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PREDICTION OF ENERGY STATES OF THE PROBE DURING QUENCHING IN ISOMAX 166 OIL APPLYING BY EXPERIMENT AND NUMERICAL SIMULATION

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ABSTRACT

In the article, the computer modelling of the energy states of the probe during quenching process in the Isomax 166 oil is presented. The probe was cooled from the initial temperature of 850 °C. The selected steady-state temperatures of the oil were from 0 °C to 120 °C. The material of the probe was non-stabilized Cr-Ni austenitic stainless steel 1Cr18Ni9. The simulation model involves nonlinear thermophysical and thermomechanical material properties. Cooling curves were obtained using the methodology of Wolfson test. Based on the numerical simulation of a cooling process and experimental temperature measurement, the combined heat transfer coefficient was calculated. To determine the combined heat transfer coefficient as a function of probe surface temperature, the inverse-numerical-correlation method was applied. The time histories of thermal elastic and plastic stress states, time dependences of residual stresses and volume plastic work as a function of chosen temperature of quenching oil were analysed using the finite element method and the engineering-scientific program code ANSYS.

KEY WORDS

Quenching, Cooling curve, Combined heat transfer coefficient, Computer modelling, ANSYS, Stress-strain state, Volume plastic work

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NOMENCLATURE

$c(T)$	[J.kg^{-1}.K^{-1}]	specific heat,
$c_p(T)$	[J.kg^{-1}.K^{-1}]	isobaric specific heat,
ε_{ij}^{p}	[-]	plastic strain,
$E(T)$	[Pa]	Young modulus of elasticity,
$E_t(T)$	[Pa]	tangent hardening modulus,
$h_{comb}(T_s)$	[W.m^{-2}.K^{-1}]	combined heat transfer coefficient,
$\dot{q}_v$	[W.m^{-3}]	volume heat source density,
R_e	[Pa]	yield limit (stress) of a material,
T	[°C]	temperature,
T_r	[°C]	temperature of unagitated cooling oil Isomax 166,
$T_s(t_i)$	[°C]	probe surface temperature in time t_i,
W_p	[J.m^{-3}]	volume plastic work,
$\alpha_l(T)$	[K^{-1}]	linear thermal expansion coefficient,
$\lambda(T)$	[W.m^{-1}.K^{-1}]	thermal conductivity,
ν	[m^{-2}.s^{-1}]	coefficient of kinematic viscosity,
ν	[-]	Poisson’s ratio,
$\rho(T)$	[kg.m^{-3}] I	density,
σ_{ij}	[Pa]	stress tensor,
σ_M	[Pa]	von Mises equivalent stress.

INTRODUCTION

Heat treatment is a multiparametric process. The selection of appropriate parameters is crucial for the achievement of required microstructure and properties of treated components. The choice of a suitable quenching medium, its temperature and state (unagitated or agitated) represents the determining factors.

Quenching oil Isomax 166 belongs to the commonly used quenching oils. Prediction of behavior of treated components during cooling process is possible only in the case when the boundary conditions of the process are known [1-4]. Numerical simulation of a cooling process requires the heat transfer coefficient on the component surface (boundary condition of the third kind) to be quantitatively defined. Then, applying the simulation model and numerical experiment it is possible to investigate the influence of single parameters of heat treatment on the immediate and final state of treated component.

The methodology of evaluation and quantification of cooling characteristics of unagitated oil Isomax 166 at chosen temperatures and their influence on the energetic state of a component after cooling process is presented in the article.

EXPERIMENTAL METHODS AND MATERIALS

Oil Characteristic

The oil Isomax 166 belongs to the intensive quenching oil with low viscosity (ν = 12.5 10^{-6} $m^2.s^{-1}$ at 40 °C) mostly applied for quenching of non-alloyed, low-alloyed, alloyed and carburized steels [5]. The grade of through-hardening is high even after application of Isomax 166 oil for the quenching of large components. It is resistant to evaporation. The range of recommended working temperatures of Isomax 166 is from 40 °C to 70 °C [5].

