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Decrease of Residual Stresses in the Elastic-Plastic-Creep Medium at Temperature Influence

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Abstract. Within the linear theory of elastic-plastic body we carried out the modeling of technological process of annealing: slow heating stage, the holding stage under constant temperature and slow cooling step. Holding stage is simulated with consideration of creeping properties of materials. Boundary value problems are examined and patterns responsible for the removal of residual stresses at temperature influence are described. An analytical solution is found. It is proved that the holding stage is essential for describing the process of residual stress relief.

Introduction

Stresses, existing in the bodies or structures in the absence of any external influences (power, heat, etc.) are called the residual. In the manufacture and hardening of metal materials the accumulation of such residual stresses takes place. Overlay of residual stress on the newly applied loads during operation adversely affects the characteristics of the materials, causing them to distort or even destruction. Therefore, there exists a necessity for application of various methods which lead to the removal of such unwanted stresses. In technological practice, such a method is an annealing process, involving heating the material to a certain temperature, holding and subsequent slow cooling.

In this article, within the mechanics of deformable solids boundary value problems are examined and the patterns responsible for the removal of residual stresses at temperature influence are described. The level of the accumulated stress taken as the basis was calculated in [1–2]. The static determination of the plastic flow [3–4] was a prerequisite for this process. In [5] based on the linear viscoelastic Voigt model, even under conditions of changes of material yield strength with increasing temperature there was set growth of stresses, leading to undesirable effects – repeated plastic flow. In this paper, using an example of a hollow sphere with accumulated irreversible strains [2] in the framework of linear elastic-plastic body it is shown that the reduction of residual stress is still possible. In this process the simulation was carried out by quasi-static process of additional deformation under slow heating, holding at a certain temperature, and slow cooling. The article shows that the holding stage itself, which was proposed to be considered in view of the creeping material properties [6–7], is essential for describing the process of residual stress relief. As a creep law, in this work the Norton creep power law [8] is used.

Medium with the accumulated residual stresses

In [2], in the framework of linear elastic-plastic body there is described the concrete possibility of determining the parameters of elastic-plastic process on the final discharge of a hollow sphere (r_0, R_0, $r_0 < R_0$) is subjected to one-dimensional deformation. Assuming irreversible incompressibility in a spherical coordinate system (r, θ, φ) two regions were formed in the body:

$r_1 < r \le R_0$ – elastic and $r_0 \le r \le r_1$ – elastic-plastic, r_1 – boundary separating elastic and elastic-plastic regions. Elastic-plastic region $r_0 \le r \le r_1$ contains irreversible plastic deformation:

$$e_{rr}^p = -2k\gamma - Ar^{-3},\ \ e_{\theta\theta}^p = e_{\varphi\varphi}^p = -e_{rr}^p/2,\ \ \gamma = (\lambda + 2\mu)(3\lambda + 2\mu)^{-1}\mu^{-1}. \quad (1)$$

These strains have been accumulated by the body under the preliminary deformation. The formula Eq. 1 λ, μ – Lame parameters, k – yield stress, A – a constant, is determined from the total deformation $d_{rr}(r_0)$ measured in the inner boundary and from given angular stresses $\sigma_{\theta\theta}(r_0) = -2k$.

In the elastic region $r_1 < r \le R_0$, plastic deformation Eq. 1 e_{rr}^p and $e_{\theta\theta}^p$ are equal to zero, and the elastic deformation e_{rr} and $e_{\theta\theta}$ displacement components depend on $u = u_r(r)$:

$$e_{rr} = d_{rr} = \partial u/\partial r,\ \ e_{\theta\theta} = e_{\varphi\varphi} = d_{\theta\theta} = d_{\varphi\varphi} = u/r, \quad (2)$$

where d_{rr} and $d_{\theta\theta}$ – components of total strains.

Level taken as the basis of residual stress is presented in Fig. 1.

