

HARDENING-RELATED DEFORMATIONS OF GEAR WHEELS AFTER VACUUM CARBURISING AND QUENCHING IN GAS

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ABSTRACT

The purpose of modern surface hardening technology is obtaining reproducible, precisely planned parameters of the carburized layer, minimizing the negative phenomena that result in dimensional changes after hardening and making it possible to determine the nature and magnitude of these changes. This concerns mainly the concept of single-piece flow in heat treatment applied for the purposes of mass production, employing a special autonomous 4D Quenching chamber for high pressure gas quenching (HPGQ). The main components of the 4D Quenching chamber include a system of cooling nozzles surrounding the processed item and providing a uniform inflow of cooling gas from all directions (3D) and a table rotating together with the item processed, contributing to uniform cooling (4D). Within the framework of this paper there was studied the impact of gear wheel quenching in a 4D Quenching chamber using nitrogen at pressure of 6 and 10 bar on changes in geometry. Geometric measurements of facewidth of gear, hole diameter and outside diameter were performed before and after carburization and quenching. The results obtained allowed us to determine the impact of quenching pressure inside a 4D Quenching chamber on dimensional changes in gear wheels analyzed. The thermo-chemical treatment resulted in a decrease in outside diameters and hole diameters measured and an increase in facewidth of gears.

Keywords: gas quenching, geometric measurement, hardening-related deformations, gear wheels.

INTRODUCTION

Carburizing followed by quenching is the most popular surface treatment method in the automotive industry. Low-pressure carburizing [6, 7, 16] is better than conventional carburizing [4, 5] in terms of efficiency and it is characterized by a number of advantages, such as lack of internal oxidation, higher uniformity of resulting layers, good energy efficiency and environmental friendliness. At the same time there is a constant increase in requirements regarding, among others, minimizing the negative phenomena resulting in dimensional changes after hardening and enabling the determination of nature and magnitude of these

changes [1, 3]. The answer to these requirements is the concept of single-piece flow treatment, in which every single item passes through the same process stages and conditions [10÷15]. While passing through the process chambers with stabilized parameters, the item is subjected to identical process conditions, which ensures very high precision and reproducible results of carburizing. In addition, the HPGQ (high pressure gas quenching) 4D Quenching chamber (Fig. 1) intended for individual gas cooling enables unrestricted adjustment of the cooling curve and obtaining the optimal microstructure and properties of steel. An important feature of this solution is the application of a system of cooling nozzles surrounding the gear wheel



Fig. 1. 4D Quenching chamber for HPGQ [14]

and ensuring uniform inflow of cooling gas from all directions (3D). At the same time, uniform distribution of cooling is supported by the table rotating together with the gear wheel (4D). This type of cooling system, using nitrogen at pressure of up to 15 bar, enables obtaining the cooling intensity comparable to oil-based systems, without the necessity of using Helium (He). The application of a method consisting in controlled hardening of individual parts reduces to minimum the deformations of every such part and provides complete reproducibility of deformations on identical parts. At the same time, it allows obtaining above-average mechanical properties.

Within the framework of this paper there were compared deformation measurement results for selected parameters of gear wheels that underwent carburization in a vacuum furnace employing the single-piece flow method and quenching with nitrogen at pressure of 6 and 10 bar in a 4D Quenching chamber.

METHODOLOGY

The experimental research involved a series of 10 external spur gears and an involute profile made of EN 20MnCr5 steel. The nominal geometric parameters of the gear wheels tested are summarized in Table 1.

Hobbed gear wheels were subjected to vacuum carburizing in a single-piece flow furnace at 950°C, achieving the effective case depth of ECD = 0.55 mm. Subsequently, 5 gear wheels were quenched in a 4D Quenching chamber at 10 bar

Table 1. The nominal geometric parameters of gear wheels tested

Parameter	Value
Normal module m_n , mm	1.75
Number of teeth z	58
Outside diameter d_a , mm	105
Root diameter d_p , mm	97.125
Pitch diameter d , mm	101.5
Hole diameter d_o , mm	30H7
Facewidth of gear b , mm	14.5
Pressure angle α , °	20
Helix angle β , °	0
Coefficient of shift profile x , mm	0

Table 2. Thermo-chemical treatment (TCT) parameters

Gear wheel designation	Parameters of treatment	
K10	Quenching in nitrogen at 10 bar and at a temperature of 850°C	Tempering at 190°C for 180 min
K06	Quenching in nitrogen at 6 bar and at a temperature of 850°C	Tempering at 190°C for 180 min

and the remaining 5 at 6 bar. In the quenching chamber, the orientation of tooth designated as no. 1 was identical for the entire gear wheel series. After quenching, the gear wheels were tempered at 190°C for 3 hours. The thermo-chemical treatment (TCT) parameters are given in Table 2.

