Journal of Applied Mechanics and Technical Physics, Vol. 51, No. 4, pp. 538–545, 2010

EXPERIMENTAL STUDY OF CHANGES IN THE FLUID STRUCTURE UNDER CONSTANT SHEAR LOADING

S. V. Stebnovskii*

UDC 532.135:532.52;539.374

Experiments are performed to study the change in the fluid structure that decreases the effective viscosity of samples of a high-viscosity polar fluid (glycerin) and a polymer (Plexiglas) under shear loading. Empirical relations are proposed for estimating the behavior of viscosity decreasing in the course of loading versus time and governing parameters of the system.

Key words: *structural viscosity, high-viscosity fluid, polymer, shear loading, plastic flow, creep.*

The process of deformation under shear loading in condensed media possessing structural strength in the initial state (polar fluids, liquid-type media, solid–plastic materials) is always accompanied by changes in the medium structure. Thus, the viscosity of plastic materials decreases under explosive loading and approaches the Newtonian viscosity of a fluid material with a destroyed structure. This feature is observed during the formation of a shaped-charge jet from the metallic liner of an armor-piercing projectile and in the contact zone of plates subjected to explosive welding [1]. The structure of some solid–plastic materials can also be destroyed at the third stage of the creep process [2, 3].

In the case of shear straining of a liquid-type medium (gel), its structure is destroyed and the structural viscosity decreases to the lower "Newtonian" limit (transition to the sol state) [4]. It should be noted that this transition is not instantaneous: it takes a certain finite time period (about 10^{-3} sec).

Structural instability of a high-viscosity polar fluid (glycerin) in the regime of a steady shear flow was established in experiments [5]: for an arbitrary small shear strain rate $\dot{\varepsilon}_\tau$, there exists a time period during which periodically alternating layers of the fluid with undisturbed and destroyed structural viscosity are formed. This result is of particular interest because the Powell–Eyring formula [6] predicts the following dependence of structural viscosity of the medium μ_s on the shear strain rate $\dot{\varepsilon}_\tau$:

$$\mu_s = \mu_0 + (\mu_* - \mu_0)\,\frac{\operatorname{arcsinh}(\dot{\varepsilon}_\tau \bar{\lambda})}{\dot{\varepsilon}_\tau \bar{\lambda}}. \tag{1}$$

Here, μ_* is the initial dynamic viscosity of the medium, μ_0 is the lower value of dynamic viscosity after destruction of the medium structure, and $\bar{\lambda}$ is the time constant. The dependence of μ_s on the shear stress τ was derived in [7] in a similar manner:

$$\mu_s = \mu_0 + (\mu_* - \mu_0)\,\frac{\bar{\tau}}{\sinh\,\bar{\tau}} \tag{2}$$

($\bar{\tau} = \tau/\tau_*$, where τ_* is the yield stress of the medium under shear loading). According to Eqs. (1) and (2), any value of $\dot{\varepsilon}_\tau = \text{const}$ or $\bar{\tau} = \text{const}$ has a corresponding constant (i.e., time-independent) value of μ_s (Fig. 1), which disagrees with the experimental results [5] and specific behavior of solid–plastic media at the third stage of creep [2, 3].

*Deceased.

Lavrent'ev Institute of Hydrodynamics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090; stest@hydro.nsc.ru. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 51, No. 4, pp. 106–115, July–August, 2010. Original article submitted August 6, 2008; revision submitted August 5, 2009.

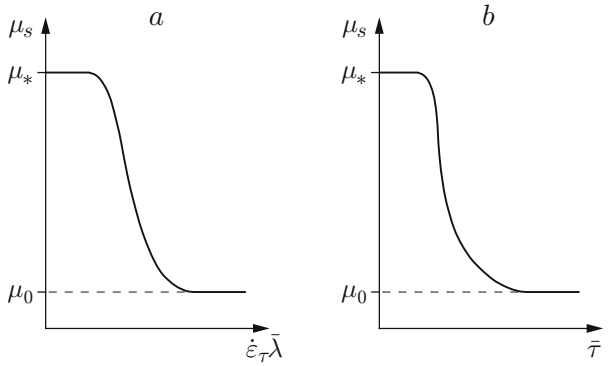

Fig. 1. Rheological curves $\mu_s(\dot\varepsilon_\tau)$ (a) and $\mu_s(\bar\tau)$ (b).

