14,01

The contribution of the work of volume changes and shear deformations to the energy balance during uniaxial stretching of metals. Experiment

© Yu.V. Sud'enkov

St. Petersburg State University,
St. Petersburg, Russia

E-mail: y.sudenkov@yandex.ru

Received September 14, 2023
Revised January 9, 2024
Accepted January 15, 2024

The results of studies of the energy balance in the process of quasi-static stretching of metals are presented. The technique of simultaneous registration of heat release and control of changes in the coefficient of transverse deformations made it possible to assess the contribution of volume changes and shear deformations to the energy balance at all stages of the plastic flow of metals. The obtained results demonstrated the decisive contribution of shear deformations to the change in latent energy during the plastic flow of metals. An optical-acoustic technique for measuring the velocities of longitudinal and transverse waves excited in materials when exposed to laser pulses in the process of quasi-static stretching is presented.

Keywords: stretching, metals, heat release, control of the coefficient of transverse deformations, volume changes, shear deformations, energy balance.

DOI: 10.61011/PSS.2024.02.57929.204

1. Introduction

There is still no sufficiently rigorous theory that fully describes the laws of the processes of nonlinear deformation of materials, in particular, the plastic flow of metals. For example, the stage of transition from the elastic reaction of metals to plastic flow usually takes a rather short time period during the deformation process, but at the same time, the processes occurring on the atomic and micro scales determine the change in the internal energy of the material, the beginning of the restructuring of its structure and the nature of the process of developed plastic flow.

In this case, the influence of anharmonicity of the interatomic interaction potential already affects the elastic stage of deformation of materials and is clearly observed in change in their temperature due to the thermoelastic effect [1,2]:

$$\frac{\Delta T}{T_0} = -\gamma(1-2\nu)\varepsilon, \qquad (1)$$

where ν — Poisson's ratio, ε — deformation, $\gamma = \beta K/\rho c_\nu$ — Grüneisen parameter, β — coefficient of thermal expansion, isothermal coefficient of volume compressibility, c_ν — specific heat capacity, ρ — density.

The Grüneisen parameter, which characterizes the anharmonicity of the interatomic potential and is determined by the totality of the thermodynamic and mechanical characteristics of the state of the material and, as shown in a number of papers, is uniquely related to the Poisson's ratio [3–5]:

$$\nu = \frac{4}{3}\frac{\gamma - 0.75}{2\gamma + 1}; \quad \gamma = \frac{3}{2}\frac{(1+\nu)}{(2-3\nu)}. \qquad (2)$$

I.e. Poisson's ratio, or the coefficient of transverse deformations in the mechanics of deformable solid, is essentially an analogue of the anharmonic Grüneisen parameter, and its relation with the ratio of the modulus of rigidity (E) and shear (G) determines the behavior of materials during deformation

$$\nu_{td} = \frac{1}{2}\frac{E}{G} - 1; \quad \gamma = \frac{3}{2}\frac{E}{(10G - 3E)}. \qquad (3)$$

Moreover, the fact that the transverse deformation coefficient is determined by deformations occurring simultaneously in mutually perpendicular directions orthogonal to the direction of action of the external force, i.e., by the actions of internal forces, expresses its potential sensitivity to structural rearrangements during deformation of materials [6–8].

In the process of nonlinear deformation, at each moment of time the tested material is in a new state, which is determined by the restructuring of the structure, caused, first of all, by the action of shear stresses, as well as by the processes of interaction and formation of mesostructures characteristic of different stages of deformation [9,10]. For example, in metals, at the stage of plastic flow, up to four stages are distinguished, differing in the nature and scale of structural transformations [11,12].

Thus, measurements of the transverse deformation coefficient open up the possibility of obtaining additional information about nonlinear deformation processes, mechanisms and stages of development of plastic flow of metals.

It is known that to assess the stress-strain state and structural transformations in solids the acoustic methods are widely used, demonstrating the relationship between changes in speed and attenuation of ultrasound both with changes in stress in materials and with changes in their structure, including during the deformation of materials [13–17].

At the same time, modern methods of laser optoacoustics significantly expand the information content of acoustic diagnostics, in particular due to the possibility of simultaneous excitation of pulses of both longitudinal and transverse waves in solids. Besides, with this method the diagnostics of the state of the medium is carried out in times much shorter than the time of change in the parameters of quasi-static loading, and the energy of acoustic pulses excited by laser radiation is much less than the characteristic activation energies of plastic deformation mechanisms.