Experimental Temperature Measurement

The experimental equipment consisted of electrical resistance furnace of LM 212.10 type, cylinder-shaped experimental probe made of non-stabilized Cr-Ni austenitic stainless steel 1Cr18Ni9, Isomax 166 oil and NI USB 9211 for digital record of measured temperatures. More details, structures, properties and experimental results about austenitic stainless steels were published for example by Číhal [6] and Dománková et. al. [7]. Geometrical and initial condition of the experiment were based on the Wolfson's quenching test [3]. The diameter of the probe was 12.5 mm and its hight 60 mm. Before quenching, the probe was heated up to the initial temperature of 850 °C. The temperatures were measured by the encapsulated 304 SS thermocouple of K type with diameter of 1.5 mm located in the centre of the probe. Temperatures were recorded 5 times per second and each set of measurement was repeated six times for each chosen oil temperature (0 °C, 30 °C, 50 °C, 60 °C, 70 °C and 120 °C). During probe cooling, the oil temperature was maintained at the constant value. The temperature records were statistically handled and consequently used for the determination of the cooling rate and the temperature dependence of combined heat transfer cofficient applying the inverse-numerical-correlation (INC) method [1, 2].

THEORETICAL BACKGROUND

The heat transfer from the cylinder shaped probe into the cooling oil was assured by the combination of radiation, boiling and convection heat transfer. The transient temperature field in the quenched probe can be described by the Fourier-Kirchhoff differential equation (FKDE) of heat conduction in cylindrical coordinate system. The FKDE was solved numerically using the finite element method and the program code ANSYS. The combined heat transfer coefficient $h_{\mathrm{comb}}(T_{\mathrm{s}})$ was determined as a function of the probe surface temperature for single Isomax 166 oil temperatures. The boundary condition of the third type given by the equation of conduction and convection heat fluxes on the probe surface in the time t_{i} was applied

$$-\lambda(T)\,\mathrm{grad}\,T(r,z)\big|_{t_{\mathrm{i}}} = q_{t_{\mathrm{i}}} = h_{\mathrm{comb}}(T_{\mathrm{s}})\left[T_{\mathrm{s}}(t_{\mathrm{i}}) - T_{\mathrm{r}}\right]. \qquad [\mathrm{W.m^{-2}}] \qquad (1)$$

It was supposed that the material of experimental probe was isotropic with the temperature dependent thermal properties $\lambda(T)$, $\rho(T)$, $c(T)$. Cooling process was isobaric, i. e. the specific heat $c(T) = c_{\mathrm{p}}(T)$. The temperature of cooling oil during the measurement was steady-state and there were no volume heat sources

($\dot{q}_v = 0$ W.m^{-3}). The elastic-plastic model with bilinear kinematic hardening was exploited to solve the structural problem. Development of plastic deformation was assumed according to the von Mises criterion [8]

$$F(\sigma_\mathrm{M},T) = f(\sigma_\mathrm{M},T) - R_\mathrm{e}(T) = 0 . \qquad \text{[Pa]} \qquad (2)$$

The increment of volume plastic work W_p is defined as [9-10]

$$\mathrm{d}W_\mathrm{p} = \sigma_\mathrm{ij}\mathrm{d}\varepsilon_\mathrm{ij}^\mathrm{p} . \qquad [\mathrm{J.m}^{-3}] \qquad (3)$$

NUMERICAL SIMULATION

Engineering-scientific program software ANSYS was chosen as an interpretation program for numerical simulation. Geometrical model of the probe was axisymmetric. Elements with quadratic shape function were used to generate progressive mesh. The accuracy of the obtained results is very strongly dependent on the material properties [6, 11, 12].

