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ON THE QUESTION OF FATIGUE WEAR OF CIRCULAR DISK AT CYCLIC BENDING BY UNIFORM PRESSURE

Abstract

On the base of damage accumulation conception the wear process of elastic-plastic, linear articulated support of circular disk at bending of cyclic symmetrically changeable uniform pressure is investigated. The components and the intensity of stress are determined at any number of loading. The number of loading preceding the appearance at the points of disk and the number of loadings before the destruction of disk material are found. The corresponding graphics are determined before the beginning of the given limit of wear.

Let's consider an elastic-plastic, linear hardening articulated-supported circular disk of thickness h, radius a, which is bending by cyclic symmetrically changeable uniform pressure $\pm q$. Such multi-repeated deformation of the disk leads to the formulation of damages and as the final result to the destruction which begins from the surface layers.

As a result. As a result destructed material of the plate is isolated from the surface layers. Process of wear begins and this process runs in the direction to the centre of disk. By attaining the limit of wear, the disk becomes unfit for the used aim. Coming from the noted we'll investigate process of fatigue wear from the point of view damage accumulation conception. Noted in [6] many investigations of different authors [7-9], in which there are experimental proof of fatigue nature of wear also accompaning such approach.

Let's write out the kinetic equation describing the process of damage accumulation at a material wears in case of non-stationary loading constructed by L.Kh.Talybly [10]:

$$\Pi(n)=H(n-N'_\sigma)\left\{-\frac{N_{1\sigma}^{1+m}\left(\sigma_+^*(n),T(n)\right)}{N_{0\sigma}^{1+m}\left(\sigma_+^*(n),T(n)\right)-N_{1\sigma}^{1+m}\left(\sigma_+^*(n),T(n)\right)}+\right.$$
$$\left.+(1+m)\int_0^n\frac{(n-k)^m\,dk}{N_{0\sigma}^{1+m}\left(\sigma_+^*(k),T(k)\right)-N_{1\sigma}^{1+m}\left(\sigma_+^*(k),T(k)\right)}\right\}. \qquad (1)$$

Here noted: n - is the number of current loading; $\Pi=\Pi(x,n)$ is a scalar value which characterizes the degree of damage of material; $(x)=(x_1,x_2,x_3)$ are coordinates of body points; $H(n)$ is a unique function of Heavyside; $\sigma_+^*(n)=\left(3S_{ij}^*S_{ij}^*/2\right)^{1/2}$; $S_{ij}^*(n)=\sigma_{ij}^*(n)-\delta_{ij}\sigma_{ij}^*(n)/3$, $\sigma_{ij}^*(n)=(-1)^n\left(\sigma_{ij}(n-1)-\sigma_{ij}(n)\right)$; $\sigma_{ij}(n)$ are the given components of stress tensors at the end of the n-th loading; $N_{0\sigma}=N_{0\sigma}\left(\sigma_+^*,T\right)$, $N_{1\sigma}=N_{1\sigma}\left(\sigma_+^*,T\right)$ are experimentally determined material functions correspondingly the number of cycle before the destruction and the number of cycles before the appearing the damage in material at different, independent of n values $\sigma_+^*=\sigma_{+0}^*=const$ and $T=T_0=const$; σ_{+0}^* - is the doubled amplitude of stresses in case of loading by the rule of symmetric cycles, in stresses, m - is an experimentally determined constant of material; N'_σ - is the number of cycles subjected to determination before the beginning of damage accumulation at arbitrary $\sigma_+^*(n)$ and $T(n)$. As we see the relation (1) takes into account the history of loading and the existence of incubation number of cycles before the damages accumulation process begins is a condition of damages; $\Pi(N'_\sigma)=0$ are conditions of cyclic stability; $N(N_{*\sigma})=1$ - is unknown desired number of cycles before the destruction.