In this regard, recording the speed c_L and c_t of longitudinal and transverse waves in the sample under study allows us to use the known relationships [13] to determine the transverse deformation coefficient (ν_{td}) and in the process of nonlinear behavior of materials during deformation. In this case, the influence of changes in the thickness of the sample during deformation does not affect the accuracy of ν_{td} determination:

$$\nu_{td} = \frac{c_l^2 - 2c_{c_l}^2}{2[c_l^2 - c_{c_l}^2]}; \text{ or } \nu_{td} = \frac{t_t^2 - 2(t_l)^2}{2[t_t^2 - (t_l)^2]}, \qquad (4)$$

where t_l and t_t — propagation times of longitudinal and transverse waves in the sample.

In studies of the solids behavior under the action of external loads, analysis of the nature of changes in the energy balance during structural rearrangements at different stages of the deformation process is of significant interest.

Traditionally, the energy balance is determined by the equality of the deformation work (W) to the sum of the released heat (Q) and hidden, latent (L) energy $W = Q + L$.

However, the traditional analysis of the energy balance does not discuss the consumption of work of external forces for volume changes and for shear deformations, which can vary at different stages of deformation, and are determined by the mechanisms of structural rearrangements under the influence, first of all, of shear microstresses [7–12].

In this regard, the limitations of the traditional analysis of the energy balance of deformation of materials are obvious and further studies are required, representing an urgent problem in mechanics and physics of solid.

To date, almost all theories of plasticity are based on dividing the rigidity of the material into two deformation mechanisms, one of which determines the change in shape, and the other determines the change in volume. In this case, the responsibility for all types of nonlinear behavior of the material is determined by the mechanism of shape change, and almost all theories of plasticity and creep are based on this [18,19].

A similar model, based on two mechanisms of the state change of solids during deformation, was proposed by Kuzmenko [7,8,17], in which the work of external forces was determined by the consumptions for changing volume and changing transverse deformations, partially compensating change in volume due to the action of volume (internal) forces

$$W = W_\nu + W_s, \qquad (5)$$

where W — work of external forces, W_ν — work consumed for volume change, W_s — work consumed for shear deformation.

At the same time, in [8,17] it was shown and justified that the amount of work for volume change and shear deformations are determined by the coefficient of transverse deformations ν_{td}:

$$\frac{W_\nu}{W} = \nu_{td}(1 + 3\nu_{td} + 3\nu_{td}^2)/(1 + \nu_{td}),$$

$$\frac{W_s}{W} = (1 - 3\nu_{td}^2 - 3\nu_{td}^3)/(1 + \nu_{td}). \qquad (6)$$

The contributions of these works can be separated during analysis of the energy balance by writing the work of external forces (5) in the following form:

$$W = (Q + L)\left(\frac{W_\nu}{W} + \frac{W_s}{W}\right) = Q_\nu + L_\nu + Q_s + L_s. \qquad (7)$$

I.e. measurements of the transverse deformations and heat release during the deformation process can make it possible to obtain additional information both on changes in the energy balance and on the stages of the nonlinear deformation process, in particular, the plastic flow of metals.

2. Study methodology

For this purpose, a method was developed for simultaneous recording of heat release and change in the transverse deformation coefficient during uniaxial tension of materials.

Quasi-static stretching of standard flat samples with dimensions of the work part $50 \times 5 \times 2$ mm was carried out on a universal testing machine SHIMADZUAG-X50v at room temperature at deformation rates of 5 and 20 mm/min. The temperature change of the samples was monitored by infrared radiation recorded by ThermaCAM SC 3000 thermal imaging camera with a frequency of 50 Hz.

To determine the coefficient of transverse deformation directly during the stretching process, an optical-acoustic method was used [15], based on sample probing with short acoustic pulses excited by nanosecond laser pulses with frequency of 1 Hz. The value of the transverse deformation coefficient during stretching of the samples was determined from the relation (4).

Figure 1, a shows the measurements scheme. The laser radiation with duration $\tau_{0.5} = 10^{-8}$ s and energy $E \leq 10^{-3}$ J was delivered using an optoacoustic fiber (1) with a diameter of 0.9 mm. Under this action the pulse of both longitudinal and transverse waves is excited in the samples under study.

