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Determination of the reduced stress and deformation occurring in the sample under thermal fatigue testing of the hot-work tool steel

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The paper presents results of the determination of the reduced stress and deformation occurring the sample under thermal fatigue testing of the experimental 47CrMoWVTiCeZr16-26-8 hot-work tool steel. In order to determine the stress values, the deformations and dislocations that occurred in the sample under thermal fatigue testing, calculations were made using the finite element approach, using experimental data of the real temperature distribution and of the mechanical properties (at elevated temperatures) of the investigated steel. Basing on the finite element computations, depth curves for the reduced stress, deformations and elongations were plotted.

1. INTRODUCTION

Hot-work tool steels, well-known in the tool steel industry, must have adequate properties to meet the increasingly rigorous demands placed on the reliability and lifetime. These steels are often used under severe conditions where there are many factors that affect the maximum tool lifetime and dimensional accuracy [1, 2]. Friction wear – both adhesive and abrasive wear – occurring at elevated temperatures, high surface load, adverse lubrication conditions and simultaneous influence of cyclic thermal and mechanical loading are the main factors that contribute to the reduction of lifetime of hot-work tools [1]. In addition, structural changes and worsening of mechanical properties at the top surface from cyclic thermal loading cause that thermal stress often goes beyond the thermal fatigue strength value and even exceeds the yield point. This leads to the formation of a characteristic crack pattern after a certain time that that tend to grow larger with further working cycles, being developed from the tool flank face towards the core [3]. Whether the tool steel has good mechanical properties, adequate thermal fatigue strength and resistance to abrasion, depends primarily on its chemical composition and the heat treatment process applied to the steel itself.

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The goal of this work is determination the reduced stress, the deformation and dislocations occurring in the sample under thermal fatigue testing of the 47CrMoWVTiCeZr16-26-8 hot-work tool steel.

2. EXAMINATION PROCEDURE

Chemical composition of this steel is given in Table 1. Heat treatment conditions and used investigation methodology have been described in detail in [4-9]. Thermal fatigue resistance of the 47CrMoWVTiCeZr16-26-8 steel was determined using a specially designed and constructed stand, its details are included in [4-6, 9].

Table 1
Chemical composition of the investigated steel

Steel denotation	Mass concentration of elements, %											
	C	Mn	Si	Cr	W	Mo	V	Ti	Ce	Zr	P	S
47CrMoWVTiCeZr16-26-8	0.47	0.13	0.27	4.04	1.97	2.60	1.10	0.26	0.1	0.06	0.012	0.008

In order to determine the reduced stress, the deformation and dislocations that occurred in the sample under thermal fatigue testing illustrated in [4 and 5], a sample model was developed and the finite element grid was generated using MSC/PATRAN 7.0 (see Fig. 1 for details). The sample was modelled with 3D octahedral solid elements. The temperature distribution over the sample was determined experimentally at 10 symmetrically spaced concentric shells while the sample was heated with thermal cycles recorded using a XY recorder receiving signals from thermocouples welded at the depths from 0.2 mm to 27.8 mm (in steps of 2.8 mm) under the heated surface. Each node of the model had its assigned temperature. The Huber-Misses yield criterion was then applied to determine the reduced stress, the deformations and dislocations using the MSC/ADVANCED FEA tool combined with the PATRAN. In calculations, mechanical properties were used for the investigated steel grade presented in Table 2 that had been previously determined, among others, in the static tensile testing at the ambient and elevated temperatures as well as in the dilatometric examinations. These values were then assigned to each model element via the linear extrapolation. The values of the heat conductivity at elevated temperatures were assumed to be average values as valid for hot-work tool steels. Assumption was also made that the material was an isotropic material. In connection to the assumed principle of a close fit between the sample and the shaft, all constrained degrees of freedom were those of the model nodes within the least diameter shell. A certain thermal load was introduced to the model adopted.

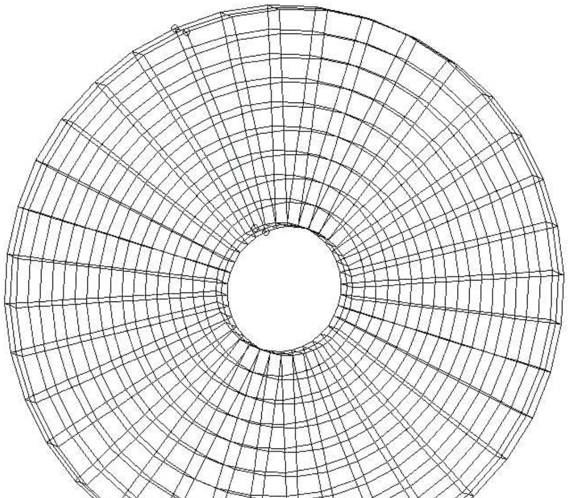

Fig. 1. Sample model

Table 2
Mechanical properties of the investigated steel used in the modelling of reduced stress, deformations and displacements of a sample under thermal fatigue testing