Following [10] for some materials we approximately can accept

$$\frac{N_{1\sigma}\left(\sigma_+^*,T\right)}{N_{0\sigma}\left(\sigma_+^*,T\right)} \approx A = const\,. \tag{2}$$

Let's denote that relation (2) are especially fulfilled for isothermal loading processes. Subject to (2) from (1) we have [10]:

$$\Pi(n)=\frac{H(n-N'_\sigma)}{1-A^{1+m}}\left\{-A^{1+m}+(1+m)\int_0^n\frac{(n-k)^m\,dk}{N_{0\sigma}^{1+m}(\sigma_+(k),T(k))}\right\}. \tag{3}$$

The number of cycles before the beginning of the damage accumulation process N'_σ is determined from the condition $\Pi(N'_\sigma)=0$. If we apply this condition for example to the relation (3) we'll get [10]:

$$(1+m)\int_0^{N'_\sigma}\frac{(N'_\sigma-k)^m\,dk}{N_{0\sigma}^{1+m}\left(\sigma_+^*(k),T(k)\right)}=A^{1+m}\,. \tag{4}$$

The condition (4) in [10] is called the damage condition and the cycle stability (small cyclic fatigue) is $\Pi(N_{*\sigma})=1$. If we use the relation (3) then we'll get [10]

$$(1+m)\int_0^{N_{*\sigma}}\frac{(N_{*\sigma}-k)^m\,dk}{N_{0\sigma}^{1+m}\left(\sigma_+^*(k),T(k)\right)}=1\,. \tag{5}$$

The condition [5] determine the numbers of cycles $N_{*\sigma}(x)$ at arbitrary given $\sigma_+^*(k)$ and $T(k)$. It coincides with the analogous condition got by V.V.Moskvitin in [4] at the assumption $N_{1\sigma}\equiv 0$. Let's denote some possible approximations of the functions $N_{i\sigma}=N_{i\sigma}\left(\sigma_+^*,T\right)(i=0,1)$ [10]:

$$N_{i\sigma}=N_{i\sigma s}\exp\left[\alpha_i\left(1-\frac{\sigma_+^*}{\sigma_s}\right)+b_i\left(1-\frac{T}{T_s}\right)\right]\quad(i=0,1) \tag{6}$$

or

$$N_{i\sigma}=N_{i\sigma s}\left(1-\frac{\sigma_s^*}{\sigma_+^*}\right)^{\delta}\left(\frac{T_s}{T}\right)^{\gamma}\quad(i=0,1). \tag{7}$$

In the relations (6) and (7) $\alpha_0, b_0, \alpha_1, b_1, \delta, \gamma$ are conditions, which are subjected to the extremal determination, σ_s^*- is stress, T_s - is temperature of reduction, $N_{0\sigma s}$ and $N_{1\sigma s}$ - are cycles before the destruction and before the appearance of damage in the material at $\sigma_+^*=\sigma_s^*$ and $T=T_s^*$.

The process of disk wear we'll investigate by using the above mentioned relations. At this it is necessary to determine the component of tensor stress at any n-th loading. First of all let's consider the problem on disk bending by uniform pressure q from the natural state (the loading). This problem is solved in [11] and we'll use this solution.

Let's apply the cylindrical system of coordinates (r,φ,z). The axis z we'll direct down. At this the surface $z=0$ will coincide with the middle of disk surface. As known the equilibrium of circular disk is described by the differential equation

$$\frac{dM_r}{dr}+\frac{M_r-M_\varphi}{r}=Q, \tag{8}$$

where M_r - is redial, M_φ - is tangential which are connected with the stresses by the formulas σ_r and σ_φ

$$M_r=2\int_0^{\frac{h}{2}}\sigma_r z dz\ ,\ M_\varphi=2\int_0^{\frac{h}{2}}\sigma_\varphi z dz\ ,$$

Q - is transverse force, expressed by the formula

$$Q=-\frac{1}{r}\int_0^r qrdr=-\frac{1}{2}qr, \tag{9}$$

r - is current radius of disk.

We'll consider the plane stress state of disk. We suppose the disk's material to be mechanically incompressible. In addition we have

$$\sigma_z=\sigma_{\varphi z}=\sigma_{r\varphi}=0,\ \varepsilon_{\varphi z}=\varepsilon_{r\varphi}=0,\ \varepsilon_z=-(\varepsilon_r+\varepsilon_\varphi). \tag{10}$$

Besides we omit the small components of stress and deformations

$$\sigma_{rz}\approx 0,\ \varepsilon_{rz}\approx 0, \tag{11}$$

Where above we'll denote; σ_{ij} - are components of tensor stresses, ε_{ij} - are components of tensor deformations. The elastic state of disk is determined from the relation

$$S_{ij}^{(e)}=2Ge_{ij}^{(e)}, \tag{12}$$

$$\theta=0. \tag{13}$$

Here $S_{ij}=\sigma_{ij}-\sigma\delta_{ij}$, $e_{ij}=\varepsilon_{ij}-\varepsilon\delta_{ij}$ are components of deviator of stresses and deformations, $\sigma=\sigma_{ij}\delta_{ij}/3$ is mean stress, $\varepsilon=\varepsilon_{ij}\delta_{ij}/3$ - is mean deformation, δ_{ij} - are Kroneker's symbols $\theta=3\varepsilon$ is relative change of volume, G - is a shear modulus.