In order to improve the measurement accuracy of t_l and t_t the simultaneous recording of longitudinal and

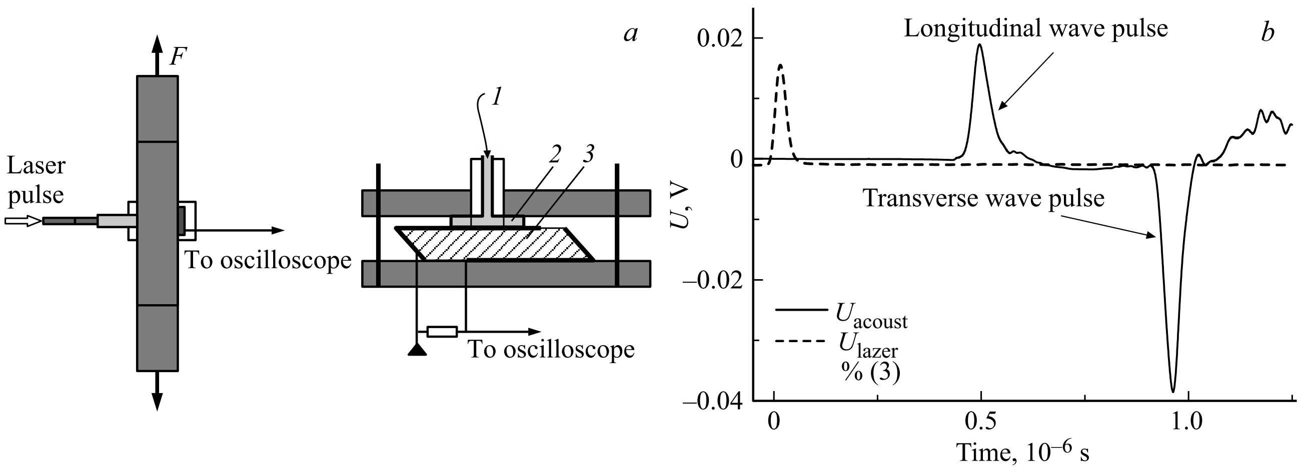

Figure 1. Measurement scheme. (*a*): *1* — optical fiber, *2* — sample, *3* — piezoelectric transducer; *b* — oscillograms of a laser pulse and typical signals from the piezoelectric transducer in steel-St3 sample.

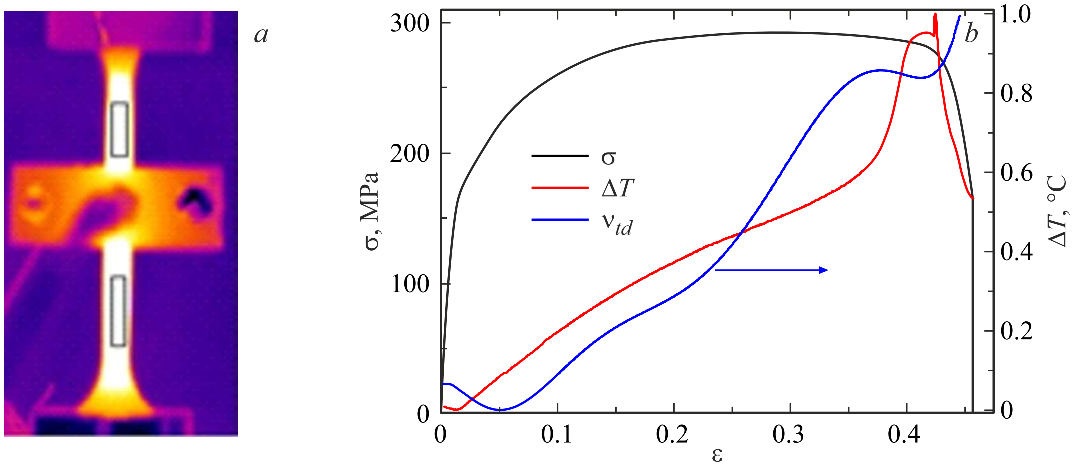

Figure 2. *a* — frame of thermal imaging and the area of temperature change recording; *b* — dependencies $\sigma(\varepsilon)$, normalized dependencies $T(\varepsilon)$ and $\nu_{td}(\varepsilon)$ in steel-St3 sample.

transverse wave pulses by one piezoceramic transducer was implemented. For this purpose, the piezoelectric plate 3 mm thick was cut from thick plane-parallel piezoceramics PZT19 at an angle $\sim 45^\circ$ to the direction of its polarization. Next, electrodes were spattered on the surface of the plate. Signals from the piezoelectric transducer (3) were recorded using Lecroy oscilloscope with $\Delta f = 600$ MHz.

