FEM STUDY ON THE STRENGTH INCREASING EFFECT OF NITRIDED SPUR GEARS

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KEYWORDS
finite element method, nitriding, DANTE heat treatment software, spur gears, surface endurance limit

ABSTRACT

In this research, the strength increasing effect of nitriding was investigated on a small series of spur gears with a module of 1 mm. The nitriding process was simulated in ANSYS FEM software with DANTE heat treatment external add-on. Only a simplified transient heat treatment model was created to study the basics and the effects of nitriding on spur gears. As a result, the nitrogen distributions, the hardness of the gear tooth flanks, the residual stresses and deformations were calculated with DANTE. Approximate surface endurance limit could be calculated analytically for the analysed spur gears according to the local endurance limit formula of Kloos and Velten. As the surface endurance limit value increased because of the nitriding process, the calculated allowable torque of the driving gear also increased. Even though the higher allowable torque and the initial residual stress increased the contact stress of the gear pairs, the calculated contact stress remains acceptable.

INTRODUCTION

Heat treatment is a controlled, predefined process of temperature variation to provide the required material properties (strength, toughness, etc.) by deliberately changing the microstructure, the initial stress state, and the mechanical, physical, or chemical properties of the finished part, without modifying its geometry (Csizmazia 2003). Properly modifying the microstructure and the material's properties can increase strength and fatigue resistance, leading to longer service life. Since it's not always required to perform heat treatment overall to the whole part, depending on the application of loads, heat treatments will be carried out only on critical surfaces of the particular section the part (Cserjésné et al. 2015). Nitriding is one of the most commonly used surface hardening processes (local heat treatment) for low-alloy steel gears, where only on the critical surface layers (gear flanks) will nitrogen be diffused to create a hardened, wear-resistant surface. Since nitriding modifies the material properties of the gear working surface (gear flanks), it's essential to analyse how nitriding affects the working conditions of the meshing gears.

The fast and continuous development of finite element software and modules allows us to analyse more and more specific engineering subjects. A general engineering problem requires several different types of calculations (structural, thermal, electromagnetic, etc.) to be carried out. The results of different types of calculations have an impact on each other, that's why it's necessary to establish a coupling between each calculation (the input of stress calculations could be a thermal calculation). Coupled FEM analysis provides an excellent tool to study complex engineering problems, so several factors that were simplified or neglected previously can be reconsidered.

In today's state-of-the-art finite element method, there is limited ability to validate realistic heat treatment parameters in FEM gear simulations. The influence of real tooth surface hardness on the tooth surface contact stress during gear mesh is significant and is essential for building an accurate finite element gear analysis. The exact nature of tooth surface hardness (which depends on given gear parameters) can be investigated using coupled finite element analysis. The hardness profile created during nitriding can be used to analytically calculate the surface endurance limit for a specified nitrided surface case layer. In order to accurately determine the contact stress during the meshing of the gears, it is necessary to know the exact tooth surface endurance stress values that will be developed during the heat treatment.

This research studied the gear nitriding capabilities of the US-developed DANTE finite element-based heat treatment software. The main objective was to calculate the actual surface hardness and endurance limit for pre-defined spur gears with FEM. In light of the findings, the allowable torque of the driving gear could be calculated, and a new study was created for analysing the effect of residual stress on the contact stress of the meshing spur gears.

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METHOD

DANTE is a standalone finite element-based heat treatment software, but it's also available as a software add-on for modern finite element software. DANTE version 5-1b with ACT2-7 was used with ANSYS 2020 R2 environment during the analyses. A small series of gear pairs was studied during the research, with the following gear parameters.

Table 1. The main geometrical parameters of the analysed gear pairs

z_1 [-]	i [-]	z_2 [-]	d_{w1} [mm]	d_{w2} [mm]	a_w [mm]	b [mm]
17	1	17	17	17	17	10.2
17	4	68	17	68	42.5	10.2
17	6	102	17	102	59.5	10.2
30	1	30	30	30	30	18
30	4	120	30	120	75	18
30	6	180	30	180	105	18
40	1	40	40	40	40	24
40	4	160	40	160	100	24
40	6	240	40	240	140	24

Only spur gears were analysed with the module of 1 mm. The gear pairs have zero-backlash and addendum modifications. The CAD models of the analysed spur gear pairs were exported from KISSsoft design software. In DANTE, the nitriding process of one gear was investigated at a time, so for each gear, a complete set of results was available. Because of the high computational time of the analyses, only a 0.1 mm slice of one gear tooth could be analysed per gear pair.

