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Energy State of a Plastically Deformed Surface Layer

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Abstract

The paper reports the results of experimental research on the substantiation of the criterion for steel strengthening effectiveness established on a basis of an energetic approach to the consideration of the mechanism for the surface layer formation with dynamic methods of plastic forming. Using the analogy between the processes of energy absorption of the crystal lattice under mechanical loading and under heating, the work demonstrates that the maximum specific energy which can absorb the crystal lattice corresponds to the value equal to the difference between the heat content (enthalpy) of the material in the solid state, at the melting temperature and enthalpy H_TS at 2930K. The proposed method and experimental device allowing to estimate the stored energy in the plastically deformed surface layer as the difference between the work expended in plastic deformation of the material and the quantity of the released heat. It was established that the energy growth limit in the local plastically deformed volume of a surface occurs at making of 11-13 acts of the action force; the further increase in acts influences the energy state of the surface as it becomes stabilized.

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Keywords: internal energ; enthalpy; surface plastic forming; deformation work; work hardening; surface layer; indenter.

1. Research target setting

According to the energetic interpretation of SPD the ultimate deformability of an element of a surface layer (SL) begins at the achievement of a critical value of density of its internal energy. When considering a physically infinitesimal volume of a solid as an open thermo-dynamic system which is under steady external conditions at the

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state of local equilibrium, that is, having a set of intensive (molar) properties, the condition of the utmost deformability of SL element of material according to [1,5,10] becomes:

$$\Delta E(\mathrm{t}) = E(0) + \Delta E(\mathrm{t}) = E^* = const \qquad (1)$$

Where E(0) - density of internal energy in SL element at the initial (before SPD) state (t=0), taking into account hereditary properties of material; ΔE(t) - change of internal energy density in SL element at i cycle of power load, kJ/mol.

A physical sense of this condition consists in that when the left part E+E(t), corresponding to internal energy increase of the system achieves the right part E* , which is fundamental power characteristic of material strength its destruction will take place.

For the quantitative estimation of the utmost density ΔE* of internal energy at which in the course of SPD process the SL maximum strengthening without destruction is achieved, we take advantage of the analogy between processes of energy absorption by a lattice at mechanical loading and at heating [2,12,20]. And in this and in other case the violation of atomic bonding begins as a result of the absorption of the energy value utmost for this lattice. So, in case of metal heating from the specified temperature T up to melting temperatureTs, the absorbed utmost energy will be:

$$\theta = \int_T^{Ts} CdT = L \qquad (2)$$

where C- specific heat; L- latent heat of melting.

This value characterizes metal enthalpy changes at heating from a specified temperature up to melting temperature and is spent for the excitation of atomic oscillations of a critical value without violation of atomic bonding. These violations arise when a lattice absorbs additional energy equal to the latent heat of melting. Similar analogy was used for the estimation of energetic state of deformed under different conditions of the power loading of local structures in crystalline solids in their investigations K.A. Osipov, I.I. Novikov, V.S. Ivanova, V.V. Fyodorov[2,3,8,14]. At the heart of such an approach are the following prerequisites. At mechanical loading up to SL destruction as at melting to the process of atomic bonding violation precedes a lattice distortion to a critical value. A difference consists in that at mechanical loading the utmost distortion of a lattice is stipulated by the accumulation of a critical density of dislocations in deforming local volumes of SL at which the further energy absorption by a lattice results in the violation of atomic bonding. If we assume that specific energy spent for the utmost distortion of a lattice does not depend upon the type of energy supplied (thermal or mechanical power), then the utmost specific energy which can be absorbed by a lattice must correspond to the value equal to the difference of enthalpy of material in a solid state at the melting temperature Hts and enthalpy at 293° K:

$$\Delta H^* = H_{ts} - H_{293^\circ} = \int_{T293}^{Tts} CdT \qquad (3)$$

Then the utmost (up to destruction) density of internal energy E*, accumulated in a deformed SL element after SPD quantitatively can be estimated by means of the thermo-dynamic constant ΔH*:

$$E^* = E + \Delta E^* = \Delta H^* \qquad (4)$$

The equation of energetic balance (3) ensuring the utmost strengthening of a SL element at SPD for definite conditions of power loading can be put down as follows:

$$A^* = \Delta H^* + q - E \qquad (5)$$

It should be expedient to emphasize a very significant circumstance that a similar analogy is correct only at the level of metal local volumes which are full of specific energy of the utmost value. But its transfer to the levels of larger volumes is wrong and because of the following reason: in the course of heating the energy is absorbed by a lattice actually evenly through the whole of the metal volume, and at plastic deformation because of anisotrophy and imperfections of a lattice the non-uniform energy absorption occurs.