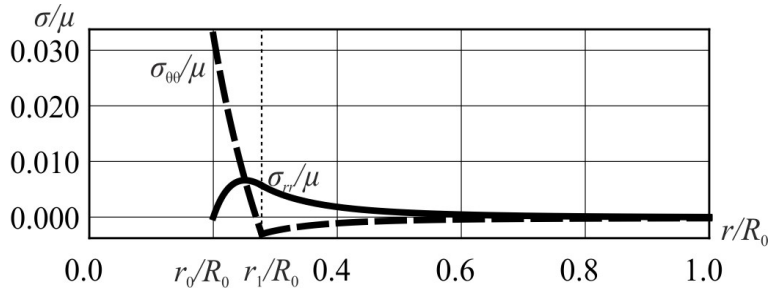

Fig. 1. Preliminary distribution of residual stresses for steel 30KhGSN2A at room temperature $T = 20^\circ C$

Calculations were performed for the steel grade material 30KhGSN2A. Material parameters: $\lambda = 1.8 \cdot 10^{11}$ Pa, $\mu = 8.1 \cdot 10^{10}$ Pa, $k = 1350 \cdot 10^6$ Pa. Geometric dimensions: $r_0 / R_0 = 0.2$, $R_0 / R_0 = 1$. Measurement readings: $d_{rr|r=r0} = 0.03812$, given $\sigma_{\theta\theta|r=r0} = -2k$ Pa. On Fig. 1 voltage on the outer and inner boundary and: $\sigma_{rr}(R_0) = 0$ and $\sigma_{rr}(r_0) = 0$. On the figures σ/μ (σ_{rr}/μ – shown by the full line, $\sigma_{\theta\theta}/\mu$ – by dotted line) are presented depending on the values r/R_0.

Simulation of slow heating stage

Let's follow changes in stresses in the material during annealing during the heating stage. We assume the above-described state of the medium as original. Slow heating stage is examined under the law Duhamel–Neumann [9] ($e_{\theta\theta} = e_{\varphi\varphi}, \sigma_{\theta\theta} = \sigma_{\varphi\varphi}$)

$$\sigma_{rr} = \lambda(e_{rr} + 2e_{\theta\theta}) + 2\mu e_{rr} - 3\alpha_T \mathrm{K}(T - T_0),\ \sigma_{\theta\theta} = \lambda(e_{rr} + 2e_{\theta\theta}) + 2\mu e_{\theta\theta} - 3\alpha_T \mathrm{K}(T - T_0). \quad (3)$$

The formula Eq. 2 δ_{ij} – Kronecker delta, α_T – the coefficient of linear thermal expansion, $\mathrm{K} = \lambda + 2/3\mu$ – the elastic bulk modulus, T – the current temperature, T_0 – room temperature.

Stresses in a medium with increasing temperature will vary according to Eq. 3. For the elastic region $r_1 < r \le R_0$ in Eq. 3 the components of the elastic strain e_{rr} and $e_{\theta\theta}$ are expressed by Eq. 2. For an area $r_0 \le r \le r_1$ with accumulated irreversible strains in Eq. 3 should be considered:

$$e_{rr} = d_{rr} - e_{rr}^p = \frac{\partial u}{\partial r} - e_{rr}^p, \quad e_{\theta\theta} = e_{\varphi\varphi} = d_{\theta\theta} - e_{\theta\theta}^p = \frac{u}{r} - e_{\theta\theta}^p, \tag{4}$$

where e_{rr}^p and $e_{\theta\theta}^p$ are defined in Eq. 1. This solution is valid if the conditions in this region $\sigma_{rr} - \sigma_{\theta\theta} < 2k_2$, where k_2 – the yield stress.

With increasing temperature, the yield strength changes $k_2 = k_2(T)$. Changing the material yield strength are defined by the interpolation function of temperature $k_2 = 1350 \cdot 10^6 - 5(T - 200)(T - 100)(T - 20)(400 + 3T)/1824$, with known experimental data [10] at different temperatures in the table.