Table 1 Thermal and mechanical properties of austenitic stainless steel 1Cr18Ni9 [6, 11, 12]

T [°C]	$\lambda(T)$ [W.m^{-1}.K^{-1}]	$c(T)$ [J.kg^{-1}.K^{-1}]	$\rho(T)$ [kg.m^{-3}]	$\alpha_\mathrm{l}(T)$ .10^6 [K^{-1}]	ν [-]	$R_\mathrm{e}(T)$ [MPa]	$E(T)$ [GPa]	$E_\mathrm{t}(T)$ [MPa]
0	14.8	455	7940	16.8	0.3	235	200	1185
100	15.8	475	7911	17.2	0.3	233	195	1175
200	17.0	495	7871	17.6	0.3	230	188	1160
300	18.4	508	7830	17.8	0.3	222	181	1080
400	20.0	525	7787	18.0	0.3	206	172	950
500	22.0	550	7745	18.3	0.3	174	165	812
600	24.0	572	7703	18.5	0.3	137	157	660
700	25.7	602	7662	18.8	0.3	94	147	470
800	27.5	620	7620	19.0	0.3	55	135	250
900	29.4	630	7578	19.2	0.3	36	100	185

RESULTS AND DISCUSSION

Time dependences (from 0 s to 140 s) of average values of measured temperatures during the probe cooling from 850 °C into unagitated oil with chosen temperatures are shown in Figure 1. In Figure 2, the detail of time dependences of average values of measured temperatures from Figure 1 is illustrated. Cooling rates (the first time derivations of measured temperature dependences shown in Figure 1) are shown in Figure 3. The cooling rates (Figure 3) are presented in the time interval from 0 s to 20 s because of better readability. The dependences of the combined heat transfer coefficient as functions of probe surface temperature for chosen temperatures of unagitated oil Isomax 166 are shown in Figure 4.

Temperature dependences of $h_{\mathrm{comb}}(T_{\mathrm{s}})$ coefficients were evaluated applying INC method with the correlation coefficients between solved and measured temperatures at the level of 0.99. The obtained values of combined heat transfer coefficient (Figure 4) were applied as the load for the nonlinear structural problem used for the analysis of thermal and thermal-stress-strain fields in the probe. The time histories of thermal elastic and thermal elastic-plastic von Mises equivalent stresses in the selected points A and B (Figure 5a) for cooling oil temperature of 60 °C are shown in Figure 6.

The distribution of volume plastic work W_{p} [J.m^{-3}] is shown in Figure 5a. The field of residual von Mises stress distribution in the probe after cooling process in unagitated oil with the temperature of 60°C in the time of 900 s is shown in Figure 5b. The influence of the oil Isomax 166 temperature on the energetic states of the probe is illustrated in Figure 7.

Maximal and average values of volume plastic work W_{p} [J.m^{-3}] as the function of selected oil temperatures are shown in Figure 7. Average values were obtained for complete volume of the cylindrical shaped probe. The lowest cooling ability of oil Isomax 166 was found to be at 0 °C, the maximal cooling ability at 60 °C.

The character of experimentally measured temperature was changed at the oil temperature of 120 °C oil. In this case, the cooling process was more intensive in the phase of film boiling as for oil with different temperatures. The amount of the probe enthalpy relaxed during cooling in oil of 120 °C was increased in the first phase of cooling as much as the amount of enthalpy relaxed during critical state of nucleate boiling is the lowest among chosen constant temperatures of oil cooling process.

Cooling rates are the reflection of measured temperature steepness. The highest cooling rate of 109 K.s^{-1} can be reached in the oil with the temperature of 60 °C. The lowest cooling rate 92.5 K.s^{-1} was recorded at the oil temperature of 120 °C. The cooling rate increases from oil temperature 0 °C to 60 °C, then decreases as the function of increased oil temperatures. Taken into account the highest cooling rate, the relative change of cooling rate is about 15.1 %. After the comparison of cooling rates in the phase of film boiling at different selected temperatures, the cooling rate in this phase of cooling is the highest for oil at temperature of 120 °C.

Oil temperature is significant parameter for values of $h_{\mathrm{comb}}(T_{\mathrm{s}})$ and also for curves shape changes. The most significant change of $h_{\mathrm{comb}}(T_{\mathrm{s}})$ was proved at 120 °C. The highest difference among $h_{\mathrm{comb}}(T_{\mathrm{s}})$ is between 0 °C and 60 °C and it reaches the value of 1050 W.m^{-2}.K^{-1}. Film boiling finishes in the temperature interval from 677 °C to 690 °C and in the same temperature interval begins nucleate boiling of Isomax 166 oil. Nucleate boiling of the oil finishes at temperatures of the probe surface from 277 °C to 310 °C. Convection heat transfer starts in the same range of temperatures (from 277 °C to 310 °C on the probe surface).