2. Investigation purpose

The experimental validation of the utmost density of internal energy at which is achieved maximum SL strengthening without destruction and ensured the effective increase of its strength properties in the course of operation.

2.1. General approach to investigation

The density of latent energy in surface layers modified in the course of SPD is an integral parameter[4,7,15,21]. Its value is equal numerically to instantaneous aggregate work of all forces spent for the activation of local instability of material deformable. At its estimation we can put aside a contribution of concrete micro-mechanisms and types of energy supplied in energy dissipation. According to the increase of plastic deformation degree the energy grows for its further activation. At that moment, when material achieves the state of pre-destruction because of fatigue brittle behavior the energy of plastic deformation activation becomes equivalent to the energy of destruction activation. The last parameter within the limits of one mechanism of damageability is a strength characteristic of each concrete material[6,9,18].

In the heart of the experimental estimation of an energetic state of plastically deformed material must be laid its activation until the point of bifurcation is achieved and the estimation of energy spent for it. For the choice of a concrete way the following factors should be taken into account:

- The chosen method for the estimation of material activation must create conditions for self-organization in material dissipative mechanisms corresponding to the process under investigation;
- The activation of surface layer material must be localized within the limits of the dissipative system investigated;
- The procedure and technical means for the material conversion in an excited state must be as simple as possible, accessible, science intensive and meeting current requirements to the means and methods of technical diagnostics. On the basis of the analysis the specificity and the state of a surface layer modified by SPD at the development of the investigation methods of its energetic state it is necessary to take into account the following circumstances:

1. The material of a surface layer after SPD preserves a crystalline structure, and the structure of a surface layer has a monogenic character.
2. In the course of SPD occurs an accumulation of damages in material of a surface layer. Under the specified conditions of SPD the thickness of a layer bordering with the environment preserves a stable value. When critical density of damages is achieved this layer is destroyed in the form of chipping or peeling particles.
3. The energetic state of a strengthened surface layer depends upon the created scheme of a stress-strained state. During the SPD a rather complex stress-strained state of surface layer material arises conditioned by normal and tangential loads, elastic strains and plastic deformations of contacting bodies which could be described approximately as a biaxial compression with superimposed gyrostatic pressure. That is why the experiments should be carried out at the creation of a stress-strain state adequate to that which is created in the area of a contact with the surface worked during a real process.
4. As a result of multiple plastic deformation of a surface layer during SPD the anisotropy peculiar to the surface before SPD is practically leveled.
5. Under SPD conditions a location sliding is a dominant mechanism of damage stipulating the activation energy of plastic deformation in a surface layer.

The structural-energetic interpretation of the SPD process considers activation energy of a plastic deformation in a surface layer as irreversible energy of thermo-dynamic changes of a local scheme at which the plastic deformation

process is followed by the irreversible accumulation of damages in material (increase of dislocation density). At the same time the mechanical work performed of deformation of a volume unit will be equal to the increase of thermo-dynamic potential of the system with the appearance of a single dislocation in the unit of volume. As dislocations during a plastic deformation are accumulated in the volume, then the system internal energy increase will grow non-linearly with the increase of their density. The mentioned approach explaining the possibilities of a system buckling failure at the macro-level at the expense of gradual accumulation of damages is based on the theory of absolute velocities of reactions and is used in the works carried out by N.F. Mott, A.S. Novik, J. Dorn, V. Kautsman, G.Eiring, V.V. Fedorov et al.[3]. It proves its physical ground and acceptability for the explanation of kinetic and energetic essence of the SPD process.

When considering the SPD process it is possible to emphasize three basic stages:

- **The first stage** – initial state of surface layer material obtained as a result of machining prior to the SPD process;
- **The second stage** – excited state corresponds to the point of bifurcation in which the material loses its stability. In order to produce this state it is necessary to pass a part of energy to material for activating mechanisms which result it in a plastic deformation.
- **The third stage** - surface layer material obtains a new steady state corresponding to the completion of a kinetic cycle of the SPD process. The deformation process is concluded with pushing activated material aside (either removal) from the area of stress operating.

The strengthened surface layer formed by free-moving indenters during the SPD process is a result of mechanical, thermal, chemical, wave and other effects upon the surface of material worked. An aggregate of effects activates thermo-fluctuation acts of material damageability at the micro-level, and kinetics of this process defines surface layer life under conditions of operation.

In the view of thermo-dynamic theory of strength it does not matter which energetic contribution is made by this or that destructive factor to the buckling failure of material, but from the point of view of the methodology of test operations on the estimation of an energetic state of strengthened surface layers there is a considerable difference in the accessibility and accuracy in the definition of their energetic parameters.

