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Enhancement of Gears Fatigue Properties by Modern Thermo–Chemical Treatment and Grinding Processes

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It was found that the application of both surface hardening processes by means of vacuum carburizing and final grinding with the use of CBN grinding wheels has a synergistic effect in the generation of favourable compressive residual stresses in the surface layer of gear teeth. This spectrum of residual stresses has a favourable effect on functional properties of gears, for example on bending and contact fatigue strength. The results of investigations on residual stress distribution after conventional and vacuum carburizing as well as after grinding with conventional and CBN grinding wheels are discussed in the paper. Also the lower scatter of gears dimensions after vacuum carburizing, which enables an application of lower grinding allowances, is presented. Examples of stresses distribution by means of FEM method modelling and stressing of gear teeth resulting from residual stresses and external loads are shown in the paper. Also, the description of the special equipment that allows the experimental evaluation of bending fatigue strength is described, followed by the results of these tests. The experiments showed an improvement of gears bending fatigue strength after a technological process which combines vacuum carburizing and subsequent CBN grinding.

Keywords: CBN grinding, fatigue strength, vacuum carburizing

1. Introduction

Gears are parts of mechanisms which work in a very complex tribological, fatigue and/or environmental functional system. This is due to the fact that the gear teeth are subjected to varying bending and contact stresses as well as sliding and rolling friction with velocities that change in magnitude and direction. Sometimes an aggressive chemical environment (e.g. in off–shore or chemical industries) may influence the functional behaviour of gear transmission as well. This is why the creation of favourable surface layer properties in the technological process applied is a crucial point in the production of high quality, highly loaded gears.

One of the most important surface layer parameters that significantly influences the functional aspects of the parts machined is the residual stress distribution. Its effect on functional behaviour of workpieces is widely described in literature [1] [2] [3] [4].

Technological processes that are applied in surface engineering in large batch and mass production of gears are continually developed aiming at their improvement in technical, economical and environmental scope. Currently, two innovative processes are undoubtedly the leading solutions: vacuum carburizing and CBN grinding.

One of the aims of both processes is to create surface layer properties that result in high contact fatigue strength, high bending fatigue strength and high wear resistance. These requirements can be satisfied by the proper structure and thickness of a hardened layer as well as by the advantageous final distribution of residual stress created in the technological process, especially in such finishing operations as grinding. Till now, there are no investigations which have shown results of application of vacuum carburizing and CBN grinding on fatigue strength of gear teeth. Nevertheless, literature analysis shows that a synergistic effect in the creation of an advantageous residual stress distribution should be observed in such a case [5]. To confirm these expectations both analytical and experimental investigations were carried out and results of this research are presented below.

2. Vacuum carburizing

The process of vacuum carburizing is carried out in the conditions which are far from thermodynamic equilibrium. Carbon atoms for austenite saturation come from the reaction of thermal decomposition of saturated or non–saturated aliphatic hydrocarbons.

Due to the high near–surface carbon concentration in austenite each vacuum carburizing process consists of the cycles of the austenite saturation in carbon–carrying gaseous atmosphere under low working pressure as well as of the ones of diffusion transfer of the excessive carbon atoms into deeper layers of the material, applied alternately with carburizing cycles in deeper vacuum conditions (without any carbon–carrying gases in the environment) [6] [7].

The control of a vacuum carburizing process is a difficult optimization problem based on affecting the process kinetics. A division of the whole process into carburizing and diffusion stages has to take into consideration the possibility to obtain the required profile of carbon saturation in the shortest possible time. Also maximal (instantaneous) carbon saturation has to be analyzed and limited in order to prevent the separation (creation) of stable carbides of alloying elements. The latter is particularly important for the high alloy steels containing carbide–forming alloying elements.