In order to determine the hardening-related deformations in gear wheels after vacuum carburization, gas quenching and tempering, the geometric measurements were conducted both before and after thermo-chemical treatment. In order to perform measurements there was used a DEA Global Performance 5.7.5 coordinate measuring machine featuring temperature compensation. The PC-DMIS CAD++ software was used to control the machine's working motion and create its measurement programs.

An original program for measuring gear wheels was created using an algorithm based on recommendations available in the literature [2, 8, 9]. The coordinate system of a gear wheel measured was defined in the machine's working space on the hole diameter, top face of toothed-wheel rim and tooth designated as no.1. [9, 17].

Three geometric parameters of the gear wheels were selected for the purposes of comparative analysis:

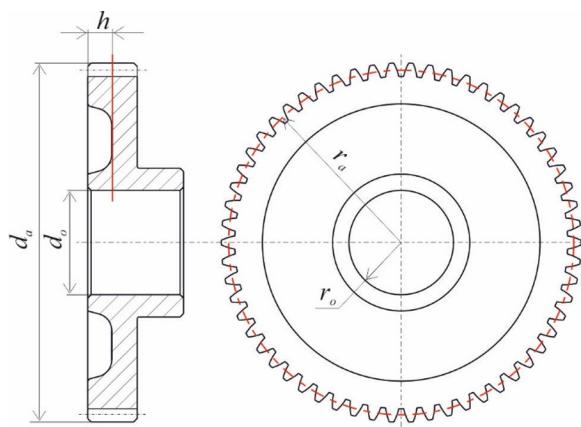


Fig. 2. Diameters, radii and measurement height for the K10 and K06 wheels

- Chordal tooth thickness s – the thickness was measured for 58 teeth. The shortest distance between two measurement points located on two flanks of measured tooth on the pitch diameter d (chord measurement), at the height h equal to half of the facewidth of gear was adopted as the thickness of a single tooth (Fig. 2).
- Hole diameter d_o – after designating the coordinate system origin, 58 measurement points located in the gear wheel mounting hole (hole diameter) at the height h (Fig. 2) were measured. Then the values of 58 radii r_o were calculated. To determine the hole diameter d_o for each gear wheel the least squares method was used.
- Outside diameter d_a – after designating the coordinate system origin, 58 measurement points on the outside diameter at the height h were measured (Fig. 2). Then there were calculated the values of 58 radii r_a , which were subsequently used to determine the outside diameter d_a using the least squares method.

Measurement uncertainty of the coordinate measuring machine is determined according to ISO 10360 standard. The maximum permissible measurement error when measuring length (distance, diameter, position) MPE_E is:

$$MPE_E = 1,5 + \frac{L}{333} [\mu\text{m}] \quad (1)$$

where: L – measurement length [mm].

The MATLAB software was used for elaborating statistics on the basis of results obtained. Due to the possibility of outliers, a median was used to determine the average values. The whole elaboration was illustrated using box plots.

RESULTS AND DISCUSSION

Chordal Tooth Thickness (s)

Figure 3 shows the graph presenting the thickness of the individual teeth of the K10 and K06 gear wheels, measured before and after thermo-chemical treatment.

It is worth to notice that the bars representing the thickness of individual teeth create waves of a certain amplitude, whereas for the values measured before and after the TCT, their courses overlap. Such form of the thickness variation course for individual teeth in a gear wheel results from radial runout of a gear blank during mechanical processing that are impossible to eliminate and is not related to the subsequent thermo-chemical treatment. At the same time, it can be observed that the thickness of individual teeth after TCT behaves in a non-uniform manner – in some cases it increases, in other – decreases. Figure 4 shows the differences in thickness between individual teeth resulting from TCT (thermo-chemical treatment).

