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ENERGY DISEQUILIBRIUM EFFECTS IN HEAT TREATMENT EQUIPMENT

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ABSTRACT

The differences found between heat fluxes in different areas of the heat treatment equipment workspace, due to energy disequilibrium or due to improper positioning of loading, can cause non-uniform temperatures and heat stress distributions which will impair the quality of heat processing.

In industrial practices, the unilateral heating is often requested for heat processing of certain products and, as a consequence, the heating rate represents a key factor which has to be known and controlled in order to avoid the possible disequilibrium occurring in the distribution of heat stresses.

The paper aims to assess by calculation of asymmetric heating effects of heat treated products occurring by improper operation of heat treatment equipment or by improper positioning of loading in the heat treatment equipment workspace.

KEYWORDS: asymmetric heating, virtual (fictive) product, temperatures distribution, heat stress distribution

1. Introduction

The operating regimes of heat treatment equipment can be various so that the selection of optimal heat treatment variant can be realized in correlation with the load geometry characteristics and with the load material physical characteristics: the aim is to ensure a high heating rate (maximum admissible) and consequently safe operation and quality products.

Independently of the selected heat treatment regime, the positioning of parts/loading in the heat treatment equipment workspace has to be realized so as to ensure a balanced distribution of the property carriers fluxes of convective type (macroscopic associations and aggregates, turbions, fluid currents) or radiant type (photons, energy quanta) [1] to every load sides surface element.

$$\mu = \frac{S}{X} = \frac{J_1}{J_1 + J_2} \tag{1}$$

When special fans, screens or other means for gas directing are available in order to ensure forced circulation of the working atmosphere with a view of heating intensification [2-4], the possibility of non-uniform heat fluxes distribution is also enhanced.

The differences found between the heat fluxes on load side surfaces generate asymmetric heating of load [5-8] and cause improper distribution of heat stresses on the parts/load section.

To estimate these effects, an asymmetric coefficient of heating, μ, with the following expression will be taken into consideration [5, 6] if $J_1 \geq J_2$ (eq. 1) or if $J_1 \leq J_2$ (eq. 2):

$$\mu = \frac{X - S}{X} = \frac{J_1}{J_1 + J_2} \tag{2}$$

where: S - is the calculation dimension (semi-dimension) of a fictive (virtual) product, where the temperatures and heat stress distributions are uniformly around its symmetry axis and its symmetry is identical with that of the real product (plane, cylindrical or spherical); X - is the real specific dimension of the product which will be heat processed; J_1, J_2 - are heat flux values on side surfaces of heat processed product which determine the temperatures and the evolution of heat stresses in fictive (virtual) products, after well-known calculation methodology [4, 5, 9-11], which suppose uniform distribution on heat fluxes on their side surfaces. Then, the results obtained by calculation for the virtual product can be extrapolated in the real product in order to determine the real distribution of temperatures and heat stresses in it.

In industrial practices, unilateral heating is often requested for heat processing of certain products, such as spherical large tanks. For these products, the heating rate represents a key factor which has to be known and controlled in order to avoid possible disequilibrium occurring in heat stress distribution.

2. Research methodology

The research aimed to theoretically substantiate the proper determination of uniform temperature distribution in the workspace of heat treatment equipment as well as to demonstrate that energy disequilibrium can strongly impair the heat processing results even starting from the first stage of heat processing of material-heating.

The heating of a product with plane symmetry (with temperature close to that of the ambient) introduced in a medium which maintains constant temperature on the heating time Tc = ct = 920 °C has been analyzed. Products have been considered to be made of steel with mean chemical composition of 0.15%C, 6%Cr, 0.5%Mo (~ C15E, acc. to SR EN 10084-00) such as heating at this temperature corresponds to the requirements of the normalizing step.

