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bainitic transformation,
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NUMERICAL EVALUATION OF GEAR RING BEHAVIOR DURING VARIOUS COOLING CONDITIONS

The phase transformation model incorporated via the user subroutines to the commercial finite element software to accurately predict changes occurring during cooling of metallic components is presented in the paper. The cooling process of steel rings used in airplanes was selected as a case study. Particular attention was put on heterogeneities occurring in temperature field, which influence phase transformations and eventually residual stresses. Developed model was used in the present work to evaluate influence of different cooling conditions on ring behaviour.

1. INTRODUCTION

Metallic components manufactured by the airplane industry are often subjected to series of complicated thermo-mechanical treatments to obtain required in-use properties. These manufacturing cycles are subjected to very strict control defined by the world standards. Thus, designing a process that will lead to the expected product properties and specific shape, requires a number of expensive laboratory tests.

Most important heat treatment processes of steel products used within jet engines to provide required microstructure are cooling/quenching. During these operations microstructural changes occur as a result of phases transformations. Unfortunately, these

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processes influence not only the properties but also the final shape of the product, and often obtained components do not meet the strict geometrical requirements.

Thus, to develop and control mentioned heat treatment operations and to provide good quality products authors decided to develop numerical model for cooling of steel components taking into account occurring phase transformations. This can broaden experimental investigation and reduce costs of development of new thermal cycles. Modelling of the heat treatment of jet engines gear rings was selected as a case study in the present investigation.

2. COOLING MODEL

Quenching is a process of rapid cooling of metal components from the austenitization to room temperature. The austenitization temperature ranges from 780°C for low carbon steels to 1250°C for high alloy tool steels. The major challenge during quenching is selection of proper process conditions, mainly cooling rates, in order to obtain the desired volume fractions of phases in the final product. At the same time, complex shape of investigated products have to be taken into account, as due to different dimensions along the cross section significant heterogeneities in temperature distribution are expected. As a result, non-uniform phase distribution is obtained within the final component eventually resulting in high residual stresses. To properly model the cooling process from numerical point of view, a number of parameters associated with the material and the process have to be taken into account. Often these parameters are dependent on each other, hence building the reliable numerical model of the cooling process is not a trivial task. In most of commercial FE software, modelling of cooling is based on classical thermo-mechanical approaches were additional heat generated during phase transformation is neglected (1–7). However, when numerical simulation of heterogeneities occurring during cooling of engine component is considered, such simplifications are not acceptable. In that case even slight geometrical changes in the component shape will directly influence its future performance. Thus, to address the challenge an in-house phase transformation code was implemented and incorporated to the commercial finite element ANSYS code via the APDL subroutine (8).

Mathematical model used in numerical solution for the heat transfer is based on the classical equation:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q=\rho C_p\frac{\partial T}{\partial t} \quad (1)$$

where: T – temperature, t – time, C_p – specific heat, ρ – density, k – thermal conductivity, Q – the heat generated per unit volume.

In eq. (1) the heat induced to the system by phase transformation is added via Q parameter. Therefore, in order to correctly model the phase transformation, it is necessary to provide the appropriate amount of the energy related to enthalpy changes during the transformation. The amount of energy, which is supplied to the system in a given time step directly depends on changes in the volume fraction of particular phase. Phase fraction evolution during transformation is replicated by Johnson-Mehl-Avrami-Komogorov equation (9-11):

$$f_i = f_i^{\max}[1 - \exp(-b_i t^{n_i})] \tag{2}$$

where: f_i – volume fraction of the analysed phase i; $f_{\mathrm{i}}^{\max}$ – equilibrium volume fraction of the phase i; b_i, n_i – parameters determining growth rate of the phase i.
The energy generated per unit time is calculated as a function of the volume fraction of the investigated phase as:

$$Q = \rho \Delta H \frac{f_{i+1} - f_i}{\Delta t} \tag{3}$$

where: ΔH – enthalpy changes as result of phases transformation, Δt – time step.
In the present investigation, model of both bainite and martensite phases transformation was incorporated into the ANSYS code via the APDL user subroutine. The model predicts the fraction of the phase (2) that is formed at time t in a given finite element, and allows to specify energy value (3), which is generated in the investigated computational domain. The APDL code containing the main algorithm loop of phase transformation model is presented in Fig. 1.

```
*DO, nn, 1, nds
*GET, temperatura, NODE, nn, TEMP
*IF, temperatura, LE, Ms, THEN
*IF, temperatura, GE, Mf, THEN
       ft = (tem1-Ms)/(Mf-Ms) - f(nn)
       qt = dH*ft/dt
       BF, nn, HGEN, qt
       f(nn) = (tem1-Ms)/(Mf-Ms)
*ENDIF
*ENDIF
*ENDDO
```