Table. Dependence of the yield strength of the steel 30KhGSN2A on the temperature

Yield stress [Pa]	Temperature [°C]					
	20	100	200	400	500	590
k_2	$1350 \cdot 10^6$	$1350 \cdot 10^6$	$1350 \cdot 10^6$	$1250 \cdot 10^6$	$1050 \cdot 10^6$	$702 \cdot 10^6$

In the process of heating to a temperature T_1 (steel grade 30KhGSN2A $T_1 = 480^\circ C$) on the elastic-plastic boundary r_1 there will be fulfilled Tresca plasticity condition [4]:

$$\sigma_{rr} - \sigma_{\theta\theta} = 2k_2(T). \tag{5}$$

From this moment the plastic flow begins to grow in both directions from the boundary r_1. The solution shows that towards the inner edge r_0 the plastic flow develops faster than towards the outer boundary R_0. At temperature T_2 (steel grade 30KhGSN2A $T_2 = 570^\circ C$) in the body is formed two regions: the elastic region $r_2 < r \le R_0$ and the active plastic flow region $r_0 \le r \le r_2$, in which Eq. 5 is true. Under the influence of temperature in the body there took place a redistribution of stresses Fig. 2.

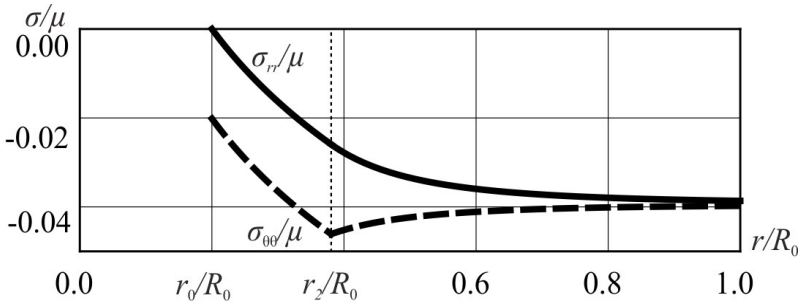

Fig. 2. Stress distribution for steel 30KhGSN2A when heated to a temperature $T_2 = 570^\circ C$, $\alpha_T = 11.5 \cdot 10^{-6}\,^\circ C^{-1}$

In the region of the active plastic flow $r_0 \le r \le r_2$ components of elastic deformations e_{rr} and $e_{\theta\theta}$ are determined by the dependence Eq. 4, provided that e_{rr}^p and $e_{\theta\theta}^p$ change:

$$e_{rr}^p = -2k_2(T_2)\gamma - Ar^{-3}, \; e_{\theta\theta}^p = e_{\varphi\varphi}^p = -e_{rr}^p/2, \; \gamma = (\lambda + 2\mu)(3\lambda + 2\mu)^{-1}\mu^{-1}. \tag{6}$$

Exposure modeling stage

In the annealing process after the heating step should be the aging process at a certain characteristic of each metal temperature. Show the need for this step in the simulated process. To do this, consider the problem of slow cooling. Let us consider that the cooling step immediately follows the step of heating Fig. 2. Over time, the temperature was slowly changed from T_2 to $T_0 = 20^\circ C$. Calculations show that with such a deformation elastic-plastic medium at $T_3 = 78^\circ C$ on the inner surface r_0 tensile stress becomes [4] and no longer satisfy $\sigma_{rr} - \sigma_{\theta\theta} < -2k_2$. In the medium, there is formed a region of repeated plastic flow $r_0 \le r \le r_3$, where r_3 – the boundary of this region [4]. Residual stress level represented on Fig. 3 increases, relative to the initial state of Fig. 1. Happened imposition of residual stresses on the newly applied load (heat), and it caused an increase in the level of residual stresses [2, 5].

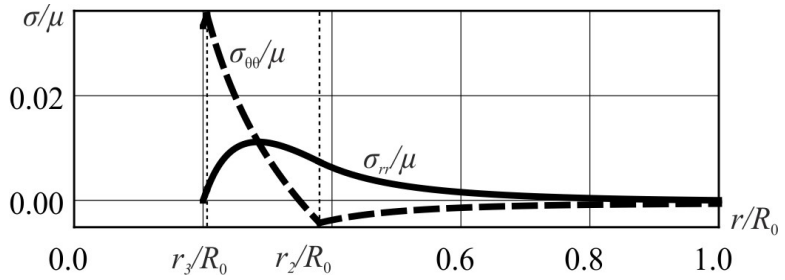

Fig. 3. The distribution of residual stresses in steel 30KhGSN2A after cooling to room temperature $T_0 = 20^\circ C$

It should be noted that such effect in the materials is undesirable and should be avoided.