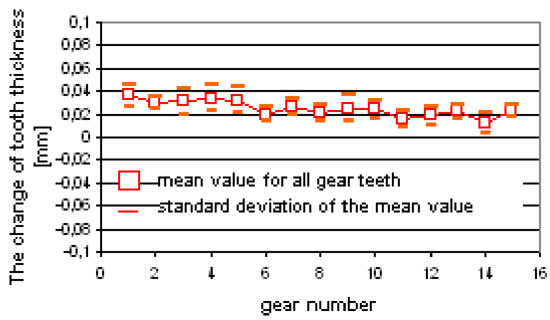
On the basis o the optimized numerical model of diffusion process developed [7], the computer program enables a dynamic observation of the near-surface carbon saturation, the carbon profile development and optimization of carbon stream delivered from the carburizing atmosphere to the charge in order to ensure maximum acceleration of the process for a given grade of steel (as a function of its chemical composition).

The following advantages of a vacuum carburizing process seem to be the most important ones:

- no environmental pollution,
- the cleanliness and metallic sheen of treated surfaces,
- lower scatter of deformations of hardened parts,
- favourable residual stress distribution in the surface layer.

Especially, the last two items determine the possibility of improvement of the functional properties of gears machined.

a)



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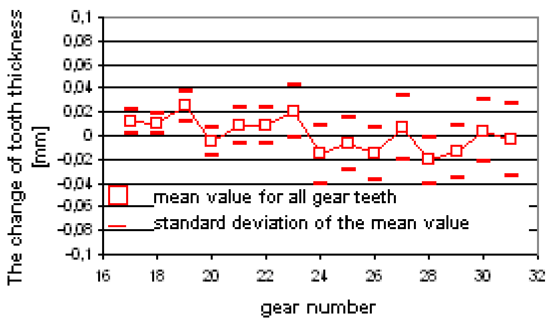

Figure 1 Changes in teeth thicknesses due to a) conventional carburizing b) vacuum carburizing

An example of a statistic distribution of dimensional changes of gear teeth thicknesses hardened with the application of conventional and vacuum carburizing methods is shown in Fig. 1 [5]. Gears after vacuum carburizing show lower scatter of deformations than the gears conventionally carburized, which enables the minimizing of allowances in subsequent machining operations, e.g. in the gear grinding process. This results in lower heat generation in this process and, in turn, may influence favourably the final residual stress distribution in the surface layer of gears.

Vacuum carburizing generates also better residual stress distribution than conventional carburizing, see Fig. 2. It can be seen from this Figure that after conventional carburizing compressive stresses at the surface reached compressive values of ca. − 550 MPa, while in vacuum carburizing these stresses are 150 MPa lower.

Such advantageous residual stress distribution obtained in vacuum carburizing can be easily destroyed in a gear grinding operation which, in most cases, follows heat treatment. Especially, grinding with aluminum oxide grinding wheels may give tensile residual stresses in the vicinity of the surface machined. Thus, grinding process conditions selection is the next important step to find synergistic effects in gears manufacturing.

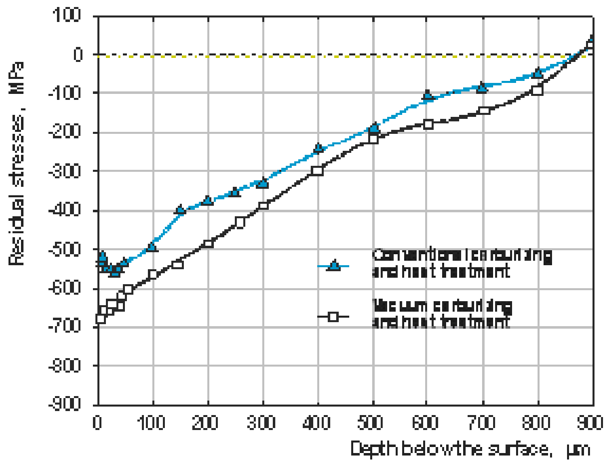

Figure 2 A comparison of residual stress distribution in surface layer of 17CrNi6-6 steel after conventional and vacuum carburizing

To find the optimal depth of carburizing, the FEM analysis of stresses generated in mating teeth contact area was carried out. It was found, that the Bielajev point of maximal stresses is located 0.4 mm below the surface. On that basis the carburizing to the depth within the range from 0.8 mm to 0.9 mm was carried out to secure the Bielajev point within the carburized layer after removing material in grinding process.

Both, conventional and vacuum carburizing parameters are presented in Tab. 1.