Fig. 1. The main loop of the phase transformation model

3. APPLICATION OF THE MODEL TO SELECTED COOLING CASE STUDY

The unconstrained cooling operation of gear ring was used as a case study of the proposed model practical application. The exact shape of the gear ring was obtained from the 3D scan (Fig. 2a) of real manufactured component. Based on the provided information the geometrical model of the investigated ring was replicated and parameterized in the 3D space as seen in Fig. 2b.

Analysed gear is manufactured from the steel containing 0.1% C, 1.2% Cr, 3.25% Ni, 0.12% Mo. To provide required material thermophysical properties i.e. specific heat and thermal conductivity, a set of laboratory experiments was realized at the Rzeszow University of Technology as well as at the AGH Krakow. Material properties were determined as a function of temperature in order to accurately account for changes that occur over the entire range of process temperatures (Fig. 3a).

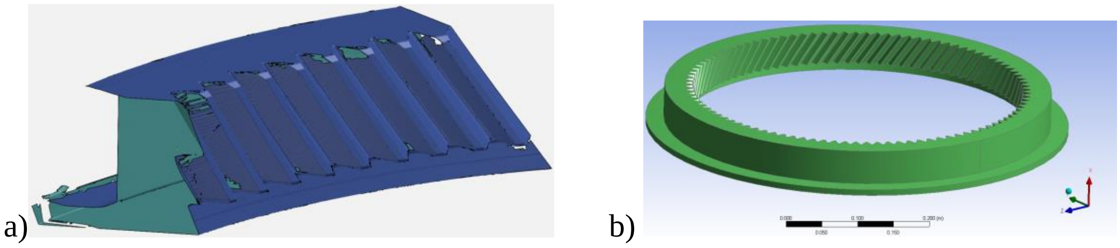

Fig. 2. a) Scan 3D and b) geometrical model of the gear ring

Information on start and stop temperatures of investigated phase transformations namely bainitic and martensitic, were evaluated during dilatometry tests and provided to the numerical model in the form of CCT constant cooling rate transformation diagram (Fig. 3b).

