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Techniques for setting modes of thermal and deformation effect at combined hardening and finishing operations

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Abstract. This paper considers the issues of setting the modes of thermal and deformation effects in the basic schemes at combined hardening and finishing operations. On the basis of solving the thermal physical problem of material high rate heating, the parameters of a thermo-hardened layer were determined within the range of the investigated modes. An algorithm for setting the mode parameters of high rate heating responsible for the hardening effect at the combined processing was proposed. The analysis of the mathematical model for forming a surface microrelief at ultrasonic deformation showed that the sizes, the form of fragments and the density of a microrelief were determined by the processing kinematic parameters. An algorithm for setting the rotation speed and feeding at ultrasonic deformation according to microrelief characteristics was developed. The conditions to form a completely regular microrelief on the processed surface that represent the ratio between a single imprint diameter at the ultrasonic deformation and the processing kinematic parameters were determined. The complex of the algorithms suggested for setting the mode parameters of high rate heating and ultrasonic deformation constitutes the techniques for setting the modes of combined hardening and finishing operations.

1. Introduction

Recent years has much contributed to the development of the effective methods for materials processing based on combining the high rate heating and plastic deformation [1, 2]. High energy techniques for creating a surface layer with high structural strength are effectively applied in technological processes of manufacturing the parts intended for using under severe operating conditions.

The techniques for combining thermal deformation processes during the surface processing of metals and alloys is given in the work [3], in which the principles and properties for developing new processing methods are described, and the criteria of combining high energy processes are stated. That allowed the development of basic schemes for combined processing which determines the location and the time of a thermal and deformation source operation in the zone of processing. Thus, the basic scheme I (TD) presupposes the deformation (D) effect from the thermal (T) source within the thermal cycle. In basic schemes II (D+T) and III (T+D), the introduction of the succeeding source of the combination into the zone of processing is performed only after all the processes induced by the preceding source in the surface layer material have been completed.

Due to reducing the number of various schemes which combine thermal and deformation sources to the three basic ones, the theoretical and experimental studies of any processing appear to be possible with the use of an integrated structure of complex modeling, which is given in detail in the work [3].

The development of foundation for theoretical research in the combinable thermo- deformational processes in the form of a complex mathematical model [1, 3] allowed the authors to determine the specific features of a development mechanism of any of the processes, identify the level of their interference, discover the emerging limitations and offer the ways of their overcoming. As a result, the developed theoretical foundation can serve as a basis for predicting the results of the combined processing of metals and alloys of various classes so as to ensure the required level of structural strength, stress state and surface microgeometry. The paper is devoted to the development of techniques for setting the thermal and deformational sources modes in the studied schemes of combined hardening and finishing of metallic materials.

2. Results and Discussion

The important stage of preparing the technological process related to setting the necessary processing modes is to obtain the generalized parameters of the technology under study which show the range of the results achieved together with the estimation of possible expenditures of energy and processing rate.

Taking into account that the thermal source used for the combined hardening and finishing operations is of surface type, the power distribution over the heating spot can be described as follows:

$$q(r) = q_0 \cdot e^{-kr^2} \tag{1}$$

The radius of the heating spot ($r_н$) is taken as the value of the radius (r), on which the power density q is equal to 0.05 q_0, where q_0 is the maximum power density in the centre of the heating spot. Then the source concentration coefficient (k), characterizing the form of the normal distribution curve is k ≅ $3/r_н^2$.

The kinetics of heating and cooling of a material surface layer in conditions of high rate heating by the concentrated power sources should be considered from the point of the classical theory of thermal conductivity. In this case the equation of heat flux distribution in a differential form appears as:

$$\begin{gathered}
VC\frac{\delta T}{\delta z} = \frac{\delta}{\delta x}\left(\lambda\frac{\delta T}{\delta x}\right) + \frac{\delta}{\delta y}\left(\lambda\frac{\delta T}{\delta y}\right) + \frac{\delta}{\delta z}\left(\lambda\frac{\delta T}{\delta z}\right); \\
\left.\lambda\frac{\delta T}{\delta x}\right|_{x=0} = 0; \qquad \left.\lambda\frac{\delta T}{\delta x} - \beta(T - T_0)\right|_{x=X} = 0; \\
\left.\lambda\frac{\delta T}{\delta y} - \beta(T - T_0)\right|_{y=0} = 0; \qquad \left.\lambda\frac{\delta T}{\delta y}\right|_{y=Y} = q; \\
\left.T\right|_{z=0} = T_0; \qquad \left.\lambda\frac{\delta T}{\delta z}\right|_{z=0} = 0; \qquad \left.\lambda\frac{\delta T}{\delta z}\right|_{z=Z} = 0,
\end{gathered} \tag{2}$$

where T = T(x, y, z) – the temperature of the part; T_0 – the ambient temperature; V – the thermal source path speed; q = q(x, z) – the density of heat flux rate on the outer surface of the part; λ = λ(T) – heat conductivity of the material being processed; C = C(T) – the volumetric specific heat of a material; β – the heat transfer coefficient; X, Y, Z – the sizes of a computational domain.

