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Features of hardening of the case parts made of aluminium alloys

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1. Introduction

Many parts of machines (in particular, the cases of gear pumps) work in conditions of sign-variable loadings. That is why there is the necessity for additional increase of endurance limit (and consequently durability) of a part's material in the zones of strain concentration.

Among various ways of hardening of machine parts the special place is occupied by the methods of superficial plastic deformation (SPD): treatment by shot, stamping, burnishing by balls and rollers, vibroburnishing, diamond smoothing and etc. They are the most effective and rather simple ways allowing considerably increase of fatigue strength, contact endurance, wear-proof and durability of the parts.

Search for optimum modes of SPD is conducted in our country and abroad rather intensively. Up to present time in literature the extensive information on the influence of basic parameters of SPD on the efficiency of hardening is presented. Recommendations for the choice of SPD modes are given, basing on the experience. It is known, that basic parameters of surface layer strength of the part, determining SPD effect are: the size and distribution of residual strains in cross-section of a part, and also physical hardening of the hardened layer. These parameters can be simply determined (up to SPD) by physical-mechanical properties of the material of a part, the intensity of plastic deformation $\varepsilon_{i,0}$ on the surface of a part and depth h_S of its distributions.

So, for example, the following problem appeared in the case of gear hydro machine (established in the mechanism of steering of a wheel tractor made of the casting aluminum alloy). On the linear side of the bottom and the lateral wall linking of the case in the zone of high pressure because of cyclic change of oil pressure during the work fatigue crack appeared (Fig. 1). Such breakdown made further operation of the product impossible.

This site was [1] additionally strengthened by the method of static stamping with the help of cylindrical indenter (Fig. 2). It is necessary to emphasize, that the appointed method appeared rather convenient technological operation: as the length of the strengthened fillet is rather small, its treatment is carried out by single loading of the cylindrical indenter (full contact cylindrical indenter). However the radius of the cylindrical indenter and working loading on it was selected from consideration of experience.

Also it is necessary to note, that cylindrical indenter (roller) as the tool for stamping is applied rather seldom. This was connected with the difficulties of parameters calculation of elasto-plastic contact of working surface of the cylindrical indenter and the part and of depth h_S of plastically deformed layer.

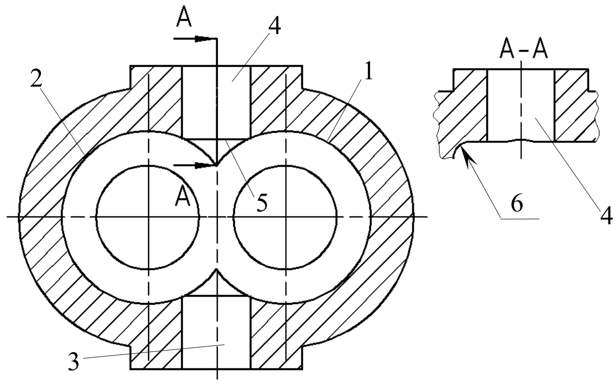

Fig. 1 The section of the case of gear hydro machine: *1* and *2* – boring under gears in the casting case; *3* and *4* – accordingly channels of low and a high pressure; *5* – strengthened linear site and the fillet radius *6*

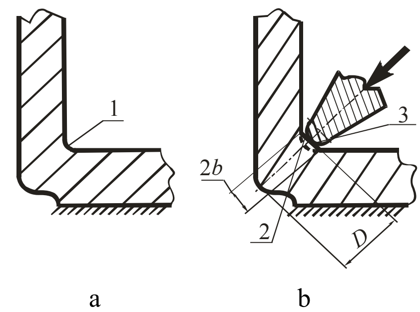

Fig. 2 Linking of the bottom *1* and the lateral wall of the case: *a*) traditional design, *b*) the advanced design with a flat platform *2* in which for the realization of SPD and for the formation of fillets the cylindrical indenter *3* is taken applied

2. Comparative analysis of the definition methods of the depth of hardened layer on the part surface

It is known that for achievement of the greatest effect from SPD it is necessary to realize two basic conditions.