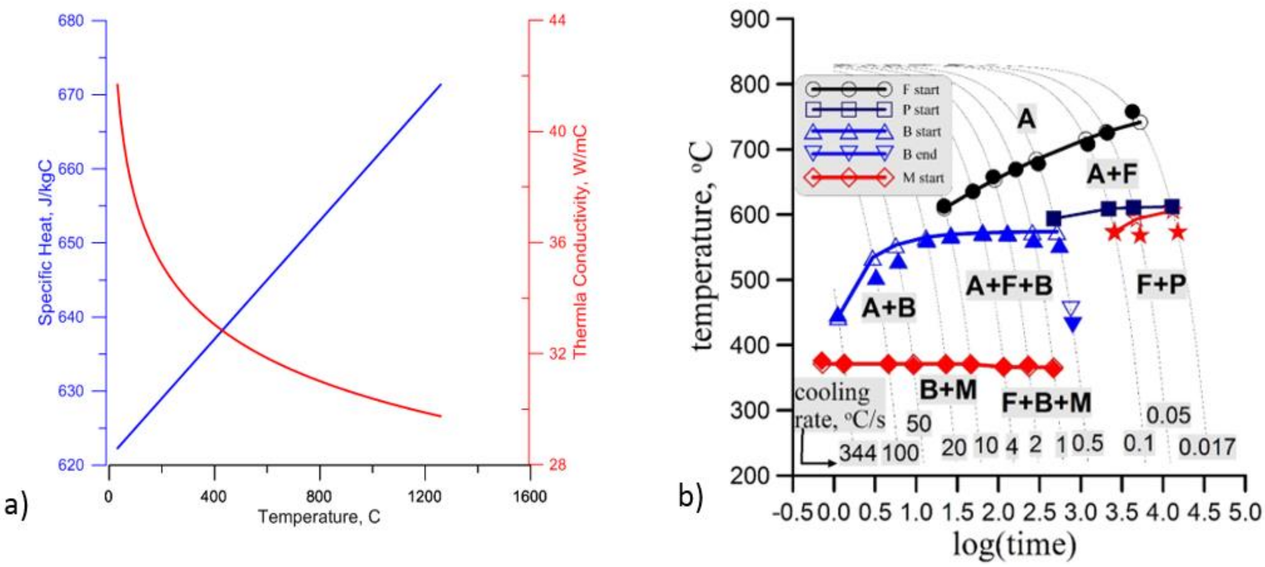

Fig. 3. Thermomechanical parameters and b) CCT diagram of investigated steel

Present investigation is focused on evaluation of influence of different cooling media on occurring phase transformations and in consequence on geometrical changes of the ring. To replicate properties of cooling media, two different values of convection parameters: 600 and 4000 $\frac{W}{m^2\,C}$ were assumed during numerical simulations. The ring was cooled from 830°C to room temperature in the period of 150 s.

To evaluate in detail local temperature changes during these different case studies, material behaviour in four characteristic FE points was compared. Positions of the first point is near the ring rim, second is situated at the inside ring surface, third at the outside ring surface and the last investigated point is located inside the ring as presented in Fig. 4ab.

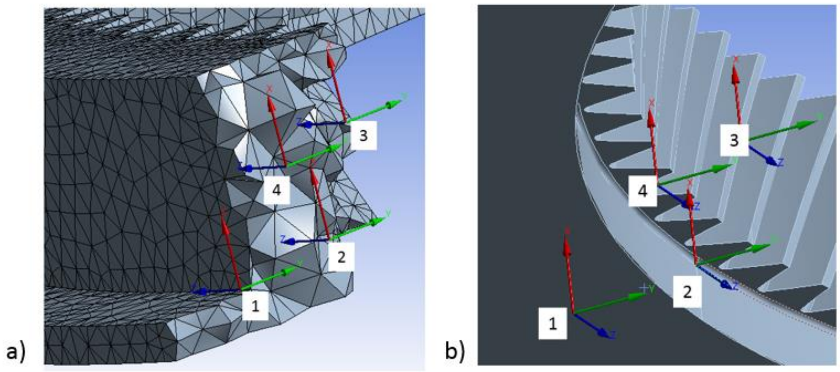

Fig. 4. Location of investigated points a) cross section view with mesh discretization, b) external view

Temperature distribution field as well as nodal temperatures from selected points, after 50, 100 and 150 seconds for two investigated convection parameters are presented in Fig. 5.