We suppose that the elastic – plastic state of disk is determined from the relations of the theory of elastic-plastic deformations of A.A.Ilyushin [11] with the linear hardening

$$S_{ij}=\frac{2\sigma_+}{3\varepsilon_+}e_{ij}, \tag{14}$$

$$\sigma_+=\lambda\sigma_s+3G(1-\lambda)\varepsilon_+, \tag{15}$$

$$\theta=0. \tag{16}$$

Here in addition noted: $\sigma_+=\left(\frac{3}{2}S_{ij}S_{ij}\right)^{\frac{1}{2}}$ are intensity of stresses; $\varepsilon_+=\left(\frac{2}{3}e_{ij}e_{ij}\right)^{\frac{1}{2}}$ are intensity of deformations, λ - are coefficients; $0\le\lambda\le 1$; σ_s is a yield point on the stresses connected with the yield point on the deformations ε_s with the relation: $\sigma_s=3G\varepsilon_s$.

From the elasticity relations (12), (13) subject to (10), (11) we have

$$\sigma_\varphi^{(e)}=2G\left(2\varepsilon_\varphi^{(e)}+\varepsilon_r^{(e)}\right), \tag{17}$$

$$\sigma_r^{(e)} = 2G\left(2\varepsilon_r^{(e)} + \varepsilon_\varphi^{(e)}\right), \qquad (18)$$

From the relation of elastic – plasticity (14)-(16) subject to (10), (11) we'll get

$$\sigma_\varphi = \frac{2}{3}\frac{\sigma_+}{\varepsilon_+}\left(2\varepsilon_\varphi + \varepsilon_r\right), \qquad (19)$$

$$\sigma_r = \frac{2}{3}\frac{\sigma_+}{\varepsilon_+}\left(2\varepsilon_r + \varepsilon_\varphi\right). \qquad (20)$$

In addition between the values σ_+ and ε_+ hold the relation (15). The value ε_+ subject to (10), (11) is expressed in the next form

$$\varepsilon_+ = \frac{2}{\sqrt{3}}\left(\varepsilon_r^2 + \varepsilon_r\varepsilon_\varphi + \varepsilon_\varphi^2\right)^{\frac{1}{2}}. \qquad (21)$$

Let's use the known hypothesis of Kirkhov-Leva disk bending. In addition we can write

$$\varepsilon_r = -z\chi_r, \quad \varepsilon_\varphi = -z\chi_\varphi, \qquad (22)$$

where χ_r and χ_φ are redial and tangential curves of disks which are formulated by the deflection of the disk $w(r)$ by the next relations:

$$\chi_r = \frac{d^2 w}{dr^2}, \ \chi_\varphi = \frac{1}{r}\frac{dw}{dr}, \ \chi_r = \frac{d(r\chi_\varphi)}{dr}. \qquad (23)$$

The curves χ_r and χ_φ connected by the bending moments M_r and M_φ [11]:

$$M_r = D(1-I)\left(\chi_r + \frac{1}{2}\chi_\varphi\right), \ M_\varphi = D(1-I)\left(\chi_\varphi + \frac{1}{2}\chi_r\right), \qquad (24)$$

where $D = Gh^3/3$. Besides

$$I = \begin{cases} 0, & for \ \ \varepsilon_+\left(\frac{h}{2}\right) \le \varepsilon_s \\ \lambda\left(1 - \dfrac{3\varepsilon_s}{2\varepsilon_+\left(\frac{h}{2}\right)} + \dfrac{\varepsilon_s^3}{2\varepsilon_+^3\left(\frac{h}{2}\right)}\right), & for \ \ \varepsilon_+\left(\frac{h}{2}\right) > \varepsilon_s \end{cases}$$

Allowing for (24) in the equation of equilibrium (8) by using (9) and the last formula (23), we get the equations for the determination of χ_φ. After the determination χ_φ, the χ_r is determined according to (23) and also the deflection $w(r)$ by integrating one of the first two relations (23). In addition we are to consider the boundary conditions for articulated – supported edge:

$$w\big|_{r=a} = 0, \quad M_r\big|_{r=a} = 0.$$

At the first loading of disk by the uniform pressure q before the appearence of plastic deformations the points deflection of middle surface $(z=0)$, according to [11] will be

$$w^{(e)} = \frac{11qa^4}{64Gh^3}\left(1 - \frac{14}{11}\frac{r^2}{a^2} + \frac{3r^4}{11a^4}\right). \qquad (25)$$

