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## CHANGING PROPERTIES OF METAL SURFACE LAYERS DURING THERMO-CHEMICAL TREATMENT

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In this article a two-stage technology for constituting surface layers is proposed. First, the material is subjected to initial hardening by burnishing and next to a nitriding process. The surface layer after such processing should have considerably better strength properties compared to those created through a conventional nitriding process. A description of the state of the surface layer after these stages of the proposed process is obtained by defining suitable energy states for the materials. These states are expressed by residual strain and stress function and also by the functions of external work during the burnishing process and thermal energy given in the nitriding process. Methods of identifying the above functions through experimental research on the residual stress state and selected parameters of the surface layer, and also through numerical analysis of the coupled processes, are also proposed. The main part of the work consists in the mathematical description of complex deformation phenomena occurring in the material during the proposed process. In the given description, coupled stress fields appear as a result of the additivity of elastic, plastic, thermal, diffusional, and phase strains.

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### 1. Introduction

The state of the surface layer strongly influences the utilisable properties of machine parts. Various technologies constituting surface layer properties are in use including mechanical, thermal and thermo-chemical technologies. However, thermo-chemical processes take a long time and consume a lot of energy. From the economic point of view it is necessary to develop methods which allow the intensification of the process. The main phenomenon occurring during the thermo-chemical process is the diffusion of chemical elements into the material. The result of this phenomenon is the creation of adequate material structures. It is also known that diffusion occurs faster in hardened material with a raised energy state than in, for

example, annealed materials. For this reason it is better to join thermo-chemical processes with other kinds of ones. This process should introduce a useful structural deformation into the material. Burnishing is ideal, one of its most important effects being the introduction of plastic deformation in the surface layer. Assumptions for a joined technological process arising from the coupling of burnishing and nitriding processes are presented in this work.

## 2. Joined (burnishing and nitriding) processes

The idea of the burnishing process is the local use of plastic strain in the surface layer of the object (material) as an effect of the action of a hard tool on the surface, which causes plastic strains in the material. It is necessary here to mention that introducing plastic deformations to the surface layer results in changes to its energy state. An effect of hardening is an accumulation of energy in the material. Some studies show that an increase in the surface layer's energy increases its capacity for diffusion. This is of essential significance in this work.

Nitriding is a process of saturating iron alloy with nitrogen in high temperature conditions. The nitrogen introduced to the structure enters into a particular reaction with the iron contained in the steel, resulting in the creation of defined metallographic structures whose characteristics includes a high degree of hardness. After this process considerable compression stresses are also found [1-4].

A fundamental phenomenon influencing the creation of the nitrated layer is the diffusion of nitrogen atoms into the treated material. It is known that in this process diffusion most often occurs along grain boundaries and areas where the density of dislocations is high. Also noteworthy is that after hardening machining, the material has the capacity for the intensification of diffusion.

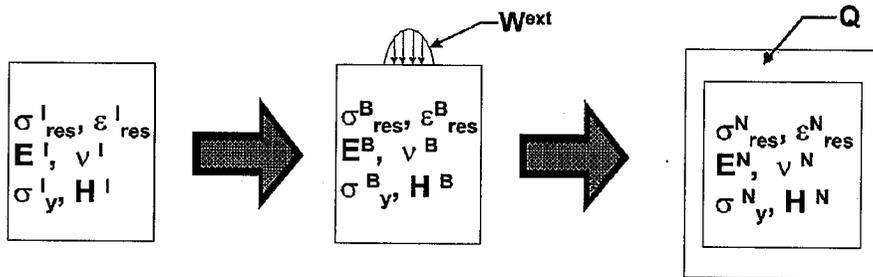


Fig. 1. The diagram of the idea of joined technology.

Research results [5, 6] allow us to conclude that if a material destined for nitriding is first subjected to burnishing machining, the resulting changes in its structure will significantly influence the kinetics of the nitriding process and the constitution of the surface layer. The execution of such joined processes is presented schematically in Fig. 1.