This method made it possible to measure $t_l$and t_t with an error of less than $\pm 0.5\%$, and the velocities of acoustic pulses of longitudinal and transverse waves with an error of less than $\pm 1.5\%$.

Typical oscillograms of the laser pulse and the signal from the piezoelectric transducer during stretching of the steel sample are shown in Figure 1, *b*.

Figure 2, *a* shows the method of simultaneous registration of heat release and determination of the coefficient of transverse deformation and during stretching of steel sample. Rectangles mark the areas of averaging of sample temperature change. Figure 2, *b* shows the dependences $\sigma(\varepsilon)$ obtained for the steel sample and the normalized dependences $T(\varepsilon)$ and $\nu_{td}(\varepsilon)$.

3. Results and discussion

The results of simultaneous registration of changes in transverse deformation coefficients, heat release and energy balance analysis for samples of three metals — copper-M1, steel-OM, titanium-VT1 are shown in Figure 3, *b*. Solid curves in all Figures correspond to deformation rate of 5, dash-dot curves — 20 mm/min.

Figure 3, *a, b, c* shows the results of measurements of the dependences $\sigma(\varepsilon)$ and $T(\varepsilon)$ under uniaxial stretching with deformation rates of 5 and 20 mm/min. The increase in the deformation rate naturally leads to increase in heat release [20].

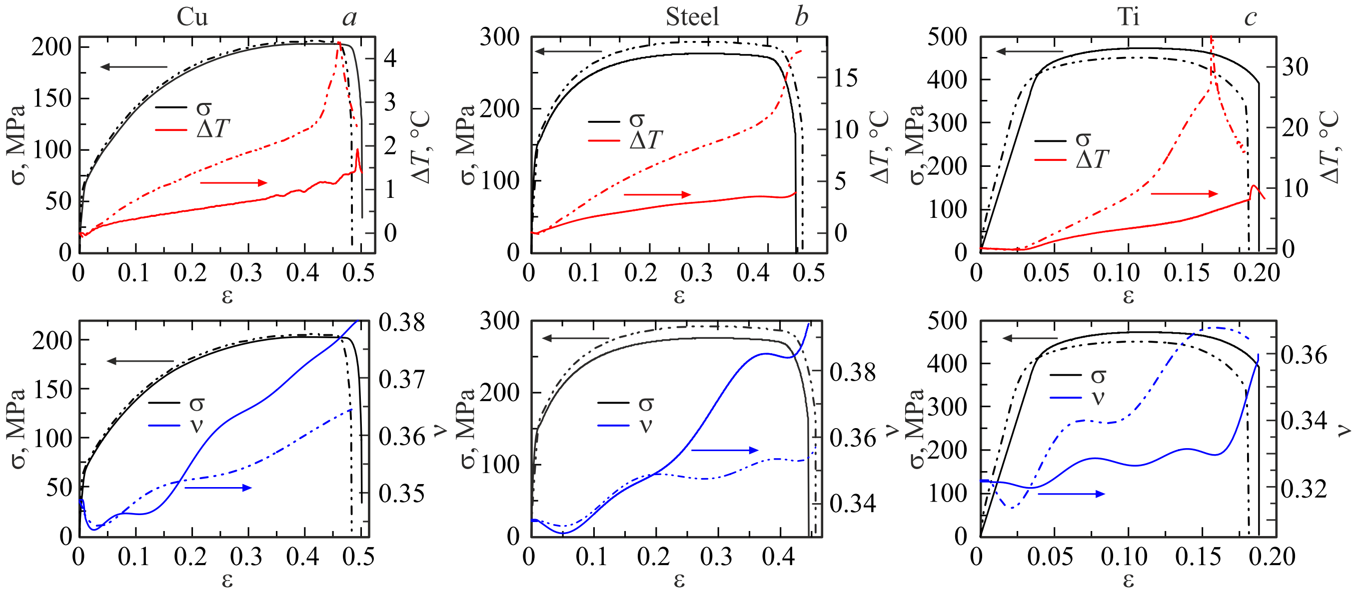

Figure 3. *a, b, c* — dependencies $\sigma(\varepsilon)$, $T(\varepsilon)$ and $\nu_{td}(\varepsilon)$ of samples of copper, steel and titanium under uniaxial stretching with deformation rates of 5 and 20 mm/min.