1) Intensity of the deformation $\varepsilon_{i,0}$ on the part surface (in the case under investigation – at the points of longitudinal axis of symmetry of contact platform of cylindrical indenter and the part) and maximal uniform deformation ε_p of the material of the part are equal [2], that is

$$\varepsilon_{i,0} \approx \varepsilon_p \tag{1}$$

2) Depth h_S of the plastically deformed layer must be equal to the optimum depth $h_{S,opt}$, calculated [3] from hardness properties of the material of the part which is strengthened.

$$h_{S,opt} = D'\left(0.5 - \sqrt{\frac{0.375S_b}{S_k + 0.5S_b}}\right) \quad (2)$$

That is why it is very important to have an opportunity at designing process of parts hardening by SPD to predict analytically h_S (for the assignment of its optimum values).

In work [4] the depth of hardened layer at strengthening burnishing of steel parts by cylindrical rollers (in conditions of originally linear contact) is determined by the equation

$$h_S = 0.664\frac{q}{\sigma_{0.2}} - 0.385b \quad (3)$$

where $\sigma_{0.2}$ is conditional yield strength; q is specific working loading determined as the ratio of working loading F on the roller and working length l of the roller; b is half-width of the residual print, determined according to the methodology [4]

$$2b = 4\sqrt{q(k_1 + k_2)R\left(1 + \frac{2h}{\alpha_y}\right)} \quad (4)$$

where R is the radius of cylindrical roller, $k_{1,2} = \frac{1 - \nu_{1,2}^2}{\pi E_{1,2}}$; $\nu_{1,2}$ and $E_{1,2}$ is Puasson's ratio and the module of normal elasticity (indexes 1 and 2 concern accordingly the material of the cylindrical roller and the part); α_y is elastic retraction in the zone of contact [5]

$$\alpha_y = 4q(k_1 + k_2) \quad (5)$$

h is the depth of residual print [6]

$$h = 0.2R\left(\frac{q - q_{cr}}{HD\ R}\right)^{1.52} \quad (6)$$

where HD is plastic hardness of the part material (contact module of strengthening according to GOST 18835).

The radius of cylindrical roller R is calculated according to [4] the equation

$$R = 0.669(1 - 2\nu_2)\frac{b}{\varepsilon_p} \quad (7)$$

In the research [7], on aluminum alloys it is shown, that coefficient in the equation

$$h_S \approx Kd \quad (8)$$

in contrast to steel parts is less than 1.5 and depends on the depth of press. For the determination of h_S the empirical equation is recommended

$$h_S = \frac{5.8hD}{d} \quad (9)$$

However the dependences which were received for the initial contact point of the strengthened part and the tool can not be applied for the initial linear contact of the part and the tool (the cylindrical roller). The calculation methods of definition h_S at the initial linear contact published in last years are correct only for the steel parts subjected to hardening. Calculation methods of the definition h_S need further research for parts from nonferrous metals and alloys (in particular, aluminum alloys).

The purpose of the present research was the evaluation of applicability of the known interrelations between width $2b$ of the residual print, radius R of the cylindrical roller, working loading on the roller, and also calculation of the hardened layer depth h_S, for hardening parts from nonferrous alloys.

3. Experimental research of the hardened layer depth and the print width

Experimental measurement of depth h_S^e of plastically deformed by static stamping superficial layer is executed on the blocks of rectangular section (10×12 mm) made of aluminum alloys: foundry casting aluminum alloy, and deformable aluminum alloy. In advance the blocks from the specified alloys were subjected to thermal hardening by hardening and artificial ageing (the casting alloy: was hardened – at the temperature 520°C during 30 minutes with water cooling, ageing – at the temperature 150°C during 3 hours with air cooling, and deformable alloy: hardening- at the temperature 505°C during 50 minutes with water cooling, ageing – at the temperature 160°C during 10 hours with air cooling). This heat treatment is carried out in electric furnace. Casting alloy was heat treated in the similar way and after case manufacturing of gear hydro machine.

