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# Impact of single-piece flow thermo-chemical treatment process conditions on hole quenching deformation

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## ABSTRACT

**Purpose:** Pulsed low-pressure carburizing (LPC) and omnidirectional high-pressure gas quenching (HPGQ) are innovative methods for quenching the surface layer. The thermo-chemical treatment carried out by this method reduces quenching geometric deformations, with detailed numerical values not available in the literature due to the short existence of this method.

**Design/methodology/approach:** Sixteen toothed elements of EN 20MnCr5 steel were subjected to pulsed low-pressure carburising with omnidirectional jet quenching in 4 groups, varying the process temperature (920°C, 960°C) and in two groups performing a tempering treatment. The elements were tested before machining by measuring their internal hole diameters, radial runout, roundness and cylindricity. These values were tested again after treatment. The direction of change and the statistical significance of the effect of treatment and its parameters, temperature and tempering were analysed.

**Findings:** Thermo-chemical treatment significantly affects geometric changes in diameters, roundness, cylindricity and radial runout compared to elements without heat treatment due to physical transformations occurring during this treatment ($p<0.05$). Changing the process temperature in the value range of 920°C-960°C affects the hole diameter (makes it smaller) ($p<0.05$), but does not affect radial runout, cylindricity and roundness. The observed dimensional changes in diameters have numerically small values (<0.005 mm). The tempering treatment can affect the values of average diameters. Its effect on roundness, cylindricity and radial runout was not observed.

**Research limitations/implications:** In the temperature range studied, the method of pulsed low-pressure carburising + omnidirectional high-pressure gas quenching makes it possible to raise the temperature of the process and shorten its duration without significant geometric changes in the treated elements.

**Practical implications:** The method of pulsed low-pressure carburising and omnidirectional high-pressure gas quenching (HPGQ) ensures the maintenance of reproducible quenching deformations at a level significantly lower than conventional processing methods.

**Originality/value:** The method of pulsed low-pressure carburising together with omnidirectional high-pressure gas quenching (HPGQ) is a method that has been used briefly in the industry, and there are few reports on it to date.

**Keywords:** Distortion, Quenching, Single-piece flow method, Case hardening, Low-pressure carburising

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MATERIALS MANUFACTURING AND PROCESSING

## 1. Introduction

Centre holes in gears are used for seating the gear on the shaft at the location intended by the designer. During this operation, the gear is moved along the shaft axis and can be rotated around its axis. For this reason, the connections of these elements are most often made using a loose fit, such as H7/h6 (according to DIN ISO 286). The use of a fit requires the hole to be produced according to the tolerances prescribed by the standard, which, due to the small order of deviation, can only be achieved by finishing machining. In addition, since steel gears are generally subjected to heat or thermo-chemical treatment, maintaining the required dimensional tolerance requires the use of hole-grinding operations to remove the allowance that occurs due to material deformation.

It should be borne in mind that although, in this case, the grinding process is a technologically sound treatment, it is also time- and energy-consuming, generating large manufacturing costs. Thus, efforts are made to achieve the smallest possible dimensional and shape deviations after the heat treatment process to enable the removal of small allowances. In addition, the deviation values in successive holes should be repeatable.

The method of pulsed low-pressure carburizing implemented by single-piece flow and unitary omnidirectional high-pressure gas quenching was developed to reduce post-quenching geometric deformations [1,2]. Quenching deformation is an invariable part of heat and thermo-chemical processing. It is associated with martensitic transformation, in which austenite cells transform into martensite cells by changing their volume [3]. The magnitude of the volume change depends, among other things, on the carbon content of the austenite. The element of high variability is the heterogeneity of the material structure and heterogeneous processing conditions. All this makes post-quenching geometric deformations in the elements difficult to control. The single-piece flow method removes the element of inhomogeneity of carburising and cooling conditions, contributing to the reduction of deformations and increasing their repeatability.

Accordingly, this article describes an experimental study to determine the effect of selected thermo-chemical treatment process conditions on deformation in the holes of gears made of 20MnCr5 steel. The gears were subjected to vacuum carburising (LPC) by the single-piece flow method and high-pressure gas quenching (HPGQ). The holes in the gears were measured twice, before and after heat treatment. The results of the measurements made it possible to analyse the deformation of the hole based on its: diameter, roundness, cylindricity and radial runout. The following null hypotheses were tested:

(1) no differences in gear parameters would be found between groups where the carburising temperature was 920°C and those where the carburising temperature was 980°C;

(2) tempering would not affect parameters.