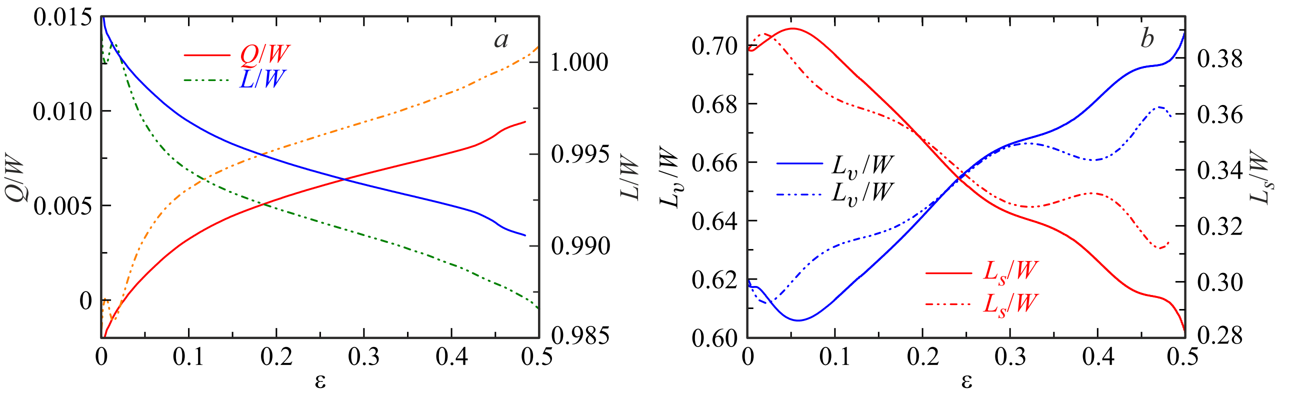

Figure 4. *a* — dependence of the heat release fraction Q/W and latent energy L/W; *b* — dependences of Lv/W and Ls/W in copper.

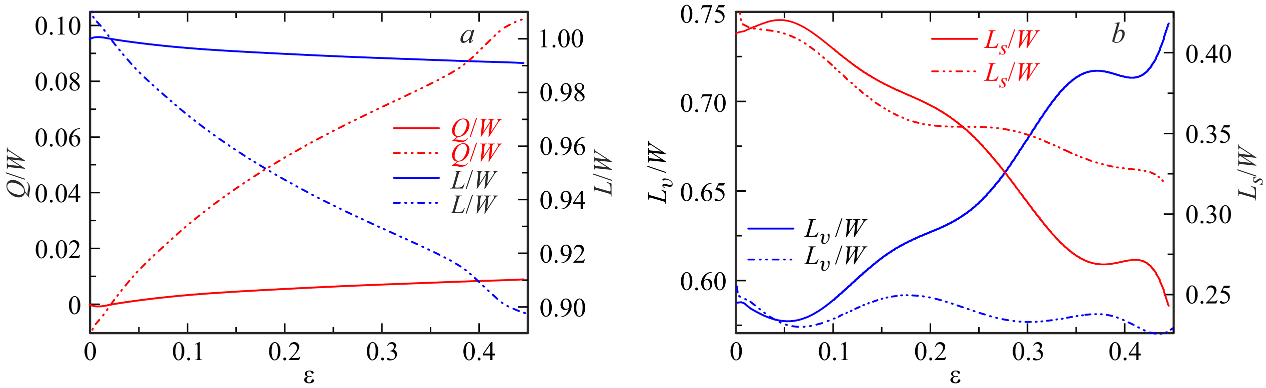

Figure 5. *a* — dependences of heat release fraction and latent energy L/W; *b* — Lv/W and Ls/W dependences in steel.