Table 1 Heat treatment parameters

Treatment	Carburized layer thickness [mm]	Hardness
Conventional carburizing 950^{o}C/3h, Quenching 780^{o}C, tempering 250^{o}C/1h	0.9	surface - 680HV, 715HVmax. at the 0.1mm depth
Vacuum carburizing 950^{o}C/1.5h, Quenching 740^{o}C in pressurized nitrogen (1.6MPa), tempering 250^{o}C/1h	0.8	surface - 720HV, 745HVmax. at the 0.4mm depth

3. Grinding technique

Grinding of gears in this experimental work was carried out by means of the so called Niles generating method, kinematics of which is shown in Fig. 3 [8].

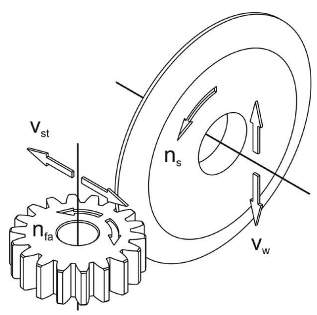

Figure 3 Kinematics of gear grinding

To check the influence of the grinding operation on the residual stress distribution in the surface layer of gears' teeth, both aluminum oxide and CBN grinding were performed. The residual stress distribution after grinding was measured. Having no possibility to measure the residual stress at the gear tooth flank by means of a material removal method, the beam shaped samples were prepared and heat treated and ground in exactly the same conditions as the gears analyzed. The following parameters: v_s = 30 m/s, a_e = 0.05 mm and v_w = 0.15 m/s were applied in wet grinding.

It was assumed that the residual stress distribution in such samples is similar to the residual stress generated in gear teeth. The results of the residual stress distribution after different technological processes are shown in Fig. 4.

The Figure shows that the best residual stress distribution was obtained after vacuum carburizing followed by CBN grinding (represented by green dots in the Figure). At the sub-surface region the residual stresses generated are compressive and vary within the range from – 400 MPa to – 700 MPa. The worst results were obtained when conventional carburizing was followed by grinding with aluminum oxide grinding wheels. In this case the tensile residual stress reached the value of 400 MPa at the gear teeth surface.

Such significant differences in the residual stress distribution due to different technological processes applied should result in the differences in fatigue strength of gear teeth. To check this assumption the fatigue tests on gears were carried out.

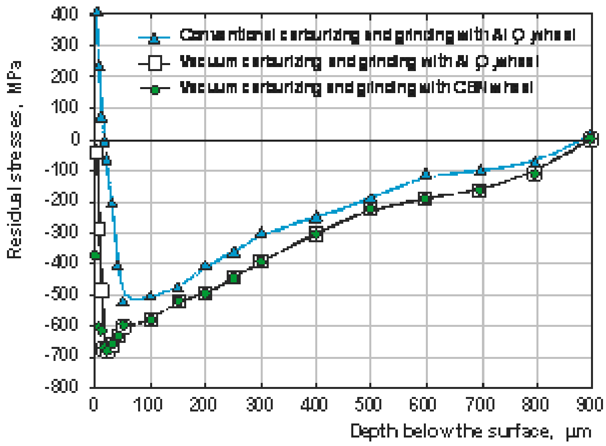

Figure 4 Comparison of residual stress distribution after different technological processes

4. Fatigue tests

Fatigue tests were carried out on spur gears of modulus $m = 5$ and the number of teeth $z = 26$. Three different technological processes were applied: conventional carburizing and aluminum oxide grinding, vacuum carburizing and aluminum oxide grinding as well as vacuum carburizing and CBN grinding.

The special equipment was developed for these tests [9], see Fig. 5, to extend the application of the standard testing machine. Also, the equipment allows to apply pulsating bending forces to two gear teeth simultaneously, which shortened the highly time-consuming fatigue tests.

The results of fatigue tests carried out on the stand described above are presented in Fig. 6. To evaluate the results obtained, regression analysis was made and the equations which describe the relations between the number of cycles and the fatigue limit were evaluated. These equations are presented also in Fig. 6.

Statistical analysis of the results obtained showed that at significance level $\alpha = 0.05$ the differences between particular lines are significant.

