the quench process

However, it can be seen (Figs. 11-12) that all samples before processing were made with the same accuracy – the median runout value was from 0.01-0.02 mm. It is also seen that the median measurement of the runout of the oil-hardened samples is significantly higher (2-3 times) than the gas-hardened samples. The obtained runout values for oil quenching exceed the runout limits (0.07 mm) imposed by the manufacturer in a significant number of samples. Statistical analysis shows statistically significant differences in IV-VI processes. As can be seen, the longer the delay of switching on the mixers during quenching in oil, the smaller the dispersion of radial runout. Oil

hardening processes were also characterized by the smallest difference between surface hardness and core. In processes I-III, the smallest spread of radial runout was obtained for 3 [bar] quench gas pressure (process III). In the case of the other two gas quenching processes (process I and II), the obtained measurements show a similar dispersion of the results of radial runout. Process III was characterized by the largest difference in hardness between the surface and the core.

The median result Δr of the difference in radial runout value (Fig. 13) showed that in each of the analysed processes there was an increase in runout compared to the initial dimensions (raw elements). The smallest changes in runout (0.005 mm) can be observed for samples hardened in gas at a pressure of 3 bar. For the other two gas quenching processes, greater heterogeneity of measurement results was obtained, and the median value was 0.02 mm. In processes with quenching in oil, although the median values (0.04-0.05 mm) were below the limit value, for some samples the runout increased above the nominal (0.007 mm).

The difference in radial runout value results from different cooling intensities of individual media used for the quenching process. This thus has influence on phase transformations causing volume changes of the material, which affect the distortion of the material not only in the surface layer, but also in the core.

4. Conclusions

In the automotive industry, heat and thermo-chemical treatment of details is directly related to the occurrence of distortions. Understanding, predictability and minimization of this phenomenon is particularly important for this industry due to the high requirements in terms of dimensional geometry that the parts must meet.

One of the requirements for quenching coolants is not to cause excessive quenching distortions, which are then eliminated by grinding treatment. Hardened elements grinding is characterized by higher energy consumption and higher costs. It is important that the grinding surplus is as small as possible, then less time is spent on the treatment of the element and less waste is produced (ecological aspect). According to statistics, the cost of grinding accounts on average from 40 to 70% of the total cost of precision products, thus this aspect is important from the point of view of treatment economics in series production.

The analysis of individual hardening processes showed that depending on the cooling medium used, different distortion values are obtained. The distortion value is also significantly affected by the parameters of the hardening process – gas pressure/oil mixers delay, which affect phase transitions.

The tests allowed to determine the most effective hardening conditions in terms of obtained distortions and costs of levelling distortions. With properly selected hardening parameters, there is no relationship between the sample location in the furnace chamber and the distortion value. The smallest hardening distortions were obtained as a result of the hardening process in gas at a gas pressure of 3 bar. However, the selection of the optimal parameters depends on whether the core hardness requirements are also set. Hardening in gas was characterized by the smallest scatter values of obtained results of radial runout. This is an extremely important technological and economic aspect, due to the cost of grinding processing.

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