In order to calculate the required temperature distribution, the numerical method for solving the boundary value problem has been utilized (2). The results obtained due to solving the thermo physical problem of a material heating by the concentrated energy source have made it possible to determine the interrelation between high rate heating parameters and such characteristics of the process as specific expenditures of energy and processing rate at achieving the maximum thickness of a thermo-hardened layer at the modes excluding the melt formation on the surface of the material (Figure 1).

These results illustrate the technological capacities of the thermal source at different values of the concentration coefficient for achieving the maximum thickness of a thermo-hardened layer. In addition, the expenditures of energy and processing rate have been estimated.

The calculation of the thermophysical problem allowed finding the maximum achievable values of the thermo-hardened layer thickness within some ranges of processing modes (the concentration coefficient and the processing rate). This is shown graphically in the upper part of Figure 2.

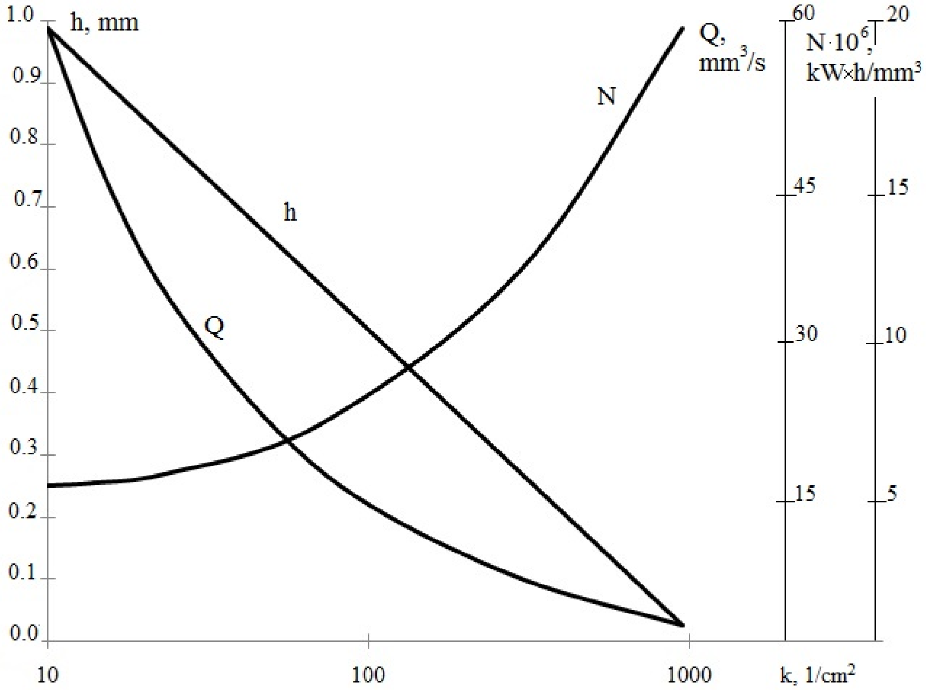

Figure 1. The ratio between the maximum thickness (h) of the thermo-hardened layer of steel 45, processing rate (Q), specific energy consumption (N) at the effect of the heating source with a different concentration coefficient (k) at the processing rate V = 1 cm/s.

As seen from Figure 2, within the chosen range of the investigated high rate heating modes, the thermo- hardened layer with the thickness of about 1mm is formed that is considered sufficient to operate the parts and tools in the conditions of friction and abrasive wear. The calculations show that, for all variants of processing which ensures the formation of the thermo-hardened layer of the uniform thickness, the power density of the thermal source remains unchanged. It is the ratio between the source concentration coefficient and the processing rate that changes.

The analysis of the results obtained by calculating the thermophysical problem concerning the estimation of the width of a thermo-hardened zone (d_{hard}) on the surface indicated its dependence only on the source concentration coefficient (see the bottom of Figure 2).