Mechanical properties of researched materials were determined by tension of flat fivefold models with the help of test unit of metals.

Cylindrical rollers (made of different steels with hardness HRC_e 62…64) and radii $R = 1.5$; 3 and 5 mm were used as strengthening tool. Break of the rollers in the lateral surface of the blocks was carried out on Brinell's press using of the device providing uniform distribution of loading on contact length (Fig. 3).

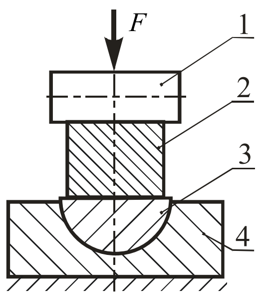

Fig. 3 Scheme of the device providing even distribution of load along contact length: *1* – cylindrical roller; *2* – sample (rectangular block); *3* – centering part; *4* – mounting

For comparison the evaluation of reliability of the known dependence (4) [8], determining width $2b$ of the residual print, with experimental data was performed. In addition the width $2b$ of the residual print was measured with the help of tool microscope in five sections on length l of contact line and average value (length of contact line l = 10 mm) was calculated. Examples of experimentally defined $2b$ are shown in the Table.

Then the depth of plastically deformed layer on the surface of the block was determined by the method using hardness measurement of the superficial layer by Vickers's method (HV_{10}). This layer was controlled with the help of the Vickers's device at loading 98 N. The distance from the hardened surface on the normal to it up to the point where hardness becomes equal the initial was considered as the depth of plastically deformed layer h_S^e. Examples of experimental definition of h_S^e are shown in Fig. 4.

Table

Comparison of experimental values of width $2b^e$ of residual prints with the results of calculation of width $2b$

Material of the part, its hardness, radius of indenter	q, N/mm	$2b^e$, mm	$2b$, mm by Eq. (4)	$\frac{b^e}{b}$
Deformable aluminum alloy *HD* 1580 MPa, R = 5 mm	446	0.60	0.69	0.89
	892	1.08	1.14	0.94
	1337	1.52	1.59	0.96
	1783	2.05	2.03	1.01
	2230	2.49	2.48	1.00
	2675	2.92	2.93	0.99
Casting aluminum alloy *HD* 1200 MPa. R = 5 mm	536	0.95	0.92	1.03
	1072	1.56	1.59	0.98
	1443	1.94	2.05	0.94
	1924	2.52	2.66	0.95
	2453	3.38	3.32	1.02
	2943	4.20	3.93	1.07

