OPTIMIZATION OF HEATING OF GEAR WHEEL USING NUMERICAL MODELING

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Resume

Successful heat treating and carburizing of gear wheels for wind turbine gear boxes requires that plastic deformation in the wheel is minimized. Numerical modeling using the DEFORM software was aimed at exploring the effects of the base, on which the gear wheel rests during heating, on the heating process. Homogeneous heating was assumed. It was found that the base heats up more quickly than the workpiece. It is the consequence of the base's shape and volume. As a result, the base expands and slides against the wheel, predominantly at the first heating stage. Later on, it prevents the gear wheel from expanding, causing plastic deformation in the wheel. The findings were used for designing new heating schedules to minimize these undesirable interactions and to reduce the plastic deformation to a negligible magnitude. In addition, this paper presents an example of a practical use of numerical modeling in the DEFORM software.

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1. Introduction

The present gear wheel of the third speed gear is used in high-performance wind turbine gear boxes. Diameters of these types of wheels may reach up to 2000 mm. This investigation was conducted as part of a research project. Numerical simulation was used for mapping the wheel deformation during heating as part of a carburizing procedure [8, 9]. The simulation was conducted using the DEFORM 3D v10.1 software [4]. This software is designed for numerical modelling of forming and heat treating processes. It uses the finite element method (FEM), in which the modelled body is divided into tetrahedral elements. The computation takes place in small time increments which are defined – as well as the number and distribution of elements – by the user. Data on the geometry of the gear wheel was provided by the wheel manufacturer in the STL format, as required by the simulation software. The heating curve was supplied by the manufacturer as well. Mechanical properties of the work were retrieved from the DEFORM database. The data for 15NiCr13 [2] steel with initial bainite microstructure [7] were used, as the chemical composition of this steel grade was the closest to that of the actual part. The temperature dependence of the heat transfer coefficient [9] for air is given in Table 1. During heating, the gear wheel rests on six spots of a flower-shaped base. Its shape and the manner, in which it supports the wheel, were derived from manufacturing experience.

First, a simplified model of the gear wheel was constructed. An approx. 31° segment with 13 teeth of the gear wheel was used, resting on a leaf-shaped part representing 1/6 of the whole base. The base material's (DIN X12CrNi188) data [3] were retrieved from the DEFORM database. The pressure at the interface between the wheel and the base found from the wheel weight and the contact area was 0.354 MPa. The friction coefficient employed in the computation was 0.01 (a value for polished surfaces).

Table 1

Temperature dependence of the heat transfer coefficient for air.

Temperature [°C]	Heat transfer coefficient [$Ns^{-1}mm^{-1}°C^{-1}$]
20	0.01
200	0.015
400	0.03
600	0.065
800	0.1
1000	0.15

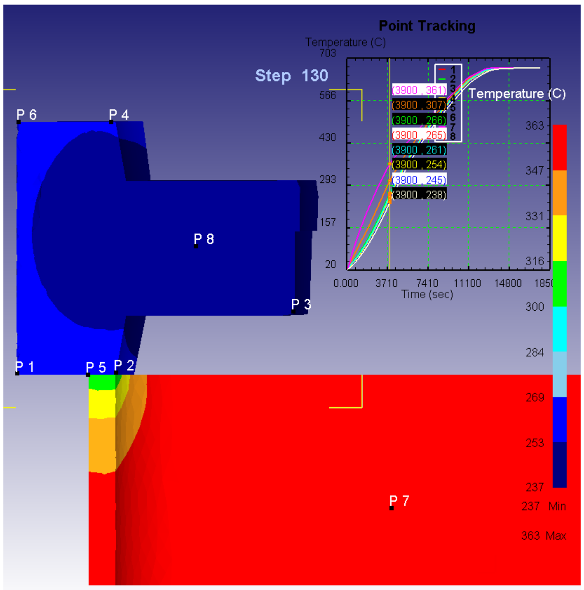

Fig. 1. Maximum temperature difference between the base and the work.
(full colour version available online)