Thus, the results obtained by calculating the thermophysical problem and presented in Figure 3 can be applied for setting technological modes of high rate heating according to the preset values of the thermo-hardened zone width and the layer thickness. In this case, the algorithm for setting the modes is as follows: $d_{hard} \rightarrow k \rightarrow h \rightarrow q_0 \rightarrow V$ presented in Figure 2 schematically by arrows. So, the source concentration coefficient is determined by the value of width of the thermo-hardened zone on the surface of the part specified by technical requirements, and the power density of heating and the processing rate is determined by the required thickness of the thermo-hardened layer.

It should be noted that the surface of a part can significantly exceed the sizes of the thermo-hardened zone covered by the power concentration source.

In this case the multiple-pass processing with the overlapping of thermo-hardening zones should be set.

The deformation effect of the ultrasonic spherical deformer in the combined processing schemes is aimed both at creating the hardening effect and at forming the surface microgeometry while processing. The choice of ultrasonic vibrations of the spherical deformer as a source of deformation effect in the schemes of the combined processing is accounted for its technological advantages in achieving the hardening and finishing effect in comparison with other methods of surface plastic deformation [4-8].

The mathematical description of the microgeometry formation process at ultrasonic plastic deformation of parts (performed according to the turning scheme) is based on the model of imposing the plastic imprints (d_{imp})of a spherical deformer on each other when the kinematic motions – rotation speed (V_d) and feeding (S) are applied to the part. As a result, a microrelief consisting of separate fragments (ABCDEF) is formed (Figure 3).

The number of fragments per surface unit (microrelief pattern density) is defined as:

$$N = \frac{60 \cdot f}{V_d \cdot S} \tag{3}$$

where f – the frequency of ultrasonic vibrations, Hz; V_d – the rotation speed of a part , mm/s; S – the feeding, mm/rev.

The height characteristic of surface roughness (h_R), given as a surface roughness parameter (R_z) takes the form:

$$h_R = R_z \cdot 10^{-3} = \frac{D_S}{2} - \sqrt{\frac{D_S^2 - l^2}{4}} \tag{4}$$

where D_S – the diameter of the ultrasonic spherical deformer, mm; R_z – surface roughness parameter, mkm; l – a step of the microrelief in the direction of V_d, mm.

Taking into account that $l = \frac{V_d}{60 \cdot f}$ and transforming the expression (4), we get:

$$V_d = 120 \cdot f \sqrt{\frac{D_S^2}{2} - \left(\frac{D_S}{2} - R_Z \cdot 10^{-3}\right)^2} \tag{5}$$

The expression (5) identifies the speed characteristics (V_d) as one of processing kinematic parameters which determines the conditions for achieving the required roughness.

The value of the second kinematic parameter – the feeding (S), on which the value of microrelief pattern density depends (N), is determined from the expression (3):

$$S = \frac{60 \cdot f}{V_d \cdot N} \tag{6}$$

Figure 4 shows the scheme of setting the kinematic parameters of ultrasonic deformation according to the specified characteristics of microgeometry (the height parameter and density of the microrelief pattern). Thus, the bottom of Figure 4 presents the dependence of the characteristic curve of the roughness parameter (R_z) on the processing rate (V_d) at various values of the diameter of the ultrasonic spherical deformer. The upper part of Figure 4 shows the relationship between V_d and S, which ensure the creating of the microrelief with a certain pattern density.

The algorithm for setting the kinematic modes of ultrasonic deformation shown by arrows in Figure 4 is the following: $R_z \rightarrow V_{dmax} \rightarrow V_d \rightarrow N \rightarrow S$.

It must be aware of the fact that the value V_d determined according to the expression (5) is the maximum permissible value for ensuring the required surface roughness.