Plastic deformations appears at pressure

$$q_s = \frac{16h^2\sigma_s}{21a^2}.$$

At $q > q_3$ it holds the approximate solution of A.A.Ilyushin [11]

$$w' = \frac{11a^2\varepsilon_0'}{28h}\left(1 - \frac{14}{11}\frac{r^2}{a^2} + \frac{3r^4}{11a^4}\right). \tag{26}$$

Here $\varepsilon_0' = \varepsilon_+$ when $r = 0,\ z = \dfrac{h}{2}$. For the determination of ε_0' by the q in [11] it is constructed a graphic between the values $\dfrac{\varepsilon_0'}{\varepsilon_s} \sim \dfrac{21qa^2}{16\sigma_s h^2}$. At full inclusion of elastic-plastic domain of the disk $\varepsilon_0' = 3{,}5\varepsilon_s$ when $r = 0, z = \dfrac{h}{2}$ [11]. In this case

$$q = 1{,}66\frac{h^2\sigma_s}{a^2},\quad \sigma_+^{\max} = 1{,}25\sigma_s,\quad z_s(0) = 0{,}286\frac{h}{2}, \tag{27}$$

where $z_s(r)$ is a boundary equation, which separates the domain by elastic and elastic-plastic deformations.

Using formulas (25) and (26) in (29) we determine the corresponding curves $\chi_r^{(e)}, \chi_\varphi^{(e)}, \chi_r, \chi_\varphi$ in future substituting their obtained values in (22) we find the elastic and the elastic plastic deformation

$$\varepsilon_r^{(e)} = z\frac{qa^2}{16Gh^3}\left(7 + 9\frac{r^2}{a^2}\right);\quad \varepsilon_\varphi^{(e)} = z\frac{qa^2}{16Gh^3}\left(7 + 3\frac{r^2}{a^2}\right), \tag{28}$$

$$\varepsilon_r = z\frac{\varepsilon_0'}{7h}\left(7 + 9\frac{r^2}{a^2}\right);\quad \varepsilon_\varphi = z\frac{\varepsilon_0'}{7h}\left(7 + 3\frac{r^2}{a^2}\right). \tag{29}$$

Allowing for (29) in (21) we'll determine the intensity of the deformation ε_+:

$$\varepsilon_+ = z\frac{2}{7}\frac{\varepsilon_0'}{h}\left(49 + 84\frac{r^2}{a^2} + 39\frac{r^4}{a^4}\right)^{\frac{1}{2}}. \tag{30}$$

By using the formulas (15) and (30) we find the expression for the values σ_+/ε_+:

$$\frac{\sigma_+}{\varepsilon_+} = 3G(1-\lambda) + \frac{21Gh\lambda\varepsilon_s}{2z\varepsilon_0'}\left(49 + 84\frac{r^2}{a^2} + 39\frac{r^4}{a^4}\right)^{-\frac{1}{2}} \tag{31}$$

Now let's find the elastic and the elastic-plastic stresses state of disk allowing for (28) in relations (17) and (18) we'll get

$$\sigma_\varphi^{(e)} = \frac{3qza^2}{8h^3}\left(7 + 5\frac{r^2}{a^2}\right), \tag{32}$$

$$\sigma_r^{(e)} = \frac{3qza^2}{8h^3}\left(7 + 7\frac{r^2}{a^2}\right). \tag{33}$$

Substituting of the relations (29), (31) in (19) in (19) and (20)

$$\sigma_\varphi = \left(7+5\frac{r^2}{a^2}\right)\left[\frac{6G(1-\lambda)z\varepsilon_0'}{7h}+3G\lambda\varepsilon_s\left(49+84\frac{r^2}{a^2}+39\frac{r^4}{a^4}\right)^{-\frac{1}{2}}\right], \quad (34)$$

$$\sigma_r = \left(7+7\frac{r^2}{a^2}\right)\left[\frac{6G(1-\lambda)z\varepsilon_0'}{7h}+3G\lambda\varepsilon_s\left(49+84\frac{r^2}{a^2}+39\frac{r^4}{a^4}\right)^{-\frac{1}{2}}\right]. \quad (35)$$