Origin of residual stresses after finished cooling process (previously indicated for example by Puškár and Hazlinger [13]) is the consequence of stresses generation (during cooling) over appropriate limit yield stress. The yield limits of 1Cr18Ni9 austenitic steel as the function of temperature is listed in Table 1. Maximal thermal elastic von Mises equivalent stresses in the probe from 398 MPa to 452 MPa were computed during cooling.

After finishing the cooling process, the residual stresses are distributed over whole volume of the probe. The highest values of residual stresses (232 MPa) were calculated in the plastic zone very close to the probe surface. The maximum value of volume plastic work (W_p = 489 kJ.m^{-3}) was reached in the zone on the probe surface in the point B (Figure 7) during cooling in the oil at the temperature of 60 °C.

CONCLUSIONS

- Applying the experiment and numerical simulation it is able in qualitative and quantitative way to study the influence of the temperature of the cooling oil Isomax 166 on the heat transfer from the probe into unagitated oil with different steady-state temperatures and to analyse the energetic state of a heat treated component.
- The influence of oil temperature on cooling process parameters is evident.
- Cooling ability of Isomax 166 is the function of oil temperature.
- Cooling ability of the oil increases for higher oil temperatures from 0 °C to 60 °C.
- The highest cooling ability of quenching oil Isomax 166 is at 60 °C.
- Cooling ability of Isomax 166 decreases when the oil temperatures are above the 60 °C.
- Combined heat transfer coefficients (values and dependences) from the probe surface into unagitated oil Isomax 166 are dependent on the oil temperature.
- The highest value of $h_{\mathrm{comb}}(T_s)$ = 4288 W.m^{-2}.K^{-1} belongs to the cooling process in unagitated oil with the temperature of 60 °C.
- The lowest value of $h_{\mathrm{comb}}(T_s)$ = 3238 W.m^{-2}.K^{-1} was reached in unagitated oil of 0 °C.
- Temperature dependence of $h_{\mathrm{comb}}(T_s)$ at 120 °C is the proof of the qualitative change during cooling process in unagitated oil Isomax 166 of 120 °C.
- Energetic states of the probe after cooling process are dependent on the oil temperature.
- The highest level of volume plastic work W_p [J.m^{-3}] generated during cooling at the rest of selected oil temperatures is lower than during oil cooling at 60 °C.
- The steepness of W_p between 60 °C and 50 °C, between 50 °C and 30 °C and between 30 °C and 0 °C is decreasing.
- The maximum of W_p decreasing steepness is between temperatures 60 °C and 50 °C.
- At higher oil temperatures than 60 °C (from 60 °C to 120 °C) is the steepness of W_p [J.m^{-3}] also decreasing.
- On the right side of the oil temperatures interval (from 60 °C), the maximal decrease in steepness of W_p is between temperatures from 60 °C to 70 °C.
- The decreasing steepness of W_p between 70 °C and 120 °C is higher than the steepness between temperatures 30 °C and 0 °C.
- At 60 °C, it is not only the highest cooling ability of oil Isomax 166 but also thermal stresses generated during cooling are the highest at 60 °C.

- If the thermal stresses generated during a component heat treatment should be lower than maximal then oil Isomax 166 cooling at higher temperatures than 60 °C is advised.