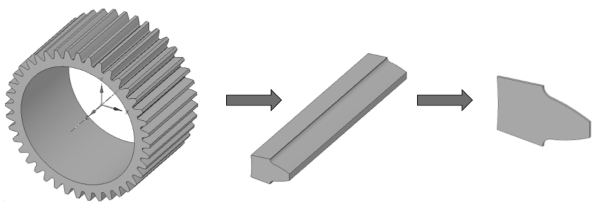

Figure 1. Simplified gear geometry for the nitriding analysis

The geometry preparation process for 2D contact stress analysis was the same as it was discussed in depth in a previous paper (Molnár et al. 2021). The applied material for the analysed gears was 42CrMo4 (AISI 4140). During the nitriding analysis, the material was directly selected from the DANTE material database. Since the contact stress analysis was performed in a standalone ANSYS study (independent from DANTE), the material properties were imported as follows:

Table 2. Material properties used for 42CrMo4 in analytical calculations and FEM contact analysis

Material property	Value of
Base fatigue limit [MPa]	785
Ultimate Strength [MPa]	950
Young's Modulus [MPa]	210 000
Poisson's ratio [-]	0.3

The residual stress results were imported as initial stress load from DANTE nitriding results for the contact analysis.

Finite Element Model

First, the nitriding process was studied with DANTE, and after that, in light of the results, a contact analysis was created to study the effect of nitriding on contact stress.

The DANTE-based nitriding process is built up from a series of coupled simulations, so the results of each sub-simulation significantly impact the results of the other simulations, making it crucial to accurately define the simulation parameters. The nitridation simulation can be divided into the following sub-simulation steps: 0. Geometry and FEM model preparation I. Nitriding model setup II. Thermal model setup III. Stress model setup. The order of the sub-simulations is not interchangeable, they are strongly dependent on each other. The relationship between each sub-simulation can be seen in the following figure.

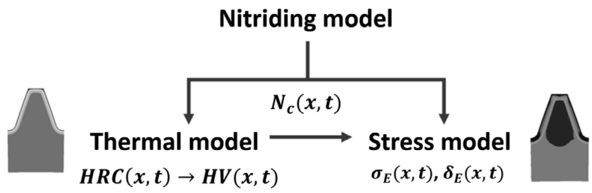

Figure 2. Process of nitriding in DANTE

The nitriding and thermal models require transient thermal simulations, while the stress model requires static mechanical simulation. In the nitriding model, the nitrogen distribution (history) will be calculated, and this result is used as an input for both the thermal and stress models. The hardness distribution and the thermal load for the stress model will be calculated in the thermal model. As a final step, the thermal history will be imported as an external load to the stress model, so can the residual stress and deformation be calculated. After the nitriding analysis, a 2D contact stress analysis was created to study the effect of residual stress and increased torque on the contact stress of the spur gears.

Preparation, the initial model

The initial step of a coupled simulation is to create the base model containing the prepared gear geometry, the FEM mesh, and base analysis settings. With the help of the initial simulation model, it can be ensured that the calculation is carried out with the same settings and geometry for each sub-simulation. As mentioned above, only a 0.1 mm-thick slice of one gear teeth could be analysed for each gear. The initial model provided the finite element mesh used in every sub-simulation for each study. According to the specifications of DANTE, only first-order linear elements can be used. The global element size was chosen as 0.1 mm equal to the gear slice thickness. During the nitriding simulation, it's crucial to properly register the amount of nitrogen diffusion, the thermal and phase transformation and stress gradients close to the surface, so a very fine mesh is required close to the gear flanks. The created nitrided layer is divided into a-few-micrometre-thick white layer and a larger diffusion zone, the finite element mesh. Since the extension of the diffusion layer is larger than the white layer, it's not required to use very fine mesh in the entire nitrided depth region. The growth rate was defined to gradually increase the element size of the mesh in the diffusion region, the maximum thickness of the refinement region was equal to the total expected case depth. The nitriding case depth can be approximate according to the research of Gustav Niemann (G. Niemann et al. 1965), in the case of spur gears with a module of 1 mm, the maximum nitriding case depth is near 0.2 mm. Since the FEM calculated case depth may differ from the recommended value, the refinement region depth was set to 0.4 mm. This study used 0.001 mm (1 μm) element size near the surface, and coarser elements were used away from the fine surface. An example of the used FE mesh structure can be seen in Figure 3.