The mean thermo-physical characteristics of this steel in the temperature range of 20÷890 °C (austenitizing temperature) are: λ=58 W/m·K, a = 0.045 m^2/h, $\beta = 13.1\cdot10^{-6}$ K^{-1}, E = $20.58\cdot10^4$ MPa [12]; concerning the heat transfer characteristics from the medium to the product surface, the global coefficient of heating transmissivity by convection and radiation is α=193.3 W/m^2·grd. The following possible situations have been considered for analysis:

a) the furnace is perfectly energy balanced and heat flux distribution on side surfaces of product ($J_1 = J_2$, on the direction of Ox axis, $\mu = 0.5$) is uniform;

b) the furnace is energy unbalanced and differences between the heat fluxes measured on different directions are possible; two extreme situations (corresponding to the end values of the interval (0÷1) related to the bilateral heating) have been considered;

b_1) $J_1 < J_2$; $J_2 \sim 2.7J_1$, which corresponds to an asymmetry coefficient of $\mu \sim 0.27$, close to the limit value of bilateral heating ($\mu = 0$ represents the limit condition for initiation of unilateral heating $J_1 = 0$, acc. to eq. 2);

b_2) $J_1 > J_2$; $J_1 \sim 4J_2$, which corresponds to an asymmetry coefficient of $\mu \sim 0.8$, very close to the limit value of bilateral heating ($\mu = +10$ represents the limit condition for initiation of unilateral heating, $J_2 = 0$, acc. to eq. 1).

The calculation aimed to determine the distribution of temperatures and heat stresses in the metallic product with plane symmetry (X = 600 mm), in the part of non-stationary regular regime of heating in the medium with constant temperature ($t \geq 0.3(X/2)^2/a$), considering a perfect isotropic product and a heat transfer in one direction (the product has not received or not released heat on the other two directions). The calculation algorithm of the distribution of temperatures and heat stresses in the real metallic product, with plane symmetry, is the following:

- determination of the heating asymmetry coefficient, μ, starting from the conditions requested to the heat fluxes ratio, measured on the heat transfer direction;
- determination of the specific calculation dimension of the fictive (virtual) product: $S = \mu X$; this product has one, or both sides surface in common with those of the real product. The virtual product has been identified with the real product when the asymmetry coefficient is $\mu = 0.5$.
- determination of the temperatures and heat stress distributions in the virtual product with plane symmetry and with the specific dimension S. Temperature distribution has been determined by using the graphical expressions of criterial solutions of heat conductivity differential equation obtained by solving in the conditions limit of III order and/or the tabular values of Russel [5, 6, 9, 11]. Heat stress distribution has been determined by using the graphical expressions of the solutions obtained by criterial solving [5, 6, 11].

It has to be considered that the distribution of the temperatures within the virtual product is symmetrical in relation to its symmetry axis, but subsequently, by extrapolation in the real product, this distribution becomes asymmetrical in the case of an asymmetry coefficient of $\mu \neq 0.5$. In the case of bodies which are strongly anisotropic or where the heating effect is significant on the other directions, the calculation procedure can be repeated similarly, the temperatures and heat stress distributions in the product volume resulting from the distributions on each transfer direction.

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3. Assessment of asymmetry effects of heat flux distribution. Results and analysis

For uniform distribution of heat fluxes within the workspace of the heat treatment equipment (energy balanced), the temperatures and heat stresses (extension stresses in the product center and compressive stresses to the surface zone) are uniformly distributed on the product section (Fig. 1) while the heat gradient on product section registers a decrease as well as the level of the heat stresses. The product is "massive" from the point of view of its thermal-technical behavior (Bi = 1.0) and the calculation of the temperature distribution (using the graphical expressions of the criterial solutions and the tabular values calculated by Russel) in non-stationary regular regime, $t \geq 0.3(X/2)^2/a \geq 0.6$ h, has led to the following values (Table 1, Fig. 1).