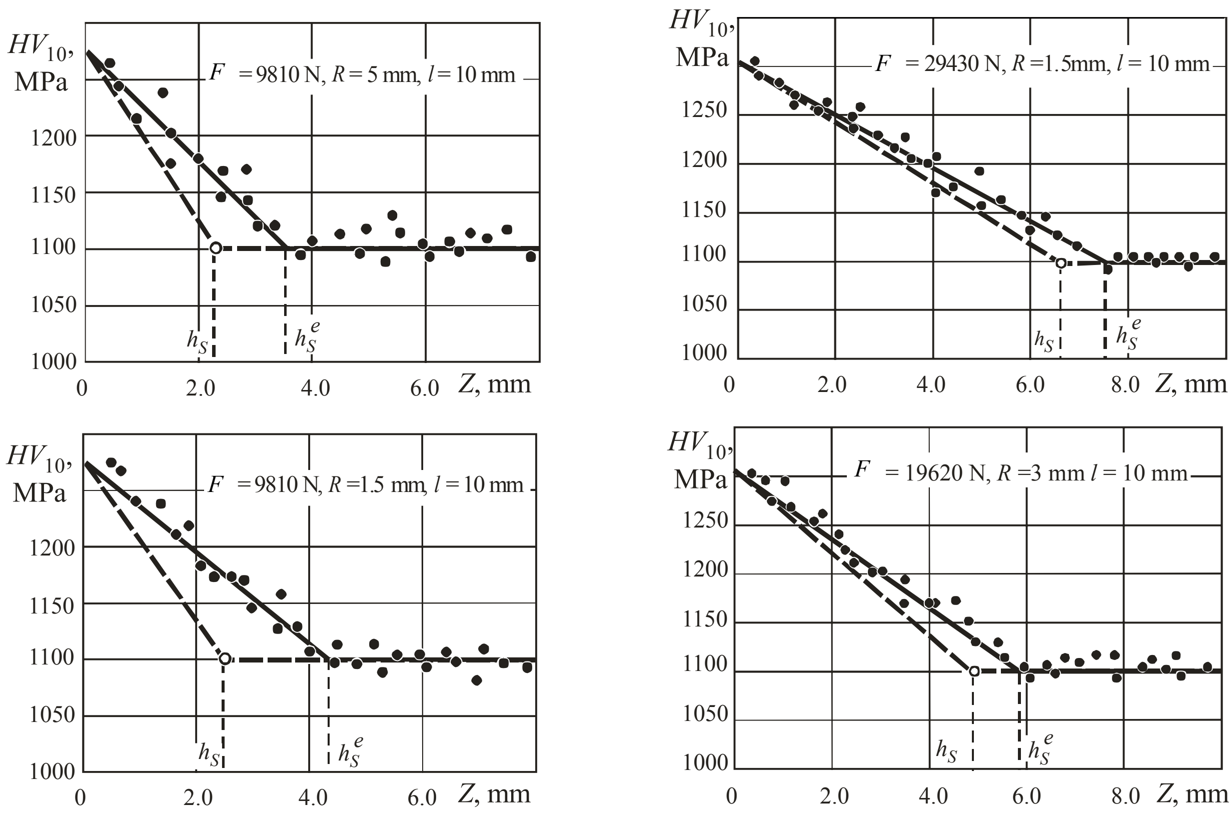

Fig. 4 Vickers hardness HV_{10} of casting aluminum alloy (dark points) variation in dependence on coordinate Z under longitudinal axis of symmetry of elasto-plastic contact area of cylindrical roller with block's surface: h_S^e is experimental value of the depth of plastically deformed layer; h_S is calculated by the Eq. (3) (light points)

4. Results discussion

Apparently from the Table and coincidence of experimental values of width $2b^e$ of the residual print with the calculated under Eq. (4) is quite satisfactorily. In the most cases the difference does not exceed (4-8) %. It means that the dependences received for steel are true also for the researched aluminum alloys [4].

Experimental results of the definition of depth h_S^e of plastically deformed layer are compared in Fig. 5 to the values h_S, calculated by Eq. (3). It is seen, that calculation results by Eq. (3) for steel plates, using real width $2b$ of the residual print well agrees with experimental data: the analysis of these results shows, that the coefficient of correlation of experimental and calculation values h_S makes 0.92.