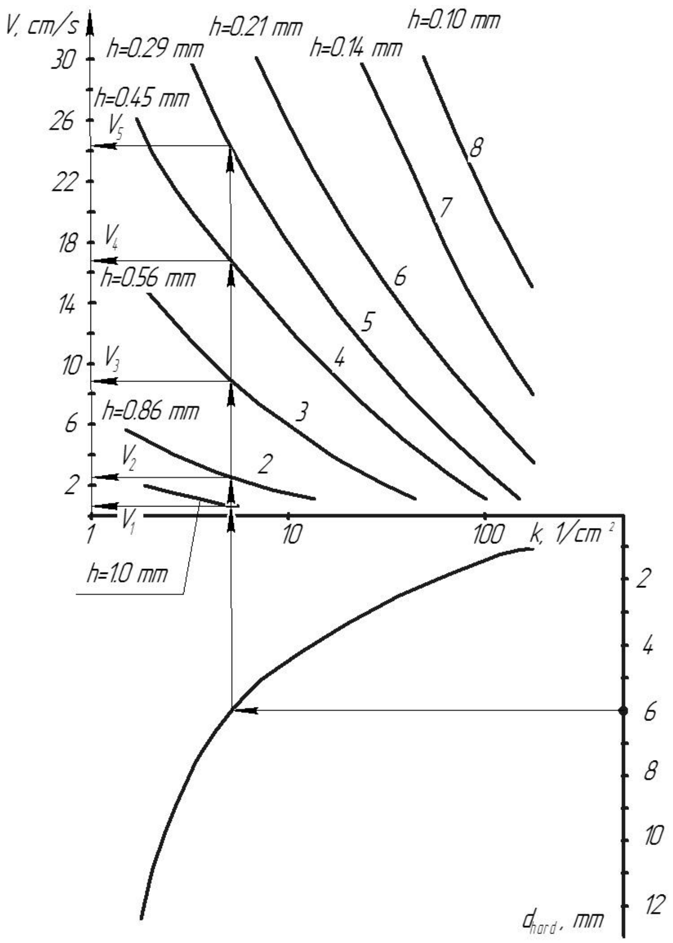

Figure 2. The correlation of parameters of the thermo-hardened layer of carbon steels on the coefficient of the source concentration and the modes of heating, the speed of treatment (V, cm/s) and the power density (q_0, W/cm^2): 1 – 3500;
2 – 4300; 3 – 7500; 4 – 10000; 5 – 13500; 6 – 15500; 7 – 17500; 8 – 20000.

The technology for ultrasonic hardening and finishing operation implies the formation of an entirely regular microrelief on the processed surface without any residual traces of previous processing.

The condition for forming this microgeometry is the limitation:

$$d_{imp} \geq \sqrt{\frac{S^2 + l^2(1-m)}{\cos\beta}}, \tag{7}$$

where m – the fractional part of the microrelief fragment which closes the unit turn of processing traces on the cylindrical surface. The value m = 0 – 1.0 determines the form of the microrelief fragment [9]; β – the angle of line inclination connecting the centers of the first and the last fragments in the neighboring turns of processing traces to the long axis of the cylindrical surface (Figure 3). The value of the angle is defined as:

$$\cos\beta = \frac{S}{\sqrt{S^2 + m^2 \cdot l^2}} \tag{8}$$

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After transformation the expression (7) takes the following form:

$$d_{imp} \geq \sqrt{\left\{S^2 + \left[\frac{V_d \cdot (1-m)}{60 \cdot f}\right]^2\right\}\sqrt{1+\left(\frac{m \cdot V_d}{60 \cdot f \cdot S}\right)^2}} \tag{9}$$

The right part of the expression (9) presents a set of kinematic processing parameters interrelated by the characteristics of the microrelief to be formed. The value of unit imprint (d_{imp}) being intended with a spherical deformer can be calculated as:

$$d_{imp} = 2 \cdot \sqrt{D_S \cdot h_{\max}} \tag{10}$$

where h_{max} – the maximum depth of the spherical deformer penetration into the processed surface; it depends on deformation mode parameters of ultrasonic processing of materials with different original hardness.

The results of modeling the ultrasonic deformation process are presented in works [10].