When analyzing the graphs shown in Figure 4 it has to be noted that the aforementioned nature of changes in thickness of individual teeth means that on the toothed-wheel rim circumference there are present, in alternating manner, the areas where chordal tooth thickness values increase as a result of TCT and the areas where these values decrease after TCT. This is caused by the arrangement of cooling nozzles, particularly during the first stage of the cooling agent feeding.

Table 3 shows the outcome of statistical elaboration of the differences between thickness of individual teeth of both gear wheels that were observed.

Figure 5 shows a graphical elaboration of results in the form of a box plot.

Table 3. Values of chordal tooth thickness difference parameters

Parameters	Values	
	K10	K06
Max.	0.032	0.032
Upper Whisker	0.032	0.032
Q3 (75%)	0.011	0.016
Q2 (50%) - median	0.004	0.008
Q1 (25%)	-0.025	-0.020
Lower Whisker	-0.058	-0.058
Min.	-0.058	-0.058
Number of points n	58	58
Number of outliers	0	0

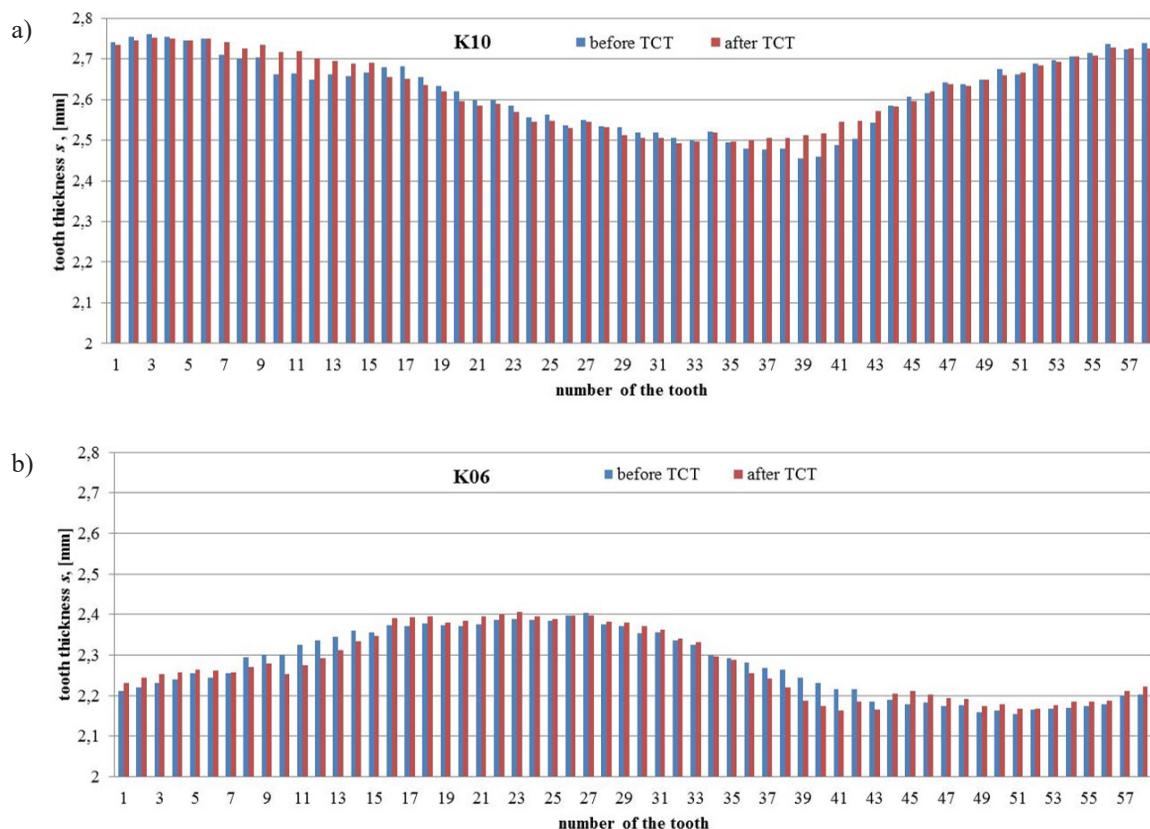


Fig. 3. Thickness of the individual teeth measured before and after the TCT: a) K10 gear wheel, b) K06 gear wheel