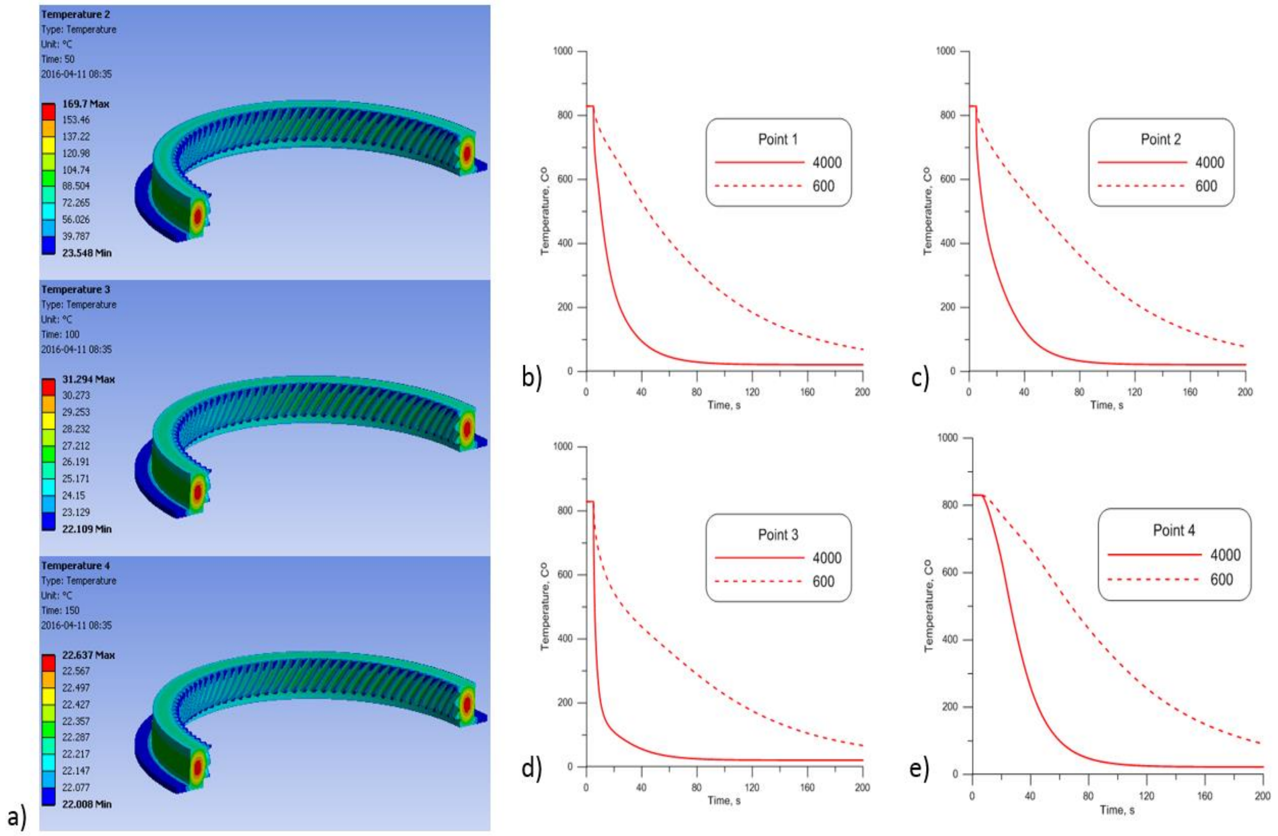

Fig. 5. Temperature distributions after a) 50, 100 and 150 seconds of cooling process with $4000 \frac{W}{m^2C}$ convection parameter and b)-e) temperature changes with time in selected points for two different convection coefficients

As presented in Fig. 5, for fast cooling temperature in the entire ring becomes uniform already after 80s of cooling. For slow cooling rate, the entire process takes significantly longer, and even after 150s the temperature in some locations can be approx. 100 ^{o}C.

4. THERMO-MECHANICAL MATERIAL DEFORMATION AFTER COOLING PROCESS

Thermal results presented in previous chapter were then used as input data for modelling corresponding ring deformation. Proper set of thermo-mechanical parameters required for mechanical simulation was determined during experimental investigation. The most important is thermal expansion, that was investigated at the Rzeszow University of Technology and is presented in Fig. 6. The thermal expansion curve is assigned to each Gaussian point in the FE mesh, thus evaluated heterogeneities in the temperature distribution affect material mechanical response.

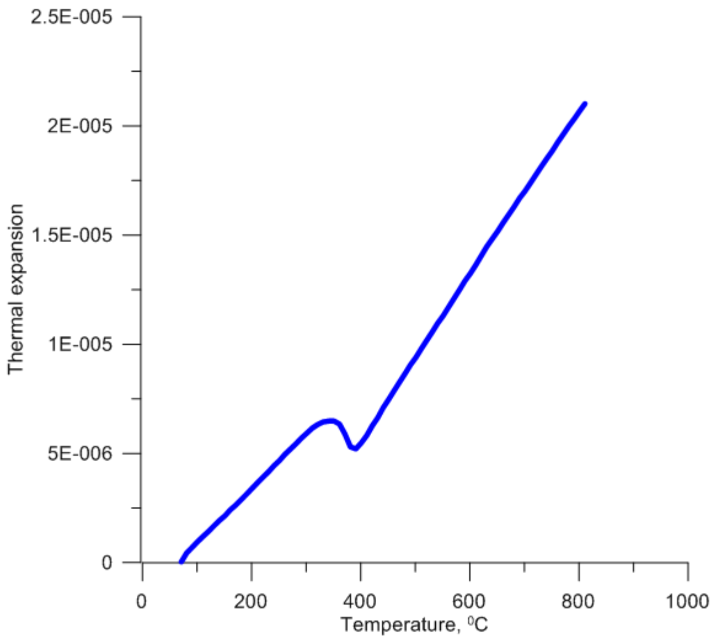

Fig. 6. Thermal expansion curve for the investigated material

Another important set of parameters required to predict material plastic deformation is represented by flow stress characteristics with respect to temperature. Tensile tests realized at the Wroclaw University of Technology were used to determine material hardening behaviour at various temperatures as seen in Fig. 7.

Eventually, calculated mechanical response for the two investigated case studies in the form of total deformation (*D* - Eq. (4)) distribution field after cooling process is presented in Fig. 8.

$$D = \sqrt{X^2 + Y^2 + Z^2} \tag{4}$$

where: X, Y, Z - directional deformations.