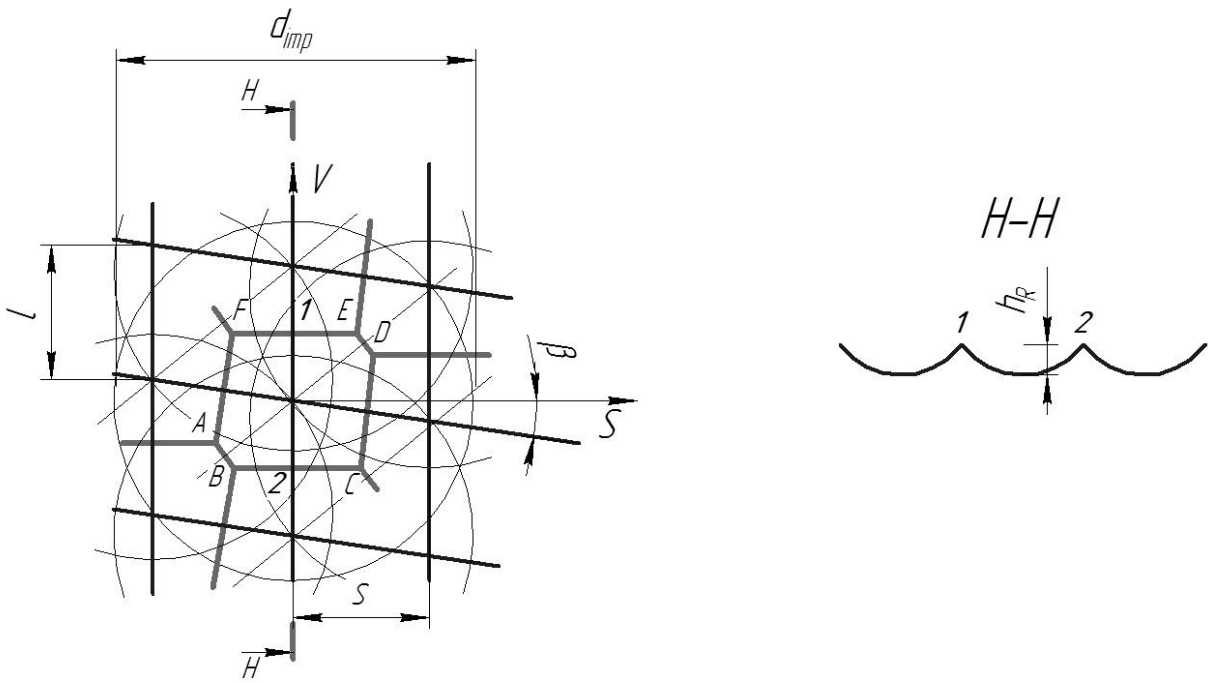

Figure 3. The scheme of microrelief fragment formation on the surface treated by ultrasonic deformation.

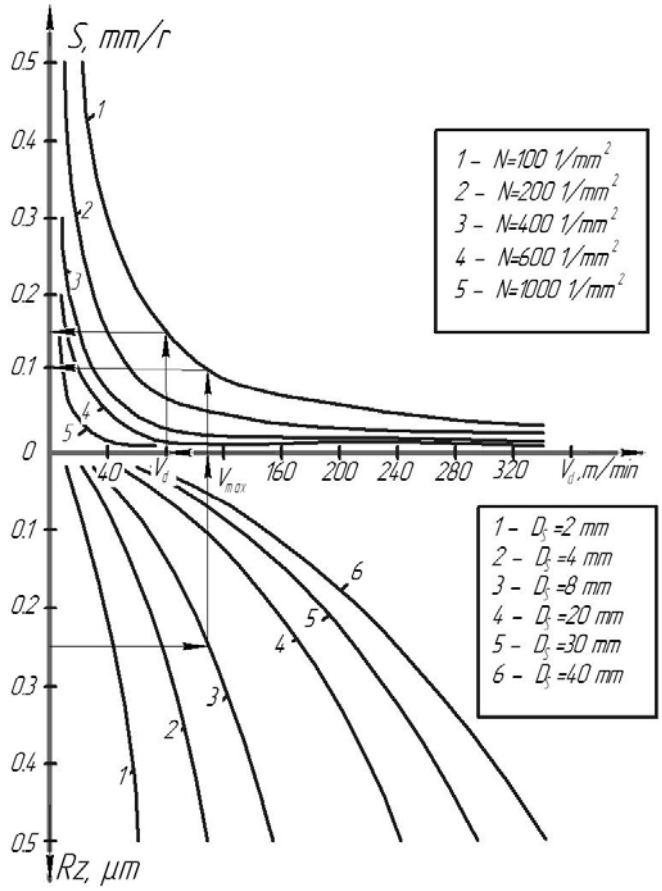

Figure 4. The scheme for setting the kinematic modes of ultrasonic deformation according to the microgeometry characteristics (f = 20 kHz).

3. Conclusion

The algorithms presented for determining the parameters of thermal and deformation processes to achieve the required hardening and finishing effects can be considered as techniques for setting mode parameters of the combined thermal deformational processing according to various basic schemes. In this case, the quantitative values of thermal source operating parameters both the power and operating ones irrespective of their basic scheme of treatment will be determined by the part specification according to the parameters of the thermo-hardening zone.

The values of kinematic parameters of ultrasonic deformation independent of the implemented basic scheme of the combined processing are determined only by the surface microgeometry requirements. The deformation modes of the ultrasonic processing specifying the necessary diameter of the plastic imprint depend on the hardness of the material deformed, which differs significantly in the basic schemes of the combined thermo-deformational processing.

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