Fig. 4. Differences in thickness between individual teeth resulting from TCT: a) K10 gear wheel, b) K06 gear wheel

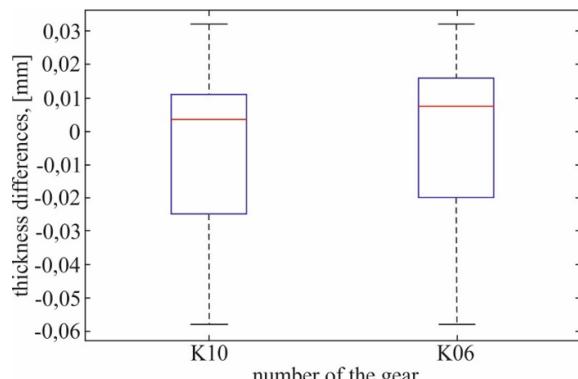


Fig. 5. Box plot for the tooth thickness difference values, K10 and K06 wheels

On the basis of median value given in Table 3 and illustrated on Figure 5, it must be stated that as a result of thermo-chemical treatment the chordal tooth thickness increased for both gear wheels. In case of the K06 gear wheel, for which a lower cooling gas pressure (6 bar) was applied, there was found a 0.008 mm increase in chordal tooth thickness. In case of the K10 gear wheel, for which a higher cooling gas pressure (10 bar) was applied, the increase in chordal tooth thickness is smaller and amounts to 0.004 mm, that is, 50% of the thickness increase value for the K06 gear wheel.

Hole Diameter (D_0)

Figure 6 presents a graph showing the shape of the mounting hole measured, resulting from

measurements of the radius r_o . The curves on the graph correspond to the values of radii measured before and after the thermo-chemical treatment.

On the basis of the above graphs it can be stated that as a result of the thermo-chemical treatment (TCT) the hole diameters of both gear wheels experienced a uniform change. This is evidenced by the graphs on Figure 7, which show the differences between values of the radii r_o of the gear wheels measured that were caused by TCT.

Table 4 contains results of the statistical elaboration of the values of differences between radii r_o of the hole diameters for both gear wheels.

Figure 8 shows the graphical elaboration of results in the form of a box plot.

Table 4. Values of difference parameters for radii r_o of hole diameters

Parameters	Values	
	K10	K06
Max.	-0.022	-0.020
Upper Whisker	-0.022	-0.020
Q3 (75%)	-0.025	-0.023
Q2 (50%) - median	-0.027	-0.024
Q1 (25%)	-0.028	-0.025
Lower Whisker	-0.032	-0.029
Min.	-0.033	-0.032
Number of points n	58	58
Number of outliers	1	2