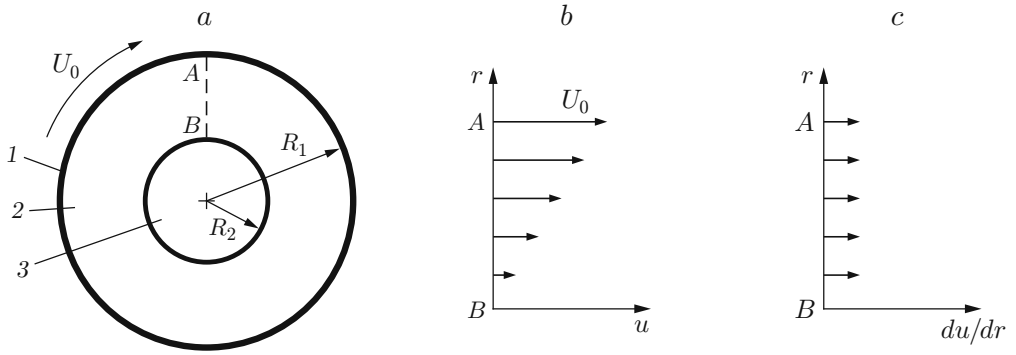

Fig. 2. Shear flow in an annular channel: (a) sketch of the setup with external rotating cylinder of radius $R_1 = 4.5$ cm (1), cylindrical layer of glycerin of thickness $H = 5$ cm (2), and motionless coaxial cylinder of radius $R_2 = 2$ cm (3); (b) diagram of velocities in the annular layer of the fluid; (c) distribution of the shear strain rate over the radius of the fluid ring.

It should also be noted that structural instability with formation of martensite lamellas (regions with a destroyed structure where the medium passes to the atom-vacant state [8]) is observed under intense shear loading of metals.

In addition, as the experiments [4, 9] showed, local destruction of the structure occurs at the contact boundary of opposing (plane–parallel and coaxial) steady flows; correspondingly, the glycerin viscosity decreases almost by an order of magnitude (at $\dot\varepsilon_\tau \geqslant 2$ sec^{-1}).

The present paper describes an experimental study of the mechanisms changing the structural viscosity of condensed media under shear loading and determining the time dependence $\mu_s = \mu_s(t)$ ($\dot\varepsilon_\tau = \text{const}$ and $\tau = \text{const}$). The experiments were performed with a high-viscosity polar fluid and a solid–plastic material.

1. Kinetics of Viscosity of Non-Newtonian Fluids. It was found [5] that a dissipative structure (regular stratification of the medium in terms of its viscosity) is formed in the glycerin sample under steady shear loading. We study the evolution of the dissipative structure and, hence, the volume-averaged structural viscosity, i.e., determine the final state of the sample structure formed under steady shear loading.

The experiments were performed in a setup whose sketch is shown in Fig. 2a (a more detailed description can be found in [5]). The system of coaxial cylinders filled with glycerin was mounted vertically. To register the processes in the glycerin layer, the system of cylinders was placed into a parallel light flux formed by an optical source of light equipped with a condenser and located below the system of cylinders. Behind the condenser, the parallel light flux illuminated the glycerin layer and was recorded by a video camera located above the system of cylinders.

The external cylinder rotates and forms the Couette flow in the fluid sample (Fig. 2b). The shear strain rate $\dot\varepsilon_\tau = du/dr$ has an identical initial value in the entire fluid volume (Fig. 2c). The value of $\dot\varepsilon_\tau$ was estimated by the formula $\dot\varepsilon_\tau = U_0/(R_1 - R_2) = \omega R_1/(R_1 - R_2)$, where ω is the angular velocity of the external cylinder. The experiments were performed with different initial values of glycerin viscosity ($\mu_* = 0.7$–2.1 Pa$\cdot$sec) in a wide range of shear strain rates ($\dot\varepsilon_\tau = 0.03$–$1.00$ sec^{-1}).

