CONSIDERATION OF SHOT PEENING IN FATIGUE STRENGTH CALCULATION OF MACHINE PARTS

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ABSTRACT

In calculations of machine parts rarely there are regard of surface layer after heats, heat-chemicals , shot peening and others processes. Some strength calculation methods take of surface layer as an experimental coefficients and then include these coefficients in calculation formulas. In paper there is made the proposals to take of surface layer in strength calculation peened machine parts. The surface layer state is determined as a function of hardness and residual stresses distributions obtained after shot peening process. The fatigue strength of machine parts is calculated as interdependence of surface layer state and external load characterization. In paper the example of calculation of carburized and peened gears will be given.

KEYWORDS

Calculation of machine parts, surface layer, shot peening, residual stresses, hardness.

INTRODUCTION

Noted methods of fatigue strength calculations of machine parts don't take into consideration in calculation process the existence of superficial layer, which is formed as a result of surface treatments /1,2,3,4/. It is premised, that material properties in machine parts section are homogeneous so the strength calculations refer to surfaces of machine parts. Practically appears that beginning of machine parts destruction take place not on the surface only but also in the material situated a little more deep specially in the transition zone from superficial layer to the core. The explanation of reasons of such destruction mechanism, specially foresight possibilities of such accident existence requires consideration of superficial layer in calculation process.

In consequence of varied superficial layer treatments to improvement of quality /exploatation properties or aestetics/ of machine parts, on their surfaces is shaped a new material state, different from starting point. Parameters value which describe this state, among others of: residual stresses, hardness, structure changes are so much essential and contrasts so much from parameters in stock material and core, that in evaluation of exploatation properties of machine parts ought to be taken into consideration also the new state of material, which is started up as a result of used traitments layer on material surface in which is prepared the new state is in technical practice called superficial layer.

METHODS OF FATIGUE CALCULATION

Factors of safety

One the methods for fatigue strength calculation are inspected calculations, based on the factor of safety. Methods of these calculations can be varied, still they drive at common goal which is determination of degree of construction accuracy.

Factor of safety for symmetrical cycles is determined from the formula:

$$n = \frac{\sigma_{-1} \cdot \varepsilon}{\beta \cdot \sigma_a} \qquad /1/$$

in which:

n - real factor of safety,

σ_{-1} - limit of fatigue strength,

ε - characteristis for section-size factor,

β - wotch-working factor,

σ_a - normal intensity of stress amplitude.

For asymetrical cycles formulas determination of factor of safety can base on Haigh's and Smithg's diagrams as well as on simpliefied diagrams σ_a, σ_m of Serensen's, Soderberg's, Goodman's and Heywood's. Calculations for more complicated loads /simultaneous bending and torsion or stretching and torsion/ can be utilized on general bases for statical calculations. It ought to be choosed only property hypothesis of effort. Out of many general accepted efforts - hypothesis most utilised are two: hypothesis of non-dilatational strain energy Huber's - Misses's - Hencky's or Guest's - Mohr's hypothesis. Lest to use complicated formulas determinative factors of safety got by utilization of two above mentioned hypothesis, are introduced satisfactory correction factors for elements with notches and for brittle materials. The calculations are received from formula:

$$\frac{1}{n^2} = \frac{1}{n_\sigma^2} + \frac{1}{n_\tau^2} \qquad /2/$$

in which: n - factor of safety /σ - bending, τ - torsion/

Fatigue calculation according to TGL 19 340 [1]

The method for calculation of fatigue strength limit presented in standard [1] considers consolidation influence of machine parts superficial layer. The dependence which determines limit of fatigue strength of machine parts is following:

$$\sigma_{-1K} = \frac{\sigma'_{-1}}{K} \qquad /3/$$

in which: σ'_{-1} - fatigue strength limit of material, determined in flexibility-rotational test or in stretching - compressing test, depending on kind of machine parts load, from dependence:

$$\sigma'_{-1} = K_1(d) \cdot \sigma_{-1} \qquad /4/$$

in which: $K_1(d)$ - technological coefficient of size influence,
σ_{-1} - fatigue strength limit of material, for small diameter semi-finished product,
K - factor depending on:

$$K = \left(K'_\sigma + \frac{1}{K_{F\sigma}} - 1\right) \cdot \frac{1}{K_V} \cdot \frac{1}{K_A} \quad ; \quad K'_\sigma = \frac{K_\sigma(d)}{K_2(d)} \qquad /5/$$

in which: $K_\sigma(d)$ - wotch functioning factor,
$K_2(d)$ - technological coefficient of size influence,
$K_{F\sigma}$ - surface roughness influence factor,
K_V - surface consolidation influence factor,
K_A - anisotropy influence factor.

