Determination of quasi-static and residual stresses in the course of the thermoplastic hardening in a boundary layer of the material

V V Zhukov$^1$, I V Kudinov$^1$, N M Kutsev$^2$, G V Mikheeva$^1$ and R M Klebleev$^{1,*}$

$^1$ Theoretical foundations of heat engineering and hydromechanics Department, Samara State Technical University, 443100 Molodogvardeyskaya street 244, Samara, Russian Federation
$^2$ CJSC “KADFEM CIS”, 443069 Avrora street 110, building 1, office 40, Samara, Russian Federation

*galinn21@list.ru

Abstract. In order to induce residual compressive stresses in the boundary layer of a steel plate heated to temperature $T_0 = 600^\circ\text{C}$, a method of jet water cooling with time-varying heat transfer coefficients is considered. By solving the corresponding heat conduction problem, it is shown that the maximum temperature difference between the surface and the center of a $2\text{ mm}$ thick plate is $105^\circ\text{C}$. It is observed within $0.02\text{ s}$ since the start of cooling, the time of its complete cooling is equal to $0.32\text{ s}$. Calculations of temperature stresses using the finite element method showed that temperature tensile stresses occur on the outer surface of the plate. They may reach $26\text{ kg/mm}^2$ which exceeds the yield strength of this material. As a result of plastic deformation, the thermal tensile stress relieving occurs in the course of cooling of the plate surface layer; when it is completely cooled, the residual compressive stresses $21.8\text{ kg/mm}^2$ (on the surface of the plate) are induced in this layer ($0.25\text{ mm}$ depth).

1. Introduction

Various methods are used to increase the wear resistance of thin boundary layers of metal products. They include methods of inducing residual compressive stresses in a thin boundary layer in order to improve materials efficiency under tensile stresses. The implementation of these methods is related to the shock cooling of the boundary layer of the preheated product so that the thermal tensile stresses in this layer would reach the values with observed material plasticity.

In the layer unaffected by cooling, the thermal compression stresses occur. The material plasticity in the boundary layer makes it possible to relieve tensile stresses, while the compressive stresses in the rest layer of the material persists.

The cooling of the main part of the material (with the exception of the boundary layer which is already cooled and relieved from thermal stresses due to plastic deformation processes) is accompanied by the compressive stresses relieving and in the boundary layer the stresses of the same sign are induced. As a result, it provides increasing the service life of products under conditions of tensile stresses on their surfaces.
With this method of improving the structures efficiency, the main task is the obtaining the sufficient temperature gradients in the surface layer to induce tensile stresses comparable to the material's yield point. Obtaining the appropriate temperature gradients for metals is a big problem due to their high thermal conductivity which leads to the equalization of the temperature field of the structure.

A key factor here is the time acceleration of the cooling process. For these purposes, jet water cooling which makes it possible to almost exclude the process of film boiling at a high flow rate of the medium is used. The reduction of heat transfer coefficients results in the significant increase of the cooling time; therefore, it leads to a decrease in temperature gradients to the values that do not allow to induce stresses leading to material plasticity, which is a necessary condition for creating residual stresses.

2. Mathematical formulation of the problem

As an example of the induction of residual stresses, consider the process of jet cooling of a steel plate with a thickness of 2 mm heated to a certain initial temperature (600°C) under symmetric boundary conditions of the third kind varying with temperature. The mathematical setting of the heat conduction problem in this case (in view of thermal symmetry, half of the plate thickness is considered) is as follows:

\[
\frac{dT(x,t)}{dt} = a \frac{d^2T(x,t)}{dx^2}; \quad (t > 0; 0 < x < \delta)
\]

(1)

\[
T(x,0) = T_0
\]

(2)

\[
\lambda \frac{dT(0,t)}{dx} = \alpha(T)[T(0,t) - T_{sr}]
\]

(3)

\[
\frac{dT(\delta,t)}{dx} = 0
\]

(4)

where \(T\) – temperature; \(x\) – coordinate; \(a\) – temperature conductivity coefficient; \(\lambda\) – thermal conduction coefficient; \(T_0\) – initial temperature; \(T_{sr}\) – ambient temperature; \(\delta\) – half of the plate thickness; \(\alpha(T)\) – temperature-dependent heat transfer coefficients.

Given data for problem solution (1) – (4) are as follows:

\[
\lambda = 60.5 \frac{W}{m \cdot K}; \quad a = 17.8 \cdot 10^{-6} \frac{m^2}{s}; \quad T_0 = 600\; ^{\circ}C; \quad T_{sr} = 0\; ^{\circ}C; \quad \delta = 2\; mm
\]

3. Numerical solution

Experimental data on temperature dependence of heat transfer coefficients for the jet cooling process are shown in table 1. [1].

Table 1.

| \(T_{kr}, ^{\circ}C\) | 0  | 50  | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 | 550 | 600 |
|---------------------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \(\alpha, \frac{kW}{m^2 \cdot ^{\circ}C}\) | 0  | 25  | 100 | 200 | 250 | 133 | 100 | 78.5| 68  | 62  | 57.5| 54  |

To solve the nonlinear heat conduction problem (1) - (4), the calculation module of the Transient Thermal program Ansys Workbench 18.2 was used.