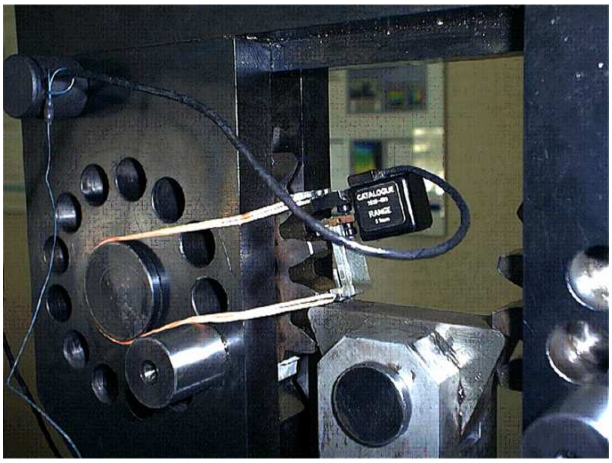

Figure 5 An experimental stand for fatigue testing of spur gears

The results presented in Fig. 6 show that the worst results were obtained when conventional carburizing was followed by grinding with conventional aluminum oxide grinding wheels. This process showed also the disadvantageous distribution of the residual stress, cf. Fig. 6, with high tensile stresses at the workpiece surface.

The improvement in fatigue strength is observed when vacuum carburizing is applied before aluminum oxide grinding. But the best results were obtained when grinding with CBN grinding wheels was applied, see the upper line in Fig. 6. In this case, also the most advantageous spectrum of residual stress was obtained, see Fig. 6.

The investigations carried out showed that only the application of two modern manufacturing processes: vacuum carburizing and CBN grinding which are combined in the technological process secure the highest quality in gears production.

Further investigations will be focused on the development and optimization of both processes applied (e.g. the application of low temperature vacuum carburizing) and application of the processes to other, highly loaded, parts like cams, bearings, etc. where advantageous surface integrity is required.

5. Concluding remarks

On the basis of the investigations presented above it was found that:

- to obtain high quality gears it is necessary to combine modern thermo–chemical treatment and CBN grinding processes. In such a case it is possible to generate synergistic effect in the creation of gear teeth surface integrity which may result in a significant improvement of functional properties of gears, e.g. fatigue strength,
- vacuum carburizing produces better residual stress distribution and lower scatter of dimensional changes than conventional carburizing. It may result

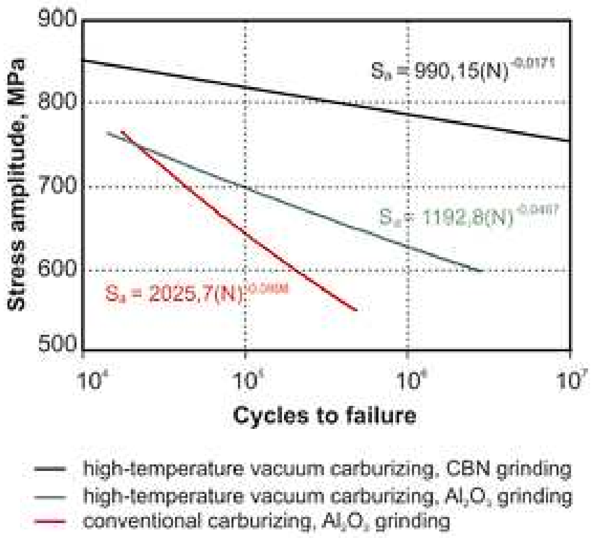

Figure 6 Results of fatigue tests for gear teeth produced with different technological processes

in smaller grinding allowances and lower thermal loading during grinding operation,

- CBN grinding shows much better residual stress distribution with high compressive stress close to the surface. Grinding with aluminum oxide grinding wheels deteriorates favourable residual stress distribution obtained in vacuum carburizing,
- the best results of fatigue strength of gears can be expected when vacuum carburizing is followed by CBN grinding,
- the complexity of both processes as well as the complexity of tribological and fatigue system where gears work make it necessary to carry out detailed optimizing research to find the best processes conditions.

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