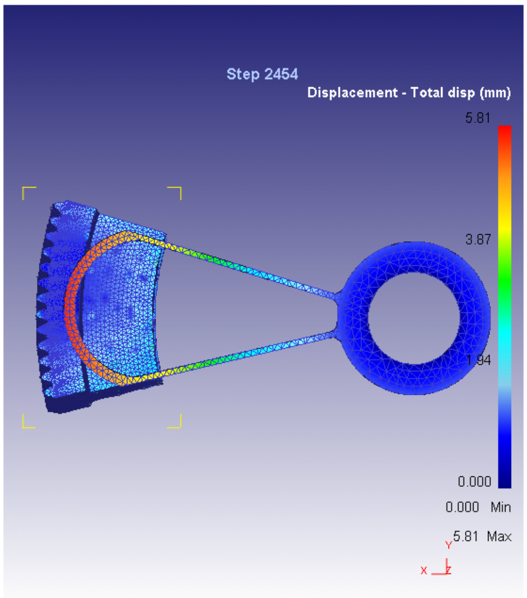

Fig. 2. Expansion of the base under the wheel at the end of the heating process.
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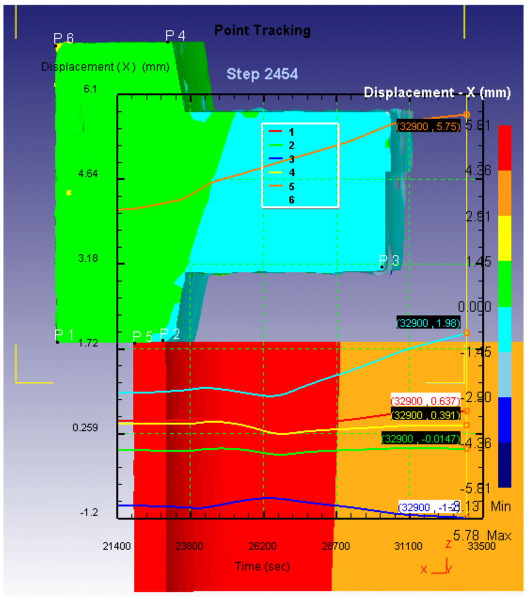

Fig. 3. Radial displacement in the simulation model.
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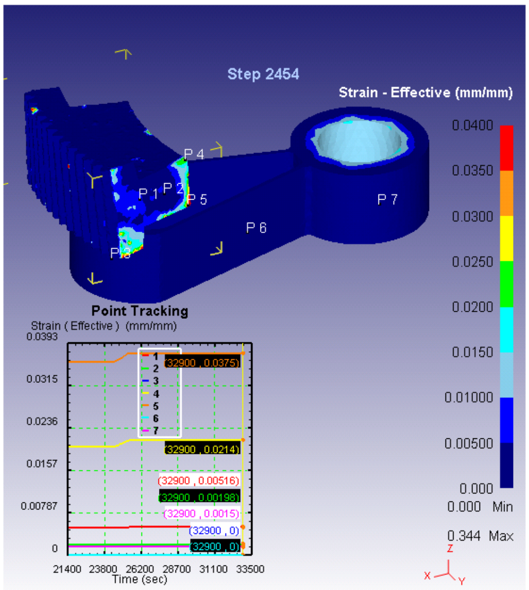

Fig. 4. Plastic deformation in the wheel segment.
(full colour version available online).

The analysed body (the gear wheel segment) was split into 80000 elements. The computational time increment was 60 s. Only one in every 10 computational increments was stored.

2. Results of heating simulation

At the first stage of the heating process [1], the base heated up more quickly than the gear wheel. The maximum difference between local temperatures of the gear wheel 60 minutes into the heating process was no more than 26 °C. The base temperature was up to 100 °C higher (Fig. 1). As a consequence of dissimilar expansion rates of the base and the wheel [6], the base slides against the gear wheel surface (Fig. 2). Figure 3 shows the radial displacements at selected points on an axial plane. Points 5 and 7 are located in the base, whereas the remaining points are in the gear wheel. The base thus slides beneath the gear wheel. Point 5 on the top surface of the base shifts by 4.11 mm in the radial direction during heating. Point 2 on the cross section of the gear wheel located near point 5 shifted in an opposite direction towards the wheel axis: -0.301 mm. This is due to the dissimilar thermal expansion resulting from different heating rates of the base and wheel caused by the differences between their weights and, possibly, their materials[5]. Friction impedes the sliding of the wheel across the base. The resulting stress is high enough for the material to enter plastic state in certain locations (Fig. 4) due to the high temperature combined with the decrease in the material's yield point. Effects of phase transformations were included in the simulation. However, the stresses caused by these transformations were not sufficient to affect the plastic deformation. (Non-symmetric deformation may, however, result from heterogeneous heating or microstructures. These cannot be revealed by the simulation method used).