Table 3. Main parameters of the FEM mesh

Property	Value
Global element size [mm]	0.1
Element size at the gear flank [mm]	0.001
Element size near case depth [mm]	0.05
Refiniment depth [mm]	0.5
Number of nodes [-]	5998
Number of elements[-]	2902

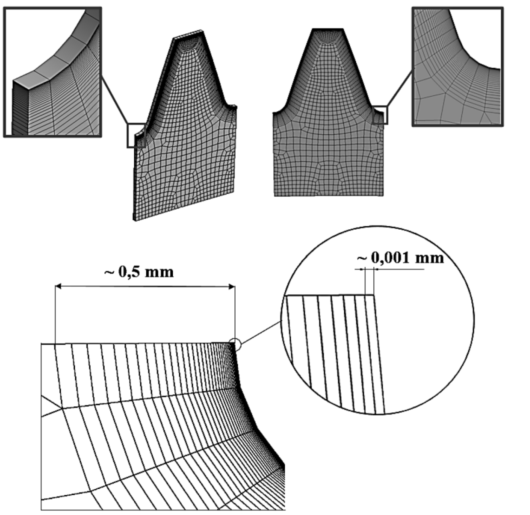

Figure 3. FE mesh of the gear slices (z=240)

Nitriding Model

In a DANTE nitridation model, a transient thermal analysis modelled the diffusion of nitrogen. This model only considers effective nitriding without pre-heating or cooling. Single-stage nitriding was defined with a constant temperature of 525 °C (Cserjésné et al. 2015). The effective nitriding time (processing steps) was uniformly predicted to be 28 880 s (8 hours) based on the research of Gustav Niemann (G. Niemann et al. 1965) and our test runs and results for the case depth thickness. Multiple nitriding time was investigated, the results of the test runs will be detailed in the next chapter. The film coefficient was set to 0.001 $\frac{W}{mm^2 \cdot °C}$. The other DANTE specific nitriding settings were left as default values. For thermal boundary conditions, the gear teeth flank surface was selected as a convection surface. The output of the nitriding model was the nitrogen distribution (history) in the gear body, which was used as an input for both the thermal and stress models.

Thermal Model

Based on the effective nitriding history, the thermal model retrieves the hardness distribution (profile) after the full heat-treatment process. In the thermal model (transient thermal analysis), not only the single-stage effective nitriding is considered, but also pre-heating and cooling during the heat treatment process, so the initial heat load for the stress model can be calculated. The complete nitriding process (pre-heating, nitriding, cooling) has to be considered in separate simulation steps with different time values. Since the effective nitriding process has already been investigated in the nitriding model, and the resulting nitrogen distribution data were imported, the duration of the effective nitriding was taken to be symbolically 1 s (DANTE recommendation). The duration of pre-heating and cooling was taken to be equal to 1800 s (0.5 hours), based on the test runs. In this case the initial temperature for the transient thermal simulation was selected to normal 20 °C room temperature. The other DANTE specific nitriding settings were left as default values. Based on the calculation, it was possible to retrieve the hardness distribution after heat treatment, and also to calculate the allowable torque for the driving gear. The output of the thermal model was the temperature distribution (history), which serves as the initial heat load input parameter for the stress model.

Stress Model

In the stress model (static mechanical stimulation), both the nitrogen distribution and the temperature history were required from the previous sub-simulations to determine the residual stress and deformation after the nitriding process. The calculated temperature history was imported and considered as an initial external load in the stress simulation. No other load was present during this simulation. The initial temperature for the static mechanical stimulation was selected to normal 20 °C room temperature. The other DANTE specific nitriding settings were the same as in the thermal model.

The static mechanical simulation required that a sufficient number of degrees of freedom of the geometry be constrained to run the static calculation successfully. Because of the cyclic symmetry of the gear teeth, frictionless contact was applied on the side slice surfaces of the gear body. Another boundary condition was the fixation of the bottom side of the gear body's face surface so as to take into account the support effect of the missing part of the gear body. The displacement of the top face surface was not fixed in the normal direction (axial displacement) because thermal expansion of the gear body is not restricted in that direction. The boundary conditions of the gear slice are shown in the following figure.