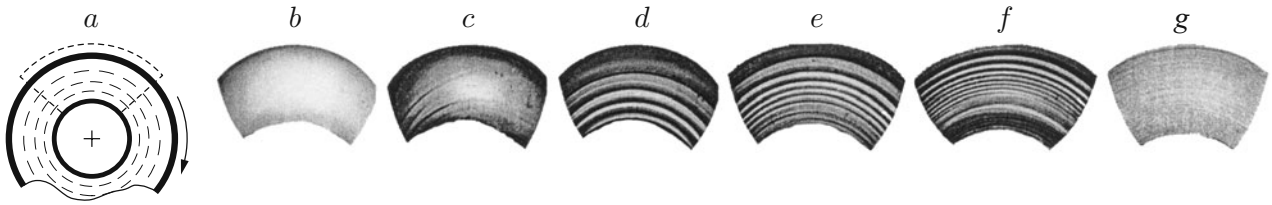

Fig. 3. Annular fluid layer (a) and formation of local zones with a destroyed structure (b–g) ($\mu_* = 2.1$ Pa·sec and $\dot{\varepsilon}_\tau = 0.25$ sec^{-1}) for $t = 0$ (b), $t^0 = 3$ sec (c), $t = 40$ sec (d), $t^+ = 100$ sec (e), $t = 220$ sec (f), and $t^* = 520$ sec (g).

The series of experiments performed provided the following data. The first local zones with a reduced value of μ_s start to form in the shear flow at a certain time t^0 (dark lines in Fig. 3c). Stratification of the entire sample is observed at a certain time t^+: zones with a destroyed structure alternate with zones that have an undisturbed structure (light lines in Fig. 3e). "Multiplication" of the zones with a destroyed structure occurs with time (Fig. 3f), i.e., the total volume of these zones increases, while the volume of the zones with an undisturbed structure decreases. Owing to interaction of layers with a destroyed structure, a volume-averaged level of viscosity μ_0 is formed by a certain time t^* (of the order of several seconds) (Fig. 3g). The process is enhanced at higher values of μ_* or $\dot{\varepsilon}_\tau$.

The effective viscosity (structural viscosity averaged over the sample volume) can be determined as

$$\bar{\mu} = \frac{1}{N}\sum_{i=1}^{N}\mu_i,$$

where μ_i is the viscosity of the ith layer and N is the time-dependent number of layers with a destroyed and non-destroyed structure. Then, the time evolution of the effective viscosity of the sample can be presented as

$$\bar{\mu}(t) \approx \begin{cases} \mu_*, & 0 \leqslant t < t^0, \\ \dfrac{1}{N}\displaystyle\sum_{i=1}^{N}\mu_i, & t^0 \leqslant t < t^*, \\ \mu_0, & t \geqslant t^*. \end{cases}$$

It is rather difficult to determine the exact values of t^0 and t^*, because their estimates depend on sensitivity of the optical tools used. In this work, however, it is not that important, because our task is to find the qualitative evolution of the medium structure in the steady shear loading mode. Thus, the process was found to include four stages: 1) nucleation of local zones with a destroyed structure during a certain time period t^0; 2) formation of a dissipative structure (regularly alternating zones with a non-destroyed and destroyed structure); 3) "multiplication" of zones with a destroyed structure in the time interval from t^0 to t^*; 4) interaction of zones with a destroyed structure and formation of the flow with smeared boundaries between the cylindrical layers stratified in terms of viscosity. As a result, the effective viscosity of the sample $\bar{\mu}$ at $t > t^*$ acquires a constant value μ_0. (Note that μ_0 is determined by the method used in [9].) The process of medium destruction is accelerated with increasing initial values of μ_* and $\dot{\varepsilon}_\tau$. For instance, at $\mu_* = 1.5$ Pa·sec and $\dot{\varepsilon}_\tau = 0.15$ sec^{-1}, we have $t^0 = 83$ sec, $t^+ = 330$ sec, and $t^* = 640$ sec; at $\mu_* = 1.68$ Pa·sec and $\dot{\varepsilon}_\tau = 0.29$ sec^{-1}, we have $t^0 = 20$ sec, $t^+ = 118$ sec, and $t^* = 300$ sec; at $\mu_* = 2.1$ Pa·sec and $\dot{\varepsilon}_\tau = 3.2$ sec^{-1}, we have $t^0 = 6$ sec, $t^+ = 82$ sec, $t^* = 210$ sec, and $\mu_0|_{t=t^*} = 0.3$ Pa·sec.