The method of calculations don't takes also into consideration the influence of superficial layer on fatigue strength of machine parts.

Methods of fabrique calculations based on probability

Based on statistical theory of the "weakest element" in the product dependence is formed for fatigue strength limit of machine parts considering consolidation of superficial layer of superficial layer of machine parts [2,4].

$$\sigma_{-1K} = \frac{\bar{\sigma}_{-1}}{K} \qquad /6/$$

in which: σ_{-1K} - limit of fatigue strength of part,
$\bar{\sigma}_{-1}$ - limit of material fatigue strength defined on samples in flexibility - rotational investigations,
K - coefficient of change of fatigue strength limit, taken from dependence:

$$K = \left(\frac{K_\sigma}{K_{d\sigma}} + \frac{1}{K_{F(Ra)}} - 1\right) \frac{1}{K_V} \qquad /7/$$

in which: $\frac{K_\sigma}{K_{d\sigma}}$ - coefficient of fatigue strength limit changes of parts in relation to sample and considering: stresses concentration gradient, similarity and size of parts, as well as material properties,
$K_{F(Ra)}$ - coefficient of decrease of fatigue strength limit, as a result of surface corrosion (F) or roughness (Ra)
K_V - consolidation factor, defined as a ratio of fatigue strength limit of consolidated part to the fatigue strength limit of unconsolidated part.

Based on dependence 3 and 6 it is possible to calculate fatigue strength of machine part taking into consideration surface consolidation treatment. This effect is still defined total, without determination of superficial layer construction and several properties in machine part section. The present methods of calculation create possibility for design of the state of machine parts superficial layer.

CHARACTERISTIC OF SUPERFICIAL LAYER

There are many models, which describe superficiallayer of metal. In the model given in 5 may be isolated:
- adsorbed layer,
- physical clean surface,
- strains zone,
- inviolate structure.

In turn, the model of superficial layer given by Kolman [6] considers: external, defined gas zone, median zone in which exist stresses, internal zone and core. This model of superficial layer considers also all the contaminations of layer, as: micro-cracks, slots, micro-shrinkages, pores, inclusions and others. It appears, that the most approximate to reality model of superficial layer is Hebda's model [7]. Among many parameters describing superficial layer state, the most essential are:
- structure,
- geometry,
- consolidation state,
- normal stresses state.

Above given parameters bind or define intermediate another important parameters, as: state and stresses-gradient in layer, thermodynamic potential of surface and chemical properties. An important parameter of superficial layer is roughness of surface; it has influence on fatigue strength.

CALCULATION MODEL OF SUPERFICIAL LAYER AFTER PEENING

Basis of the model

Above given parameters of superficial layer are difficult to use in calculation practice. Because of this reason it is advantageous to propose a model describing superficial layer by useful parameters strength calculations. It is nessesery apart from usefullness in calculations practice, the parameters taken to layer description ought to be parameters, which in essential and possibly full procedure describes the state of superficial layer strength. Accepted model of superficial layer ought to make possible consideration of varied kinds of outer loads, which are derived from variable in time loads and are result of machine parts work method, fatigue strength, contact fatigue, or sliding friction. In hither to practice such usable properties as fatigue strength or wear resistance are defined as function of mechanical properties: hardness or tensile strength. There are adapted even some calculations formulas; e.g...it is possible to calculate from the dependance of fatigue strength limit σ_{-1}, as a function of tensile strength Rm

$$\sigma_{-1} = (0{,}55 - 0{,}0001 R_m) R_m \qquad /8/$$

or function of hardness A measured Rockwell's method /scale C/

$$\sigma_{-1} = 156 \exp(0{,}02\,\mathrm{HRC})^{\pm 2\mathrm{HRC}} \qquad /9/$$

Above given dependences, which determine fatigue resistance as a function of mechanical properties of material, ought to be taken as dependences, which describe useful properties of homogeneous materials, in which hardness or stretching strength in section of part of machines or samples is stable.

The useful characteristic is showed in this case on fig.1 as straight line. Transferring this argumentation into consideration related to the case there should be noticed a phenomenon of mechanical properties which will change with a distance from a surface. Many investigations have shown that changes of hardness and internal stresses occur within the case as exemplarily shown in fig.2 and fig.3. So similarly should occur changes also in the fatigue limit. Fig.4 shows conventional cross section of a part, where curve 1 represents utilizable properties characteristic for machine part in the cross section.