The given material of known properties and determined initial residual strain-stress state  $\sigma_{res}^I$  and  $\epsilon_{res}^I$  is subjected to burnishing. The effect of hardening is a change in the strain-stress state to as  $\sigma_{res}^B$  and  $\epsilon_{res}^B$  (after burnishing). The material prepared in this way is then subjected to nitriding treatment. The

final state of the material is defined by residual stress and strains  $\sigma_{\text{res}}^{\text{N}}$  and  $\epsilon_{\text{res}}^{\text{N}}$  (after nitriding). The aim of the process is the formation of modified surface layer properties.

### 3. Energy description of the material in individual stages of the process

The mechanical properties of the initial material may be described by the Young elastic modulus ( $E^{\text{I}}$ ), the Poisson coefficient ( $\nu^{\text{I}}$ ), yield stress ( $\sigma_{\text{Y}}^{\text{I}}$ ), hardening modulus ( $H^{\text{I}}$ ) etc. We can assume that the above magnitudes represent not only the surface layer but also the core of the treated material.

The first stage of treatment — burnishing — produces significant changes in the mechanical properties of the material's surface layer. As an effect of hardening treatment, microstructural changes arise, followed by a strengthening of the surface layer and anisotropy of the mechanical properties appears (orthotropy in particular). The material of the surface layer is now characterised by the following quantities: the Young elastic modulus ( $E_i^{\text{B}}$ ), the Poisson coefficient ( $\nu_i^{\text{B}}$ ), yield stress ( $\sigma_{\text{Y}_i}^{\text{B}}$ ), hardening modulus ( $H_i^{\text{B}}$ ) (for  $i = 1, 2, 3$ ) etc. Surface layer properties differentiate themselves further from the properties of the base material. However, the properties of the core approach those of the initial material as described above.

Thermo-chemical treatment deepens the anisotropy of the material's mechanical properties. Therefore, it is possible to speak of the distinct mechanical properties of each newly arisen zone as differentiated from those of the base material. In the formation of the nitrated surface layer, there appear zones of ferric nitrides  $\epsilon$  ( $\text{Fe}_{2-3}\text{N}$ ),  $\gamma'$  ( $\text{Fe}_4\text{N}$ ) and also a diffusional zone. The first two zones can be assumed to be uniform considering their very small thickness (in the order of a few micrometers). The diffusional zone, however, is very thick in comparison. Parameters describing the material properties are: the Young modulus for each zone, the Poisson coefficient, yield stress, and hardening modulus.

We currently define the strain energy accumulated in the material of volume  $V$  in particular states such as initial (index I), after burnishing (index B) and nitriding (index N). We obtain respectively

$$E_{\text{I}} = \int_V \sigma_{\text{res}}^{\text{I}} \epsilon_{\text{res}}^{\text{I}} dV, \quad E_{\text{B}} = \int_V \sigma_{\text{res}}^{\text{B}} \epsilon_{\text{res}}^{\text{B}} dV, \quad E_{\text{N}} = \int_V \sigma_{\text{res}}^{\text{N}} \epsilon_{\text{res}}^{\text{N}} dV. \quad (1)$$

Energy state changes produced by the successive treatments are defined as the differences between the deformation energy of the burnishing treatment and that of the initial state as well as the deformation energy of the nitriding treatment and that of the burnishing treatment

$$\Delta E^{\text{B}} = E^{\text{B}} - E^{\text{I}}, \quad (2)$$

$$\Delta E^{\text{N}} = E^{\text{N}} - E^{\text{B}}. \quad (3)$$

In the proposed process it is also possible to define an external force work corresponding to the burnishing process  $W^{\text{ext}}$  as well as heat applied in the nitriding process  $Q$ . From the energy balance of the systems it results that the deformation energies in models (2) and (3) are equivalent to the corresponding

external force work  $W^{\text{ext}}$  and thermal energy  $Q$  and are decreased by the corresponding dissipation energies  $Q_{\text{dis}}^{\text{B}}$  and  $Q_{\text{dis}}^{\text{N}}$  in these processes. Investigations show that these above-mentioned energies carry about 0.7–0.9 of the exchanged work or the heat applied in the burnishing and nitriding processes, from which we obtain respectively