Thus all the unknown values at the first loading of disk by the uniform pressure q are known. Now let's consider the question on determination of stress components at symmetric cyclic q, i.e. at cyclic loading of disk by the uniform pressure $\pm q$. Let's suppose that disks material has the cyclic hardening [12]. In this case for the determination of stress components at n-th (in odd) loading we can use the V.V.Moskvinin formula [12]:

$$\sigma_{ij}^{(n)} = [\beta+(1-\beta)f(n)]\sigma_{ij} + [(1-\beta)(1-f(n))]\sigma_{ij}^{(e)}. \quad (36)$$

Here $\sigma_{ij}^{(n)}$ - are the stress components at n-th (in odd) loading: the constant β $(0\le\beta\le 1)$ and the function $f(n)$ are determined from the experiment [12]: σ_{ij} - are the stress components which appears at the first elastic-plastic loading; $\sigma_{ij}^{(e)}$ - are some imaginary stress which are determined as solution of the corresponding problem of the theory of elasticity of initial loading at $q>q_3$.

Corresponding to (32) we can write

$$\sigma_\varphi^{(n)} = \beta\sigma_\varphi + (1-\beta)\sigma_\varphi^{(e)} + (1-\beta)f(n)\left(\sigma_\varphi - \sigma_\varphi^{(e)}\right), \quad (37)$$

$$\sigma_r^{(n)} = \beta\sigma_r + (1-\beta)\sigma_r^{(e)} + (1-\beta)f(n)\left(\sigma_r - \sigma_r^{(e)}\right), \quad (38)$$

Here σ_φ and σ_r are determined by the formulas (34) and (35), $\sigma_\varphi^{(e)}$ and $\sigma_r^{(e)}$ by the (32) and (33) but addition $q>q_s$ and there is a connection between q and $\varepsilon_0' = (\varepsilon_+)_{z=-\frac{h}{2}}^{r=0}$ [11], established from the solution of the problem on elastic-plastic bending of disk at the first loading. In the formulas (37) and (38) n is a number of odd loading.

Since we consider the cyclic hardening material of the disk and symmetric cycles of loading then after the significant number cycles which hold at wear at every next cycle loading the area of loop of the hysterises becomes small and we can neglect this area. It means that at the limits of every cycle the component of stress at even numbers of looking can be accepted equal by absolute value of stresses components at corresponding odd numbers of loading.

Starting from this we accept

$$\sigma_\varphi^*(n) = 2\sigma_\varphi^{(n)},\ \sigma_r^*(n) = 2\sigma_r^{(n)}. \quad (39)$$

Now in formulas (39) n is any number of loading. The intensity of stresses $\sigma_+^* = \left(\frac{3}{2}S_{ij}^*S_{ij}^*\right)$ in this case is represented by the formula

$$\sigma_+^* = \left[\left(\sigma_r^*\right)^2 - \sigma_r^*\sigma_\varphi^* + \left(\sigma_\varphi^*\right)^2\right]^{\frac{1}{2}},$$

which allowing for (39) is represented in the next form

$$\sigma_+^* = 2\left(\sigma_{\varphi n}^2 - \sigma_{rn}\sigma_{\varphi n} + \sigma_{rn}^2\right)^{\frac{1}{2}}, \qquad (40)$$

where $\sigma_{\varphi n} = \sigma_\varphi^{(n)}$, $\sigma_{rn} = \sigma_r^{(n)}$.

We are interested in the process of wear at $r = 0$ (in the direction z) and the beginning of the process at $r = a$. Starting from this, from (32)-(35) we determine

$$\sigma_\varphi\big|_{r=0} = \sigma_r\big|_{r=0} = \frac{6G(1-\lambda)z\varepsilon_0'}{h} + 3G\lambda\varepsilon_s, \qquad (41)$$

$$\sigma_\varphi^{(e)}\big|_{r=0} = \sigma_r^{(e)}\big|_{r=0} = \frac{21qza^2}{8h^3}, \qquad (42)$$

$$\sigma_\varphi\big|_{r=a} = 0{,}86\sigma_r\big|_{r=a} = 0{,}86\left(\frac{12G(1-\lambda)z\varepsilon_0'}{h} + 3G\varepsilon_s\lambda\frac{14}{13}\right), \qquad (43)$$

$$\sigma_\varphi^{(e)}\big|_{r=a} = 0{,}86\sigma_r^{(e)}\big|_{r=a} = 0{,}86\frac{21qza^2}{4h^3}. \qquad (44)$$

