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NUMERICAL MODELING OF THE THERMAL REMOVAL OF BURRS BY CONCENTRATED ENERGY FLOW

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Thermal conditioning is one of the most promising methods of removing burrs from metal products [1]. Such conditioning is done inside a chamber via the combustion of a gas-oxygen mixture. The combustion heats the burrs locally to their melting or combustion point. Another thermal conditioning technique is based on the use of concentrated energy flows – especially laser radiation. This approach results in melting and vaporization of the burrs [2]. The treatment regimes for machine parts are usually determined experimentally [3].

The goal of the present investigation is to numerically study the removal of burrs from the surface of a wall through fusion and vaporization occurring under the influence of concentrated energy flows. Determining the laws governing the burr-removal process as different parameters are varied makes it possible to devise a method of selecting heat-treatment regimes and optimizing existing technologies.

It is now possible to thermally load substances with a short-lived heat flow by using lasers, explosive plasma sources, high-enthalpy gas jets, and other means. The main factors determining the thermal regime in the material in such processes is the acting heat flux, its duration, and the form of the surface. The material undergoes thermal decomposition as a result of melting and vaporization (the combustion of thin burrs will not be examined here). In cases where convection is also a factor, it is also necessary to consider the spreading of molten material on the surface and its flow from the surface. In connection with this, it is important to study the dynamics of melting and vaporization and the laws governing the motion of the phase boundaries, as well as to evaluate the heating of the product near burrs.

We will examine the action of a heat flux $\mathbf{Q}$ on the surface of a semifinished product with burrs on it (Fig. 1). The heat flow is uniform with respect to both time and space. For the sake of definiteness, we choose the geometric form of the burrs to be isosceles triangles. Since burrs are generally much smaller than the product on which they are found, it is sufficient to examine a finite region $\Omega(t)$. The size of this region changes over time due to possible motion of the external boundary ω during melting and vaporization.

The temperature field in the region $\Omega(t)$ can be evaluated on the basis of Stefan's mathematical model in the two-dimensional formulation, with allowance for features of the phase transformations on the surface of the wall:

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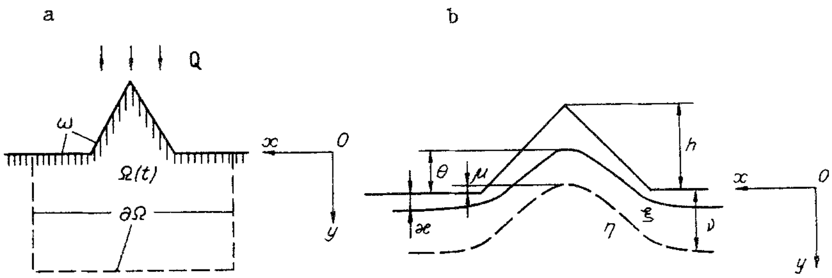

Fig. 1

$$c\rho\partial T/\partial t = \lambda(\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2),\ (x,\ y) \in \Omega(t),\ t > 0; \tag{1}$$

$$\rho G\frac{d\xi}{dt} = [\mathbf{q}]_\xi,\quad T|_{(x,y)\in\xi} = T^{**}; \tag{2}$$

$$\rho L d\eta/dt = [\mathbf{q}]_\eta,\ T|_{(x,y)\in\eta} = T^*; \tag{3}$$

$$T|_{t=0} = 0,\ (x,\ y) \in \Omega(0); \tag{4}$$

$$q|_{(x,y)\in\omega,\xi-0} = \mathbf{Q}; \tag{5}$$

$$\partial T/\partial \mathbf{n}|_{(x,y)\in\partial\Omega} = 0. \tag{6}$$

In the problem being solved here, we need to find the temperature T(x, y, t) and the laws of motion of the phase boundaries ξ(x, t) and η(x, t) from heat-conduction equation (1) and Stefan conditions (2)-(3) with assigned initial (4) and boundary (5)-(6) conditions. Here, $\mathbf{q} = -\lambda$ grad T is the heat-flux vector; G, T^{**}, L, and T^* are heat and temperature of vaporization and melting, respectively; n is a normal to the boundaries of the region Ω. We assume that the thermophysical properties of the material of the wall (heat capacity c, density ρ, and thermal conductivity λ) are constant and independent of the coordinates and temperature.