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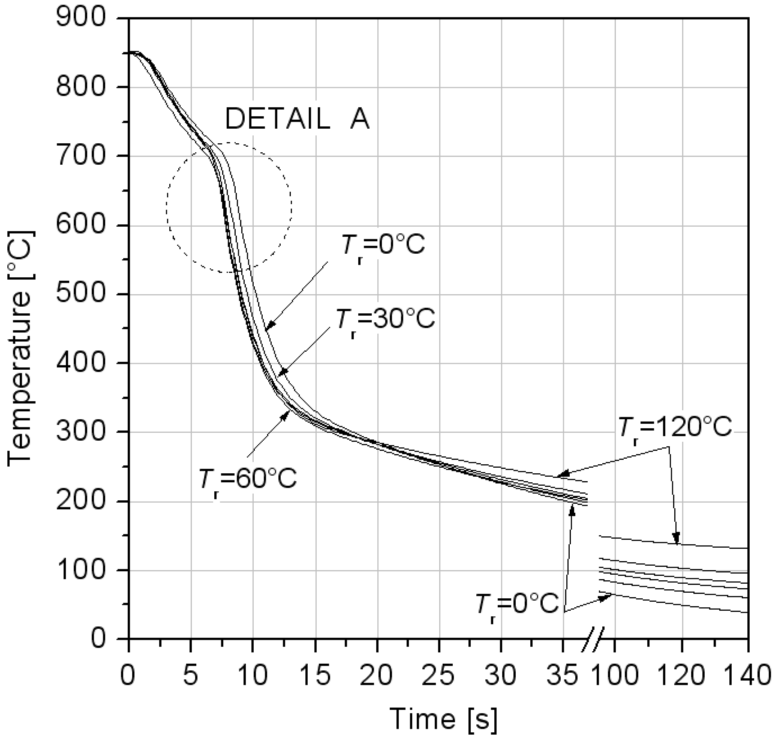


Figure 1 Time dependences of average values of measured temperatures

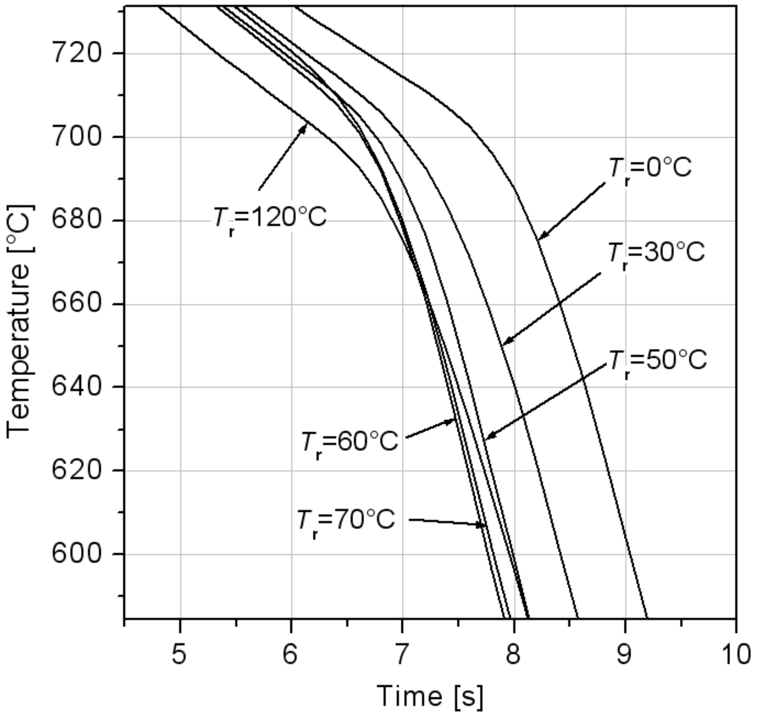


Figure 2 The detail A of time dependences of average values of measured temperatures from Figure 1