Section 2 presents the conditions of the experimental research, along with a description of the test benches. The results of the study with their analysis are presented in Section 3, discussed in Section 4 and summarised in Section 5.

## 2. Experimental tests

### 2.1. Workpiece

Sixteen toothed elements (gears) were used in the study. External spur gears manufactured from 20MnCr5 steel were drilled centre holes for seating the gears on the shaft. These holes, with a length of $l = 20$ mm, corresponding to the width $b$ of the gear rim, were finish-ground to a D = ø30 H7 mm diameter. Tolerance H7 is often used in motion joints, such as the hub of a gear with a shaft, ensuring a loose fit of these elements. The geometric parameters of the made gears are summarised in Table 1.

Table 1.
Gear wheel parameters

| Parameter | Value |
|---|---|
| Hole diameter $D$ | ø30 H7 mm |
| Hole length $l$ (face width $b$) | 20 mm |
| Outside diameter $d_a$ | 160 mm |
| Module $m$ | 5 mm |
| Number of teeth $z$ | 30 |
| Pressure angle $\alpha$ | 20° |
| Helix angle $\beta$ | 0° |
| Profile shift coefficient $x$ | 0 mm |

## 2.2. Single-piece flow low-pressure carburizing and quenching

The fabricated gears were subjected to a thermo-chemical treatment process using an innovative vacuum furnace with a stream flow of elements (Seco/Warwick, Poland) shown in the figure (Fig. 1). The unit is used for single-piece flow thermo-chemical processing, which includes pulsed low-pressure carburizing and unitary quenching in high-pressure gas.

The elements in the furnace pass in a stream (consecutively) through three horizontally spaced process chambers, described in Figure 1 as heat-up, LPC and diffusion. The chambers are housed in a common vacuum space with gas-tight separation. The element moves between process chambers in transport chambers (elevator) equipped with loading and unloading systems. External access to the transport chambers is realised through a loading lock (IN) and an unloading lock (OUT). This furnace design ensures that each element goes through identical positions and process conditions in the furnace. As a result, carburisation is characterised by high precision and repeatability with respect to conventional methods [4-6].

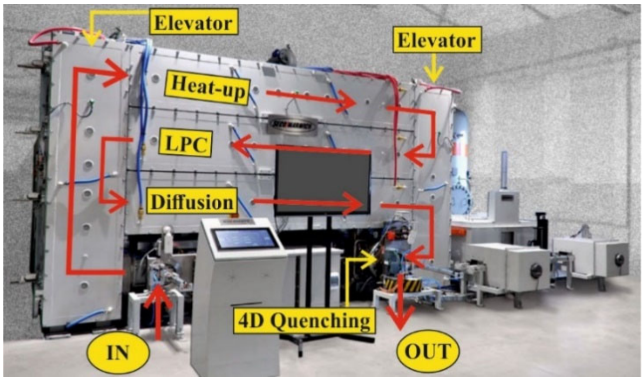

Fig. 1. A furnace for low-pressure carburising with a single-piece flow of elements (Seco/Warwick, Poland)

After the carburising process, the elements are individually subjected to high-pressure gas quenching (HPGQ) in a 4D Quenching chamber [7-10]. It allows the cooling curve to be freely shaped and makes achieving the appropriate microstructure and material properties possible. It is worth noting that the innovative chamber design features a system of cooling nozzles that surround the element and ensure an even flow of cooling gas from all sides. In addition, the quenching chamber is equipped with

Table 2.
Heat treatment (LPC+HPGQ+T) processes parameters

| Process type | Process parameter | Process number (gear numbers) | | | |
|---|---|---|---|---|---|
| | | P1/T (1-4) | P1/- (5-8) | P2/T (9-12) | P2/- (13-16) |
| LPC | Temp., °C | 920 | | 960 | |
| | Tact, sec. | 240 | | 160 | |
| | Boost, sec. | 6 | | 8 | |
| | Flow, dm$^3$/min | 5 | | 7 | |
| | Pressure, hPa | 3 | | 3 | |
| HPGQ | Gas | nitrogen | | nitrogen | |
| | Pressure, MPa | 0.7 | | 0.7 | |
| | Precooling temp., °C | 860 | | 860 | |
| T | Temp., °C | 190 | - | 190 | - |
| | During, min | 180 | - | 180 | - |

LPC – low-pressure carburizing
HPGQ – high-pressure gas quenching
T – tempering
HT – heat treatment

a table that rotates with the element and aids in uniformity of cooling (4D). This cooling system solution allows cooling intensity comparable to oil systems without the need for helium (He).