We will solve the problem with the use of the numerical algorithm presented in [4]. The algorithm permits explicit representation of the phase boundaries and allows us to work in a nonchanging theoretical region Ω(t) - which is typical of the given model.

We will examine two types of thermal loading of the semifinished product: for the first type (radiant transfer), the heat flux is directed parallel to the Oy axis (Fig. 1a), such as in laser radiation [2]. For the second type (convective transfer), heat flux is directed perpendicular to the surface at all points. This is the situation in cases where the specimen is loaded by explosive gas mixtures [5]. For the second type of loading, sections of the specimen surface that are of the same area absorb the same amounts of energy.

The thermal destruction of burrs involves melting and vaporization, with subsequent removal of the melt from the surface or its spreading on the surface under the influence of shear stresses and surface tension. Here, it is important that the shape of the product not change. This can be assured by setting appropriate conditions for the action of the heat flow. The form of these conditions depends to a large extent on the geometry of the burr.

Figure 1b shows characteristic profiles of the wall-surface–vaporization-front ξ (solid line) and the fusion boundaries η (dashed line). Small heat fluxes ($Q \le 10^3$ W/cm^2) result in heating of the product to a considerable depth and lead to nearly uniform heating of the entire surface. This precludes the geometry of the surface from having an effect on the process. In the case of powerful flows ($Q \ge 10^5$ W/cm^2), a thin layer of the wall and

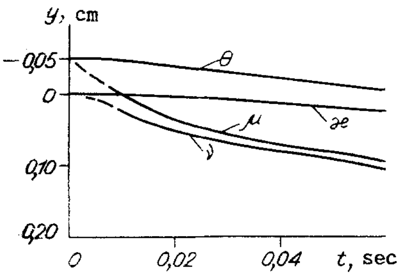

Fig. 2

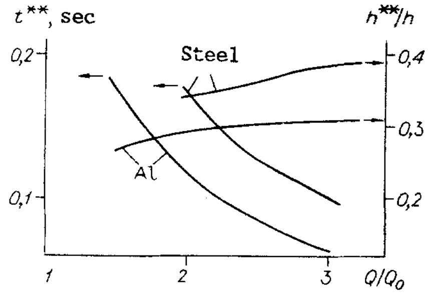

Fig. 3

the burr undergo rapid heating to their respective melting and boiling points. In connection with this, in the numerical modeling we can limit ourselves to the interval $Q \in [0.5Q_0;\ 5Q_0]$, where $Q_0 = 10^4$ W/cm^2.

We introduce quantitative characteristics to analyze the thermal process (Fig. 1b): h is the initial height of the burr (in our calculations, we took h = 0.05 cm, with the width of the base of the burr being equal to 0.1 cm); κ is the depth of erosion of the wall due to vaporization; θ is the residual height of the burr; μ is the size of the unmelted portion of the burr; ν is the depth of fusion of the wall. Figure 2 shows the time dependence of these parameters with a radiant heat flux $Q = 5Q_0$ on a steel semifinished product. The chosen thermophysical parameters of the steel were: p = 7.8 g/cm, c = 0.45 kJ/(kg·deg), λ = 74.4 W/(m·deg), L = 293 kJ/kg, T* = 1530°C, G = 6300 kJ/kg, T** = 3050°C.

The calculations showed that vaporization of the wall begins almost immediately after the beginning of vaporization of the burr. The dependence of θ and κ on t is nearly linear. The rate of erosion of the burr $\partial\theta/\partial t$ is only slightly greater than the rate of wall erosion $\partial\kappa/\partial t$. At the moment of complete removal of the burr ($\theta = 0$), the depth of erosion of the wall is usually ~h/2 and the depth of fusion is ~2h. For aluminum (p = 2.7 g/cm, c = 0.88 kJ/(kg·deg), λ = 209 W/(m·deg), L = 390 kJ/kg, T* = 659°C, G = 9220 kJ/kg, T** = 2300°C) or copper (p = 8.9 g/cm, c = 0.39 kJ/(kg·deg), λ = 389 W/(m·deg), L = 214 kJ/kg, T* = 1083°C, G = 5410 kJ/kg, T** = 2360°C) semifinished products, ~4h. Meanwhile, the fusion front has a rectified profile. The time of complete removal of the burr t^{**} by vaporization is ~0.05 sec. An increase in heat flux intensifies erosion of the wall, while a decrease in heat flux increases the depth of the melted region.