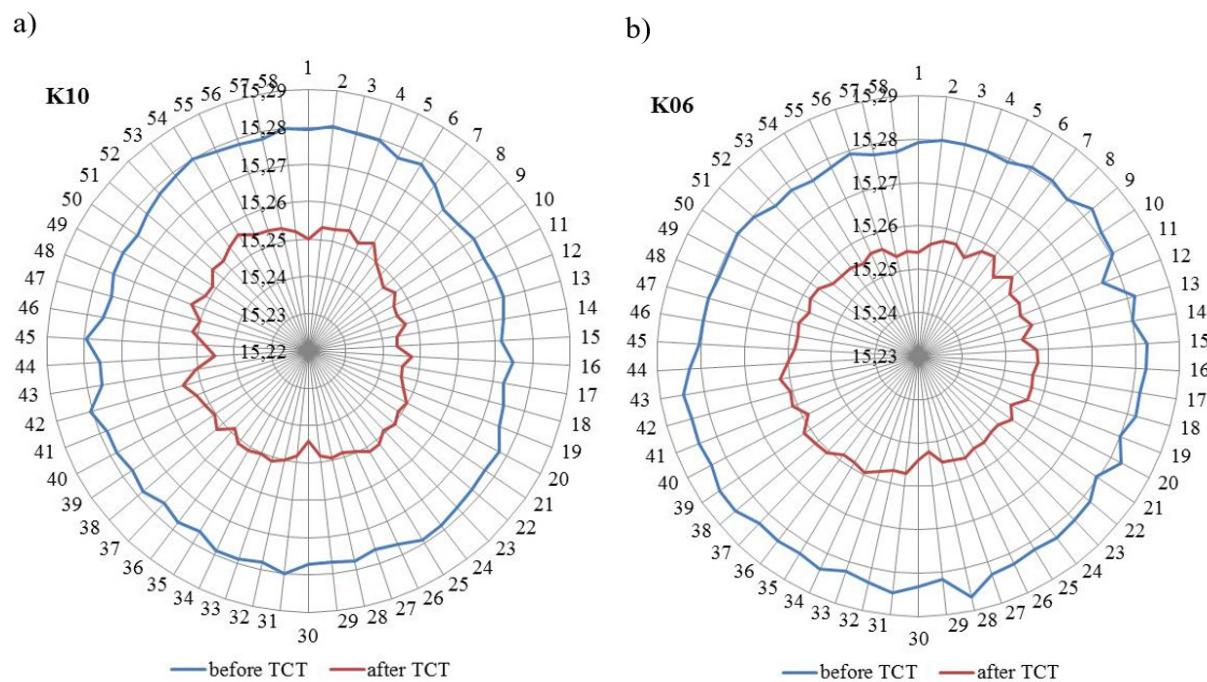


Fig. 6. Graph of changes in the radius r_o before and after TCT: a) K10 gear wheel, b) K06 gear wheel

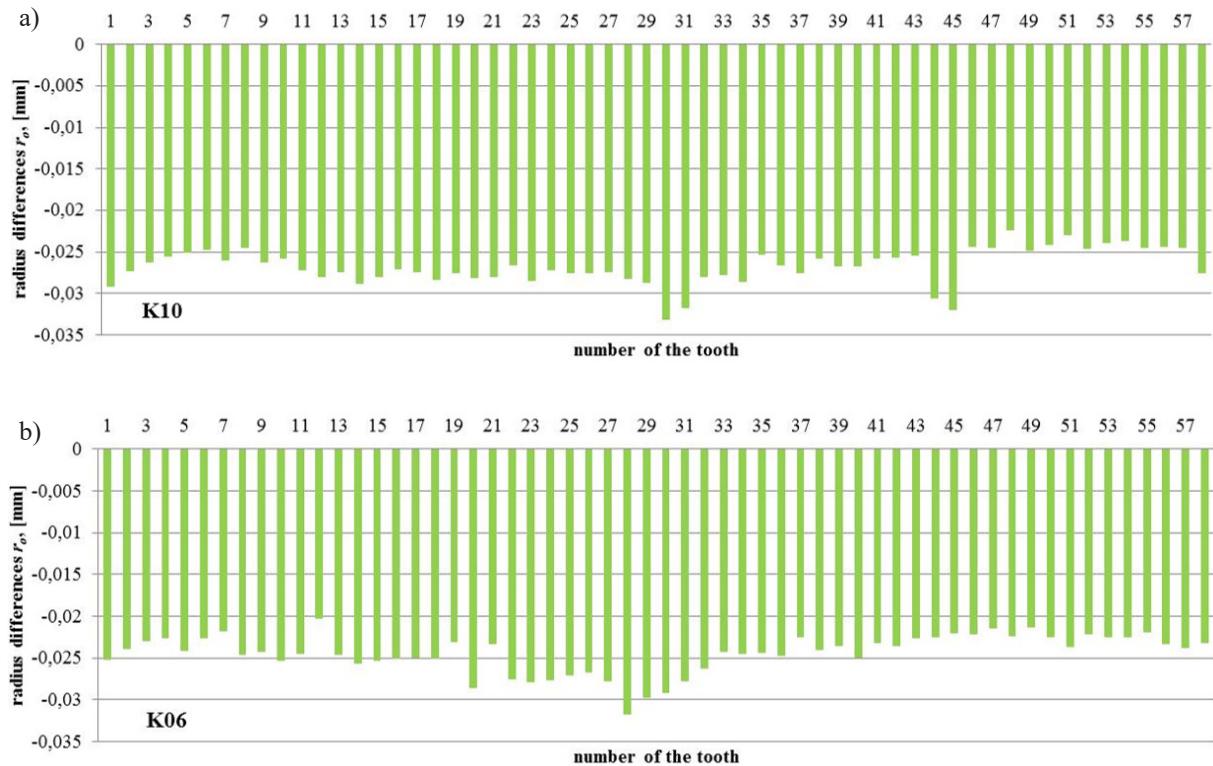


Fig. 7. Differences in the radius r_o values resulting from TCT: a) K10 gear wheel, b) K06 gear wheel

