

TOOTHED WHEEL OPTIMIZATION BY MEANS OF THE FINITE ELEMENT ANALYSIS

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Abstract

The mathematical models for superposing residual stresses and those coming from external loads were elaborated on the example of a toothed wheel with a small module.

The computer simulation was made by means of the Finite Element Method (FEM) [5,8] and the standard ANSYS 5.5 program.

On the basis of the superposed stress analysis, the optimum nitriding structure that increases the reliability and efficiency of the above-mentioned element was defined.

1. Introduction

The tribological wear is the result of the simultaneous action of friction elements and is understood as a damage and removal of the material from surfaces, i.e. the processes connected with friction and applied loads. It causes continuous dimensional and shape changes of friction elements. The factor that significantly increases the operational reliability of tools, machine parts and devices is the properly formed technological surface layer that would act against disadvantageous phenomena taking place in the operating surface layer.

The present paper deals with a new engineering design procedure from the field of materials selection and procedures for their improvement. The so far existing engineering design connected with the above-mentioned problems was based on the knowledge of basic mechanical and thermal material properties. Those data are not, of course, sufficient to design properly various friction couples, in particular those acting under fatigue wear conditions. There is a need, in such cases, to know values and a distribution of residual stresses in surface layers of elements, because they influence stability and reliability of a friction couple.

The intensive progress in the field of computer science causes that modern structural treatments, as well as engineering design are more and more often effects of computer simulations and experiments [1,2,6]. Owing to numerical methods, it is possible now to design optimum technological treatments from the point of view of both virtual mechanical and thermal loads, which significantly shortens the time needed for implementation of a new technology into industry.

On the basis of the experimentally calculated, by means of the Waisman-Philips method [7], series of residual stresses in the surface layer of steel after the heat treatment and the low pressure NITROVAC nitriding [4], the computer simulation was carried out by the FEM. It was based on superposing the calculated residual stresses in hardened surface layers with the stresses caused by external mechanical and thermal loads. This simulation was carried out for real material and technological solutions of a selected toothed wheel with a small module.

2. Experimental investigations

2.1. Specimens

Quenching and tempering are the basic treatment applied to toothed wheels of a small module and there is a necessity of grinding the gear surface after the above mentioned treatment or nitriding in regulated atmospheres, which causes that finishing grinding is not necessary any more.

40HM steel samples (120x20x3.5mm) underwent quenching in oil from the temperature of 1113K and tempering in the temperature equal to 823K for 2h. The hardness of the samples after such a heat treatment was 38 ± 2 HRC. The selected samples were nitrided using the NITROVAC method at the ammonia partial pressure $p = 4 \times 10^3$ Pa. The chosen nitriding parameters allowed one to obtain a thin ($\sim 2 \mu\text{m}$) γ' nitride layer in the surface layer, and, below, an inner nitriding zone of the thickness equal to $140 \mu\text{m}$. The maximum hardness was 915HV on the surface.

2.2. Residual stress examination

The Waisman-Philips method was applied to calculate the class of residual stresses in the surface layer of the heat-treated and low-pressure nitrided (NITROVAC) 40HM steel. The electroetching with the affected electrolyte flow was applied to remove thin surface layers from the investigated specimens. A water solution of citric and muriatic acids was the electrolyte for the nitrided samples and 10% HNO_3 for the samples after quenching and tempering. The current density was about 0.3 A/cm^2 . The results of the investigations are shown in fig. 1.

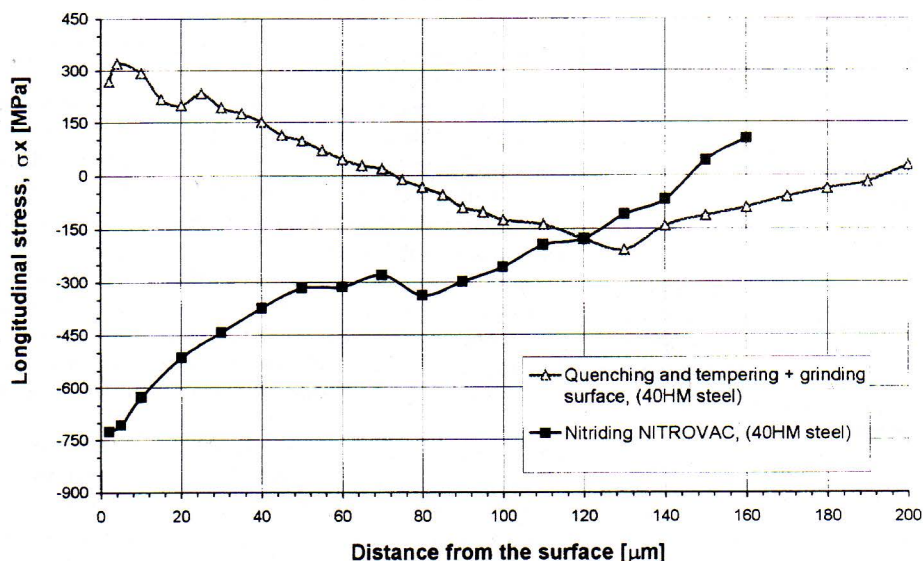


Fig. 1. Distribution of the mean residual stresses in the near-surface layer of 40HM steel.