The relation (41)-(44) simplify the expression (40):

$$\sigma_+^*\big|_{r=0} = 2\sigma_{\varphi n}\big|_{r=0} = 2\sigma_{rn}\big|_{r=0} = 2\left[\beta\left(\frac{6G(1-\lambda)z\varepsilon_0'}{h} + 3G\varepsilon_s\lambda\right) + \right.$$

$$\left. + (1-\beta)\frac{21qza^2}{8h^3} + (1-\beta)f(n)\left(\frac{6G(1-\lambda)z\varepsilon_0'}{h} + 3G\varepsilon_s\lambda - \frac{21qza^2}{8h^3}\right)\right], \qquad (45)$$

$$\sigma_+^*\big|_{r=a} = 1{,}876\sigma_{rn}\big|_{r=a} = 1{,}876\left[\beta\left(\frac{12G(1-\lambda)z\varepsilon_0'}{h} + \frac{14}{13}3G\varepsilon_s\lambda\right) + \right.$$

$$\left. + (1-\beta)\frac{21qza^2}{4h^3} + (1-\beta)f(n)\left(\frac{12G(1-\lambda)z\varepsilon_0'}{h} + \frac{14}{13}3G\varepsilon_s\lambda - \frac{21qza^2}{4h^3}\right)\right], \qquad (46)$$

Now it is necessary to determine the expression $\dfrac{\sigma_+^*}{\sigma_s^*}$. At this we can accept $\sigma_s^* = 2\sigma_s$. In this case from (45) and (46) we have

$$\left.\frac{\sigma_+^*}{\sigma_s^*}\right|_{r=0} = \frac{\sigma_+^*\big|_{r=0}}{2\sigma_s} = L_1 + f(n)L_2, \qquad (47)$$

$$\left.\frac{\sigma_+^*}{\sigma_s^*}\right|_{r=a} = \frac{\sigma_+^*\big|_{r=a}}{2\sigma_s} = 0{,}938\left(L_3 + f(n)L_4\right). \qquad (48)$$

Here

$$L_1 = \beta\left(\frac{6G(1-\lambda)z\varepsilon_0'}{\sigma_s h} + \lambda\right) + (1-\beta)\frac{21qza^2}{8h^3\sigma_s}, \qquad (49)$$

number of loading before the destruction of disk edges $(r = a)$ are determined, which became equal to the number of loading before destruction of the point $r = 0$, $z = 0{,}23h$ (fig.1). The weared (destructed) region of disk is shown in fig.2.

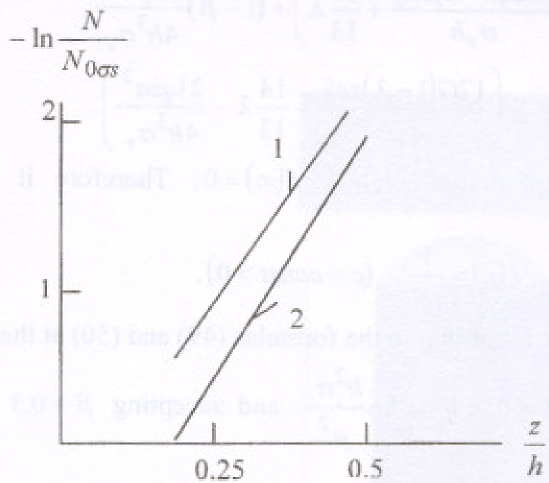

Fig.1. *The curve of damages* $(1 - N = N'_{\sigma})$ *and destruction* $(2 - N = N_{*\sigma})$ *of points of disk at* $r = 0$

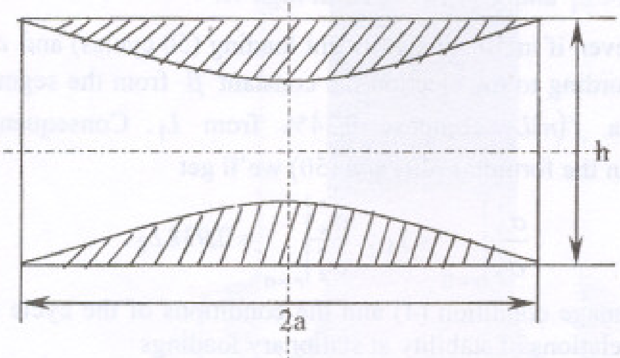

Fig.2. *The weared (destructed) region of disk*

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