This paper presents a comparison of the deformations and residual stresses in gear wheels after vacuum carburizing process with quenching in high-pressure nitrogen and oil. The comparison was made on a medium-sized gear wheels, made of AMS6265 (AISI 9310) steel. This steel is applied in the aerospace industry for gears. The study has provided grounds for an assessment of the effect of the method of quenching on the size of deformations. Compared to oil quenching, high-pressure gas quenching following vacuum carburizing resulted in more uniform and smaller deformations.

Keywords: thermo-chemical treatment, vacuum carburizing, carburized layer, quenching, quenching deformations, low-pressure carburizing
are two-chamber furnaces, additionally equipped with an oil bath in which items are quenched. While oil quenching has the disadvantages mentioned above, it has one advantage compared to gas quenching this is higher heat transfer coefficient, which enables the quenching of parts made of steel of lower hardenability; therefore, this cooling method is still applied in industry [10-14,16].

The aim of this study is to compare the deformations of medium-sized gear wheels made of AMS6265 (AISI 9310) steel, after vacuum carburizing process with high-pressure gas-quenched or oil-quenched, to identify the beneficial conditions of thermal treatment.

2. Material and methods

Gear wheels made of AMS6265 steel (chemical composition Tab. 1), of module m = 5 and the number of teeth = 30 were vacuum carburized (Fig. 1). Carburizing was done in a one-chamber furnace with high-pressure nitrogen cooling and in a two-chamber furnace with an oil bath – both devices manufactured by Seco/Warwick S.A. The dimensions of the furnace heating chamber: 400×400×600 mm. Each gear wheel was positioned vertically in the middle area of the furnace chamber on a special device, which guaranteed the well-defined and repeatable deployment during carburizing and cooling. The first two teeth of each wheel were marked permanently on their side surfaces to ensure the repeatable conditions of the experiment (as shown in Fig. 1). Gear wheels, before the carburizing process, were annealed in vacuum at 860°C for 3 hours. The carburizing atmosphere consisted of a mixture of acetylene – ethylene – hydrogen. Carburization was done in the FineCarb® technology [17]. The parameters of the carburized layer were designed: surface carbon concentration = 0.75%wt., effective case depth = 0.5 mm (for criterion = 0.4%wt.C). In order to achieve the desired carbon concentration profile, the duration of the boost/diffusion process segments was selected based on the simulation made using the SimVaCPlus® program.

The vacuum carburizing process stages are described below:
- pumping up to pressure 10 Pa,
- soaking for 20 min. at 950°C,
- vacuum carburizing at 950°C, at pressure 300÷800 Pa, boost/diffusion time [min.]: 6:00/13:00, 4:00/34:30, 3:30/16:00,
- heating up to temperature 950°C with ramp 10°C/min.,
- precooling to temperature 860°C and soaking for 20 min.,
- gas quenching (nitrogen) to 50°C at a pressure of 1.4 MPa or oil quenching at a temperature of 50°C in an oil bath with stirring.

TABLE 1

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,126</td>
<td>0,530</td>
<td>1,017</td>
<td>3,243</td>
<td>0,137</td>
<td>0,243</td>
</tr>
</tbody>
</table>

3. Results and discussion

The martensitic structure with retained austenite of similar concentrations was obtained in both cases (Fig. 2 and 3). The amount of retained austenite was 21±2% after gas quenching, and 19±3% after oil quenching. The content of retained austenite was determined by X-ray method with use of PROTO iXRD diffractometer. The surface layer carbon profiles obtained in the vacuum carburizing processes are shown in Fig. 4. The carbon concentration in a layer was measured with a glow discharge optical emission spectrometer – LECO GDS850A.

Retained austenite content was measured in compliance with ASTM E-975. Since steel contains crystalline phases such as ferrite or martensite and austenite, a unique X-ray diffraction pattern for each crystalline phase is produced when the steel sample is irradiated with X-radiation. For a randomly oriented sample, quantitative measurements of the relative volume fraction of ferrite and austenite can be made from X-ray diffraction patterns because the total integrated intensity of all diffraction peaks for each phase is proportional to the volume fraction of that phase.

For steel containing only ferrite (α) and austenite (γ) and no carbides, the integrated intensity from the (hkl) planes of the ferrite phase is expressed as.

\[ I_{α}^{hkl} = K R_{α}^{hkl} V_{α} / 2μ \]

Where K is a constant which is dependent upon the selection of instrumentation geometry and radiation but independent of the nature of the sample. The parameter, R, is proportional to the theoretical integrated intensity. The parameter, R, depends upon interplanar spacing (hkl), the Bragg angle, θ, crystal structure, and composition of the phase being measured.

A similar equation applies to austenite. For any pair of austenite and ferrite (or martensite) hkl peaks:

\[ \frac{I_{α}^{hkl}}{I_{γ}^{hkl}} = \left( \frac{R_{α}^{hkl}}{R_{γ}^{hkl}} \right) \times \left( \frac{V_{α}}{V_{γ}} \right) \]
The volume fraction of austenite \( (V_\gamma) \) for the ratio of measured integrated intensities of ferrite (or martensite) and austenite peak to \( R - \) value is

\[
V_\gamma = \frac{I_\gamma}{R_\gamma} \left( \frac{I_\alpha}{R_\alpha} + \frac{I_\gamma}{R_\gamma} \right)
\]

To characterize the concentration of retained austenite using PROTOiXRD four diffraction peaks are collected by the instrument, two for the austenite, namely \{200\} and \{220\} and two for martensite, namely \{200\} and \{211\}. A comparison of the intensities of the 4 peaks yields the volume percent concentration of retained austenite in the sample.