Table 1. *Calculated values of the temperatures in different micro-volumes of the product section with the calculation dimension S=300 mm, heated in the furnace with Tm = ct= 920 °C (Bi = 1.0, μ = 0.5)*

x/S	0	0.5	0.8	1.0	0	0.5	0.8	1.0	0	0.5	0.8	1.0
t, h, Fo	1.0 h, Fo = 0.5				3.0 h, Fo = 1.5				8.0 h, Fo = 4.0			
Θ	0.774	0.703	0.597	0.504	0.369	0.335	0.285	0.240	0.058	0.0527	0.0448	0.0378
T, °C	223.4	287.3	382.7	466.4	587.9	618.5	663.5	704	867.8	871.4	879.6	885.98
ΔTm, °C	243 °C				116.1 °C				18.18 °C			

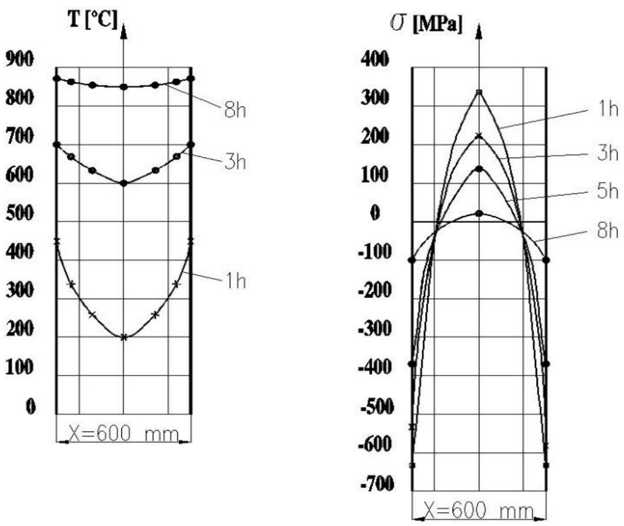

Fig. 1. *Distribution of temperatures and heat stresses in the heat processed product (plate with effective thickness X = 600 mm), heated in a medium with constant temperature, Tm = 920 °C, in the conditions of a symmetric distribution of heat fluxes (Bi = 1.0, μ = 0.5, $J_1 = J_2$)*

Table 2. *Calculated values of heat stresses in different micro-volumes of the product section with the real dimension X=600 mm, heated in the furnace with Tm = ct = 920 °C (Bi = 1.0, μ = 0.5)*

T, h, Fo	1 h, Fo = 0.5		3 h, Fo = 1.5		5 h, Fo = 2.5		8 h, Fo = 4	
x/[X/2]	0	1	0	1	0	1	0	1
f	-0.1	+0.18	-0.07	+0.17	-0.05	+0.11	-0.01	+0.03
σ, MPa	+346.5	-623.7	+242.5	-589	+173.2	-381.1	+34.64	-103.9

With regard to the heat stresses, their values can be calculated (Table 2, Fig. 1) starting from the criterial solution of the heat conductivity equation obtained by solving in condition limits of 3rd order and replacing the obtained result in the equation which gives the relation between the heat stresses and deformations implied (rel. 3). Thus, for the situation taken into consideration (asymmetric heating), different data was obtained.

The analysis of temperatures and heat stresses distributions on the section of the products which has been heated symmetrically (μ = 0.5) in the medium with constant temperature has led to the following conclusions:

- the temperatures and heat stress distributions are absolutely symmetrical around the symmetry axis of the real product;

- the heat gradient maximum value on the product section (between its surface and center) is attained in the first moments of the initiation of the nonstationary common regime and does not exceed 250 °C;

- the heat stresses are compressive in surface and extension stresses in the product center; those of extension which are extremely dangerous are permanently under steel yield point, independently of temperature (Fig. 1, Fig. 2).

The disequilibrium of heat treatment equipment, indicated by the heat flux differences on the symmetrically opposite parts of the heat processed products/loads, determines a heating asymmetry the intensity of which increases with the increase of these differences.

When the asymmetry coefficient is about 0.27 (corresponding to the analyzed situation), thus when the heat flux from a sense of the direction of heat transfer becomes about two times higher than that occurs from the opposite sense, the asymmetry is high, the regime is not stabilized and regular (the dependence of the temperature on coordinate and time is relatively simple and poor influenced by the initial temperature distribution) and it is initiated in this new situation after a longer time (t ≥ 1.279 h) by comparison with the previous case of the symmetrical heating (t ≥ 0.6 h), because the semi-dimension of the virtual body is higher by comparison with that of the real body (S = 0.438 m, comparatively with X/2=0.3 m).