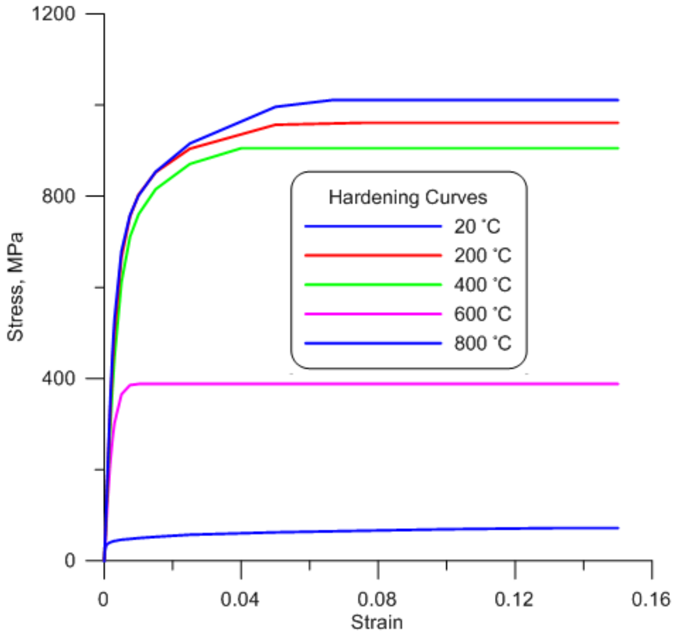

Fig. 7. Tensile stress-strain curves at various temperatures

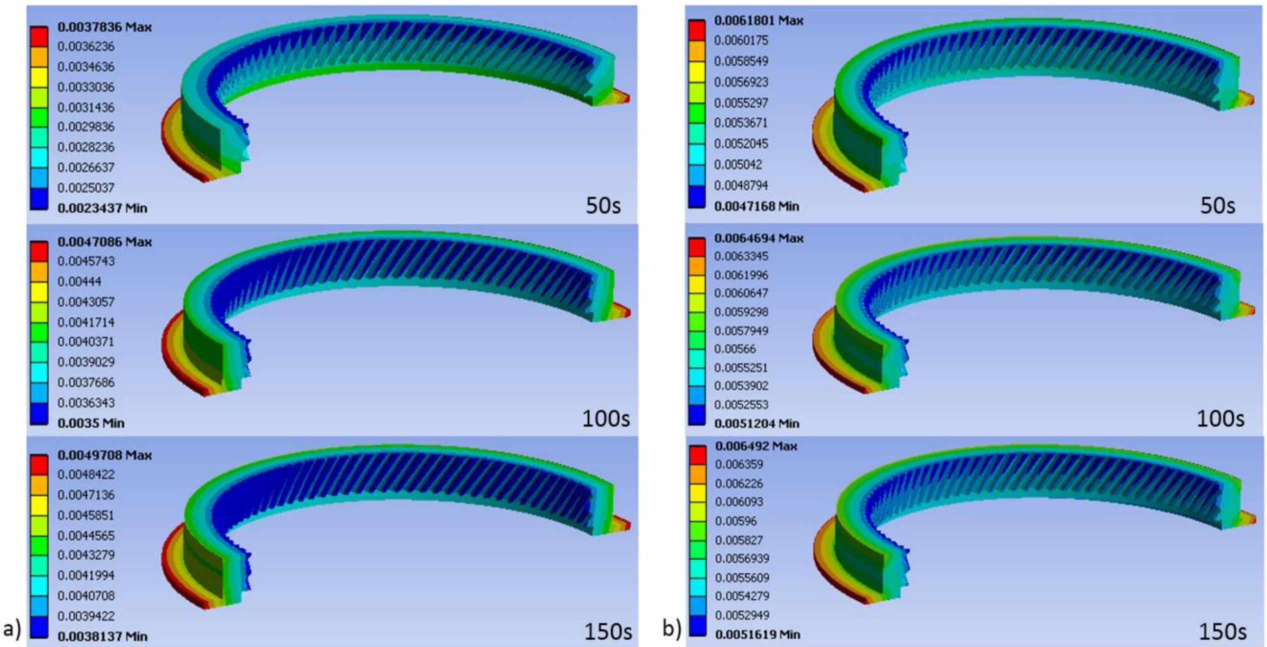

Fig. 8. Deformation distribution at 50, 100 and 150 second for two investigated case studies a) 600 $\frac{W}{m^2\,C}$ and b) 4000 $\frac{W}{m^2\,C}$

As seen in Fig. 8, the deformation in the ring's rim area is significantly larger than in other regions. Such difference is due to higher cooling rates in these regions as seen in Fig. 5. Rings rim is quite thin in comparison to the rest of the investigated component. During fast cooling, compression stress state is generated in the area by incompatible behaviour of the rest of the ring, which remains in higher temperature ranges longer. That leads to clearly visible geometry changes as presented in Fig. 9.