Two thermo-chemical treatment processes (LPC+HPGQ) were carried out on the test bench, treating eight elements in each process. The planned effective case depth (ECD) in both cases was 0.6 mm. The test processes (P1, P2), differed in using different carburisation temperatures. The remaining parameters, the length of the saturation tact and stage, gas flow rate and pressure, were selected for the conditions of the process at 920°C and 960°C, based on the work of A. Brewka-Stanulewicz [11]. Four gears from each process were tempered. Table 2 shows the thermo-chemical treatment conditions for the cases discussed above.

### 2.3. Distortion measurement

Deformations in the holes were measured on a test bench equipped with a coordinate measuring machine (CMM) DEA Performance 5.7.5 and a computer with PC-DMIS CAD++ software. The CMM enabled measurements whose MPEE (Maximum Permissible Error for length measurement) uncertainty, according to ISO 10360, was ± 0.003 mm.

The gear hole was measured twice before and after thermo-chemical treatment. In order to make it easier to identify the teeth of the gear during the measurements, one of the teeth was marked as "1" before the thermo-chemical treatment. It was assumed that successive tooth numbers would increment in a clockwise direction. In addition, each gear was placed in the UCM furnace chamber in such a way that tooth No. 1 faced the same direction, and the marking was visible on the face of the gear.

Each settling hole was measured in three sections (Fig. 2). The sections were arranged along the axis of the hole at a distance *h*, measured from the top face of the gear and equal to respectively: 3 mm (level L1), 10 mm (level L2) and 17 mm (level L3). At each of the three levels, 30 measurement points were planned, spread out around the perimeter of the measurement circle every 12°. The number of measurement points corresponded to the number of teeth of the gear, and the numbering of measurement points at each level corresponded to the tooth numbers.

Four parameters were chosen to evaluate hole deformation: one related to hole dimension and three to hole shape. These were hole diameter *D*, roundness, radial runout and cylindricity, respectively (according to PN EN ISO 1101:2012). The first three parameters were determined at three levels (L1, L2, L3).

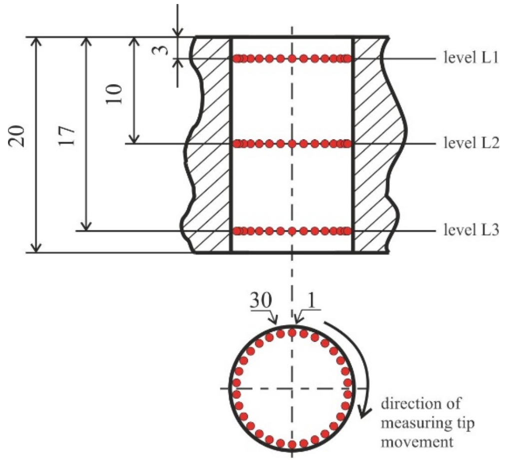

Fig. 2. Method of arranging measuring points inside the measured hole

## 3. Results and discussion

Table 3 summarises the average values of hole diameters measured at three levels (L1, L2, L3) before and after thermo-chemical treatment for four process conditions (according to Tab. 2). In addition, the following table summarises the calculated diameter differences and provides the standard deviation. The small standard deviation values indicate that individual measurement results are highly clustered around the mean.

For four variants of HT process conditions, there was a reduction in the diameter *D* of the hole after heat treatment. It should be noted that all differences are small and do not exceed 0.005 mm (Fig. 3), but they are statistically significant ($p<0.05$) (Fig. 4).

Table. 3.
Measuring results of holes diameter

| Proc. no | Meas. level | Hole diameter *D*, mm | | | |
|---|---|---|---|---|---|
| | | Green part, mm | After HT, mm | Diff., mm | SD |
| P1/T | L1 | 31.757 | 31.733 | -0.024 | ±0.003 |
| | L2 | 31.761 | 31.741 | -0.020 | ±0.003 |
| | L3 | 31.764 | 31.744 | -0.020 | ±0.003 |
| P1/- | L1 | 31.755 | 31.738 | -0.017 | ±0.002 |
| | L2 | 31.761 | 31.747 | -0.014 | ±0.002 |
| | L3 | 31.758 | 31.745 | -0.013 | ±0.003 |
| P2/T | L1 | 31.754 | 31.721 | -0.032 | ±0.003 |
| | L2 | 31.757 | 31.727 | -0.030 | ±0.002 |
| | L3 | 31.757 | 31.731 | -0.027 | ±0.002 |
| P2/- | L1 | 31.755 | 31.727 | -0.028 | ±0.003 |
| | L2 | 31.759 | 31.733 | -0.025 | ±0.002 |
| | L3 | 31.760 | 31.737 | -0.023 | ±0.002 |