The calculation concerning the new distribution of temperatures (Table 3) and the heat stresses (Table 4), performed on this specific case of virtual product with S = 0.438 m, also massive by point of view of thermal-technical behavior (Bi = 1.46), have confirmed the significant effect of the disequilibrium of heat stresses and, more importantly, the fact that the distribution of heat stresses is extremely non-uniform in relation with the symmetry axis of the product which has been heat processed.

$$\frac{\sigma(1-\nu)}{E}\cdot\frac{1}{\beta(T_0-T_m)} = f\left(\frac{at}{\left(\frac{X}{2}\right)^2};\frac{\alpha\frac{X}{2}}{\lambda};\frac{x}{\frac{X}{2}}\right) \quad (3)$$

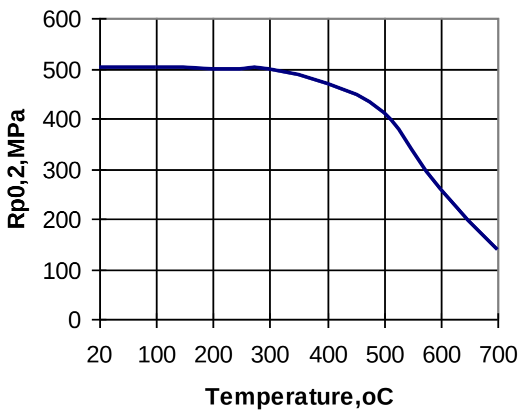

Fig. 2. *Dependency of yield strength $Rp_{0.2}$ on temperature, for steel with 0.15%C, 6%Cr and 0.5% Mo* [13]

Table 3. *Calculated values of the temperatures in different micro-volumes of the product section with the calculation dimension S = 438 mm, heated in furnace with Tm = ct = 920 °C (Bi = 1.46, μ = 0.27)*

x/S	0	0.7	1.0	0	0.7	1.0	0	0.7	1.0	0	0.7	1.0
t, h, Fo	2 h, Fo ~ 0.47			4 h, Fo = 0.936			8 h, Fo = 1.872			10 h, Fo = 2.34		
Θ	0.77	0.55	0.42	0.46	0.37	0.25	0.18	0.17	0.11	0.12	0.1	0.063
T, °C	227	425	542	506	587	695	758	767	821	812	830	863.3
ΔTm, °C	315			189			63			51.3		

Notice that, in this new case corresponding to the asymmetric heating, the explanation of heat stress values becomes possible by using calculation relation (rel. 4) and graphical expressions (graphical expression corresponding to the function Φ[μ;x/(X/2)], rel. 5) [5, 6] different by those used in the case of symmetric heating.

$$\frac{\sigma(1-\nu)}{E}\cdot\frac{1}{\beta\Delta T_m} = \Phi\left(\mu,\frac{x}{X/2}\right) \quad (4)$$

where:

$$\Phi\left(\mu,\frac{x}{X/2}\right) = \left[\frac{1}{3\mu^2}-\frac{1}{\mu}-\frac{\left(\frac{1}{2}\cdot\frac{x}{(X/2)}+\mu-\frac{1}{2}\right)^2}{\mu^2}+1\right] \quad (5)$$

and ΔTm represents the maximum temperature difference between the surface and center of virtual product which has been determined at a certain time.