On the basis of the median value provided in Table 4 and illustrated on Fig. 8 it must be stated that as a result of thermo-chemical treatment the value of radii r_o of mounting hole decreased in both cases. It is obvious that the hole diameters d_o changed as well in consequence. In case of the K06 gear wheel, for which a lower cooling gas pressure (6 bar) was applied, there was found a decrease in the retaining radius r_o by 0.024 mm. In case of the K10 gear wheel, for which a higher cooling gas pressure (10 bar) was applied, the radius decreased by 0.027 mm.

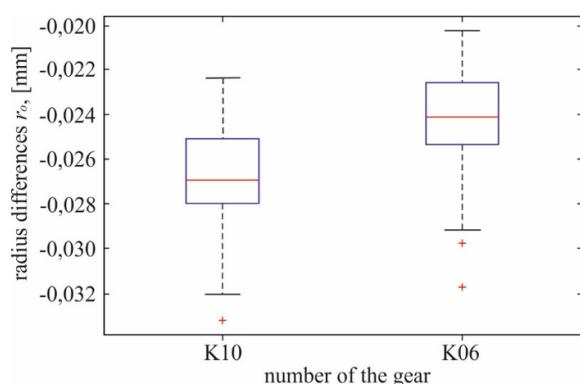


Fig. 8. Box plot for values of differences between the radii r_o of mounting hole; K10 and K06 gear wheels

OUTSIDE DIAMETER D_A

Fig. 9 presents a graph showing the shape of circle measured on the outside surface, resulting from measurements of the radius r_a . The curves on the graph correspond to the values of radii measured before and after the thermo-chemical treatment.

On the basis of the above graphs it can be stated that as a result of the thermo-chemical treatment there occurred a decrease in diameters of circles measured on outside diameters of both gear wheels. It is easy to notice the asymmetry of the measured circles' location in relation to the determined origin of the coordinate system. This is caused by errors in generation of the cylindrical surface of gear blank that are impossible to eliminate entirely and is not related to the subsequent thermo-chemical treatment.

Graphs on Fig. 10 show the differences between the radii r_a values resulting from TCT.

When analyzing the graphs shown on Fig. 10 it should be noted that on the toothed-wheel rim circumference there are present, in alternating manner, the areas where differences between the outside radii r_a values either increase or decrease. According to the authors, this is caused by the arrangement of cooling nozzles,