$$\Delta E^{\text{B}} = W^{\text{ext}} - Q_{\text{dis}}^{\text{B}}, \quad \Delta E^{\text{N}} = Q - Q_{\text{dis}}^{\text{N}}, \quad (4)$$

where  $Q_{\text{dis}}^{\text{B}} = k^{\text{B}} W^{\text{ext}}$ ,  $Q_{\text{dis}}^{\text{N}} = k^{\text{N}} Q$  and  $k^{\text{B,N}}$  — a suitable coefficient of the dissipation process.

The external force work of the burnishing process  $W^{\text{ext}}$  can also be expressed as being dependent on the parameters of the burnishing treatment, that is, on the distribution of external force acting upon the treated object  $p^{\text{B}}(x, t^{\text{B}})$ , on the rapidity of treatment  $v$ , and on the efficiency of the process  $\eta^{\text{B}}$ . Similarly, the value  $Q$  can be dependent on the technological parameters of the nitriding. Those parameters are: temperature  $T$ , duration of the nitriding  $t^{\text{N}}$ , pressure  $p$ , composition of the nitriding atmosphere (expressed, for example, as the relation of contents  $\text{H}_2/\text{N}_2$ ) and efficiency of the process  $\eta^{\text{N}}$ . Analysis of the energy states of the processes then allows us to define a function  $f(\sigma_{\text{res}}, \varepsilon_{\text{res}})$  for the strains and stresses, which can be expressed by the means of an appropriate dependence

$$f(\sigma_{\text{res}}^{\text{I,B,N}}, \varepsilon_{\text{res}}^{\text{I,B,N}}) = \frac{\Delta E^{\text{N}}(\sigma_{\text{res}}^{\text{B,N}}, \varepsilon_{\text{res}}^{\text{B,N}})}{\Delta E^{\text{B}}(\sigma_{\text{res}}^{\text{I,B}}, \varepsilon_{\text{res}}^{\text{I,B}})} k, \quad (5.1)$$

as well as an energy/work function of the processes carried out  $f(Q, W^{\text{ext}})$  in the form

$$f(W^{\text{ext}}, Q) = \frac{Q(T, t^{\text{N}}, p, \text{H}_2/\text{N}_2, \eta^{\text{N}})}{W^{\text{ext}}(p(x), t^{\text{B}}, \eta^{\text{B}})}, \quad (5.2)$$

where  $k = \frac{1-k^{\text{B}}}{1-k^{\text{N}}}$  is the coefficient of losses in the joined processes.

Functions (5.1) and (5.2) are equivalent to each other, from which

$$f(\sigma_{\text{res}}, \varepsilon_{\text{res}}) = f(Q, W^{\text{ext}}). \quad (5.3)$$

The first function (5.1) is directly linked to the description of the state of surface layer. Through studies of the stress and strain states we can define the energy changes occurring in the material during the series of processes. This in turn allows us to define the deformation energy accumulated in the material. On the other hand, studies of the metallographic structure allow not only the precise recognition of the formation of the layer, but also the precise description of the thickness of individual zones of the layer. This is of importance that, in this way, the connection (correlation) of the layer's energy state with its structure can be defined. It is then possible to state what influence the individual zones have on the final properties of the near-surface zones. The final effect of such research will be the practical utilisation of data in the creation of a surface layer being appropriate for working loads. Research should be connected on the distribution of microhardness. In this way the energy state will remain strictly related to engineering research. Further investigations are also possible with the aim of further improving the description of the properties of the surface layer constituted — for example tribological and fatigue research, etc.

Identification of the function by its fields of stresses and strains is also convenient from the point of view of the physical and mathematical modelling of the process. It is possible in this way to utilise numerical methods to simulate these fields.