![Fig. 2. Microstructure of the surface layer of AMS6265 steel after low pressure carburizing and gas quenching](image)

Fig. 2. Microstructure of the surface layer of AMS6265 steel after low pressure carburizing and gas quenching

![Fig. 3. Microstructure of the surface layer of AMS6265 steel after low pressure carburizing with oil hardening](image)

Fig. 3. Microstructure of the surface layer of AMS6265 steel after low pressure carburizing with oil hardening

Figure 5 shows the distribution of micro-hardness as a function of the distance from the surface for AMS6265 steel obtained by vacuum carburizing and gas- and oil-quenching. Hardness tests were made in accordance with standard PN-ISO 2639:2005, at load 10 N (HV1).

![Fig. 5. Microhardness profiles of AMS6265 steel after low pressure carburizing with hardening](image)

Fig. 5. Microhardness profiles of AMS6265 steel after low pressure carburizing with hardening

This was followed by determination of internal stresses in gear wheels subjected to two variants of thermal treatment. The measurements were conducted for the same teeth on each wheel, no. 1, 6, 12, 18 and 24 (Fig. 6). Stress measurements were conducted by the X-ray method \( \sin^2\psi \) with use of the x-ray diffractometer, in accordance with standard SAE HS-784. Residual stresses distribution was measured by X-ray \( \sin^2\psi \) diffraction method on PROTO iXRD analyzer. X-ray tube generating characteristic CrK\( \alpha \) radiation was applied. Characteristic ferritic peak positions were measured at 2\( \Theta \) angle equal 156° giving diffraction patterns from \( \{211\} \) planes. Measurements were performed for eleven (five positive, five negative and “0”) \( \psi \) (\( \psi \)) angles in the range from \(+ 30^\circ\) to \(– 30^\circ\) in relation to \( \beta \) angle. Diffraction peak positions were analyzed by Pearson VII peak fit function. Measurements were performed on the pitch diameter of examined teeth.

The geometry of the measurement is presented in Figure 7 [20].
Measurements of the gear wheels used in the experiment were performed in order to determine the effect of thermal treatment on deformations. Radial run-out was measured on the pitch diameter before and after carburizing with quenching. Radial run-out was measured with an accuracy of ±1 μm by gearwheel measurement device manufactured by Carl Zeiss Jena. The measurements were performed for each gear wheel by determination of the radius from the rotation axis to the pitch diameter. The measurement results are shown in the diagrams presented in Figures 8 and 9. The mean deformation is 6 ±4 μm after gas quenching and 12 ±9 μm after oil quenching. Next measurement was made of the tooth thickness of each of the gear wheels on three different heights: on the head tooth (h₁), on the pitch diameter (h₂) and on the foot of the tooth (h₃). The measuring position from the top of a tooth was: 1.5 mm (h₁), 5.0 mm (h₂) and 9.5 mm (h₃), as shown in Figure 10. The results of these study are presented in Figures 11 and 12. The average size of the deformation the thickness of the teeth for the gear wheels after gas – and oil – quenching presented in Table 2.

<table>
<thead>
<tr>
<th>Quenching method</th>
<th>Tooth thickness [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t₁</td>
</tr>
<tr>
<td>gas</td>
<td>9 ±6</td>
</tr>
<tr>
<td>oil</td>
<td>56 ±8</td>
</tr>
</tbody>
</table>

Table 2: The average size of the deformation the thickness of the teeth for the gear wheels after gas- and oil-quenching.
The treatment performed in this experiment resulted in the correct structure of the surface layer of AMS6265 steel, typical for carburized and quenched layer with the same phase composition, regardless of the method of quenching applied (Fig. 2, 3). Layers consistent with the design, with the specified carbon distribution of and hardness profile, were obtained in each of the treatment variants (Fig. 4, 5). Residual stresses in gear wheels after low pressure carburizing with gas quenching were about 100MPa lower than in gear wheels after oil hardening. The pitch diameter was found to increase around the whole perimeter of the gearwheel after the treatment. A comparison of the deformations for each gearwheel has shown that vacuum carburizing followed by high-pressure gas quenching resulted in lower deformations than vacuum carburizing followed by oil quenching (Fig. 8, 9). The average radial deformation was measured on the pitch diameter is about 50% lower, although higher the residual stresses after oil quenching. Unlike with oil quenching, the deformations formed with gas quenching are more uniform.

Fig. 10. Places of the thickness measurement of teeth

Deformation of the head tooth is many times higher than the foot of the tooth. This is due to the difference in cooling rate between gas and oil. In the case of hardening in oil higher cooling rate resulted in an increase in deformation of the head tooth.

4. Conclusions

The following conclusions can be drawn from this experiment:
1. Compared to high-pressure gas quenching after vacuum carburizing, oil quenching resulted in the increase of deformations.
2. Unlike with oil quenching, deformations formed with gas quenching were more uniform, which helps to predict the deformation and the size of excess to correct the dimensions following heat treatment.
3. In the case of gear wheels made of steel of higher hardenability, cooling the gas after vacuum carburizing is better than oil quenching, taking into account the size and character of deformation.

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REFERENCES