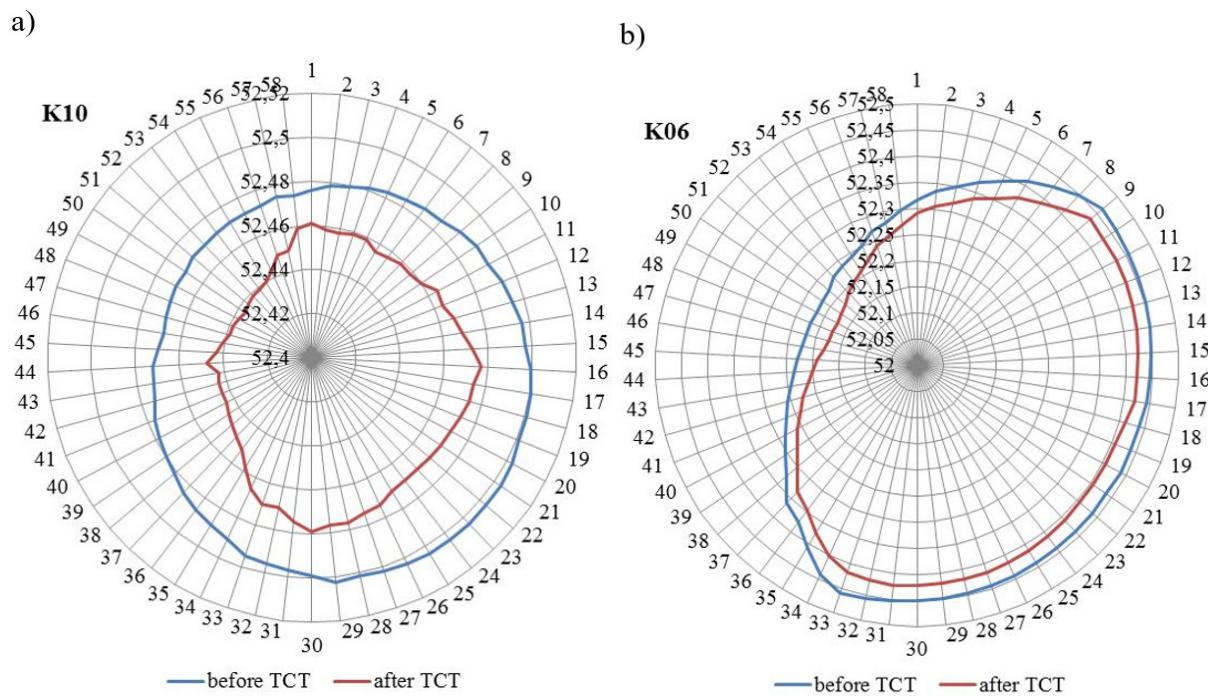


Fig. 9. Graph of changes in the radius r_a before and after TCT: a) K10 gear wheel, b) K06 gear wheel



Fig. 10. Differences in radius r_a values resulting from TCT: a) K10 wheel, b) K06 wheel

particularly during the first stage of cooling agent feeding, similarly to the case of chordal tooth thickness.

Table 5 contains the results of statistical elaboration of the differences between the outside

radii r_a for both gear wheels. Figure 11 shows a graphical elaboration of results in the form of a box plot.

On the basis of median value provided in Table 5 and illustrated on Figure 11 it must be

Table 5. Values of difference parameters for outside radii r_a

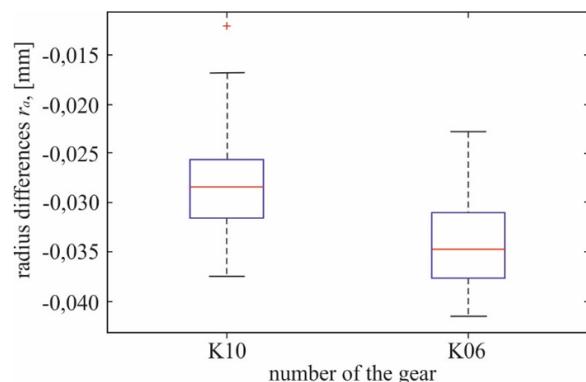
Parameters	Values	
	K10	K06
Max.	-0.017	-0.023
Upper Whisker	-0.017	-0.023
Q3 (75%)	-0.026	-0.031
Q2 (50%) - median	-0.028	-0.035
Q1 (25%)	-0.032	-0.038
Lower Whisker	-0.038	-0.042
Min.	-0.038	-0.042
Number of points n	58	58
Number of outliers	1	0

stated that as a result of thermo-chemical treatment the values of outside radii r_a decreased in both cases. It is obvious that the d_a outside diameters decreased as well in consequence. In case of the K06 gear wheel, for which a lower cooling gas pressure (6 bar) was applied, there was found a decrease in the mounting hole radius by 0.035 mm. In case of the K10 gear wheel, for which a higher cooling gas pressure (10 bar) was applied, there radius decreased by 0.028 mm.

CONCLUSIONS

On the basis of the results obtained it is possible to formulate the following conclusions:

1. The chordal tooth thickness value s increases under the influence of thermo-chemical treatment, whereas the greater thickness values were obtained at the lower gas pressure.
2. As a result of thermo-chemical treatment there occurred a decrease in value of mount-

**Fig. 11.** Box plot for the values of differences between the outside radii r_a ; K10 and K06 gear wheels

ing hole radii r_o , whereas the greater values of radii were obtained at the lower gas pressure. Therefore, the application of higher cooling gas pressure results in smaller hole diameter d_o than in case of application of lower cooling gas pressure.

3. As a result of the thermo-chemical treatment the outside radii r_a decreased, whereas the greater values of radii were obtained for higher gas pressure. Therefore, the application of higher cooling gas pressure results in smaller diameter of the cylindrical outside surface than in the case of application of lower cooling gas pressure.
4. In order to minimize the amplitude of deformations after quenching, the operation of HPGQ 4D Quenching chamber has to be optimized with regard to the changes in shape of nozzle manifold and the operating parameters.

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