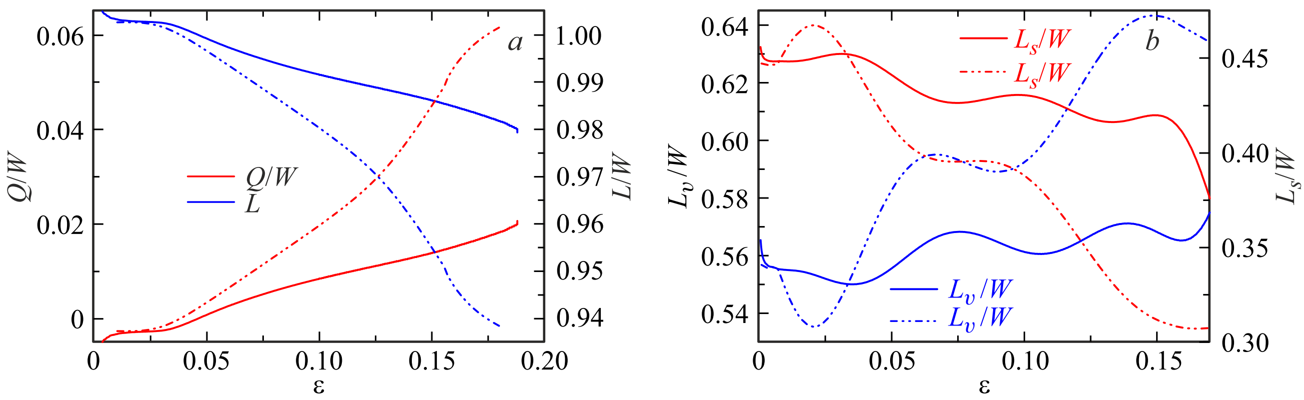

Figure 6. *a* — dependence of the heat release fraction Q/W and latent energy L/W; *b* — Lv/W and Ls/W dependences in titanium.

Figure 3, $a-c$ also shows the dependences of transverse deformation coefficients for copper, steel, and titanium samples. Curves $\nu_{td}(\varepsilon)$ are characterized by significantly non-monotonic dependences on deformation and also demonstrate a significant dependence on the deformation rate. At the same time, we note a qualitative difference in the dependence on the deformation rate for Ti samples with HCP lattice.

So, the results of simultaneous monitoring of changes in $\sigma(\varepsilon)$, $T(\varepsilon)$ and $\nu_{td}(\varepsilon)$, presented in Figure 3, can perform based on the relations (5)–(7) the analysis of the energy balance during the deformation of materials, taking into account the consumptions of work of external forces for both volume change and for shear deformations. Figure 4–6 shows the results of such analysis for the metals studied.

Figure 4–6, *a* shows the dependences of the heat release fraction and latent energy for samples of copper, steel and titanium, obtained by traditional analysis of the energy balance $(Q/W + L/W = 1)$. For all tested metals, the results of traditional analysis are characterized by rather smooth curves of heat release growth and latent energy decreasing depending on deformations, and the influence of deformation rate on these dependences is also observed.

A more informative picture is observed from the results of the energy balance analysis, taking into account the work consumptions of external forces for volume changes and shear deformations.

Figures 4, 5, 6, *b* show the dependences of the latent energy fraction due to changes in volume (Lv/W) and shear deformations (Ls/W) for the three metals studied.

There is non-monotonic nature of the change in latent energy and a qualitative difference in the change in the latent energy fraction due to changes in volume and shear deformations. With deformation increasing Lv/W increases, and Ls/W decreases.

This nature of changes in Lv/W and Ls/W dependencies is determined by the change in the transverse deformation coefficient. The competition between the processes of volume change and the development of shear deformations is caused by the restructuring of the microstructure.

Note that the decrease in the total latent energy (L/W = Lv/W + Ls/W) is due to the predominant contribution of shear deformations for all metals studied. Note also that there is significant difference in the influence of deformation rate for different metals.

The relationship between the transverse deformation coefficient and the nonlinear Grüneisen parameter (2), or rigidity moduli (3), determines the change in the ratio of central and tangential interaction forces (E/G) of structural elements, which determines the restructuring of the microstructure during deformation. At that the mutual influence of changes in the microstructure and the ratio of central and tangential forces of interaction between structural elements is obvious.