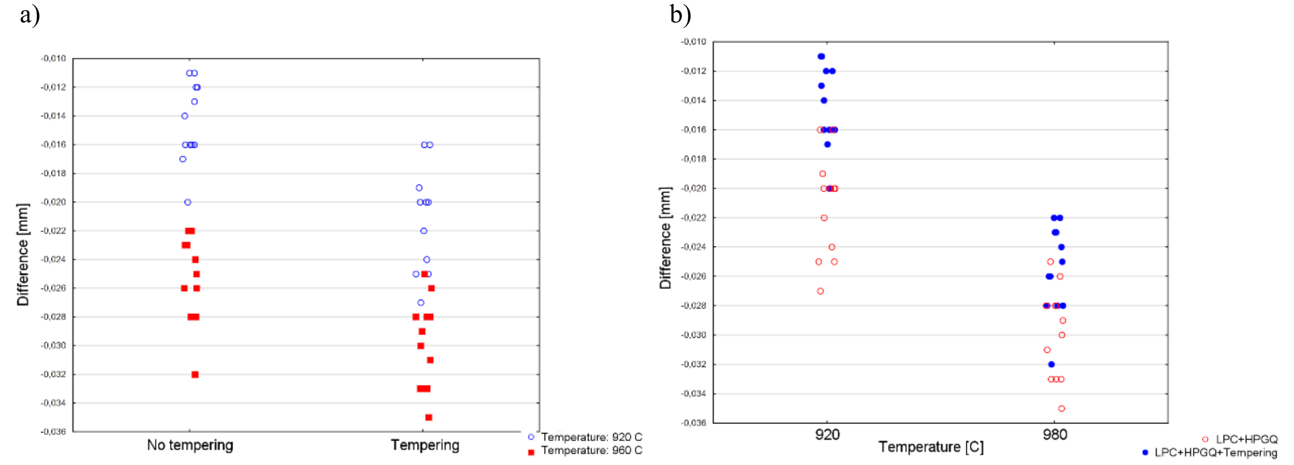

Fig. 3. Dispersion of diameter differences before and after thermo-chemical treatment in groups (a) where tempering was/was not performed, (b) where process temperatures were 920°C and 960°C

Statistical analysis of the data (2-way ANOVA) reveals the statistical significance of the effects of both temperature and tempering process on these differences (dimensional deformations obtained) ($p<0.05$). Within 920°C, conducting tempering does not significantly differentiate diameter changes. Running the process at 960°C causes a greater reduction in diameter, and conducting tempering at this temperature further intensifies this phenomenon, as revealed by Tukey's posthoc test (Fig. 5).

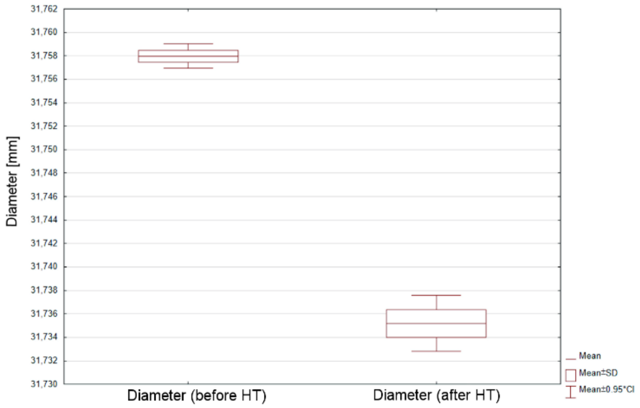

Fig. 4. Illustration of t-Student's test of statistical significance of the mean differences in inner hole diameters *D* before and after thermo-chemical treatment

The dispersion of roundness differences among the groups is shown in Figure 6. Statistical analysis (Student's t-test) indicates that there are significant differences between the mean values of roundness before and after treatment, both in the group of elements that underwent tempering (t=4.41) and in the group where only carburising and quenching were carried out (t=3.20) ($p<0.05$). However, these differences are not significant in the 920°C and 960°C temperature groups, which means that in this temperature range, increasing or decreasing the temperature does not affect roundness (Fig. 6).