3. Newly proposed heating schedules

The effect of the base on the heating process can be diminished by, for instance, reducing the friction between the base and the gear wheel or by reducing the temperature difference between both pieces. Therefore, four new heating schedules were proposed. Their primary goal was to reduce the temperature difference at the first stage of the heating process. Upon their analysis (given in section 3), two additional schedules with shorter durations were designed.

These schedules were as follows:

Heating schedule 1: heating at the rate of 1.5 °C/min with a 1 hour hold at 750 °C

Heating schedule 2: heating at the rate of 1 °C/min up to 500 °C, followed by heating at 2 °C/min to 920 °C

Heating schedule 3: heating at 1 °C/min up to 400 °C, followed by heating at 3 °C/min to 700 °C and then heating at 1 °C/min to 920 °C

Heating schedule 4: slow heating at 1 °C/min

Heating schedule 5: it was derived from the analysis of schedules 1 through 4. It is characterized by a varying heating rate, an initial hold and low initial and final heating rates (S-shaped temperature curve)

Heating schedule 6: it was derived from the analysis of schedules 1 through 4. It is characterized by a varying heating rate, an initial hold, low initial and final heating rates and a 43-minute hold at 740 °C.

4. Assessement of data from databases

In the course of the heating process, the material of the gear wheel undergoes changes from elastic through elastic-plastic into plastic state. In general, yield stress of a material decreases with increasing temperature. If the stress within a body exceeds its current yield stress, be it due to an increase in stress or a decline in yield strength, plastic deformation occurs. It can be described through effective strain given by the following formula:

$$\sigma_{eff} = \sqrt{1/2 \cdot \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]}$$

where σ_1, σ_2 a σ_3 are principal normal stresses.

The model of the work piece in this simulation is in the elastic-plastic condition. Consequently, some elements of its mesh may be in the elastic state, whereas others may be in the plastic state, depending on the temperature and stress. This is why the assessment of deformation was aimed at strain magnitudes at random points. It is useful to focus on relative strain values, rather than the absolute strain magnitude. The lowest strain values should be sought and compared with strains found for the existing heating schedule. Simulations of various heating schedules must be performed under identical conditions (mesh and computation step; identical tracking points throughout the work).

Table 2 lists effective strain values for five points located on the inner side of the geared rim and, at the same time, on a section plane running parallel to and in the distance of 1 mm from the base surface. It is the distance where largest deformation is expected to be caused by the friction and sliding between the base and the wheel – Fig. 5.

In order to get a better idea of the strain magnitude and to simplify the comparison, the magnitudes for individual points have been added. The sums are shown in 4^{th} column of Table 2.

The least deformation was found upon the heating schedule 2 (Fig. 6) in which the strain introduced during the early stages of the heating process was reduced. However, the overall amount of deformation was very similar in all new heating schedules, being much lower than the deformation caused by the existing schedule. Whereas the sum of the strain magnitudes for selected points in the existing schedule was 0.1454, the proposed heating schedules led to effective strains between 0.018 and 0.013, where the latter relates to schedule 2. For this drop in effective strain values to be confirmed, another array of points was analyzed. These new points were located on the same section plane within the geared rim, about 6 mm from its inner side. The analysis was conducted for the heating schedules which led to the least deformation.