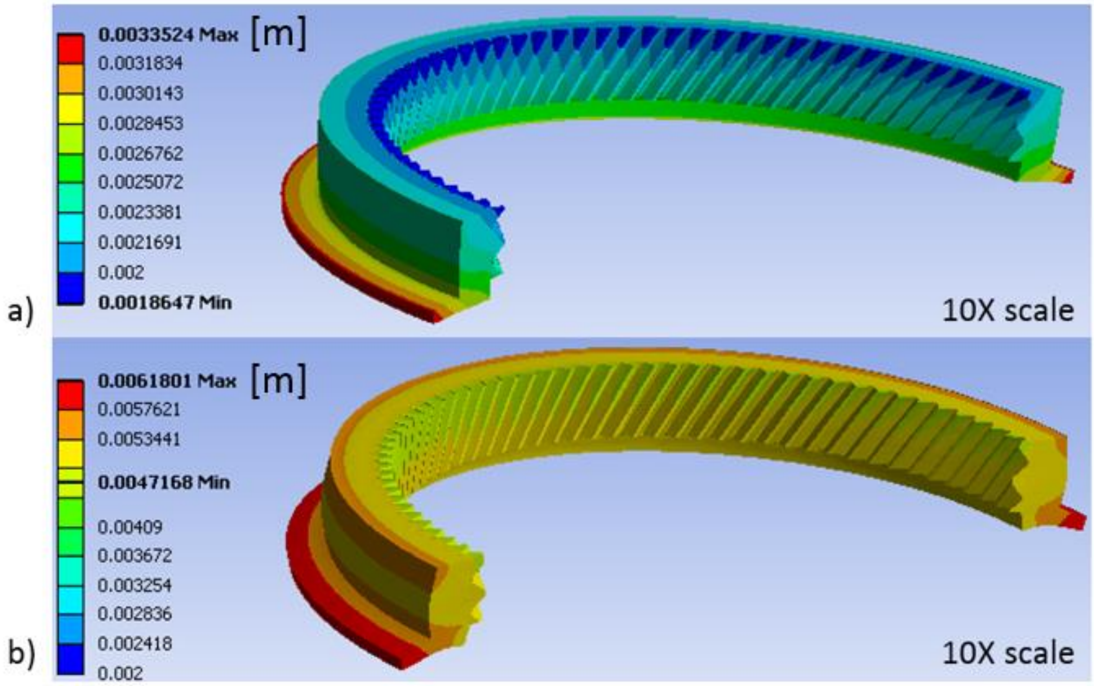

Fig. 9. Total deformation distribution, artificially scaled 10x, after a) 600 $\frac{W}{m^2\,C}$ and b) 4000 $\frac{W}{m^2\,C}$ case studies

The inhomogeneity is more pronounced when cooling is faster (higher convection coefficient). At the same time fast cooling provides required properties in case of martensite phase fraction. Thus, the developed model will be used during further research to identify proper cooling conditions in order to minimise geometrical errors and to provide required properties of products.

5. CONCLUSIONS

A numerical model of the cooling process of the ring gear with bainitic and martensitic phase transformation was presented within the paper. The model was developed in a commercial finite element package and required modifications to the system of equations, which was realised via the user APDL subroutines. Such an approach allowed direct use of the proposed solution in the industrial practice as only standard knowledge of the software is required.

As presented, the deformation of the ring is sensitive to applied cooling conditions. The faster the cooling is the more inhomogeneous material behaviour is. This is related to occurrence of phase transformation in different regions of the ring at different times, what affects its mechanical response. Slow cooling provides more uniform material response, however inappropriate properties are obtained. Future work will be focused on application of the developed model to design a special cooling equipment that will provide a possibility to properly cool different sections of the investigated ring to minimise geometrical defects and to provide required properties.

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