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Weakening or Dispersion Hardening Assessment of the Metal Alloys in Dynamic Creep and Fatigue in Biaxial Stress States

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ABSTRACT: For the design of the construction which in the dynamical creep and fatigue work conditions knowledge of the modified Haigh's curve of the equal limiting dynamical creep strain in the dependence form σ_i^m *- stress intensity of the mean stress tensor* σ_{ij}^m *and* σ_i^a *- intensity of stress amplitud tensor* σ_{ij}^a *is wanted. A problem of the phenomenon is very complicated because the investigations results are dependent from of the: 1.material type, 2.temperature, 3.cycle numbers, 4.stress states. The several qualitative methods for the interpretation and assessment of the observed are possible, namely: metal physics, micropolar waves theory, non-potential creep theory. In this last method it is necessary applay the creep anisotropy evolution which show the dispersion hardening, neutral state or weakening,*

Introduction

The assessment hardening, weakening and damages of the metal alloys in vibrocreep and fatigue processes for by the investigators have been immensely essential tasks for several years. The mechanical creep strength theories are based on the material structure change in the process damage. Such damage theory by Kachanov (1) was presented. By this theory to the general creep equation the scalar parameter ω is ushered which is damage measure.

Nextly Rabotnov's (2) the second rank damage tensor Ω was used and the creep equation system was formulated in the form:

$$\mathbf{d} = f(\sigma, \Omega), \quad \dot{\Omega} = q(\sigma, \Omega) \tag{1}$$

where: $\mathbf{d}$ - small strain tensor, $\dot{\Omega}$ – second rank damage velocity tensor, σ - Cauchy's stress tensor.

In paper (3) Murakami and Ohno the certain application suggestion of the second rank damage tensor for the creep tubular sample creep description was given.

The sugestions of Murakami and Ohno were applied in paper (4) by Sawczuk and Litewka namely, to the damage simulation by the regular sample (with sheet alumminium) perforation in the form of system slits, which mutually parallel in each system were. The investigations of Young's modulus dependence from an angle were shown. These investigations also showed that internal damages can describe a certain second rank tensor and this was a confirmation of sugestions in paper (3). The equations were described in the form:

$$\mathbf{E} = \mathbf{E}(\mathbf{T}, \mathbf{D}), \quad \dot{\mathbf{D}} = \dot{\mathbf{D}}(\mathbf{T}, \mathbf{D}) \tag{2}$$

where: $\mathbf{E}$, $\mathbf{T}$, $\mathbf{D}$ - second rank tensors - Euler's strain, Pioli Kirchhoff's stress tensor, $\mathbf{D}$ - damage tensor. Definitively the general constitutive relation, i.e. Eq. (2) was limited by Litewka (5) to the form

$$\mathbf{E} = \mathbf{A}^{(4)}\mathbf{T} \tag{3}$$

where anisotropy tensor $\mathbf{A}^{(4)}$ is depended only from the independent damage tensor $\mathbf{D}^{(2)}$.

Except from the papers mentioned above one can still indicate on an interesting paper on the creep in multiaxial stress states by Murakami and Sauomura (6) which also the damages takes into account.

The examined papers regard for to the second rank damage tensor in the immediate load and creep conditions.

The correct description of the dynamic creep fatigue one can obtain when the rank anisotropy tensor is applied. In this paper the thesis is formulated that such possibilities give the „No-potential theory of the construction of anisotropic creep constitutive laws" by Jakowluk and Mieleszko (7) in the form:

$$\mathbf{d} = G(\sigma_{red})\mathbf{A}^{(4)}(t)\sigma \quad \text{or} \quad \mathbf{d} = G(\sigma_{red})\mathbf{A}^{(4)}(t')\sigma \tag{4}$$

where: **d** - Euler's strain velocity tensor; $G(\sigma_{red})$ - nonlinearity function, σ_{red} - reduced stress; $A^{(4)}(t')$ - fourth rank anisotropy tensor which the time process of the evolution subject; t'(0, 1) - normalized time; σ - Cauchy's tensor.

The main task of this paper is to investigate the variable of the some anisotropy tensor co-ordinates for $A^{(4)}(t')$ in the time in the cyclic load process which the hardening, weakening or failure cause.