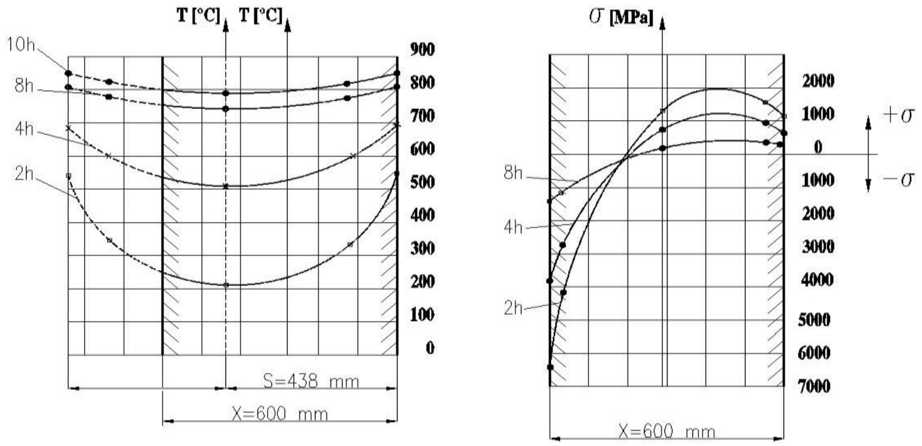

***Fig. 3.** The distribution of heat stresses and temperatures in the heat processed product (plate with the effective thickness X = 600 mm and semi-dimension of fictive product S = 438 mm), heated in a medium with constant temperature, Tm = 920 °C in the case of asymmetric distribution of heat fluxes (Bi = 1.46, μ = 0.27, $J_1 < J_2$)*

***Table 4.** The calculated values of heat stresses in different micro-volumes of the product section with real dimension, heated in furnace with Tm = ct = 920 °C (Bi = 1.46, μ = 0.27)*

x/(X/2)		0	+0.8	-0.8	+1	-1
t = 2.0 h	**Φ**	+1.144	+1.473	-3.571	+0.869	-5.441
	σ, MPa	+1386	+1786.4	-4330.7	+1053.8	-6598.5
t = 4.0 h	**Φ**	+1.144	+1.473	-3.571	+0.869	-5.441
	σ, MPa	+831.6	+1071.6	-2598.7	+631.2	-3957.6
t = 8.0 h	**Φ**	+1.144	+1.473	-3.571	+0.869	-5.441
	σ, MPa	+272.2	+357.2	-866.2	+210.4	-1319.2
t = 10.0 h	**Φ**	+1.144	+1.473	-3.571	+0.869	-5.441
	σ, MPa	225.7	+290.8	-705.4	+171.3	-1074.2

The distribution of heat stresses in the real product, which has been asymmetrically heated, with the symmetry coefficient of μ = 0.27, close to the limit conditions of the bilateral heating, is extremely inconvenient in relation to its integrity: the very high extension stresses on one of its sides of about 1786.4 MPa (much higher than the yield point of the product steel - Fig. 2) at 60 mm from surface (x/(X/2)= +0.8) and the extremely high compressive stresses on the other side of the product, starting with the first moments of the initiation of the non-stationary regular regime will certainly affect the integrity of the product from the heating stage (obviously in the above mentioned conditions). Another extreme situation taken into analysis is determined also by major differences between the values of heat fluxes, $J_1 \sim 4J_2$, differences which ensure a high heating asymmetry degree μ = 0.8.

The nonstationary regular regime is installed in this new situation for S = 0.48 m (semi-dimension of virtual product) after more than 1.536 h.

The calculation concerning the distribution of temperatures (Table 5) and heat stresses (Table 6) in this new hypothetical situation on a product which is also massive from the thermal-technical point of view (Bi = 1.6), have been performed in accordance with the algorithm mentioned previously.

In this new heating asymmetry case, the stress distribution is also non-uniform, with high extension stresses on one product side and extremely compressive high on the other product side.

It is true that the maximum extension stress calculated after 2 h from the beginning of the heating process has the maximum value ~ 400 MPa in the zone which is highly strained (at x/(X/2) ~ 0.8) and is below the yield point at the temperature related to this zone after this heating time (~440 °C, after 2 h). However, it is also very probable that during non-regular non-stationary regime (t << 1.536 h), therefore close to the moment of charge loading in the furnace, the expansion stresses level from the zones which are in the vicinity of the surface to be much higher than the yield point and thus the integrity of the product to be impaired earlier.