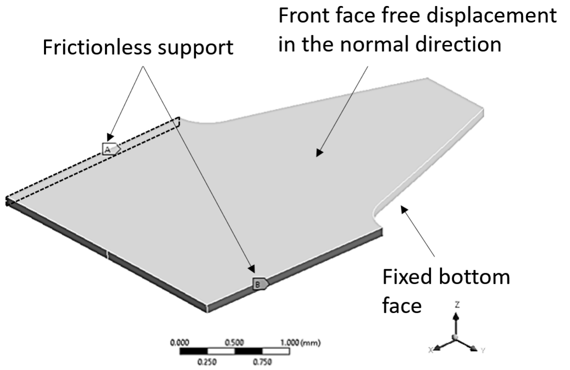

Figure 4. Boundary conditions for stress model

The output of the stress model was the residual stress and residual deformation of the gear body. The contact analysis model used the residual stress tensor as an input stress state.

Contact Analysis Model

In the contact analysis model, the effect of the residual stress with increased driving gear torque was analysed on the surface contact stress. A static mechanical model was created with linear elastic mechanical properties. In the present study, the analysed spur gears had a gear width - operating pitch diameter ratio $\left(\frac{b}{d_w}\right)$ of 0.6 (disc-type components), that's why 2D plane stress was considered. The corresponding elements of the residual stress tensor were imported to the 2D analysis as an initial stress state. The surface endurance limit and the applied driving gear torque were calculated from the thermal model's surface hardness results. The driven gear was fixed in each case, and the driving gear was loaded with the calculated torque. The model settings, boundary conditions and FEM mesh were the same as it was detailed (see above) in our previous paper (Molnár et al. 2021). The boundary conditions of the simulation can be seen in Figure 5.

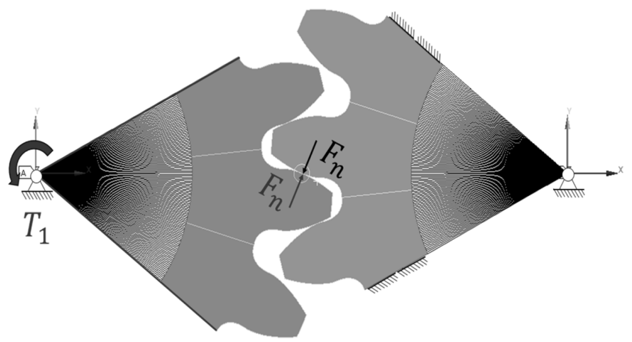

Figure 5. Boundary conditions for contact analysis

RESULTS

In this chapter, the calculated parameters will be discussed. The result of the nitriding model was the nitrogen distribution (history) of the effective nitriding process, which was an input for both the thermal and stress analyses. In the thermal analysis, the hardness distribution (profile) was calculated. An example can be seen for the hardness distribution after the heat treatment process in the following figure.

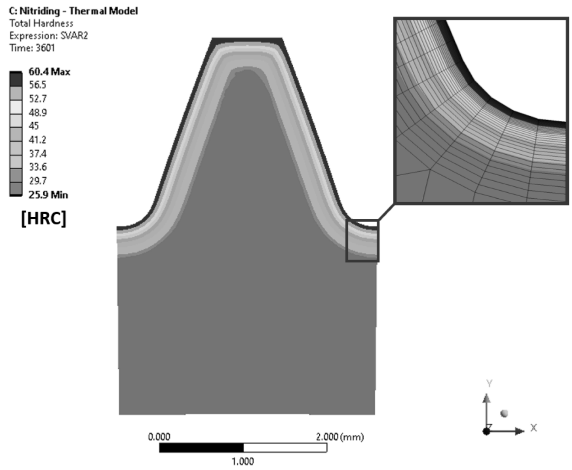

Figure 6. Visualization of hardness distribution after nitriding (z=240)

The hardness values were calculated as Rockwell's (HRC) hardness values. Figure 6. confirms that the simulated hardness distribution is reasonable for the thermal model. A uniform hardness distribution was achieved, the profile of which corresponds to the curvature of the gear tooth surface. The hardness value was maximal at the gear tooth surface, and it decreased continuously far from the gear tooth surface, there was no abrupt change in the hardness values. The resulting distribution pattern is in accordance with the hardness profiles found in the literature (M. A. Terres et al. 2017). The average surface hardness was 60 HRC for the analysed spur gears, the difference was negligible. The nitriding time and case depth were determined based on different hardness profiles. The hardness distribution and case depth for the different test durations are shown in the following figure.