A similar relationship can be traced in the Berlin, Rotenberg model [21] when analyzing the mechanical behavior of randomly packed spheres interacting with each other by two types of forces — normal to the contact plane and tangential, proportional to the corresponding displacements from the equilibrium position — $F_n = K_n\delta_n$ and $F_t = K_t\delta_t$. It was shown that ν_{td} of such bodies depends on the ratio $\lambda = K_t/K_n$ and is equal to $\nu_{td} = 1 - \lambda/4 + \lambda$.

4. Conclusion

Thus, the presented method of simultaneous monitoring of heat release and changes in the transverse deformation coefficient makes it possible to obtain significant information based on the analysis of the energy balance during the deformation of solids.

The results obtained demonstrate the decisive contribution of shear deformations to the plastic flow of metals and also contain information about the stages of this process.

Conflict of interest

The author declares that he has no conflict of interest.

References

[1] G. Leibfried, W. Ludwig. Teoriya garmonicheskikh effektov v kristallakh. IL, M. (1963). 229 s. (in Russian).
[2] N. Ashkroft, N. Mermin. Fizika tverdogo tela. Mir, M. (1973). T. 2, 422 s. (in Russian).
[3] K.L. Leontiev. Akust. zhurn. **27**, *4*, 554 (1981). (in Russian).
[4] V.N. Belomestnykh, E.P. Tesleva. ZhTF **74**, *8*, 140 (2004). (in Russian).
[5] D.S. Sanditov. FTT **6**, 224 (2022). (in Russian).
[6] I.I. Cherkasov. ZhTF, **11** (1834) (1952). (in Russian).
[7] V.A. Kuz'menko. Razvitie predstavlenij o protsesse deformirovaniya materialov. NIITI, Kiev (1968). (in Russian)
[8] V.A. Kuz'menko. Problemy prochnosti **3**, 97 (1969). (in Russian).
[9] V.I. Trefilov, V.F. Moiseev, E.P. Pechkovsky. Deformatsionnoe uprochnenie i razrushenie polikristallicheskikh metallov. Nauk. dumka, Kiev (1987), 236 s. (in Russian).
[10] V.E. Panin. Fiz. mezomekhanika **1**, 5 (1998). (in Russian).
[11] N.A. Koneva, E.V. Kozlov. V sb.: Strukturnye urivni plasticheskoy deformatsii i razrisheniya / Pod red. akad. V.E. Panina. Nauka, Novosibirsk (1990). S. 123. (In Russian).
[12] V.E. Panin, V.A. Likhachev, Yu.V. Grinyaev. Strukturnye urovni deformatsii tverdykh tel. Mauka, Novosibirsk (1985). S. 22. (In Russian).
[13] R. Truell, C. Elbaum, A. Hikata. Ultrazvukovue metody issledovaniya plasticheskoj deformatsii Mir, M. (1969), 307 s. (in Russian)
[14] V.E. Gusev, A.A. Karabutov. Lazernaya optoakustika. Nauka, M. (1991). 304 s. (in Russian).
[15] Yu.V. Sud'enkov, I.V. Smirnov. Ustrijstvo dlya opredeleniya i kontrolya skorostej poverkhnostnykh i prodol'nykh akusticheskilh voln v materialakh pri kvazistaticheskilh i tsiklicheskikh nagruzkakh. Patent na izobretenie № 2652520 s1, 26.04.2018. Zayavka ot 28.12.2016.
[16] B.A. Zimin, I.V. Smirnov, Yu.V. Sudienkov. Dokl. RAN, **474**, *4*, 1 (2017). (in Russian).
[17] V.A. Kuzmenko. Novye skhemy deformirovaniya tverdykh tel. Nauk. Dumka, Kiev (1973). 200 s. (in Russian).
[18] W. Prager. Problemy teorii plastichnosti. Fizmatgiz, M. (1958). 136 s. (in Russian).
[19] L.M. Kachanov. Osnovy teorii plastichnosti. Nauka, M. (1969), 420 s. (in Russian).
[20] B.A. Zimin, V.E. Sventitskaya, I.V. Smirnov, Yu.V. Sudienkov. FTT **60**, *4*, 754 (2018). (in Russian).
[21] Al.Al. Berlin, L. Rotenberg, R. Basert. Vysokomolekulyar. soedineniya **T(A) 34**, 1 (1992). (in Russian).

Translated by I.Mazurov