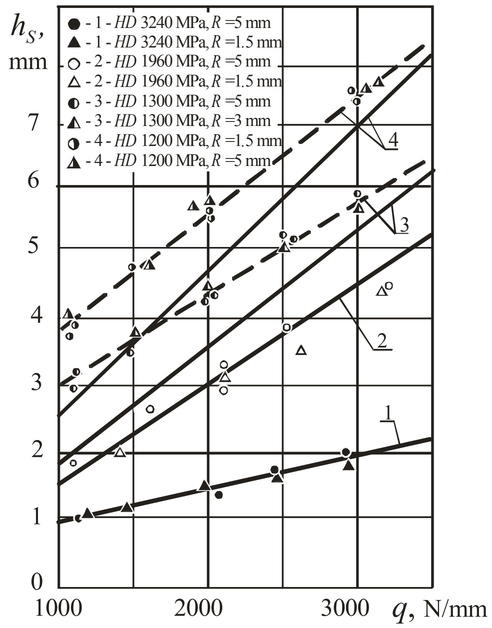

Fig. 5 Depth h_S of the hardened layer in dependence on specific loading q: continuous lines – calculation by Eq. (3); lines *1* and *2* correspond to steel block materials (*HD* 3240 MPa) and (*HD* 1960 MPa); lines *3* and *4* – hardness *HD* of the plate's material from deformable alloys (*HD* 1300 MPa) and casting alloys (*HD* 1200 MPa) accordingly; signs – experimental results; dotted lines – calculation by Eq. (11)

Direct use of Eq. (3), for the definition of depth h_S at hardening of the parts made from aluminum alloys, can bring to essential (in the investigated cases up to 60 %) to underestimation of calculation depths of the hardened layer comparing with experimental values.

It is apparent from Fig. 6 that the results given in Fig. 5, reconstructed in coordinates h_S^e / h_S from q, appear rather close to exponential curve of the approximation which using the method of the least squares has allowed receiving the following dependence

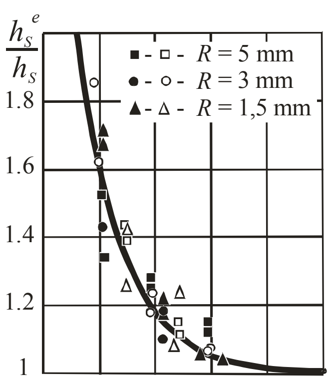

Fig. 6 Dependence of correction coefficient K on specific loading q on the cylindrical roller: points – experimental data, where dark points – casting alloy, and light points – deformable alloy; the line – calculation by Eq. (10)

$$K = \frac{h_S^e}{h_S} = 1 + \frac{1}{0.5\,exp\left(0.0012q\right)} \qquad (10)$$

Thus, taking into account Eq. (10) dependence (3) for the definition of plastically deformed layer depth h_S for the parts made of nonferrous alloys will become

$$h_S = K\left(0.664\frac{q}{\sigma_{0.2}} - 0.385b\right) \qquad (11)$$

where the value q is substituted in N/mm.

Some experimental results for the validation of the Eq. (11) are given in the Table. Processing of mathematical data has shown, that the deviation of h_S does not exceed 7% (with probability 0.95).

5. Calculation technique for the selection of hardening modes

On the basis of regularities elasto-plastic contact of a cylindrical roller with the surface of a part [8] and additional experimental research [5] the calculation method of the basic parameters of static stamping [6] was developed. The method is reduced to the definition of such basic parameters as specific working loading q and radius of the cylindrical roller (tool) R at simultaneous execution of two appointed above criterions of optimization ($\varepsilon_{i,0} = \varepsilon_p$, $h_S = h_{S,opt}$). The time of the application of working loading corresponds to the time of loading (necessary for full end of plastic deformation) at hardness measuring; for example, for nonferrous metals and alloys this time is 30 s [10].

The method is realized in the following order:

1. A conditional yield strength $\sigma_{0.2}$, true limit of strength S_b, true resistance to break S_k and limiting uniform deformation ε_p are determined by tensile test in according to GOST 1497 of standard tenfold cylindrical models (made of the material of the case). Plastic hardness *HD* of the material of the case is measured according to GOST 18835 [10].