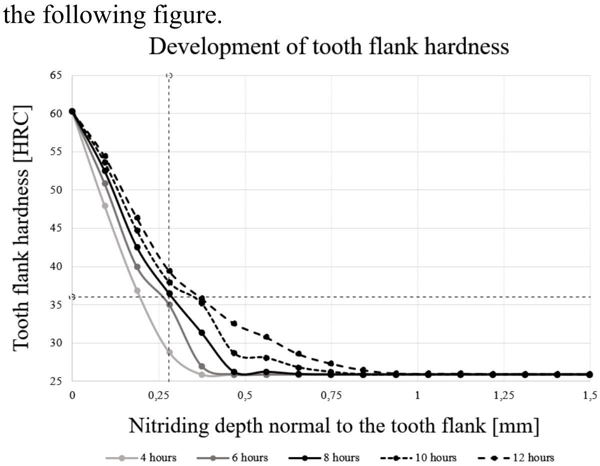

Figure 7. Development of tooth flank hardness for different nitriding time (z=17)

The nitriding time is the duration needed for the required case depth to form below the tooth surface. The required case depth can also be approximated from the core hardness. Approximately the effective case depth is given at a value of 10 HRC from the core hardness. As it was mentioned above, in the case of spur gears with a module of 1 mm, the maximum nitriding case is near 0.2 mm, according to Gustav Niemann (G. Niemann et al. 1965). The nitriding time was tested with 2-hour increments in the time range of 4, 6, 8, 10, 12 hours respectively. As shown in Figure 7, the nitriding time of 8 hours meets both the depth and hardness conditions for the required case depth, the optimal nitriding time is 8 hours.

The residual stress and deformation can be calculated based on the previously calculated nitriding and thermal (load) history in the stress model. The calculation generated a residual stress tensor, which contains the residual stress state after the heat treatment process. This tensor can be used as an input initial stress state in further analyses. An example can be seen in the next two pictures for the distribution and development of the residual stress tensor's Normal-Z component.

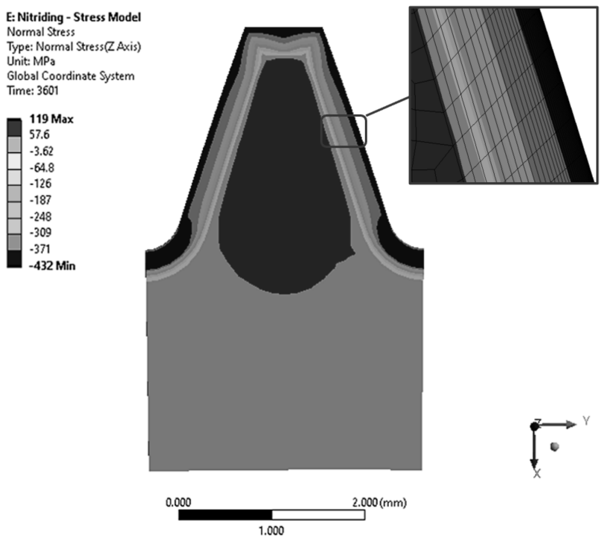

Figure 8. Normal-Z component of the residual stress tensor (z=240)

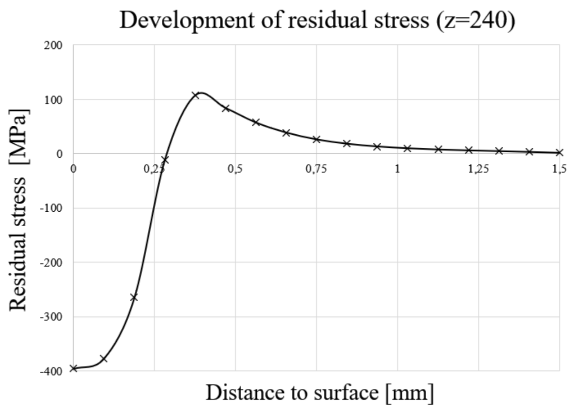

Figure 9. Development of the residual stress tensor's Normal-Z component (z=240)