It follows from the energetic model of the SPD process that a basic contribution to the buckling failure of material activated and, as a consequence, to its strengthening is made by thermal and mechanical factors. The thermal part of internal energy is conditioned by thermal fluctuations of atoms in material of a surface layer caused by a thermal effect. The mechanical part of internal energy is formed at the expense of mechanical stresses and plastic deformations.

It is established that metals subjected to SPD get warm. The phenomenon of temperature increase in metal plastically deformed as a result of the external force effect is called thermo-plasticity. In such a way, when measuring a value of temperature increment of metal deformed with the aid of a calorimetric method it is possible to determine the true amount of heat evolved as a result of a thermo-plastic effect. Then, the energy saved in a plastically deformed surface layer can be defined as a difference between the work spent for material deformation and the amount of heat evolved.

3. Equations

In Fig. 1 is shown the schematic diagram of the device for investigations of the energetic state of a plastically deformed surface layer of a sample through a calorimetric method the essence of which consists in the following.

Metal sample 1 with a diameter of 20 mm and thickness up to 5 mm is located in cylindrical calorimetric chamber 2, made of textolite. The location of a sample in the chamber is carried out on a plane and cylindrical hole. In chamber 2 there is a hole through which sensor 6 for temperature measurement is introduced. The chamber is closed with cover 3 made also of textolite. The hole in the cover ensures an access to the sample of the indenter 4 screwed into plunger 5 carrying out a percussion-power effect upon a sample. The results of temperature measuring recorded by a sensor are sent to a measuring instrument. A cylindrical calorimetric chamber is installed in metal case 7 which is fixed to the bottom of basic device 8 realizing percussion-power impact through case elements 9. A shock upon the sample is carried out by means of indenter 5 supplied with a spherical face. In such away, the SPD process was imitated by dynamic methods.

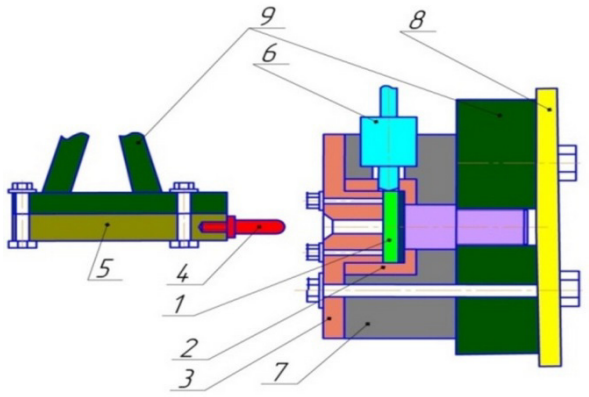

Fig. 1. Schematic diagram of the device for the estimation of an energetic state of a sample surface layer in the course of SPD process.

For temperature measurement in samples there is chosen professional surface thermometer TESTO 905-T2 with a spring-loaded cruciform probe including a multi-functional clamp and a cell. The advantages of this sensor: a spring-loaded thermocouple (optimum solution for uneven surfaces); high accuracy and performance; convenient measurement data reading due to rotating display. Technical data of the device: measurement range 50…+350°C, error 0.1°C. For investigation carrying out there were used samples made of carbon steel: steel 20, 35, 45.

Saved (absorbed) energy from the first law of thermodynamics is defined as a difference between the work spent for material plastic deformation and quantity of heat evolved

$$Eci = Ai - Qi \tag{6}$$

For the estimation of heat quantity evolved during a deformation process there was used a dependence defining a connection of heat accumulated in a local plastically-deformed volume with an experimentally defined metal temperature increment as

$$Qi = C\mu(Tk - Th) \tag{7}$$

where Qi - thermal effect of a plastically deformed sample, J/mol; Cμ - molar thermal capacity of the sample, J/K×mol; Tk- final temperature of the sample, k; Th- initial temperature of the sample, k.

The work spent for the plastic deformation of a local micro-volume is defined from the ratio

$$Ai = Vm \cdot 10^{-6} \cdot \sigma d \cdot \frac{di}{2R} \tag{8}$$

Where Vm- molar volume of sample material, m^3/mol;σd=c×σs– dynamic yield stress of sample material, n/mm^2; c=2.5-3- dynamic index;σs– static yield point of sample material; R- radius of indenter spherical surface, mm; di- experimentally defined diameter of a plastically deformed area, mm.