To build a finite element mesh, the Sweep Method algorithm was used. It is applied to problems with a predominant one-dimensional change of the sought-for function and provides creating a
structured hexahedral mesh of finite elements. The cooled plate was divided into 1800 hexahedral elements, the mesh consisted of 8672 nodes (figure 1).

The results of temperature field calculations are shown in figure 1, 2. From their analysis it is observed that with such a high intensity of cooling, the time of cooling the plate to the temperature of the cooling water is 0.32 s. Here, the maximum temperature gradients in the range \(0 \leq x \leq 0.25 \text{mm}\) are observed at \(t = 0.02\) s (the temperature difference in the specified range of coordinates is about \(105^\circ\text{C}\)).

Figure 1. Scheme of plate partitioning into finite elements and temperature field at the moment of time \(t = 0.001\) s.

Figure 2. The temperature distribution in time from the edge to the middle of the plate.

The temperature distribution found was used to calculate quasi-static temperature stresses by the finite element method [2-7] using the Static Structural module of Ansys Workbench 18.2. In this case,
we consider a plate free from surface loads, the temperature of which varies only in thickness. It can be found from the solution of the heat conduction problem obtained above. Representing the body considered as a three-dimensional one, where dimension along the $x$ axis is much smaller than dimensions along the $y$ and $z$ axes, we can write the relations as follows

$$
\sigma_x = \tau_{xy} = \tau_{xz} = \tau_{yz} = 0; \quad \sigma_y = \sigma_z = \sigma_{y,z} (x) = \sigma (x)
$$

Using the finite-element method, a general system of algebraic linear equations is built for the entire finite element model of a deformable body. For quasi-static problems solved with the help of the Static Structural module, it can be written as [7]

$$
[K] \{U\} = \{P\} + \{P\}^s + \{P\}^e + \{P\}^\sigma
$$

where $[K]^T$ – tangent stiffness matrix of a finite element model; $\{U\}$ – nodal displacement vector; $\{P\}$ – general vector of specified external nodal forces; $\{P\}^s, \{P\}^e, \{P\}^\sigma$ – general nodal force vectors equivalent to distributed, respectively, surface forces, mass forces, initial deformations and initial stresses.

The relation (6) represents a system of algebraic linear equations with respect to the nodal displacements of a finite element model. The finite element method makes it possible to obtain strongly disperse stiffness matrices of a tape type which are symmetric with respect to the main diagonal. For such matrices, an important characteristic is the tape width determined by the difference in node numbers for the element in which this difference is greatest.

Consequently, the tape width depends on the method of automatic partitioning of the area into finite elements. The boundary conditions are specified in the form of the absence of stresses on the circuit in the direction perpendicular to the tangent at a given point of the boundary (in the absence of external forces). The conditions should also be specified for the absence of displacements of any point along all coordinate axes in order to exclude the movement of the body as a single whole, and the absence of displacement at some other point along one of the coordinate axes to prevent rotation of the body.

4. Analysis of the results

The temperature distribution over the plate thickness for individual cooling time points was used to calculate temperature stresses $\sigma (x)$ by the finite element method. The calculation results are shown in figure 3. Their analysis shows that 1 second after start of cooling, residual compressive stresses equal to $\sigma (0) = -21.8 \text{ kg} / \text{mm}^2$ are induced on the plate surface.

![Stress distribution in time from the edge to the middle of the plate.](image-url)
5. Conclusions

- Using experimental data on time-dependent heat-transfer coefficients observed during jet water cooling of a plate, the calculations were made to determine its temperature state. Their analysis shows that the complete cooling time of the plate is 0.32 s. The maximum temperature difference in the range \(0 \leq x \leq 0.25 \text{ mm}\) is observed after 0.02 s after the start of cooling and is equal to \(\Delta T \approx 105^\circ\text{C}\).

- If the temperature tensile stresses on the plate surface at the described temperature difference exceed the yield strength of the material considered (steel 25 kg / mm\(^2\)), they cause its plastic deformation accompanied by a complete tensile stress relieving. Upon further (complete) cooling of the plate, the residual compressive stresses (21.8 kg / mm\(^2\)) are induced in its surface layer.

Acknowledgments

The work was supported by the Ministry of Science and Higher Education of the Russian Federation within the framework of the basic part of the state task FSBEI of Higher Education "Samara State Technical University" (project №1.555.2017 / 8.9)

References

[1] Kravchenko B A, Krutsilo V G and Gutman G N 2000 Thermoplastic Hardening - a Reserve to Increase the Strength and Reliability of Machine Parts (Samara: Samata State Technical University Press) p 216

[2] Zenkevich O 1975 Finite Element Method in Engineering (Moscow:Mir) p 541

[3] Segerlind L 1979 Application of the Finite Element Method (Moscow:Mir) p 392

[4] Norrie D and de Vries G 1981 An Introduction to the Finite Element Method (Moscow:Mir) p 304

[5] Strang G and Fix J 1977 The Theory of the Finite Element Method (Moscow:Mir) p 349

[6] Kartashov E M, Kudinov V A and Kalashnikov V V 2018 Theory of Heat and Mass Transfer: Problem Solutions for Multilayer Structures (Moscow: Uranit Publishing House) p 435

[7] Bruyaka V A, Fokin V G, Soldusova E A, Glazunova N A and Adeyanov I E 2010 Engineering Analysis in ANSYS Workbench (Samara: Samata State Technical University Press) p 271