The curve 1 can illustrate:

- distribution for fatigue strength limit,
- distribution for contact strength limit,
- distribution for wear resistance.

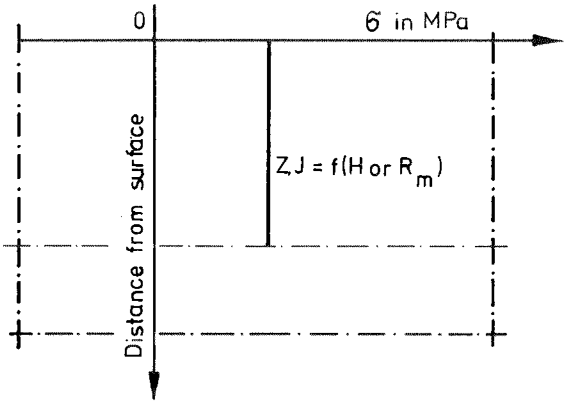

Fig.1. Cross section of homogenous machine part /without case layer/ showing marked utilizable characteristic.

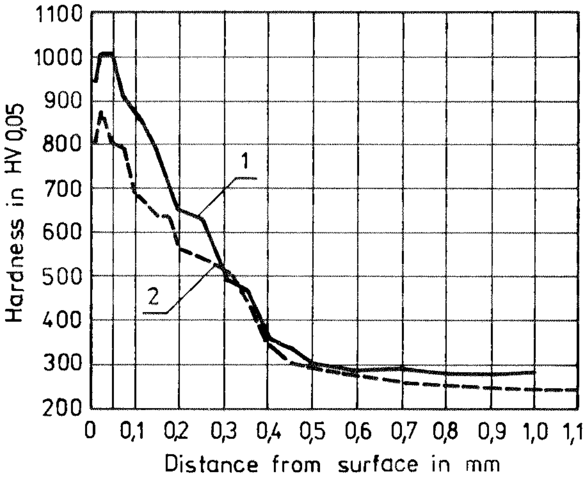

Fig.2. Material hardness change in function of distance to surface.

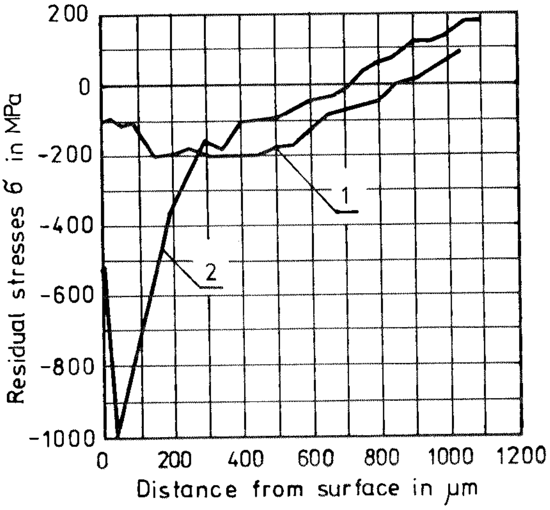

Fig.3. Residual stresses change in function of distance to surface.

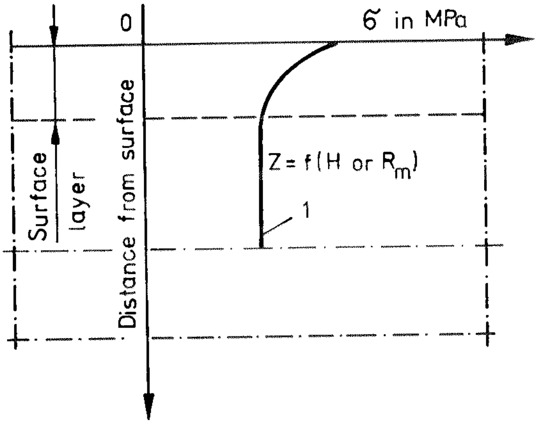

Fig.4. Conventional cross section of part with indicated case and curve illustrating characteristics of utilizable property.