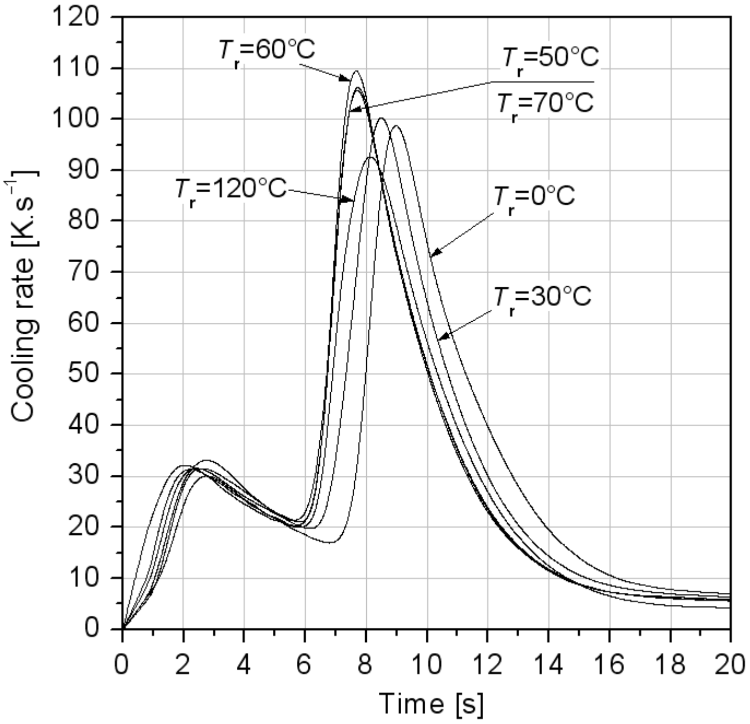


Figure 3 Time histories of cooling rates for selected oil temperatures

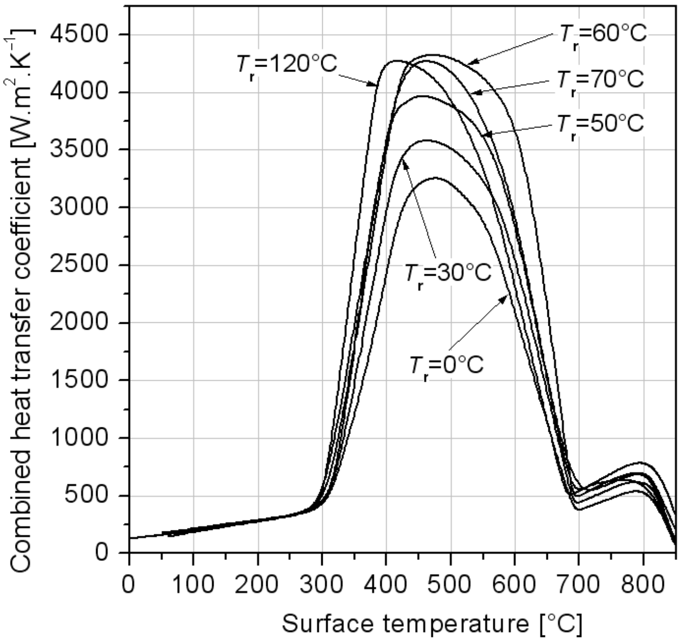
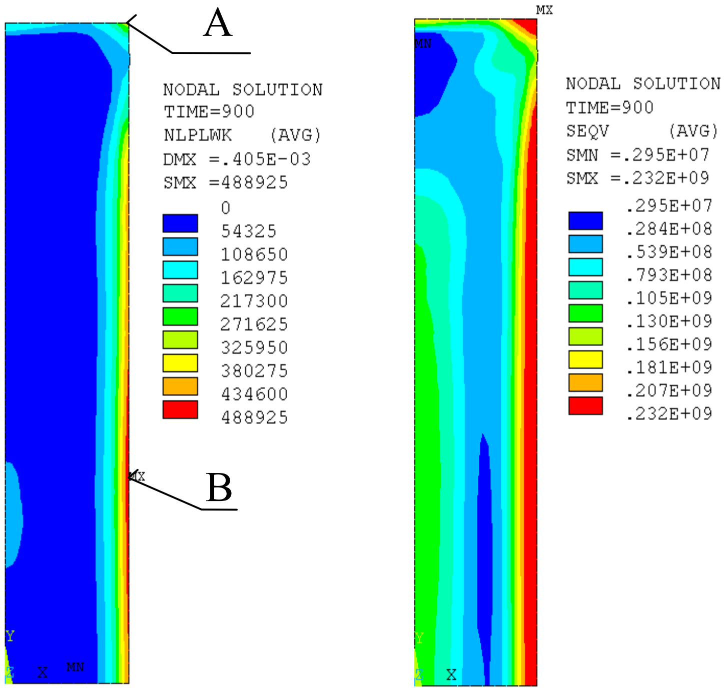


Figure 4 Combined heat transfer coefficients $h_{\text{comb}}(T_s)$ as a function of surface temperature



a) b)