2.3. Discrete model framework

The most important technical data for modelling two discrete models of gear wheels with a small module (fig. 2) by the ANSYS package are shown in table 1.

Table 1

Selected technical data of the modelled toothed wheel.

Module	$m=1$	[mm]
Number of teeth	$z_1=z_2=54$	
Pitch diameter of the gear	$d=54$	[mm]
Tooth depth	$h=2,25$	[mm]
Centre distance	$a=54$	[mm]
Torque	$M=121,5$	[Nm]

The submodel of the dimensions equal to a few hundred microns at the contact surfaces between the wheels was selected to analyse the stresses in the micro zone of the working wheels (fig. 3). An occurrence of the γ' nitride layer that formed during the nitriding process, and, which follows, a change in the Young's modulus (table 2) were taken into consideration in the design of the second model.

Table 2.

Microstructure characteristics and mechanical and thermal properties of the nitrified layer assumed to build the discrete model.

Type of the treatment	Type and thickness of the layer [μm]		Inner nitriding zone [μm]	Young's modulus [GPa]	Coefficient of thermal conductivity [$\frac{\text{W}}{\text{m}\cdot\text{K}}$]	Coefficient of thermal expansion [$\frac{1}{\text{K}}$]
Nitriding NITROVAC $p=4\times 10^3\text{Pa}$	γ'	$\sim 2\div 3$	~ 140	211,0	23,6	9.75×10^{-6}
Quenching and tempering				206,0	42	11.2×10^{-6}

The distributions of the reduced stresses σ_{red} and the longitudinal ones σ_x occurring in the surface layers of the wheels after the heat treatment and the low-pressure NITROVAC nitriding were obtained. The location of the Bielajev point Z_B was calculated as well.

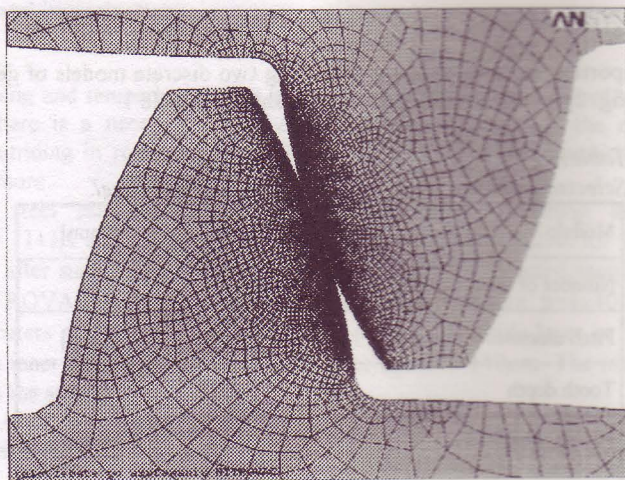


Fig. 2. Discrete model of the friction pair under consideration.

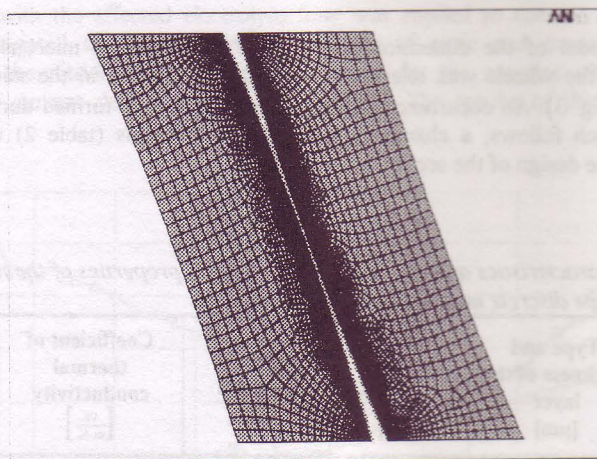


Fig. 3. Selected submodel at the contact point of toothed wheels.

3. Results

The calculated distributions of the mean residual stresses (fig. 1) show that after the NITROVAC nitriding process, at the ammonia partial pressure $p=4 \times 10^3 \text{ Pa}$, the compressive stresses of the average value -740 MPa occurred on the surface of the specimen. Such high compressive stresses are the effect of the γ' ($2\text{--}3 \mu\text{m}$) bulk nitride forming on the surface of the nitrided steel. This layer protects the discussed friction node against seizing the working surface of the wheels [3].