The form of the stress-strain function presented in (5.2) allows us to identify the influence of technology on the state of the surface layer. As can be seen, this function is dependent on the energy  $Q$  and work  $W^{\text{ext}}$ . These quantities are in turn expressed with the aid of fundamental technological parameters of the nitriding and burnishing processes. Execution requires complex studies having as their goal the definition of the influence of the individual parameters on the final state of the material. It is then necessary to relate the results of these investigations to the above-mentioned results of material, strength and working investigations. Finally, a complex description of surface layer is obtained allowing the complete identification of its properties after the process proposed herein. Such a description provides a fuller picture of the state of the surface layer.

#### 4. Mathematical modelling of the joined processes

A description of how the surface layer of the deformed material behaves during the processes of burnishing and thermo-chemical nitriding is dependent on the type and scale of deformations considered [7-10].

The initial state of the material contains, for example, deformations which are effects of the cutting treatment. This treatment is intended to conform the object to a defined form. The state of stress and strain existing in the material is thus an effect of the action of the cutting tool and, usually, these already existing elastic and plastic deformations are insignificant. In general, we describe the additive decomposition of strains (strain rates) as follows:

$$\dot{\epsilon}^I = \dot{\epsilon}_e^I + \dot{\epsilon}_p^I \quad (\dot{\epsilon}^I = \dot{\epsilon}_e^I + \dot{\epsilon}_p^I). \quad (6)$$

The first stage of the treatment is burnishing. The hardening process is related to elastic-plastic deformations and the resulting phenomena of non-uniform hardening of the material's surface layer depending on the technology employed (static or dynamic burnishing) as well as on the technological parameters according to which treatment is carried out, the forces introduced during the process produce varying degrees of elastic-plastic deformation in the material. The plastic deformations arising occupy a depth in the material of up to a few millimeters. The accumulation of these deformations is analogously expressed as

$$\dot{\epsilon}^B = \dot{\epsilon}_e^B + \dot{\epsilon}_p^B. \quad (7)$$

The nitriding process, during which various phenomena occur, is of key significance in the formation of the final material properties. These phenomena, depending of the scale and range, can alter the material's state considerably. For example, the distribution, amount, and depth of the deposition of the strains can all change. The initial residual stresses are subjected to partial stimulated relaxation by the temperature field. Simultaneously, a new strain state is generated as an effect of the nitriding process, and considerable differentiation of the mechanical properties occurs. The hardness of the material also undergoes significant

differentiation. The coupled thermal and diffusional processes lead to the appearance of a new material structure characterised by a multi-component formation. Non-uniform distribution of the products of the chemical reactions throughout the sample's depth also takes place.

In general, we can assume that the deformation state appearing during the nitriding process  $\dot{\epsilon}^N$  can be described also as the sum of the elastic and plastic strain rates

$$\dot{\epsilon}^N = \dot{\epsilon}_e^N + \dot{\epsilon}_p^N. \quad (8)$$

However, it is possible to separate the so-called dilatational strains, which are effects of the action of the fields appearing during nitriding process, i.e.

$$\dot{\epsilon}_{dil}^N = \dot{\epsilon}_{th}^N + \dot{\epsilon}_{dif}^N + \dot{\epsilon}_{tip}^N + \dot{\epsilon}_{crp}^N, \quad (9)$$

where the individual components describe the strain rates which result from the action of the fields of temperature (th) and diffusion (dif), as well as those which arise as an effect of creep (crp) and the phase changes induced (tip) in the material.

We can describe the final state of the deformation of the material through the additive decomposition of the strain rates after stage of the joined processes

$$\dot{\epsilon}^F = \dot{\epsilon}_e^{IBN} + \dot{\epsilon}_p^{IBN} + \dot{\epsilon}_{dil}^N, \quad (10)$$

where from the relations (6), (7) and (8) result

$$\dot{\epsilon}_e^{IBN} + \dot{\epsilon}_p^{IBN} = (\dot{\epsilon}_e^I + \dot{\epsilon}_p^I) + (\dot{\epsilon}_e^B + \dot{\epsilon}_p^B) + (\dot{\epsilon}_e^N + \dot{\epsilon}_p^N). \quad (11)$$