2. Optimum depth $h_{S,opt}$ of plastically deformed layer is calculated by Eq. (2).

3. Rational value of specific loading at the first approaching is found using Eq. (3) determining the depth h_S of plastically deformed layer at contact cylindrical indenter with the part

$$q'_{rat} = 1.5 h_{S,opt}\sigma_{0.2} \qquad (12)$$

4. The radius of cylindrical indenter with using Eq. (5) (at $K = 1$ and $b = 0$) is determined (as a first approximation) proceeding from the first condition of optimization that intensity of deformation $\varepsilon_{i,0}$ at the points of longitudinal axis of symmetry of the contact platform, must be equal to limiting uniform deformation ε_p of the material of the strengthen part

$$R' = 0.669\left(1 - 2\mu_2\right)\frac{b}{\varepsilon_p} \qquad (13)$$

where b is determined by Eq. (4) taking into account Eq. (5) and (6) at the value $q = q'_{rat}$, that is

$$R' = 0.669\left(1-2\nu_2\right)\frac{1}{\varepsilon_p}\sqrt{2R'\left[0.2R'\left(\frac{q'_{rat}-q_{kr}}{R'\,HD}\right)^{1.523}+2q'_{rat}\left(k_1+k_2\right)\right]} \tag{14}$$

where q_{kr} is critical value of specific loading corresponding the occurrence of plastic deformation of the points of longitudinal axis of symmetry of contact platform and determined according to [11]

$$q_{kr} = \frac{R\left(k_1+k_2\right)\pi^2\sigma_{0.2}^2}{\left(1\text{-}2\nu_2\right)^2} \tag{15}$$

R' is determined by the method consecutive approximations from the Eq. (14).

5. Value q''_{rat} in the second approaching is determined by Eq. (3) using the found value of R'.

$$q''_{rat} = 1.5\left(\frac{h_{s,opt}}{K}+0.385b\right)\sigma_{0.2} \tag{16}$$

Thus the values of K and b are calculated (at $q = q'_{rat}$ and $R = R'$) accordingly by Eq. (10), and b are calculated by Eq. (4) using the depth h value of the residual print, determined by Eq. (7).

6. The radius R'' of cylindrical indenter is determined from the Eq. (16) at $q = q''_{rat}$. If the difference of R' and R'' is higher than the given tolerance the calculation is repeated, since point 4.

6. Numerical example of the determination of hardening modes of the case of the gear hydro machine

The definition of rational modes of static stamping will be shown by an example of hardening of the linear site of the bottom and the lateral wall linking of case of the gear hydro machine (from the casting aluminum alloy) in the zone of high pressure taking root by the cylindrical indenter. It is required to determine the specific working loading and the radius of the cylindrical indenter (HRC_e 65).

The decision:

1. The definition of mechanical properties at tension is carried out, for example, with the help of test unit for metals

$\sigma_{0,2}$ = 260 MPa, S_b = 344 MPa, S_k = 464 MPa
$E_2 = 0.71\cdot10^5$ MPa, $\nu_2 = 0.33$

Plastic hardness of the case material is determined (according to GOST 18835) by the method of pressing of the sphere (with radius R = 5 mm and loading F = 4905 N) HD 1200 MPa, thickness of the case's wall D' = 14 mm.

In addition elastic constants for the material of strengthened part

$$k_2 = \frac{1-0.325^2}{\pi 0.71\cdot10^5} = 4.03\cdot10^{-6}\ \text{MPa}^{-1},$$

and for the cylindrical indenter are calculated ($\nu_1 = 0.3$, $E_1 = 2\cdot10^5$ MPa)

$$k_1 = \frac{1-0.3^2}{\pi 2\cdot10^5} = 1.45\cdot10^{-6}\ \text{MPa}^{-1}$$

2. The necessary value $h_{S,opt}$ of plastically deformed layer is determined by Eq. (2)

$$h_{S,opt} = 14\cdot\left(0.5-\sqrt{\frac{0.375\cdot344}{464+0.5\cdot344}}\right) = 0.70\ \text{mm}$$