2. Destruction of the Polymer Structure. The third stage of the creep process of solid–plastic materials includes accelerated deformation of the medium [2, 3]. The reason for this phenomenon is as follows. It follows from the generalized rheological model of shear straining of condensed media [10] that the creep velocity in the case of steady creep with the shear stress τ lower than the yield stress can be estimated by the formula $\dot{\varepsilon}_c = (\eta_*^{-1} + \mu_c^{-1})\tau/2$, where η_* is the plastic viscosity of the medium and μ_c is the shear viscosity of the medium in the creep mode. As $\tau < \tau_*$, then $\eta_* \gg \mu_c$; therefore, we can write

$$\dot{\varepsilon}_c \simeq \tau/(2\mu_c). \tag{3}$$

As $\tau = \text{const}$ by definition, then the medium viscosity μ_c is constant if $\dot{\varepsilon}_c = \text{const}$. At the third stage of the creep process, the values of $\dot{\varepsilon}_c$ start to increase rapidly, which leads to an intense decrease in viscosity μ_c due to destruction of the medium structure, as is predicted by Eq. (3).

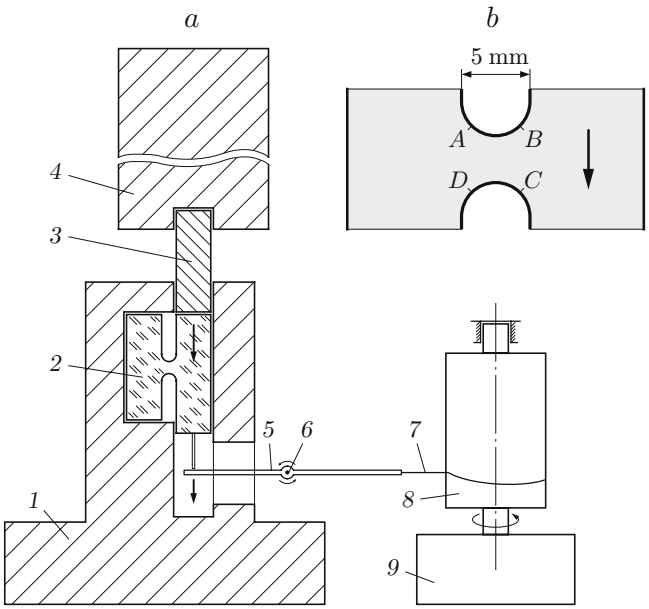

Fig. 4. Setup for studying the shear flow in the PMMA sample: (a) sketch of the setup with bed plate (1), sample loaded by the system consisting of a rod and a replaceable load (2), rod (3), replaceable load (4), yoke plate (5), yoke axis (6), needle registering sample deformation (7), rotating drum covered by paper with a wax layer (8), and clock mechanism rotating the drum (9); (b) central part of the sample before its deformation (the arrow indicates the shear straining direction).

The experiments on studying the changes in the structure and structural (plastic) viscosity of the polymer μ_c at a fixed value of τ were performed in a setup whose sketch is shown in Fig. 4a. The setup elements are a bed plate (1), a polymethylmethacrylate (PMMA) sample (2) loaded by a system consisting of a rod (3) and a replaceable load (4) inducing shear straining of the sample in the creep regime with a constant stress, a yoke plate (5) rotating around its axis (6) in the course of shear straining of the sample, a needle (7) registering sample deformation, a rotating drum (8) covered by paper with a wax layer, and a clock mechanism (9) rotating the drum. The velocity of drum rotation was at least 0.042 rounds per hour. Figure 4b shows the central part of the PMMA sample before its straining.