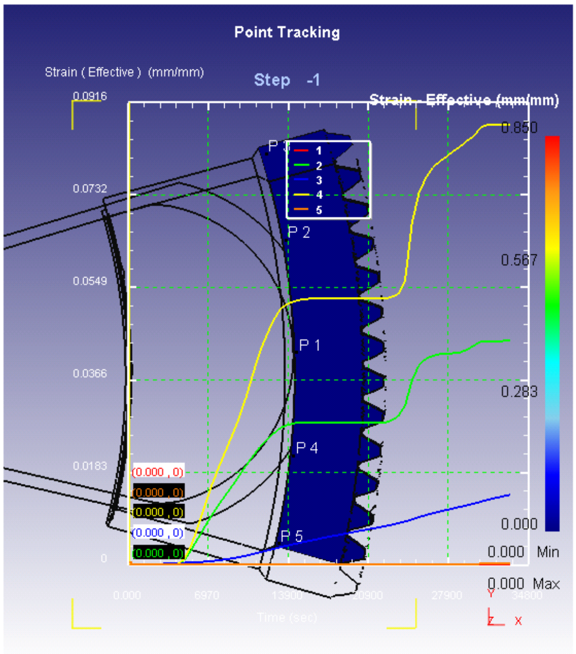

Fig. 5. *Effective (plastic) strain in the existing heating schedule.*
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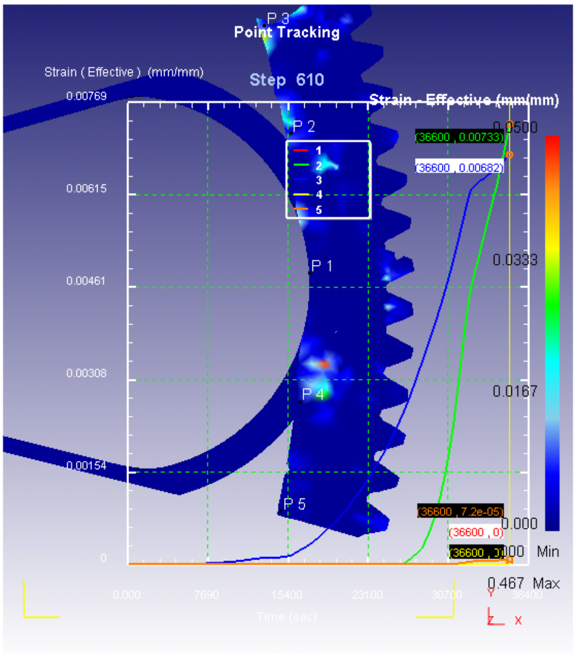

Fig. 6. *Effective (plastic) strain in the heating schedule 2.*
(full colour version available online).

Table 2

Effective strains at selected points and their sums.

Heating		**Effective (plastic) strain Points identified in Fig. 7**	**Sum of eff. strains**	**Effective strain Points within the rim**	**Sum of eff. strains for points within the rim**
Existing schedule	1	0.0000	0.1454	0	0.0659
	2	0.0443		0.0201	
	3	0.0138		0.0045	
	4	0.0872		0.0392	
	5	0.0001		0.0011	
Heating schedule 1	1	0	0.0201		
	2	0.00945			
	3	0.0105			
	4	0			
	5	0.000185			
Heating schedule 2	1	0	0.014	0	0.0102
	2	0.0071		0.0041	
	3	0.0068		0.0035	
	4	0		0.0018	
	5	0.0001		0.000869	
Heating schedule 3	1	0	0.0173		
	2	0.00908			
	3	0.00809			
	4	0			
	5	0.00008			
Heating schedule 4	1	0	0.0190		
	2	0.0093			
	3	0.0096			
	4	0			
	5	0.0001			
Heating schedule 5	1	0	0.0175	0	0.013
	2	0.0085		0.0055	
	3	0.0090		0.0040	
	4	0.0000		0.0023	
	5	0.0001		0.0013	
Heating schedule 6	1	0	0.0182		
	2	0.0091			
	3	0.009			
	4	0			
	5	0.0001			

The fifth column of Table 2 shows strain magnitudes for these five points. The next column lists their sums. In all proposed heating schedules, the effective strains were substantially lower than those caused by the existing heating schedule. The drawback of the heating schedule 2 – which causes the least deformation – is its duration, as it exceeds that of the existing schedule by approx. one hour (taking 10.16 hours). Consequently, its shorter alternatives were proposed (schedules 5 and 6). They involved very slow heating during the first hour, in which the furnace temperature increased by a mere 20 °C. The effective strain resulting from schedule 5 was slightly greater than that caused by schedule 2 but it was still very low. Schedule 5 was even 15 minutes shorter than the existing schedule.

5. Conclusion

It was shown by numerical simulation that the main source of plastic deformation occurring during heat treatment of the gear wheel is the difference between heating rates of the base and the wheel, primarily given by the shape and weight of the base. Upon expanding beneath the wheel, the base prevents the wheel from free expansion, causing the wheel to develop stress. These stresses, combined with the drop in yield strength of the wheel's material at high temperatures, result in plastic deformation. Six new heating schedules were proposed to alleviate this problem. The main difference between the new and the existing schedules was the slow heating rate applied during the first stage of the heating process. In terms of the resulting deformation, the optimum schedule appears to be the schedule 2 (Tab. 2). It comprises heating at 1 °C/min to 500 °C, followed by heating at 2 °C/min. However, this schedule was approximately one hour longer than the existing one. From the cost viewpoint, this is undesirable. This is why the modified heating schedule 5 was proposed (with an S-shaped temperature curve). It is shorter than the existing schedule and leads to very small effective strain.

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