3. The rational value of specific loading as the first approximation is determined by Eq. (12)

$$q'_{rat} = 1.5\cdot0.70\cdot260 = 271\ \text{N/mm}$$

$$R' = 0.669\left(1-2\cdot0.33\right)\frac{1}{0.039}\sqrt{2R'\left[0.2R'\left(\frac{271}{R'\,1200}\right)^{1.52}+2\cdot271\cdot\left(4.02\cdot10^{-6}+1.45\cdot10^{-6}\right)\right]} = 2.69\ \text{mm}.$$

4. Proceeding from the first condition of optimization, the necessary radius R' of cylindrical indenter is calculated (also as a first approximation) from the Eq. (14)

5. Using the found value of R', q''_{rat} is determined in the second approximation by Eq. (12)

$$q''_{rat} = 1.5\cdot\left(\frac{0.70}{2.44}+0.385\cdot0.29\right)\cdot260 = 154\ \text{N/mm}$$

thus K is calculated by Eq. (8)

$$K = 1+\frac{1}{0.5\,exp\left(0.0012\cdot271\right)} = 2.44$$

and the residual print width $2b$ is calculated by Eq. (5)

$$2b = 4\cdot\sqrt{271\cdot\left(4.02\cdot10^{-6}+1.45\cdot10^{-6}\right)\cdot2.69\cdot\left(1+\frac{2\cdot0.0125}{5.9\cdot10^{-3}}\right)} = 0.58\ \text{mm}$$

where $\alpha_y = 4 \cdot 271 \cdot \left(4.02 \cdot 10^{-6} + 1.45 \cdot 10^{-6}\right) = 5.9 \cdot 10^{-3}$ mm,

$$h = 0.2 \cdot 2.69 \cdot \left(\frac{271}{1200 \cdot 2.69}\right)^{1.52} = 0.0125 \text{ mm.}$$

Thus, half-width of the residual print is $b = 0.29$ mm.

6. We determine (at $q = q''_{rat}$) the specified value of radius R'' of the cylindrical indenter from the Eq. (14)

$$R' = 0.669 \cdot (1 - 2 \cdot 0.33) \frac{1}{0.039} \sqrt{2R' \left[0.2R' \left(\frac{154}{R'\,1200}\right)^{1.52} + 2 \cdot 154 \cdot \left(4.02 \cdot 10^{-6} + 1.45 \cdot 10^{-6}\right)\right]} = 1.52 \text{ mm}$$

As the difference of R' and R'' is higher than the given allowable value (in the considered example $\Delta R = 0.01$ mm is accepted) we specify $2b$ and K at $q'_{rat} = 154$ N/mm by equations (5) and (8) accordingly

$$K = 1 + \frac{1}{0.5\,exp\left(0.0012 \cdot 154\right)} = 2.66$$

$$2b = 4 \cdot \sqrt{154\left(4.02 \cdot 10^{-6} + 1.45 \cdot 10^{-6}\right) \cdot 1.53 \cdot \left(1 + \frac{2 \cdot 0.007}{3.4 \cdot 10^{-3}}\right)} =$$

$= 0.58$ mm

where $\alpha_y = 4 \cdot 154 \cdot \left(4.02 \cdot 10^{-6} + 1.45 \cdot 10^{-6}\right) = 3.4 \cdot 10^{-3}$ mm

$$h = 0.2 \cdot 1.53 \cdot \left(\frac{154}{1200 \cdot 1.53}\right)^{1.52} = 0.007 \text{ mm}$$

$$q''_{rat} = 1.5 \cdot \left(\frac{0.70}{2.66} + 0.385 \cdot 0.164\right) \cdot 260 = 127 \text{ N/mm}$$

$$R'' = 0.669 \cdot (1 - 2 \cdot 0.33) \frac{1}{0.039} \sqrt{2R'' \left[0.2R'' \left(\frac{127}{R''1200}\right)^{1.52} + 2 \cdot 127 \cdot \left(4.02 \cdot 10^{-6} + 1.45 \cdot 10^{-6}\right)\right]} = 1.25 \text{ mm.}$$

The calculation is repeated up to achievement of $R' \approx R''$ (up to a divergence in 0.001).