Therefore, after the heating stage it is advisable to consider the holding stage. Since the materials under the influence of prolonged constant temperature are characterized by manifestation of creep properties, the holding stage will be modeled based on these properties. At temperatures close to the melting point difference between creep and plasticity becomes less pronounced [11]. Creep is described using Norton power law [8]. For power $n = 3$ the analytical solution is reached. For permanent deformation the following ratio is obtained:

$$e_{rr}^v = -(Bt\gamma^{-2} + c)^{-1} - A_1 r^{-3},\ e_{\theta\theta}^v = -e_{rr}^v / 2,\ \gamma = (\lambda + 2\mu)(3\lambda + 2\mu)^{-1}\mu^{-1}. \quad (7)$$

The formula Eq. 7 B – material parameter, c – is determined by $e_{rr}^v(t=0) = e_{rr}^p$, , A_1 – a constant determined by the stress strain state of the medium.

Changing permanent deformation Eq. 7 now should be noted both in the region $r_2 < r \le R_0$ and in the region with the accumulated $r_0 \le r \le r_2$ plastic deformation Eq. 6. Then the c parameter in region $r_2 < r \le R_0$ is determined under the condition that the time $t = 0$ (start of the process associated with holding). In the region $r_0 \le r \le r_2$ with accumulated plastic deformation Eq. 6 $e_{rr}^p = -2k_2(T_2)\gamma - Ar^{-3}$: $c = r^3(A - A_1 + 2k_2(T_2)r^3\gamma)^{-1}$.

Fig. 4 shows the calculation of the stress distribution in exposure $t = 1.5$ hours at T_2. At a constant total strain, stresses in a loaded body decreases with time due to creep, i.e. stress relaxation occurs. Thus, it was shown that already at the stage of holding we can see the decrease in the levels of preliminary stresses.

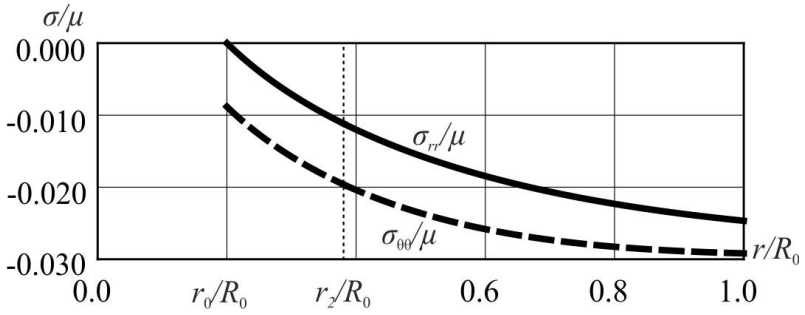

Fig. 4. Stress distribution for steel 30KhGSN2A Exposure hours at $t = 1.5$ a temperature $T_2 = 570^\circ C$, $\alpha_T = 11.5 \cdot 10^{-6}\ ^\circ C^{-1}$

If the body is cooled to room temperature in the body there do not occur the previously mentioned negative effects, furthermore in the vicinity r_0 of the level of residual stress is significantly reduced. Thus, it is the consideration of creep at the holding stage allows us to reach the result which takes place in practice.

Summary

Calculations of residual stresses on the dependence of the exact solutions showed that a noticeable relaxation of stresses occurs during heating. This experimental fact can be simulated on the basis of linear elastic-plastic model under the condition of the fall of material yield strength with increasing temperature only taking into account the creeping properties of materials at the holding stage. For modeling of technological method of annealing, considering of creep at the holding stage allows us to reach the result which takes place in practice.

Acknowledgments

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