Fatigue strength or wear resistance however not always can be interpreted by increased hardness. There are known cases, where increased hardness does not effect in respective increase of fatigue strength. Wöhler's curve shown in fig.5 illustrate fatigue strength for 18 HGT grade steel after carbonitriding and ionitriding treatments. Fig.2 shows hardness distribution within nitrided and ion-carbonitrided layers. It is seen that considerable increase of microhardness in the ion-carbonitrieded layer as related to ion-nitrided layer is not accompanied by significant increase of fatigue strength .
Analogically for aluminium alloys increase of theirs hardness in result of plastic working does not cause an increase in fatigue strength. The phenomenon can be explained by an influence of internal compression stresses. This effect is conected with a character of relationships between stress amplitude limit values, in asymetrical cycles of load, fig.6.

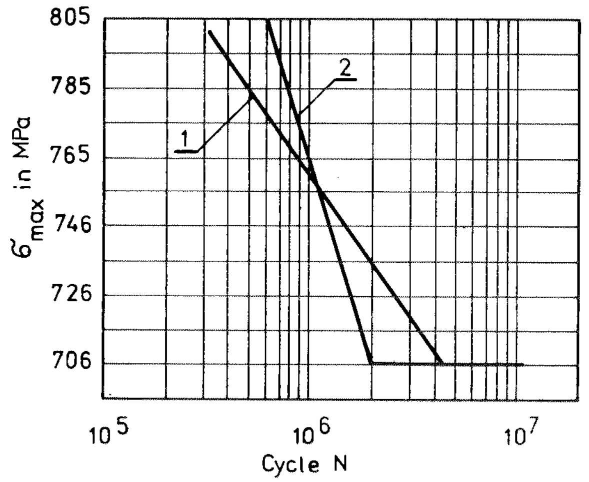

Fig.5. Wöhler curves for 18HGT steel; 1 - after carbonization, 2 - after nitridization.

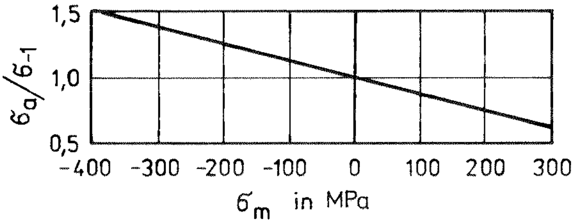

Fig.6. Limit values in relation to average stresses.

DETERMINATION OF UTILIZABLE PROPERTY CHARACTERISTIC

Distribution pattern of utilizable property characteristic within a test piece /for fatigue strength or wear resistance/ should be a function of the hardness and internal stresses:

$$\sigma_{-1} = f(H, \sigma) \qquad /10/$$

where: σ_{-1} - fatigue limit,
H - hardness,
σ - internal stresses.

Method of construction of the characteristic for utilizable properties which is a distribution of fatigue strength limit within a cross section in a function of hardness and internal stresses, described in References [4,8] is shown in fig.7 . The curve 1 defines a distribution pattern for fatigue strength limit in a function of hardness. For determination of internal stresses influence there should be known a pattern of $\sigma_a = f(\sigma_m)$ and change of σ - internal stresses within the cross section area, what is illustrated in fig. 7, by curve 2.

An influence of internal stresses on the fatigue strength shall be consistent with relationship illustrated by fig.6. For a definite value σ_m there is an increase of fatigue strength in accordance with relation $\sigma_a = f(\sigma_m)$. If a value of strength limit on the curve 1 is multiplied by a value readout from Haigh's diagram for known stress /curve 2/, in result a distribution of fatigue strength can be obtained, respecting influences of internal stresses. The distribution of utilizable property /limit of fatigue strength/ is represented by curve 3 in fig.7 as a function of hardness and internal stresses.

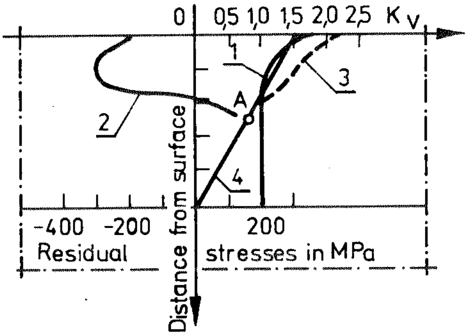

Fig.7. Characteristic of utilizable property /fatigue strength/ in relation to hardness and internal stresses.