Temperature at testing, °C	Young's modulus E, MPa	Heat conductivity coefficient, $W \cdot m^{-1} \cdot K^{-1}$	Linear expansion coefficient, K^{-1}
20	207 000	38.0	$15.0 \cdot 10^{-6}$
200	180 000	38.5	$15.2 \cdot 10^{-6}$
300	163 000	39.2	$15.8 \cdot 10^{-6}$
400	155 000	39.3	$15.7 \cdot 10^{-6}$
500	138 000	41.8	$16.1 \cdot 10^{-6}$
600	117 000	41.4	$15.9 \cdot 10^{-6}$
Poisson coefficient	0,321	Density, $g \cdot cm^{-3}$	7,78

3. DISCUSSION OF THE INVESTIGATION RESULTS

Basing on the finite element computations, depth curves for the reduced stress, deformations and elongations were plotted. It was found from the reduced stress analysis (Fig. 2) that the maximum stress within the thermal fatigue tested sample occurred at the approx. depth of 3 mm under the surface and assumed the value of about 385 MPa. It corresponds to approx. 70% yield strength for the 47CrMoWVTiCeZr16-26-8 steel at the temperature range of 500-550°C. Distribution of the reduced stress within the sample is strictly related to the distribution of the temperature responsible for its origin. The rise in the stress level in the area close to the hole where the sample had been attached was associated with the close fit between the sample and the drive shaft. From the analysis of the resultant deformation (Fig. 3) and displacement it was found, that albeit being small, when repeated many times during thermal cycles they contributed to the growth of fatigue cracks. The maximal value of deformation during a thermal cycle was approx. 0.0043 mm whilst that of displacement was approx. 0.213 mm respectively and both were attributable to the element having the highest temperature during the thermal fatigue testing.

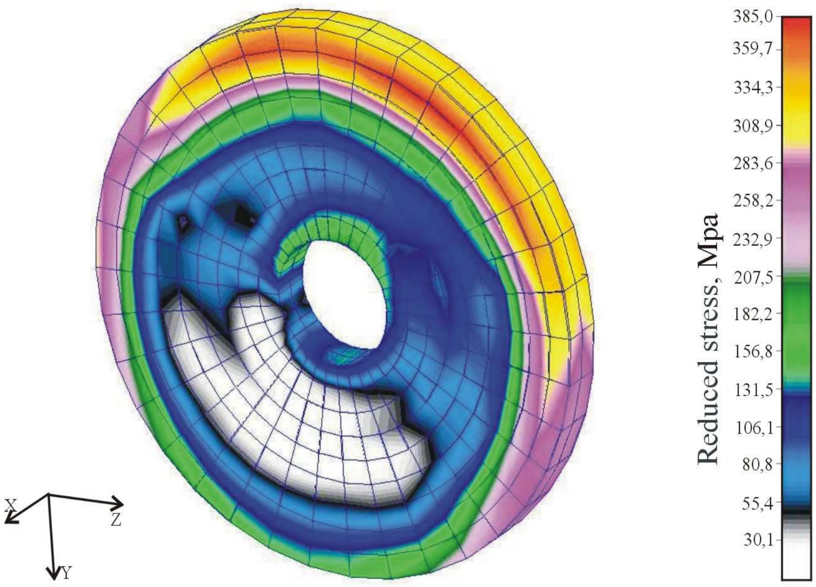

Fig. 2. Depth curves for the reduced stress for the investigated steel

4. CONCLUSIONS

In order to determine the stress values, the deformations and dislocations that had occurred in the sample under thermal fatigue testing, were calculated using the finite element. It was found from the analysis, that the maximum stress during the thermal cycle was 385 MPa which corresponds to approx. 85% of the yield strength for steel at 548 °C in the point of maximum stress.

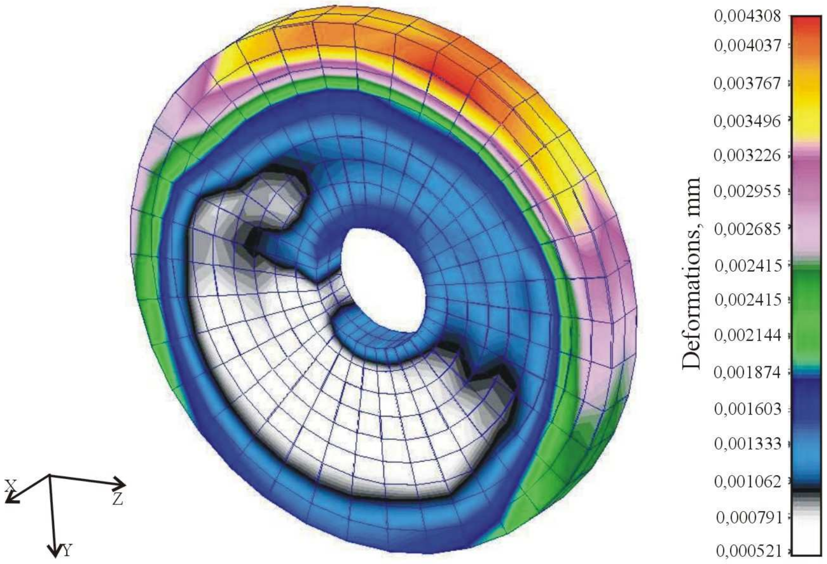

Fig. 3. Deformations of the investigated steel

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