On the other hand, the final elastic strain rates

$$\dot{\epsilon}_e^F = \dot{\epsilon}_e^{IBN} = \dot{\epsilon}^F - \dot{\epsilon}_p^F - \dot{\epsilon}_{th}^N - \dot{\epsilon}_{dif}^N - \dot{\epsilon}_{tip}^N - \dot{\epsilon}_{crp}^N \quad (12)$$

is related to the following constitutive equation for elastic range:

$$\dot{\sigma} = M\dot{\epsilon}_e^F + \dot{M}\epsilon_e^F, \quad (13)$$

where  $\sigma$  is the tensor of stresses,  $M$  is the tensor of material modulus,  $\epsilon^F$  is the tensor of the total strain ( $\epsilon = \frac{1}{2}(\nabla u + \nabla u^T)$ ).

The strain rates appearing in Eq. (12) are effects of the existence in the material of coupled fields resulting from thermal and diffusional phenomena and from changes in phase. The thermal and diffusional field equations (14), (15) and the constitutive relations (13) take the form of the system of the differential equations

$$\dot{T} = \nabla(D_T \nabla T) + q, \quad q = \rho c_f v, \quad (14)$$

$$\dot{C} = \nabla(D_f \nabla C) + \nabla(D_\epsilon \nabla \epsilon) + D_t v, \quad (15)$$

where  $q$  is the generated (latent) heat source during phase changes of the component with density  $\rho$ , its specific heat  $c_f$  at the rate  $v$  of the component's expansion. The material parameters  $D_{T,f,\epsilon,t}$  characterise the properties of the thermal diffusion, thermo-chemical diffusion, deformational diffusion, and transformation (phase change).

The following constitutive equations for the assumed models of strain rates may be expressed:

$$\dot{\epsilon}_p^F = \lambda \frac{\partial f}{\partial \sigma}, \quad \dot{f} = 0, \quad f = 0, \quad (16)$$

$$\dot{\epsilon}_{th}^N = \alpha \dot{T} + \dot{\alpha} T, \quad (17)$$

$$\dot{\varepsilon}_{\text{tip}}^{\text{N}} = K(1 - \xi)\dot{\xi}S, \quad (18)$$

$$\dot{\varepsilon}_{\text{dif}}^{\text{N}} = k \frac{V}{\Delta V} \Big|_{\text{N}} \dot{C}I, \quad (19)$$

$$\dot{\varepsilon}_{\text{crp}}^{\text{N}} = C_1 \sigma_{\text{eqv}}^{C_2} \varepsilon_{\text{eqv}}^{C_3} e^{-C_4/T}, \quad (20)$$

where  $f$  is yield function,  $\alpha$  is coefficient of thermal expansion;  $\lambda$  is thermal conductivity coefficient;  $S$  is deviatoric stress;  $\xi$  is volume fraction of the transformed phases by Avrami expression  $\xi(t) = 1 - \exp(-bt^n)$ ;  $\frac{V}{\Delta V} \Big|_{\text{N}}$  is volume misfit between nitride and matrix;  $I$  — unit tensor;  $K$ ,  $k$ ,  $b$ ,  $n$ ,  $C_1$ ,  $C_2$ ,  $C_3$ ,  $C_4$  are material constants;  $\sigma_{\text{eqv}}$ ,  $\varepsilon_{\text{eqv}}$  is equivalent stress and strain respectively.

The complexity of the physical problem and the complicated mathematical form of Eqs. (12)–(15) and the modelled constitutive equations (16)–(20) make a direct solution impossible. Separation of the fields equations and their direct solution, as well as simple additivity in accordance with (12) by using the above modelled constitutive equations seems to be only the alternative method of the stress problem (13) solving.

## 5. Conclusions

In this paper, basic theoretical assumptions for a joined technological process for constituting a surface layer through hardening and glow nitriding treatments have been presented. The entire research process requires experimental investigation and theoretical work in the form of physical and mathematical modelling, as well as numerical analysis of the fields presented in the above equations. An effect of such research will be the methodology of the surface layer design in the technological process described.

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