Theoretical base description of the evolutional anisotropy changes for the in cycles variable loads

The tubular samples one can load as follows: axial force, internal pressure and torsion moment. This gives the following stress tensor co-ordinates

$$\sigma_{kl} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & - \\ \sigma_{21} & \sigma_{22} & - \\ - & - & \sigma_{33} \end{bmatrix} \tag{5}$$

The σ_{33} co-ordinates is a radial stress σ_r which generally is overlooked for the thin-walled samples. However it is equal 3-5% of the stress $\sigma_\theta = \sigma_{22}$. From here one can describe $\sigma_{33} = m\sigma_{22}$, where m - coefficient. For such approach in the investigations is possibility more of the anisotropy matrix co-ordinates A_{ijkl} applay.

It taking into account and triple the A_{ijkl} matrix symmetry, from the following equalities: $\sigma_{kl} = \sigma_{lk}$, $\varepsilon_{ij} = \varepsilon_{ji}$ and $\partial \sigma_{ij} / \partial \varepsilon_{kl} = \partial \sigma_{kl} / \partial \varepsilon_{ij}$ at that time Eq.4 one can describe in the following matrix form:

$$\begin{bmatrix} d_{11} \\ d_{22} \\ d_{33} \\ - \\ - \\ 2d_{12} \end{bmatrix} = \tilde{G}(\sigma_{red}) \begin{bmatrix} A_{1111} & A_{1122} & A_{1133} & 2A_{1123} & 2A_{1113} & 2A_{1112} \\ A_{2211} & A_{2222} & 2A_{2233} & 2A_{2223} & 2A_{2213} & 2A_{2212} \\ A_{3311} & A_{3322} & A_{3333} & 2A_{3323} & 2A_{3313} & 2A_{3312} \\ 2A_{3211} & 2A_{3222} & 2A_{3233} & 4A_{3223} & 4A_{3213} & 4A_{3212} \\ 2A_{3111} & 2A_{3122} & 2A_{3133} & 4A_{3123} & 4A_{3113} & 4A_{3112} \\ 2A_{2111} & 2A_{2122} & 2A_{2133} & 4A_{2123} & 4A_{2113} & 4A_{2112} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ m\sigma_{22} \\ - \\ - \\ \sigma_{12} \end{bmatrix} \tag{6}$$

Taking into account that $d_{13} = d_{23} = 0(\sigma_{13} = \sigma_{23} = 0)$ and also the anisotropy tensor symmetry, at that time the independent co-ordinate matrix of the tensor $\mathbf{A}^{(4)}$ will be in the form

$$A_{ijkl} = \begin{bmatrix} A_{1111} & A_{1122} & A_{1133} & - & - & 2A_{1112} \\ & A_{2222} & A_{2233} & - & - & 2A_{2212} \\ & & A_{3333} & - & - & 2A_{3112} \\ & & & - & - & - \\ & & & & - & - \\ & & & & & 4A_{2112} \end{bmatrix} \tag{7}$$

The whole matrix by Eq. (7) dividing on A_{1111} and simultaneously on this quantity multiplied the $\tilde{G}(\sigma_{red})$ one obtain, $\tilde{G}(\sigma_{red})A_{1111} = G(\sigma_{red})$. From matrix (7) we can obtain 10 anisotropy co-ordinates on the general number 21 independents.

Immediate determination of the anisotropy co-ordinates A_{ijkl} by anisotropic Eqs.(6) the co-ordinates d_{ij}, σ_{kl} and nonlinearity function $G(\sigma_{red})$ knowledge is required. This one can achive by the general functional minimization in the form

$$M(B, n, A^{(4)}) = \sum_{\{d_{ij}\}} (G_{ex} - G_t)^2 \tag{8}$$

where: G_{ex} - experimental function $G(\sigma_{red})$ values which is determined by the following equation

$$G_{(red)} = d_{ij} / \left(\sum_{kl} A_{ijkl} \sigma_{kl} \right) \qquad (9)$$

G_t - theoretical function values by $G(\sigma_{red}) = G_1[\mathbf{B}, \sigma_{red} (\mathbf{n}, \sigma)]$. The knowledge of matrix $[d_{ij}]$ the creep, vibrocreep or fatigue strain investigations are obtained. The numbers of the measured strains, as it is known, is limited. The number of the functional by Eq.(8) variables decrease if earlier the vectors **B** and **n** are pointed or tensor co-ordinates A_{ijkl}. Beyond in the investigated process the veryfication of the creep velocity curve similarity is demanded. For example, in the tension and torsion, applying, for example 1) $\kappa_1 = 2d_{12}/d_{11}$ for $\lambda_1 = \sigma_{12}/\sigma_{11} = 0.5$; 2) κ_2 for $\lambda_2 = 2$. At that time in the system $2d_{12}$ - d_{11}, by the positive veryfication two different experimental straight lines are obtained.