In the case of convective loading, the depth of erosion of the wall h^{**} at the moment of time t^{**}, when $\theta = 0$, is ~h/3 (Fig. 3). The depth of the fused region is ~3h. The dependence of h^{**} on heat flux is weak.

A decrease in heat flux leads to an increase in treatment time, which in turn creates the conditions necessary for removal of the burr by spreading of the melt. We can obtain an upper bound by examining the behavior of just the fusion phase boundary, while a lower bound can be established by assuming that the melt—solid phase transition occurs on the outside surface of the wall, i.e, in the case of instantaneous removal of the melt. Figure 4 shows the upper bound of the time of fusion of a burr to the base t^* and the depth of fusion of the wall at this moment h^* in relation to the intensity of radiant loading. The quantity h^* characterizes the undesirable effect of thermal radiation on the wall, since it determines the possible ablation or change in form of the semifinished product due to spreading of the melt. The dependence of h^* on heat flux differs considerably for different materials, but h^* does not reach zero for any of the tested metals. The dependence of the time of complete fusion of the burr to the base on heat flux is characterized by a monotonic, rapidly descending curve.

In the case of convective loading, the time until complete melting of the burr t^* is roughly 1.5 times shorter than for radiant heating, while the profiles of the relations $t^*(Q)$ are roughly the same. However, the dependence of the depth of fusion of the wall h^* on heat flux has characteristic differences (Fig. 5). On the average, h^* is four times less than for radiant heating. Despite this, the upper bound (curves 1) show that it is possible to remove a burr with almost no melting of the wall for $Q < Q_0$. The lower bound of h^* (curve 2) turned out to be somewhat higher than the upper bound, and we found a nearly linear dependence on heat flux. The inversion of the upper and lower bounds also held for the time of complete fusion of the burr t^* and the time of beginning of fusion of

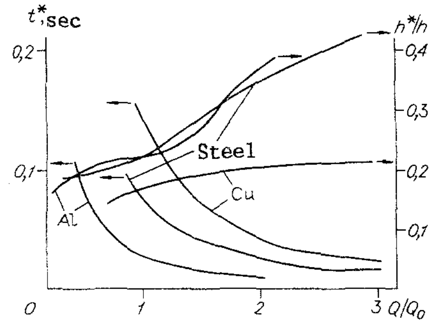

Fig. 4

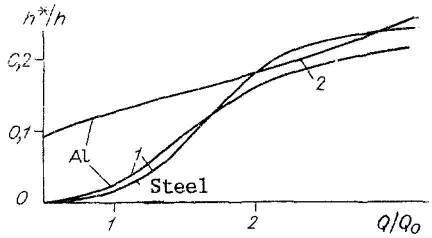

Fig. 5

the wall. The height of the unmelted part of the burr at the beginning of melting of the wall for aluminum (compared to radiant heating) was half as great and can be evaluated as 0.2h for $Q < 1.5Q_0$.

The character of the upper and lower bounds seen in our case can be explained as follows. The condition of perpendicularity of the vector of the external heat flux to the surface of the body creates the most intensive regime for heating of projecting parts (burrs). By definition, the upper bound implies that the molten burr retains its shape and, thus, that an optimum heating regime is realized during the entire loading. In turn, the method used to obtain the lower bound causes the fusion front to coincide with the external boundary of the burr. This leads to smoothing of the surface and equalization of heating conditions for all parts of the wall.

We performed calculations for the case of a fixed heat flux $Q = 10^4$ W/cm^2 on an aluminum wall with burrs of different height and different initial temperatures. The width of the base of the burr remains equal to 0.1 cm. A fourfold increase in height h (from 0.025 to 0.1 cm) leads to an increase in t^* and h^* by a factor of ~1.5 and tripling of h^{**}. An increase in the initial temperature from 0°C to $2/3T^*$ leads to a threefold reduction in t^* and a twofold increase in h^* and h^{**}. Meanwhile, h^* increases fairly substantially in both cases.

The completed numerical analysis permits the following conclusions. Removal of burrs by vaporization is impossible by any of the above-examined methods, either as a result of significant erosion of the wall when burrs are completely removed or due to insufficient reduction in burr size by the time the wall begins to vaporize. Removal of burrs by melting is techically feasible.

For the method involving instantaneous removal of newly formed molten material from the surface, it was shown that it is possible to select thermal loading regimes in which a minimum wall-fusion depth is attained with complete fusion of the burr. Convective loading is better suited for industrial practice.

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