Figure 8-9. shows that residual compressive stress is generated near the gear flank surface, and tensile stress is generated in the core below the gear tooth surface. The residual compressive stress follows the curvature of the gear tooth flank, and its maximum value is located at the close subsurface layers of the gear tooth surface, where nitrogen concentration and hardness were maximal. The residual stress was uniformly distributed along with the elements, there was no sudden change in the stress value. The average surface residual compressive stress was 400 MPa for the analysed spur gears, the difference was negligible. The characteristics and the values of the residual stress are in good correspondence with X-ray diffraction measures in the literature (M. A. Terres et al. 2019). Because of the compressive characteristic of the residual stress, it can be predicted that the residual compressive stress present in the nitrided case will prevent crack propagation, however, further studies would be necessary to prove this hypothesis.

An example of the residual deformation after the nitriding process can be seen in the following figure.

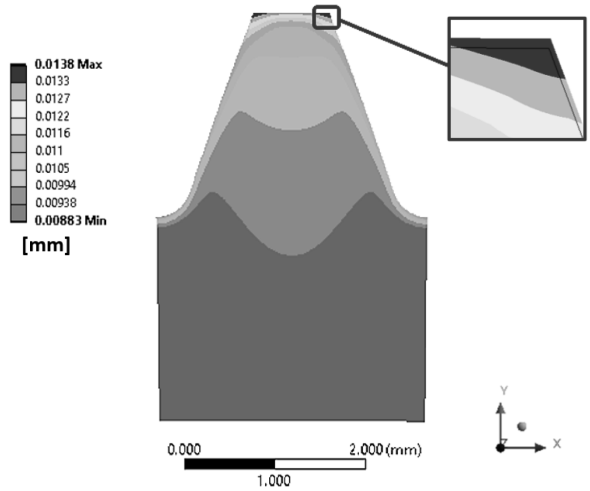

Figure 10. Distribution of the residual deformation after nitriding process (z=240)

As shown in Figure 10, the residual deformation was negligible, but the curvature of the gear flank influenced it. The maximal deformation value was 0.014 mm for spur gear with gear teeth of 240. These results confirm the hypothesis that deformations after nitriding are negligible (Cserjésné et al. 2015). In the case of pre-heat treatment gear modifications, it is recommended to consider the deformation value before prescribing the modification parameters.

Based on the average tooth surface hardness and residual compressive stress values, the local fatigue limit of the tooth surface could be calculated. The local surface endurance limit can be estimated according to the Kloos and Velten (K.H. Kloos et al. 1984) formula:

$$\sigma_{Hlim} \approx \sigma_{Wo}\left(1 - \frac{\sigma_m + \sigma_{res}}{R_m}\right)\left(1 + \sqrt{\frac{1600}{HV^2} \cdot \chi^*}\right) \quad (1)$$

Where σ_{Hlim} is the local surface endurance limit, σ_{Wo} is the base fatigue limit, σ_m is the mean applied stress, σ_{res} is the residual stress after heat treatment, R_m is ultimate tensile strength, HV is the average hardness of the tooth flank, χ is the applied relative stress gradient factor (reciprocal of the gear width). In this study, fully reversed loading was considered (zero mean stress), and only the hardness and residual stress parameters were used from the results of DANTE nitriding, the base endurance limit and ultimate strength were present as initial parameters before nitriding, they were not recalculated. The hardness value in Rockwell was converted to Vickers hardness. The difference of the calculated endurance limits for each gear was negligible, therefore a global surface endurance was considered. The calculated global surface endurance limit was multiplied by reducing factors from DIN 3990-2. The calculated value of the endurance limit for contact stress is 1065 MPa (for spur gear with a module of 1 mm). The result shows good correspondence with the values found in the literature (DIN 3990-5 1987).

After calculating the global surface endurance limit of the analysed spur gears, the allowable torque could be analytically calculated for the driving gears, according to Gy. Erney (Gy. Erney 1983):

$$T_1 \leq \frac{{a_w}^3 \cdot {\sigma_{Hlim}}^2 \cdot \sin(\alpha) \cdot \cos(\alpha) \cdot \frac{b}{d_w} \cdot u}{(u+1)^4 \cdot K_A \cdot C_B \cdot E \cdot 87{,}5} \quad (2)$$

Where: T_1 is the calculated torque of the driving gear, a_w is the centre distance, α is the pressure angle (in this study 20°), $\frac{b}{d_w}$ is the gear width – working pitch diameter factor, u is the gear teeth ratio, K_A is the service factor, C_B is a stress factor, E is Young's modulus of the analysed gear material. The calculated torques were used as the load of the driving gear in the contact analysis, the calculated torques can be found in Table 4.