The paper task is to prove that in the temporal processes as the vibrocreep and fatigue the weakening, neutral or dispersion hardening processes, at the dependence from kind of steel alloy and temperature are dependent.

Anisotropic hardening description of the steel FeMnAl alloy in the creep and vibrocreep processes

For the static anisotropic creep of the steel FeMnAl alloy at the room temperature and in biaxial stress states (tension and torsion) Eq.$(4)_1$ by Jakowluk and Mieleszko (8) receivs the following system equations:

$$d_{11} = G(\sigma_{red})[\sigma_{11} + l\sigma_{12}], \qquad 2d_{12} = G(\sigma_{red})[l\sigma_{11} + k\sigma_{12}] \qquad (10)$$

where:

$$a_{1111} = 1,\ a_{1112} = ... = a_{21111} = l/2, \qquad a_{1212} = ... = a_{2121} = k/4, \qquad (11)$$

he course of the creep anisotropy curves l^c and k^c are shown in Fig.1.

Vibrocreep tests were performed also on the tubular samples on the vibratory tension and static torsion room temperature. Stress state variability of vibrocreep for 50Hz the following tensor $\sigma(t)$ co-ordinates are characterized:

$$\sigma_{11}(t) = \sigma_{11}^{m} + \sigma a \sin \omega t, \quad \sigma_{12} = \text{const}, \ \sigma_{12}/\sigma_{11}^{m} = \lambda \ \text{– stress state,} \tag{12}$$

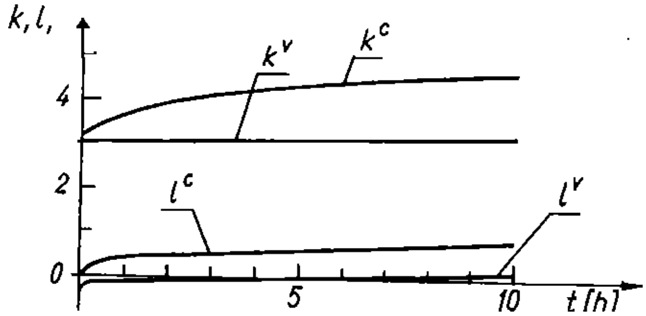

Fig.1 Creep anisotropy coefficient evolution k^c, l^c and vibrocreep anisotropy evolution k^v, l^v for steel FeMnAl alloy

but stress intensity has the form

$$\sigma_i(t) = \sigma_i^s\left(1 + A_{\sigma_i} \sin \omega t\right), \quad A_{\sigma_i} = \sigma_i^a / \sigma_i^m, \quad \sigma_i^a = \sigma_{11}^a \tag{13}$$

$$\sigma_i^s = \left[\left(\sigma_{11}^m\right)^2 + 3\sigma_{12}^2\right]^{1/2} \tag{13}$$

For the vibrocreep description by Jakowluk and Mieleszko (9) the substitute static stress tensor on the vibration direction was applied

$$d_{ij}^s = \sigma_{ij}^m + p\sigma_{ij}^a \quad \text{and} \quad \sigma_i^s = \left[\left(\sigma_{ii}^m + p\sigma_{ii}^a\right)^2 + 3\sigma_{12}^2\right]^{1/2} \tag{14}$$

In this paper statistical was shown that for the metals, for small A_{σ_i} values one can receive the mean value p = 0.5. The tests were performed by A_{σ_i} = 0.01, 0.1; 0.2 for stress intensity values σ_i = 455, 470, 486, 502 [Mpa] and λ = 0; 0.5; 0.2 and also strains were measured ε_{11}, $2\varepsilon_{12}$ but velocity were calculated d_{11} and $2d_{12}$.

In the task of the anisotropy coefficients k and l determination Eq. (10) are transformed applying

$$\kappa = A\lambda \tag{15}$$

and taking out $\kappa_i = 2d_{12}/d_{11}$ for different time t values and $\lambda = 0.5$ and 2.0 we obtain:

$$k + [2 - \kappa_1(t)]l = 2\kappa(t), \quad k + [0.5 - \kappa_2(t)]l = 0.5\kappa(t) \tag{16}$$

Solving the equation system towards k and l for the vibrocreep - k^v and l^v coefficient values for different time were obtained. The results are shown in Fig.1. From this figure results that for $t = 0$ the anisotropy coefficients $k_o \approx 3$ but $l_o \approx 0$, i.e. a material was isotropic applied for HMH criterion. This is, from here, of anisotropy in this stress state the coefficient l decides. It is interesting that vibrations nearly completely the creep anisotropic strain hardening annihilate because $l^v(t) \approx 0$.