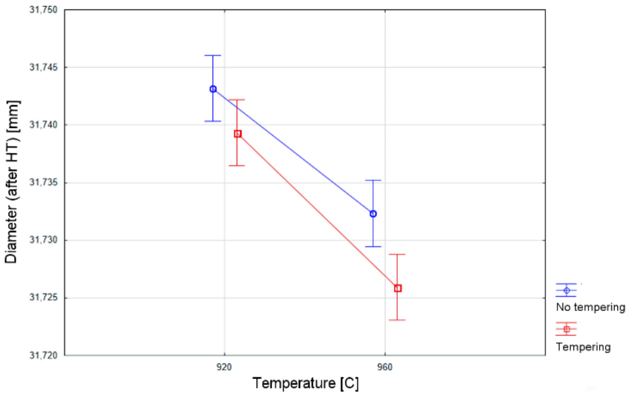

Fig. 5. Effect of temperature and tempering on the change in inner diameter *D* of the gear

Analysis of the results of radial runout (Wilcoxon test) shows that thermo-chemical treatment significantly affects radial runout toward negative values ($p<0.05$), although the change of process temperatures in the value range of 920°C -960°C and the use of a tempering process have no significant effect on the obtained values.

The effect of the thermo-chemical treatment performed on the average cylindricities was observed only in the group of elements without tempering ($p<0.05$). After the tempering process, the variation in this geometric dimension disappears. Changing the processing temperature from 920°C to 960°C does not significantly affect geometric changes in cylindricity.

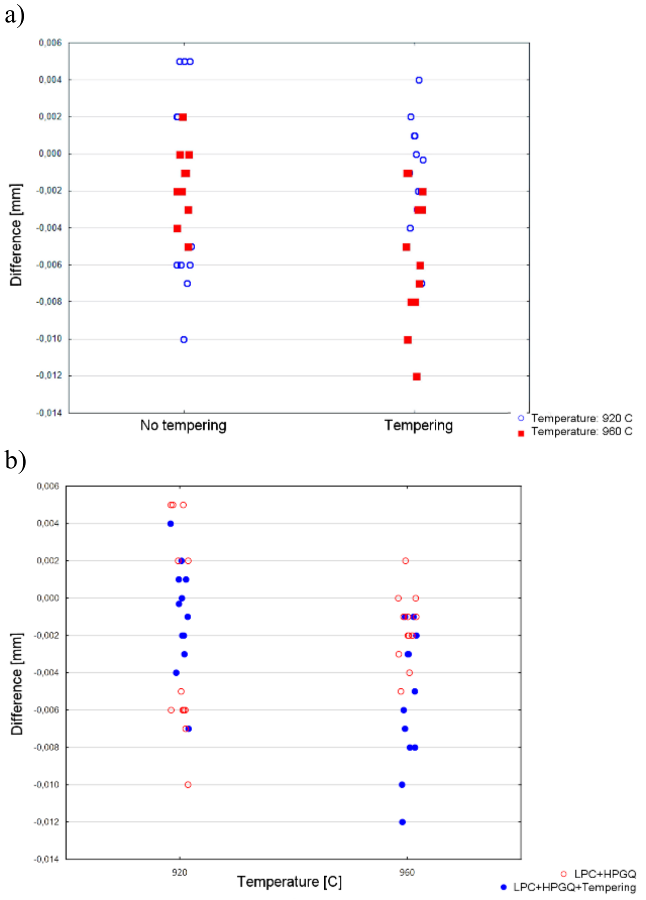

Fig. 6. Dispersion of roundness differences before and after thermo-chemical treatment in groups (a) where tempering was/was not performed, (b) where process temperatures were 920°C and 960°C.

## 4. Conclusions

Based on the results obtained for the test conditions used, the following conclusions can be drawn:

(1) heat treatment at the applied temperature level (920°C-960°C) significantly affects geometric changes in diameters, roundness, cylindricity and radial runout compared to elements without heat treatment,

(2) changing the process temperature in the value range of 920°C-960°C affects the hole diameter (makes it smaller) but does not affect radial runout, cylindricity and roundness. These parameters, allows to rise the temperature of the process and shortens its duration without harmful effects. For these diameters, a change in this parameter will occur, but these values are numerically small (<0.005 mm),

(3) the tempering process can affect diameter values. No effect was observed on roundness, cylindricity and radial runout.

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