In the course of shear straining of the sample in the creep regime with a constant shear stress, the yoke plate rotates around its axis, and the needle draws a line on the waxed paper, which characterizes the evolution of the sample deformation in time.

The following laws of the evolution of the PMMA sample structure were found at a constant shear stress ($\tau = 396 \cdot 10^5$ Pa). Localization and growth of shear bands occur in the central part of the sample $ABCD$ (see Fig. 4b), which is further called the sample neck. Frames 1 in Figs. 5a and 5b show the sample neck covered by a network of shear bands in 336 and 504 h after the beginning of shear loading, respectively. Frames 2 and 3 in Figs. 5a and 5b show the up-scaled images of the shear bands near the upper and lower surfaces of the sample neck, respectively. Frame 1 in Fig. 5c shows the up-scaled image of the central part of the sample neck shown in frame 1 in Fig. 5b. Frames 2 and 3 in Fig. 5c show the fragments of the network of shear bands with different degrees of up-scaling.

It follows from the analysis of experimental results that systems of shear bands "growing" inward the sample neck are formed in the field of the constant shear stress, beginning from the free surfaces of the PMMA sample neck. By a certain time t_*, the third system of bands (frames 1 in Figs. 5b and 5c) is formed in the middle part of the neck; in the course of time, this third system merges with the upper and lower systems of shear bands. After that, shear straining transforms to the regime of an unbounded shear flow with an increasing shear rate: $\dot{\varepsilon}_\tau = 0.85 \cdot 10^{-5}$ sec^{-1} at $t = 505$ h, $\dot{\varepsilon}_\tau = 1.12 \cdot 10^{-5}$ sec^{-1} at $t = 506$ h, and $\dot{\varepsilon}_\tau = 2.30 \cdot 10^{-5}$ sec^{-1} at $t = 507$ h (Fig. 6), which leads to subsequent destruction of the sample. The character of the shear flow observed is consistent with the known statement, which says that forced elastic deformation can occur in a polymer in the case of long-time loading [11].