Evolution fourth rank anisotropy tensor in the vibrocreep process to the fourth rank damage tensor

Vibrocreep of the grey cast iron Zl200 is examined. These investigations by Jakowluk and Mieleszko (10) were presented. The tests at temperature 573K and in biaxial stress states for the $\lambda = \sigma_{12}/\sigma_{11} = 0$, 1/2, 2 for the range of stress intensity $\sigma_i = 165 - 220$ MPa and for frequency 50 Hz were performed. On the tension direction very small vibration of stress amplitude coefficient $A_\sigma = \sigma_{11}^a / \sigma_{11}^m = 0.007$ and for frequency 50 Hz were applied. Practically it gave that $\sigma_{11}^m \approx \sigma_{11max}$. The experimental investigations in the diploma paper by Suchwalko (11) were performed. The general equation of the non-potential anisotropic creep theory, i.e.

$$\begin{gathered} \mathbf{d} = G(\sigma_{red}, t')A^{(4)}(t')\sigma, \quad G(\sigma_{red}, t') = B\,\sigma_{red}^n \\ \sigma_{red} = \beta\sigma_{max} + (1 - \beta)\sigma_i \text{ - Sdobyrev's criterion} \end{gathered} \tag{17}$$

which to the unsteady creep description in the first and third stages is generalized. From here for the tension with torsion of the tubular samples two equation system was obtained, i.e.

$$d_{11}(t') = G(\sigma_{red})[\sigma_{11} + l(t')\sigma_{12}],\ d_{21}(t') = G(\sigma_{red})[l(t')\sigma_{11} + k(t')\sigma_{12}] \quad (18)$$

where σ_{red} Eq. $(17)_3$. The courses of the anisotropy coefficients k(t') and l(t') are presented on Fig.2.

From Fig.2 results that material in intial state was isotropic bacause for t' = 0, the coefficient l = 0. In the vibrocreep process we have anisotropy evolution but in the third stage we see the intensive damage process and a

failure. Because the material is brittle from here the third creep stage is very short, i.e.

$$0.98 < t_3^{'} \leq 1.$$

and one can assume that the whole creep process σ_{red} = constant.

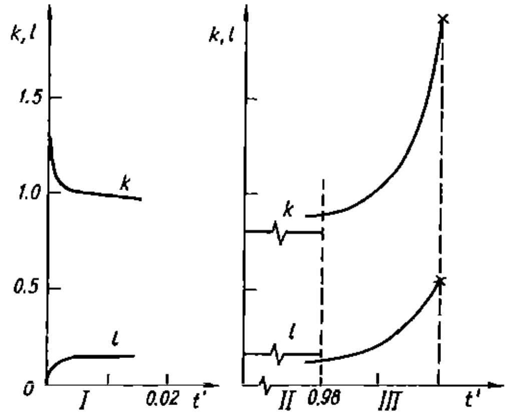

Fig.2 Anisotropy coefficients k(t') l(t') evolution in vibration in vibrocreep process tension with torsion: grey airon 200 Zl, T = 573K, A_{σ_i} = 0.007.

The failure condition one of two Eqs.(18) and strength criterion by Eq.$(17)_3$ is determined. Instead the nonlinear function $G(\sigma_{red})$ by Eq.9, from experimental data, is appointed. From the confounded equation for normalized time $t_r^{'}$, when $t_r^{'}$ = 1, one can determine the failure time t_r for the brittle material.

For the ductile material problem is complicated because at the third creep stage also the reduced stress can be of the damage anizotropy tensor function $A^{(4)} \equiv D^{(4)}$, i.e.

$$G(\sigma_{red}) = G(\sigma, t', A),\ \sigma_{red} = \sigma_{red}(\sigma, A) \quad (19)$$

Fatigue interpretation possibilities of weakening character or dispersive hardening

For the design of the constructions which in the dynamical creep and fatigue conditions work, the knowledge of the modified Haigh's curve of the equal limiting dynamical creep strain in the dependence from σ_i^m - stress intensity of the mean stress tensor σ_{ij}^m and σ_i^a - intensity stress amplitude tensor σ_{ij}^a and wanted. The problem of the phenomenon assessment is very complicated because the investigation results are dependent from of the: 1. material type, 2. temperature, 3. cycle numbers, 4. stress states. The several qualitative methods for the interpretation and assessment of the observed phenomena are possible, namely: metal physics, micropolar waves theory by Jakowluk (12).