In an engineering practice it is important, that the curve representing distribution of utilizable property could be defined as accurately as possible. Distribution of utilizable property depending on hardness appeared insufficient. Much more precise consideration has been proven with influence of internal stress, as proposed by Kogayev and Wohlfahrt's investigations,[3,8] and respectively. From publication survey as well as self-made investigation it results that beside mechanical and physical properties as hardness and internal stresses on mechanical properties a significant and even crucial influence has a material structure. The structure in turn is mostly influenced by carbon content. Hereby, useful characteristic in a function of hardness internal stresses and structure can be defined.

$$\sigma_{-1} = f(H, \sigma, C) \qquad /11/$$

Equivalent load

Description of the case layer through a distribution of utilizable characteristic has, in the material point of view, such advantage that enables to connect strength of material properties with external load, and define in this way a location of the highest effort in the material. Fig.8 shows schematically these conditions which lead to create a fatigue node beneath surface - curve 5 or on the surface - curve 5'. From analysis of the diagram it occurs that character of failure beneath surface or on the surface will be influenced by:

- value and distribution of internal stresses,
- value and distribution of hardness,
- structure,
- value of external loads.

It can be noticed here that a point matter of increase in fatigue strength requires both harder core case layer to be used together with introduction of high compressive stresses.

AN EXAMPLE OF CASE LAYER DESIGN

As an example there will be considered a determination of case layer requirements on a gears which gear-tooths has been strengthened by carburizing and shot peening.

Determination of fatigue strength limit distribution

Distribution of fatigue strength limit will be defined in a point of the highest concentration of stresses. For determination of fati-

gue strength distribution there are required:
- hardness distribution within a cross section,
- internal stresses distribution,
- relationship between amplitude of external load stresses and average value of stresses

Follow described procedure to obtain a distribution of fatigue strength limit in the case layer and it is shown in fig.9. The distribution of fatigue strength within the cross section is a function of hardness H and internal stresses distributions σ

$$\sigma_{-1_D} = f(H, \sigma) \qquad /12/$$

When requirements for the case layer conditions are calculated using computer technique, it is convenient to present table pattern distribution of fatigue strength limit as a function of a distance from a surface Z. Therefore it can be written:

$$\sigma_{-1_{D_i}} = f(Z) \qquad /13/$$

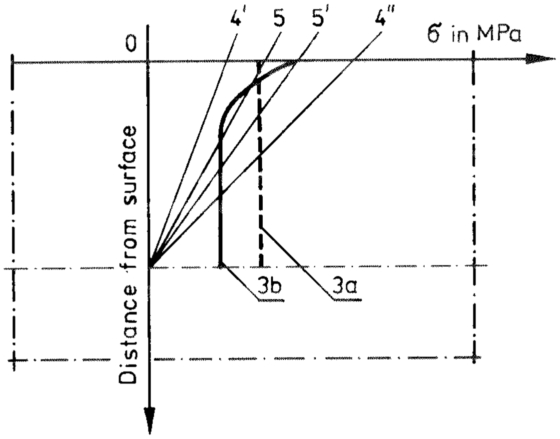

Fig.8. Fatigue properties characteristic and various values of external load: 4' - stresses from external load lower than strength of material; 4''- external stresses highly exceeding strength of material; 5 - external loads value quantitatively equal to material strength beneath the case layer; 5' - external loads value quantitatively equal to material strength on the case layer.

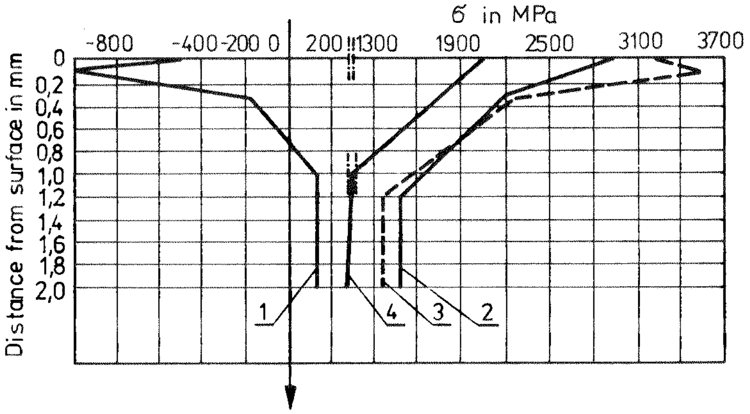

Fig.9. Distributions of fatigue strength and external load on a surface of gear - tooth after carburizing and peening
1 - residual stresses; 2 - hardnes; 3 - fatigue strength; 4 - external load ($\alpha_\sigma = 2,7$)

Determination of stress distribution for external loads

External load distribution can be defined by equation:

$$\frac{\sigma_{max}}{\sigma_{nom}} = \alpha_\sigma\left[1-\left(\frac{2z}{d}\right)\right]^{3\alpha_\sigma-2} \qquad /14/$$

where: σ_{max} - value of external stresses in distance from surface
σ_{nom} - value of nominal stresses
α_σ - stress concentration coefficient
d - thickness of gear-tooth.