Figure 5a The distribution of volume plastic work [J.m^{-3}]
Figure 5b The field of residual von Mises stress distribution of the probe after cooling at unagitated oil of 60°C [Pa]

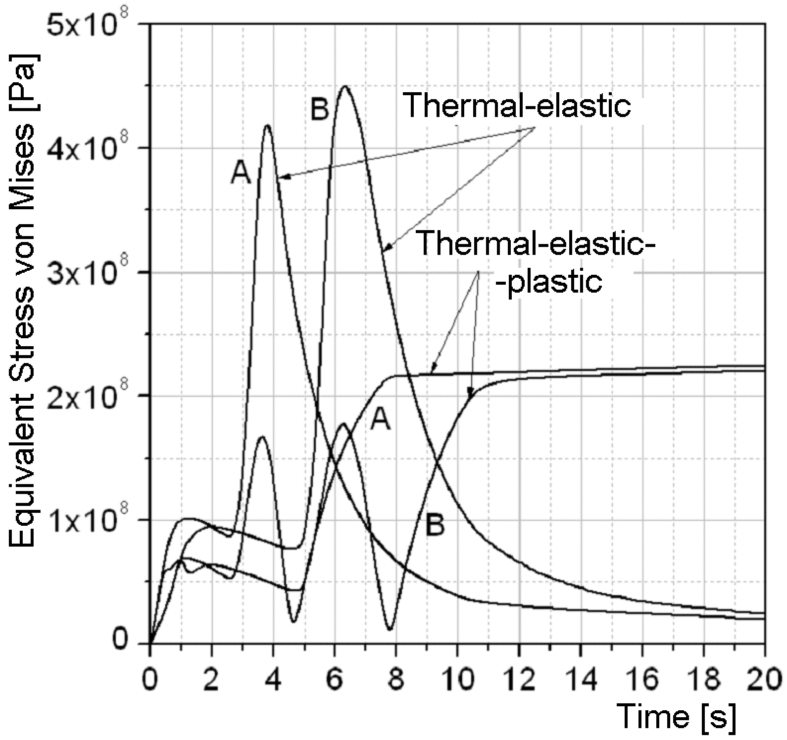


Figure 6 Time histories of thermal-elastic and thermal-elastic-plastic von Mises equivalent stresses in selected probe points A and B for oil cooling at 60 °C

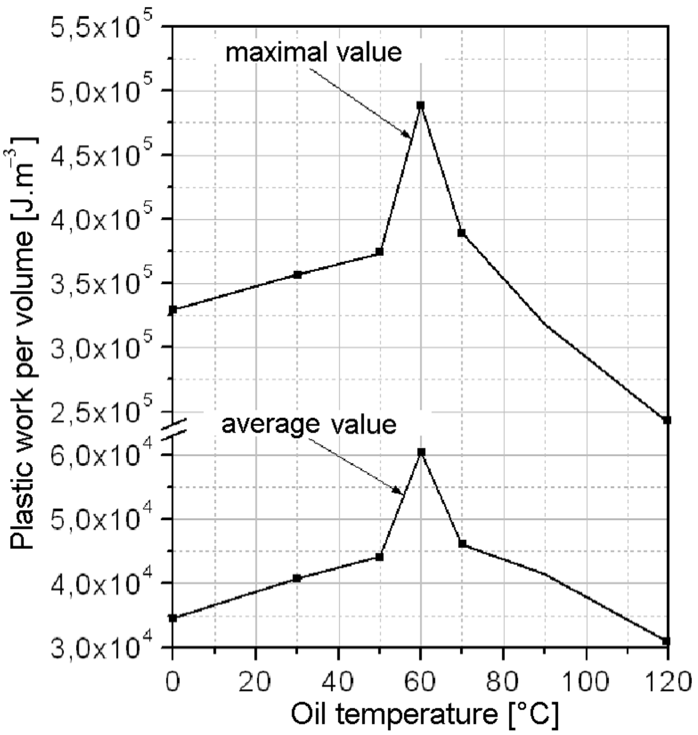


Figure 7 The influence of the temperature of oil Isomax 166 (from 0 °C to 120 °C) on energetic states of the probe for selected oil temperatures from interval 0 °C to 120 °C