Several authors, summing up the investigation result, two different curves types in the Haigh's system by Fig.3 were offered.

Curve I by Vitovec (13) the metal alloy curves represents which by the dispersion, at high temperatures, are strengthened but curve II, by Kennedy (14) and by Jakowluk (15) represents the curves for the pure metals and simple alloys which at lowered temperatures are weakened.

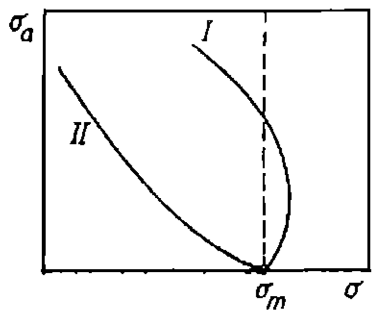

Fig.3.Possible curve types, characterized the σ_a and σ_m action, which to equal strain in creep for the estabilished time or to identical life t_r leads: I - for metal alloys dispersion hardening at the high temperatures, II - for pure metals and simple alloys at the low temperatures.

The fundamental investigations on the fatigue temperature influence of the steel S-816 alloy in the uniaxial tension by Vitovec and Lazan (16) were performed. The generalized Haigh's diagram form in the σ_m/R_m - σ_a/σ_f co-ordinates is presented on Fig.4, where R_m - steel alloy strength.

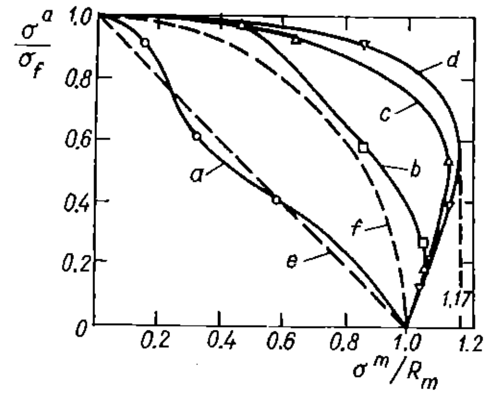

Fig.4. Haigh's diagrams in the nondimensional co-ordinates for the samples an alloy steel S-816 at the temperatures [K]: a-297, b-1009, c-1090, d-1173, e-linear failure law, f-nonlinear law in the form a circle

Presented investigation results of the alloy steel S-816 at different temperatures carry in the very important conclusions, namely: 1) The alloy steels at the elevated and high temperatures experience the considerable dispersion hardening at the vibration existence conditions. 2) For the economical regard the alloy steels it is necessary applay at the optimum work temperature.

Material fatigue in biaxial stress states

In the dynamical creep processes in complex stress states how the correct sterngth criterion for the metals one can assume the formulated criterion by Sdobyrev, i.e.

$$\sigma_{red} = \sigma_1\beta + (1-\beta)\sigma_i \qquad (20)$$

where: σ_1 - maximal principal stress, $\sigma_i = f(I_{2s})$, β - material constant for the isothermal and static processes of which the values are within the range of $0 \le \beta \le 1$, for $\beta = 1$ - britle rupture, $\beta = 0$ - ductile rupture. The generality of this criterion is due to the fact that it is function F dependent on the three invariants by Jakowluk (12), i.e.

$$F(I_{1\sigma}, I_{2s}, I_{3s}) = 0 \tag{21}$$

For the vibrocreep and fatigue conditions the Sdobyrev's criterion by Eq. (24) is modified. Namely, material constant β exceeds on the material function by Jakowluk and Plewa (18), i.e.

$$\beta = \beta(A_{\sigma_i}) \tag{22}$$

For the axial vibration and static torsion of the tubular sample for the aluminium AlMgSi alloy at the room temperature investigations by Jakowluk and Jermolaj (19) were obtained and are presented on Fig.5.

From Fig.5 results that in biaxial stress states vibration action on the aluminium alloy structure at the room temperature nearly no induces of the strain hardening.