Value of max. stresses on the journal surface /Z=0/ will found from equation:

$$\sigma_{nom} = \frac{6Mg}{bh^2} \qquad /15/$$

where: Mg - bending moment
b,h - gear dimensions

for calculated value of stresses intensity coefficient α_σ there can be obtained value of nominal stresses from equation:

$$\sigma_{nom} = \frac{\sigma_{max}}{\alpha_\sigma} \qquad /16/$$

By introduction a surface distance value into the equation we can find stresses, within the cross section caused by external load. Material strength condition for the case layer takes the form:

$$n = \frac{\sigma_{a\,max}}{\sigma_{-1D}} \qquad /17/$$

A failure in material occurs when: $n = \sigma_{a\,max}/\sigma_{-1D}$
and for $n>1$ failure occurs an the machine part surface
$n=1$ failure occurs both on the surface or beneath the surface
$n<1$ failure will not occur.

After developing this relationship the following can be written:

$$n = \frac{\sigma_{a\,max}}{\sigma_{-1D}} = \frac{\sigma_{a\,nom}\left[1-(2z/d)\right]^{3\alpha_\sigma-2}}{f(H,\sigma_{ost})} \qquad /18/$$

For n < 1, i.e. for safe condition:

$$\sigma_{a\,nom}\,\alpha_\sigma\left[1-\left(\frac{2z}{d}\right)\right]^{3\alpha_\sigma-2} < \sigma_{-1D} = f(H,\sigma_{ost}) = f(z) \qquad /19/$$

This means that for every point within cross section of the gear we can determine a value of hardness H and internal stresses σ. This also means that with known value of external loads distribution we can find basic date requested in process engineering /hardness value, case layer thickness, internal stresses condition/ to enable creation of required layer.
Fig. 9 shows distribution of fatigue strength limit on a gear-tooth after carburizing and shot peening, as well as external load distribution for which value of $\sigma_{a\,max}$ loads has been found in a result of tensometric measurements.

SUMMARY

There has been proposed a design procedure for a state of case layer on machine parts as appropiate in operational conditions. Proposed method can be employed for operational conditions with alternating loads.
This method finds strong argumentation in up-to-date achievements of material strength /including sliding friction and contact strength/, physical metallurgy and heat treatment. For application of this method into calculation the data are required as follows:

1. Load conditions for a part.
2. Data concerned to the case layer which is obtained in a result of defined technology:
   - distribution of hardness,
   - distribution of internal stresses,
   - structure.
3. Knowledge of classic calculation method in material strength for machine parts.
4. As it is pointed out, the calculation method can be fully automatized through creating appropiate calculating program.
5. IMP /Precision Engineering Institute/ offers these calculations for such machine parts as orankshafts, gears, axles, and others components intended for heat treatment by induction hardening, carburizing, nitriding or carbonitriding.

REFERENCES

[1] DDR - Standards TGL 19340.

[2] GOST 25.504-82. "Rasčoty i spytanija na pročnost". Metody rasčota charakteristik soprotivlenija ustalosti. Izd. standardov, Moskwa, 1982.

[3] Wolak Z., Pacula B., "Ocena wytrzymałości stali na zmęczenie na podstawie jej twardości". Wiadomości Hutnicze, nr 6, 1985, p. 163-165.

[4] Kogaev V.P., Machutov H.A., Gusenkov A.P.: "Rasčoty detalej mašin i konstrukcji na pročnost i dolegovečnost". Mašinostrojenie, Moskva, 1985, p. 150-152.

[5] Szulc I., Struktura i własności fizyko-mechaniczne obrobionych powierzchni metali. Zeszyt specjalny Politechniki Warszawskiej. Wyd. PW, Warszawa 1965.

[6] Kolman R., Mechaniczne umacnianie powierzchni części maszyn, PWN, Warszawa 1965.

[7] Hebda M., Janecki J., Tarcie, smarowanie i zużycie części maszyn, WNT, Warszawa 1972.

[8] Wohlafahrt H., "Verhalten von Stahl bei Schwingender Beanspruchang". Herausgegeben von Dahl W.Verlag Stahleisen M.B.H. Düsseldorf. /Russian translation/ Moscow, Metalurgia, 1983, p. 243-277.