Table 4. Calculated driving gear torques

z_1 [-]	i [-]	z_2 [-]	d_{w1} [mm]	d_{w2} [mm]	T_1 [Nmm]
17	1	17	17	17	2000
17	4	68	17	68	3100
17	6	102	17	102	3400
30	1	30	30	30	10700
30	4	120	30	120	17000
30	6	180	30	180	18200
40	1	40	40	40	25200
40	4	160	40	160	40300
40	6	240	40	240	43200

In the 2D contact analysis, both the calculated torque and the corresponding elements of the residual stress tensor were taken into account. The residual stress created an initial stress state for the analysis, and the increased torque condition assumed the nitrided state of the spur gear with linear elastic properties. Since the contact stress generally is a compressive stress type, the minimum principal stress was analysed during the studies.

The following figure shows an example of the resulting contact stress distribution.

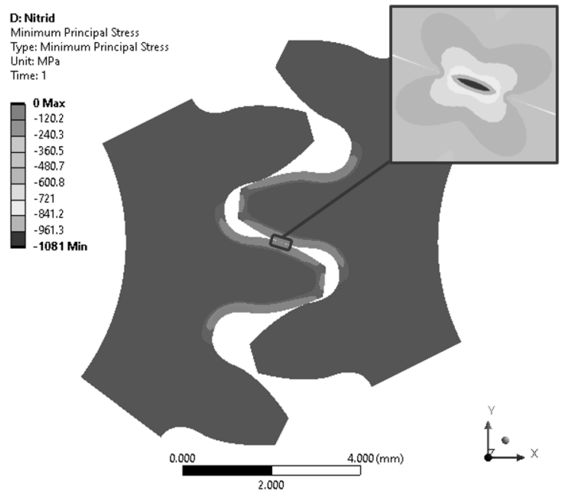

Figure 12. Contact stress distribution with imported residual stress (z=17)

In this model, numerically calculated contact stress values (without considering the residual stress) provide sufficiently accurate results with the analytically calculated Hertzian contact stress values, as it was demonstrated in our previous paper (Molnár et al. 2021). Considering the residual stress, the calculation gave the value of contact stress as the sum of the theoretical contact stress and the residual compressive stress, because the gear teeth were already in a pre-stressed initial compressive state before the engagement. The maximal principal stress was achieved. The maximum contact stress value was achieved during the analysis of the gear pairs with the smallest number of gear teeth (z=17), the peak value of the contact stress was 1080 MPa, as it is shown in Figure 12. The figure shows that the contact distribution is slightly distorted in the contact point, but its character is still Hertzian. It can be established that the calculated maximum contact stress (1080 MPa) reaches the calculated endurance limit (1065 MPa). The results show that although the higher allowable torque and the initial residual stress increased the contact stress of the gear pairs, the calculated contact stress remains acceptable.

Summary

Increased pinion torque can be calculated for nitrided spur gears, based on the increased hardness and tooth surface fatigue limit. The optimum nitriding case depth provides excellent operating properties, deeper case was not necessary for this study. It turned out that the number of teeth has no effect on the nitriding case depth or the nitriding time, but the module had a significant influence on both nitriding time and nitriding depth. After the nitriding process, residual stress and deformation were present, which influenced the operating condition of the spur gears. The residual deformation was negational. In the case of pre-heat treatment tip relief modification, the effect of residual deformation should be considered when specifying the tip relief parameters. The residual compressive stress present in the nitrided case will prevent crack propagation, however, further studies would be necessary to prove this hypothesis. The results show that although the higher allowable torque and the initial residual stress increased the contact stress of the gear pairs, the calculated contact stress remains acceptable. According to my experiment with the heat treatment module of DANTE, I can establish that the software provides an excellent tool for simulating heat treatment of spur gears.

DISCUSSION

The presented study was limited only to cylindrical spur with zero modification and backlash. Neglections and simplifications were made in the construction process of the studies. Because of the high computational time of the heat treatment analyses, only a 0.1 mm slice of one gear tooth could be studied per gear pair in the nitriding analyses. In the future, we aim to compare our results from the FEM heat treatment model with laboratory test results.

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