A maximum permissible value of energy saved in a local plastically deformed volume of the surface at which the highest effect is achieved in surface strengthening for material of samples was computed from the supposition

$$Eci \approx \Delta H \tag{9}$$

Where ΔH- difference of enthalpy of material in the solid state at the melting temperature Hts and enthalpy at 293°K (Table 1)

Table 1. The value of critical internal energy for the materials tested.

Steel grade	Critical internal energy, [kJ/mol]
20	37.685
35	37.433
45	37.232

On the basis of experimental design data, there were formulated dependences of changes in plastic deformation functioning A, energy stored Es and quantity of heat evolved Eh depending on a number of strokes N, shown in Fig. 2, at the same time there were established: limiting number of acts of a stroke-force impact at which ceased the growth of a plastically deformed area without its destruction; value of energy accumulated in a local plastically deformed volume of the surface at the limiting number of acts of stroke-force impact and its commensurability with the difference of material enthalpy in a solid state at the melting temperature Hts and enthalpy at 293°K (Fig.3).

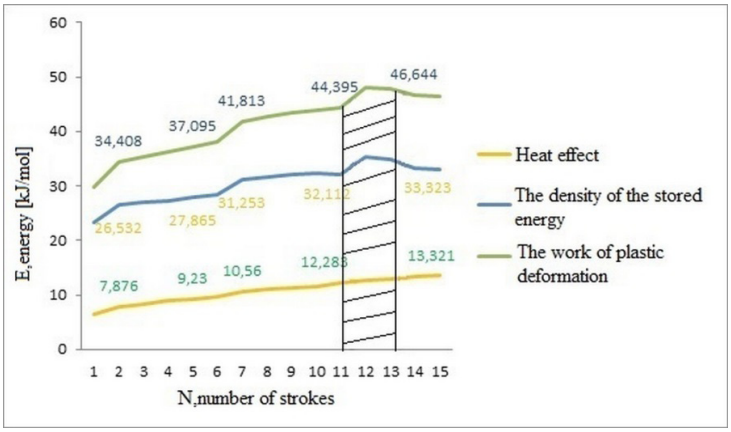

Fig. 2. Diagrams of work changes of plastic deformations A, energy stored Es and quantity of heat evolved Eh depending on the stroke number N.

Besides, on the basis of the experimental computation data obtained there was estimated a share which make energy stored in a local plastically deformed volume of the surface of the whole of work spent for the deformation of a local micro-volume (Fig. 3).

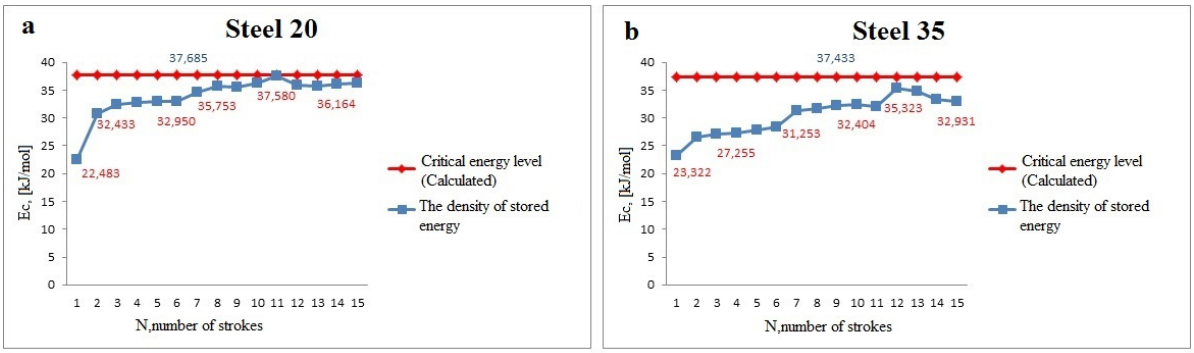

Fig. 3. Changes in energetic state of a metal surface layer in the course of SPD process: (a) steel 20; (b) steel 35.

4. Conclusions

For the chosen in the work conditions for the carrying out experimental investigations it is established that the critical growth of energy in a plastically deformed local volume takes place at the realization of 11-13 acts of a force impact. At the further increase of force impact acts the energetic state of a surface is stabilized.

The value of critical energy in a plastically deformed local volume of a surface at which stopped the growth of a surface plastic deformation is commensurable (with the error within the limits of 15%) with the value equal to the difference of material enthalpy at the solid state at the melting temperature Hts and enthalpy at 293°K. It allows this value to accept as a criterion of effectiveness of surface strengthening by SPD dynamic methods.

The share of plastic deformation work spent for the surface strengthening in the course of the SPD process makes 70%.

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