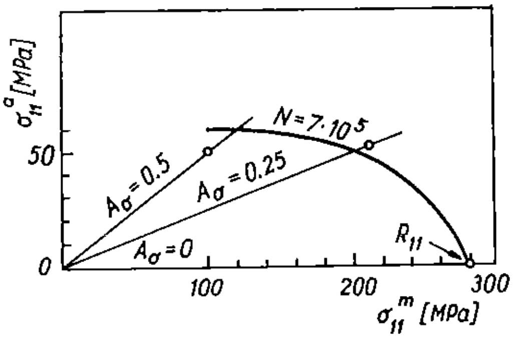

Fig.5 Haigh's curve fatigue for the aluminium AlMgSi alloy at room temperature.

The investigation results of the steel 15HM alloy for the fatigue in biaxial stress states (axial, vibration and static torsion) at 823K temperature by Jermolaj (20) are presented in Fig.6.

Instead from Fig. 6 results that in the biaxial stress states the vibration action at the elevated temperature just as uniaxial stress state induces the dispersion hardening.

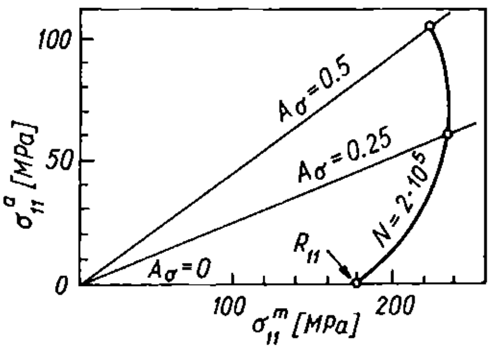

Fig.6 Haigh's curve fatigue for the steel 15HM alloy in biaxial stress states at temperature 823K

Additional information and conclusions

Very efficacions mathematical model of the hardening or weakening metallic material in the vibrocreep and fatigue is no-potential theory of the anisotropic creep by Eqs.4. In Fig.1 it was shown that the temporary anisotropy functions $k^c(t)$ and $l^c(t)$ for the tension and torsion of the tubular samples in the static creep process of the steel FeMnAl alloy at the room temperature increased. This effect is of the strain hardening results.Instead in the vibrocreep process the anisotropy functions $k^v(t)$ and $l^v(t)$ have nearly constant values. This is the equilibrium results of the strain hardening.

The vibrocreep investigations results of the grey iron Zl200 at temperature 573K in tension with torsion in the function from of the anisotropy coefficients k(t') and l(t') gave the possibility to investigate a evolution these anisotropy coefficients in the all three creep stages. For so brittle material as the grey iron, third creep stage was contained at the very narrow normalized time interval, i.e. $0.98 \leq t_3' \leq 1$, where

$$t' = t/t_r \quad (23)$$

t' - normalized time, t_r - rupture time. From here results one generality applications of the no-potential anisotropy creep theory by Eq.(4) because the anisotropy tensor $\mathbf{A}^{(4)}$ can be applied as the damage tensor $\mathbf{D}^{(4)}$.

In the biaxial stress states fatigue of the aluminium AlMgSi alloy at the room temperature (Fig.5) has weakening character likewise as uniaxial stess state.

The fatigue in biaxial stress states of the steel 15HM alloy at elewated temperature likewise as uniaxial stress states has the dispersion hardening character (Fig.6).

The dispersion hardening and weakening phenomena of the materials in the fatigue processes one can interpretate using the micropolar waves which by Parfitt and Eringen (21) were formulated. Generally one can confirm that by the micropolar waves in the investigated sample the matter transport is induced in the form: free atoms, vacancies, dislocations and other physical microobjects. In the effect these processes give in the suitable conditions the dispersion hardening or weakening of the metal alloys.

These waves action the probabillity efficacy from here results that in the classical for the vibrated sample tension we have only one longitudinal plane wave, while in the micropolar body four micropolar plane waves by Fig.7 are propagated. It is necessary still the multitude of the reflected waves.

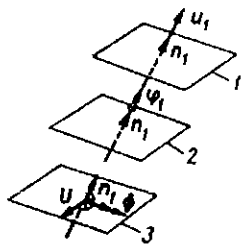

Fig.7.Displacement and wave microrotation: n_l - wave propagation direction, 1 - plane wave u_l for propagation velocity v_1, 2 -longitudinal rotation of plane wave φ_l for v_2, 3 - transverse wave U for propagation velocity v_3, microrotaion transverse wave Φ for propagation velocity v_4

Investigations of the static and dynamic micropolar strains in the several solid body their existence were confirmed. From here the indirectly existence micropolar waves by Jakowluk A. et al (22) were performed.

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