The compressive stresses occur in the whole inner nitriding zone whose thickness is about $140 \mu\text{m}$ (fig.1). The thickness of this layer is about twice as high as that in the Bielajev

point location and it protects the surfaces of the wheels against contact wear, in particular pitting [3].

The izoline of the reduced stress distribution with the Bielajev point location at $70\mu\text{m}$ is shown in fig. 4.

The contact stresses obtained after the heat treatment (fig.1) are of a completely different character than those after the low-pressure NITROVAC nitriding. The tensile stresses of approximately 300MPa, which change their sign twice at the distance of $70\mu\text{m}$ and $190\mu\text{m}$, occur after the heat treatment. The maximum compressive stresses (about -210 MPa) occur at the distance of $130\mu\text{m}$. The oscillatory character of the residual stress distribution can cause a significant decrease in the fatigue wear resistance of the elements working under cyclic contact operating conditions.

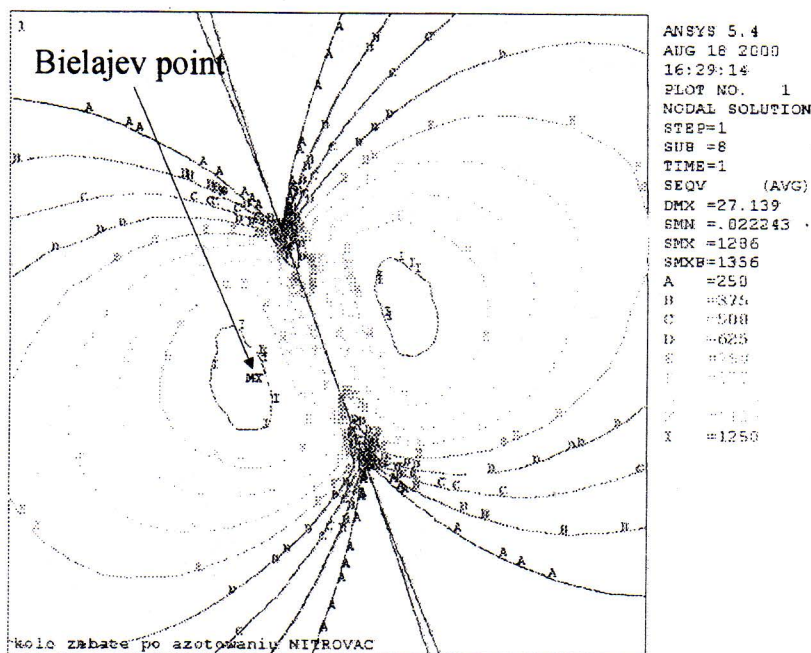


Fig. 4. Model of the real distribution of the reduced stresses in the surface layer of the toothed wheel after the low-pressure NITROVAC nitriding.

There are tensile stresses of about 150 MPa mainly on the side surface of the wheel, which can be clearly seen from the calculated distributions of the longitudinal stresses σ_x . The compressive stresses (about -1950MPa) occur near the contact point between the wheels only.

While analysing the stress superposing (fig.5), one can notice that the heat treatment causes an increase in the tensile stresses on the wheel side surface up to the value of about 400MPa. It is a very undesirable phenomenon that is propitious to pitting growth.

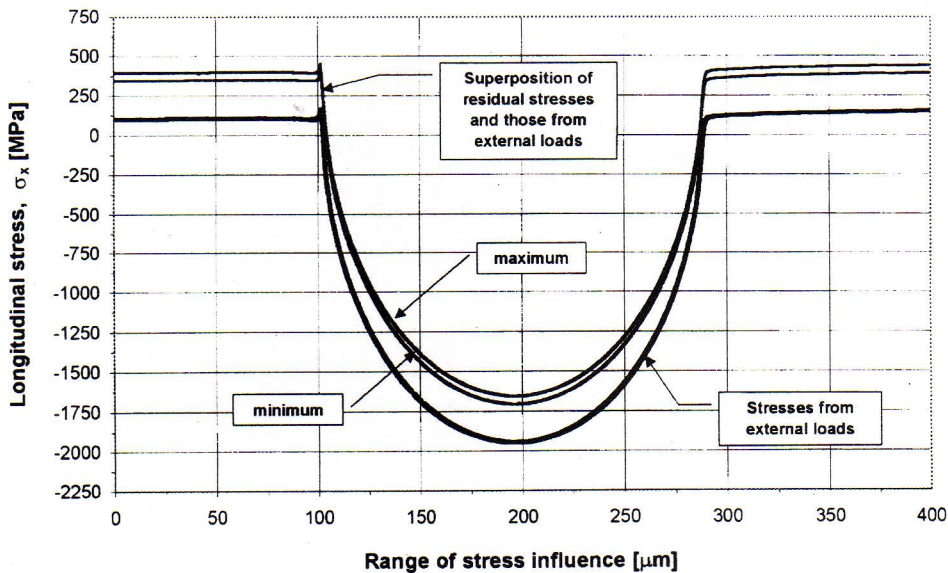


Fig. 5. Superposing the residual and external load stresses for the extreme operating conditions of the toothed wheel after the heat treatment.