As a result of calculation by the offered technique it was received, that the necessary radius of cylindrical indenter $R = 1.17$ mm, rational specific loading $q_{rat} = 118$ N/mm, the depth of plastically deformed layer thus will make $h_{S,opt} = 0.70$ mm, width $2b$ of residual print – 0.25 mm.

Results of the above mentioned calculation were compared to the modes of hardening of the bottom and a lateral wall linking of the case of hydro machine, received earlier by means of experiment: radius of cylindrical indenter $R = 1.5$ mm; specific working loading $q = 150$ N/mm.

At the appointed mode of hardening by static stamping there were calculated the intensity of deformation (on Eq. 1) $\varepsilon_{i,0} = 0.024$, and the depth of plastically deformed layer (on Eq. 2) $h_S = 0.87$ mm.

Obviously, that the optimum mode of processing found from experiment is objectively not the best of all possible, and it is only one of the most rational from those which were realized in tests.

The tests [6] of cases of gear hydro machines at working pressure which pulsed up to 16 MPa, have shown, that the durability of the case after hardening by static stamping has increased in 3 times and has made over 6 thousand motor-hours.

7. Conclusions

1. A dependence for the determination of the hardened layer depth at element's surface for elements made of aluminum alloys (deformable and founding) at initially linear elasto-plastic contact is presented.

2. It is shown that the accuracy of the hardened layer depth calculation using the obtained equation is within 7% (with probability of 0.95).

3. The calculation method for the definition of optimum values of specific working loading q on cylindrical indenter and of indenter radius R at static stamping is developed. The greatest durability of the part is determined by the proposed method. This method was put into practice for the definition of hardening modes of the bottom and lateral wall linking (on a linear part) of the case of gear hydro machine, made from casting aluminum alloy.

4. The method is presented as a convenient for direct use by engineers - technologists at the definition of the modes of superficial plastic deformation of parts.

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IŠ ALIUMINIO LYDINIŲ PAGAMINTŲ KORPUSINIŲ DETALIŲ KIETINIMO YPATUMAI

R e z i u m ė

Žinomų dėsnių teisingumui įvertinti, kietinant detalę linijinių deformacijų sąveikos su apdirbimo įrankiu diapazone, darbe eksperimentiniu būdu tyrinėta sukietinto sluoksnio gylio priklausomybė nuo paviršiaus apdirbimo režimo. Pasiūlytas metodas apskaičiuoti optimaliai apkrovai, veikiančiai į kietinamąjį įrankį (plieninį cilindrinį ritinėlį) ir jo spindulį statinio apspaudimo metodu. Ši metodika taikoma iš aliuminio lydinių pagamintoms korpusinėms detalėms.

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FEATURES of HARDENING of the CASE PARTS MADE OF ALUMINIUM ALLOYS

S u m m a r y

The dependence of the hardened layer depth on the modes of superficial treatment is experimentally investigated, with the purpose of evaluation of known laws of initial linear contact of the strengthening part and the tool. The method of the definition of optimum loading on strengthening tool (the steel cylindrical roller) and its radius at static stamping is offered. The technique is examined with the reference to the case parts made of aluminum alloys.

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ОСОБЕННОСТИ УПРОЧНЕНИЯ КОРПУСНЫХ ДЕТАЛЕЙ, ИЗГОТОВЛЕННЫХ ИЗ АЛЮМИНИЕВЫХ СПЛАВОВ

Р е з ю м е

В работе экспериментально исследована зависимость глубины наклепанного слоя от режимов поверхностной обработки, с целью оценки справедливости известных закономерностей первоначально линейного контакта упрочняемой детали и инструмента. Предложен метод расчетного определения оптимальной нагрузки на упрочняющий инструмент (стальной цилиндрический ролик) и его радиус при статической чеканке. Методика рассматривается применительно к корпусным деталям, изготовленным из алюминиевых сплавов.

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