Table 5. *Calculated values of temperatures in various micro volumes in the product section with the calculation dimension S = 480 mm, heated in furnace with Tm = ct = 920 °C (Bi = 1.6, μ = 0.8)*

x/S	0	0.7	1.0	0	0.7	1.0	0	0.7	1.0	0	0.7	1.0
t, h, Fo	2 h, Fo ~ 0.4			4 h, Fo = 0.8			7.68 h, Fo = 1.5			10.24 h, Fo = 2		
Θ	0.78	0.644	0.4	0.52	0.42	0.26	0.27	0.23	0.118	0.16	0.13	0.09
T, °C	218	340.4	560	458	542	686	677	713	814	776	803	839
ΔTm, °C	342			228			137			63		

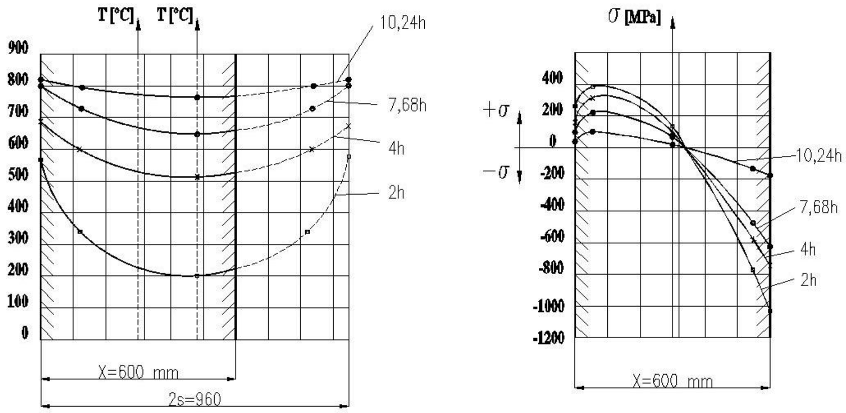

Fig. 4. *The temperatures and heat stresses distributions in the heat processed product (plate with effective thickness X = 600 mm and fictive product semi-dimension S = 480 mm), heated in medium with constant temperature, Tm = 920 °C for asymmetric distributions of heat fluxes (Bi = 1.6, μ = 0.8, $J_1 > J_2$; $J_1 \sim 4J_2$)*

Table 6. *Calculated values of heat stresses in different micro volumes of product section with real dimension X = 600 mm, heated in furnace with Tm = ct = 920 °C (Bi = 1.6, μ = 0.8)*

x/(X/2)		0	+0,8	-0.8	+1	-1
t = 2.0 h	**Φ**	+0.15	-0.56	+0.3	-0.81	+0.21
	σ, MPa	+197.5	-737.3	+395	-1066.5	+276.5
t = 4.0 h	**Φ**	+0.15	-0.56	+0.3	-0.81	+0.21
	σ, MPa	+135	-504.5	+270.3	-729.7	+189.2
t = 7.68 h	**Φ**	+0.15	-0.56	+0.3	-0.81	+0.21
	σ, MPa	+113.7	-424.7	+227.5	-614.3	+159.3
t = 10.24 h	**Φ**	+0.15	-0.56	+0.3	-0.81	+0.21
	σ, MPa	+36.4	-135.8	+72.65	-196.4	+51

4. Conclusions

The energy disequilibrium within the heat treatment equipment for the heat processing of metallic products can cause major heating asymmetry with very severe consequences on the distribution of heat stresses on the products section. It is compulsory to perform permanent and rigorous control of temperature within the heat treatment equipment so that the temperature differences occurring between different zones of the working space be known and kept at minimum level. The situations considered for analysis obviously represent extreme situations. At lower differences between the heat fluxes, the asymmetry coefficients have values close to μ = 0.5 (which corresponds to the energy balanced state), but there are also temperatures and non-uniform distributions of heat stresses that can cause deformation and even deterioration of the heat processes products/load.

In the case of unilateral heating, when requested, a rigorous control of the heating rate has to be performed so as the temperature evolution in the heated wall to avoid unusual distribution of temperature and heat stresses that can cause undesired effects.

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