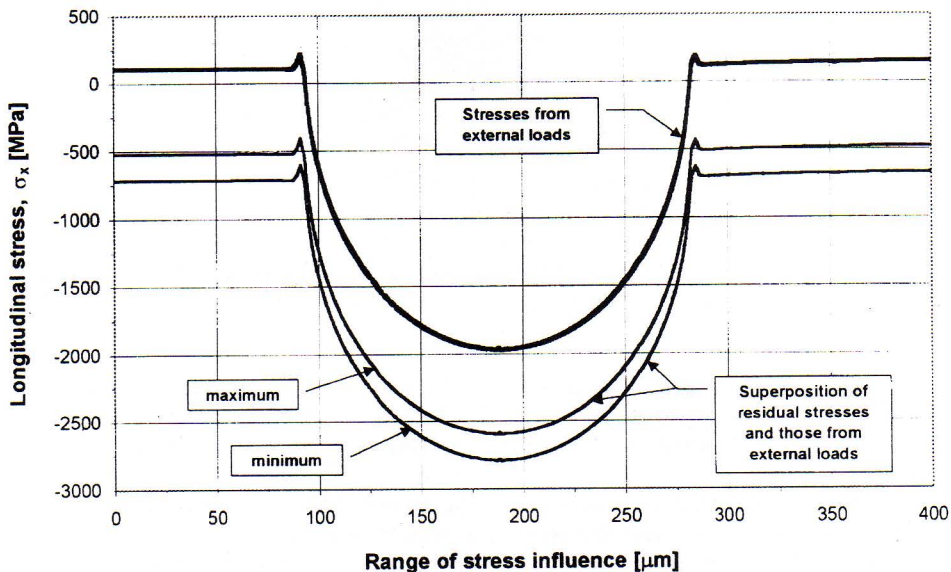


Fig. 6. Superposing the residual and external load stresses for the extreme operating conditions of the toothed wheel after the low-pressure NITROVAC nitriding.

Figure 6 shows that the compressive stresses (as a superposing effect) of the values from -500MPa to -2750MPa occur after the low-pressure NITROVAC nitriding ($p=4\times 10^3\text{Pa}$) in the whole wheel interaction zone. This distribution of the stresses results in complete protection of the wheel surface layers against catastrophic fatigue crack growth, and thus it guarantees high stability of the discussed friction node.

4. Conclusions

1. The visualisation of the contact stress state by means of iteration methods is an extremely effective tool of modern engineering design and structure and properties optimisation of hardened surface layers with a non-homogenous structure for actual non-conform contact conditions with an arbitrary geometry.
2. The FEM analysis allows for consideration of the anisotropy of elastic properties of such modern materials as composites, as well as hardened surface layers and coatings. It allows for finding and pointing out the local discontinuity ranges as the places where contact stresses concentrate.

References

- [1] Gawroński Z.: „Nowa procedura projektowania inżynierskiego z zakresu doboru materiałów i technologii ich uszlachetniania“, Inżynieria Materiałowa, No. 3, 2000 (*in Polish*)
- [2] Gawroński Z.: „Wpływ stanu naprężeń własnych w warstwach azotowanych na zużycie o charakterze zmęczenia stykowego“, D.Sc. Dissertation, TUL Scientific Bulletin No. 755, 1999 (*in Polish*)
- [3] Haś Z.: „Kryteria wyboru obróbki warstw wierzchnich kół zębatach“, Proc. of 2nd Polish Scientific Conference on Surface Treatment, Kule 13 ÷ 15.10.1993, pp. 21÷26 (*in Polish*)
- [4] Haś Z.: Europäische Patentenschrift Nr. 0034761
- [5] Kędziora S., Kubiak T.: „O metodzie elementów skończonych“, TUL Publishers 1999 (*in Polish*)
- [6] Kula P., Gawroński Z., Siniarski D., Sawicki J.: “Designing of structure and properties of composite coatings for special applications“, Proc. of 12th Summer School „Modern Plasma Surface Technology“, Kołobrzeg 2000
- [7] Waisman J., Phillips A.: Proc. of the Soc. Experimental Stress Analysis, vol. XI, No. 2, 1952, 102 p.
- [8] Zienkiewicz O.C.: „Metoda elementów skończonych“, Arkady, Warsaw 1972 (*in Polish*)