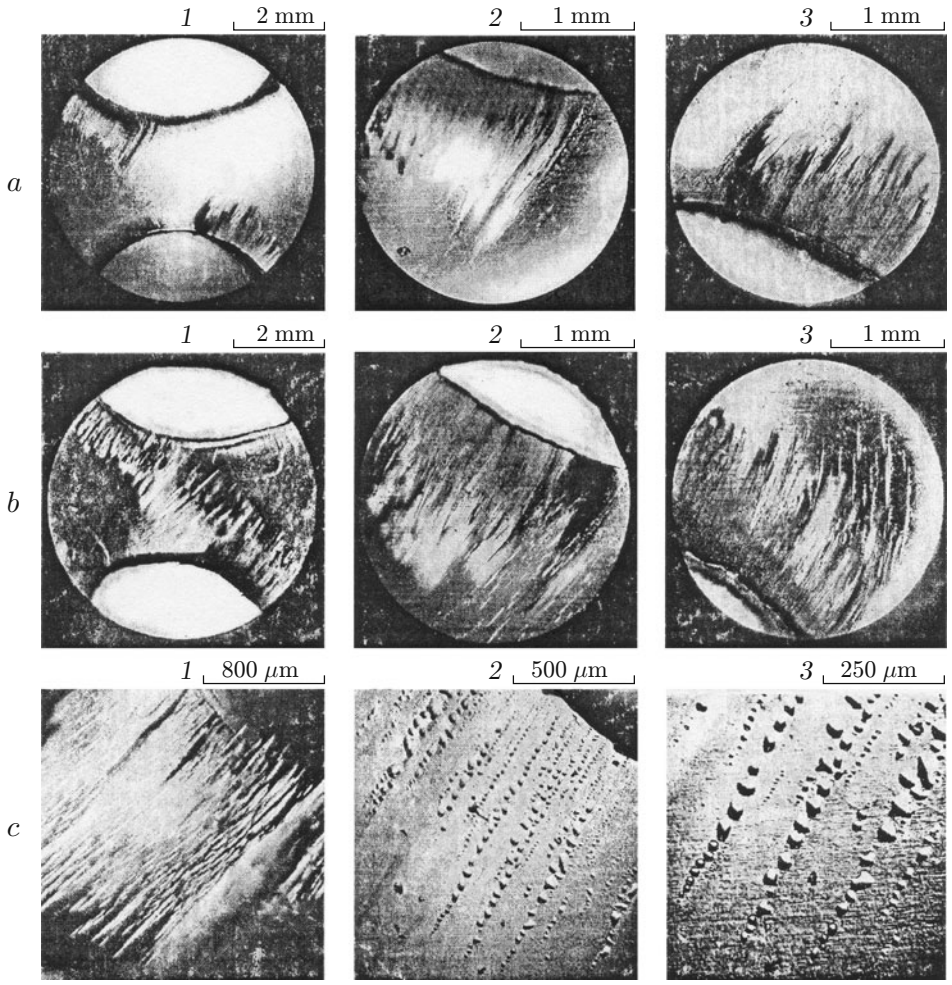

Fig. 5. Evolution of the structure of the PMMA sample neck under constant shear loading ($\tau = 396 \cdot 10^5$ Pa) after 336 (a) and 504 h (b and c).

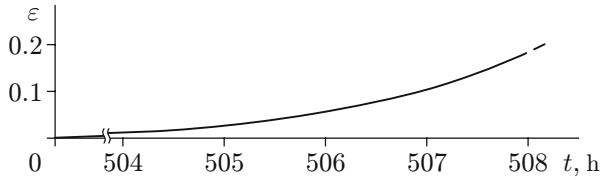

Fig. 6. Shear strain of the PMMA sample versus time under constant shear loading ($\tau = 396 \cdot 10^5$ Pa).

At this stage, the process can be modeled by a viscous flow of a rheologically equivalent high-viscosity fluid medium, i.e., it is assumed that $\tau = \bar{\mu}\dot{\varepsilon}_\tau$. As $\tau = \text{const}$ by definition and $\dot{\varepsilon}_\tau$ increases with time (see Fig. 6), $\bar{\mu} = \bar{\mu}(t)$ is a decreasing function of time, i.e., the effective viscosity of PMMA decreases at the last stage of shear straining (in the creep mode).

Note that the fine structure of the shear bands requires a more detailed study and is not considered in the present paper. It should only be noted that some shear bands form a chain of pores (frames 2 and 3 in Fig. 5c). The hairline cracks observed in experiments with polymer samples [12] transform to planes perpendicular to the sample tension direction; therefore, it does not seem reasonable to identify the shear bands in Fig. 5 with these cracks.

Thus, a decrease in the effective viscosity under constant shear loading is preceded by the development of a system of local zones with a destroyed structure in high-viscosity fluid samples and by the development of a system of shear bands in polymer samples. In other words, the formation of local zones with a destroyed structure is the governing condition of reduction of structural viscosity in both fluid and solid–plastic media.

3. Analysis and Generalization of Experimental Results. The experimental study performed showed that qualitatively identical processes (decrease in viscosity in the course of shear straining) are observed in high-viscosity polar fluids and polymers. It was found that instability of structural viscosity μ_s is spontaneously developed in the case of however slow, but sufficiently long-time shear straining in these media. This instability is not described by the Powell–Eyring [6] and Mikhailov–Lichtheim [7] models, because these models establish only the equilibrium dependences $\mu_s = \mu_s(\dot{\varepsilon}_\tau)$ and $\mu_s = \mu_s(\tau)$, respectively. In addition, according to these models, a small increase in $\dot{\varepsilon}_\tau$ or τ leads to an insignificant decrease in μ_τ, whereas μ_s monotonically decreases from the initial value μ_{s*} to a certain value μ_0 in experiments, even at constant values of $\dot{\varepsilon}_\tau$ and τ other than zero.

Based on the analysis of experimental results, the mechanism of destruction of structural viscosity can be presented as follows. First, local zones of reduced viscosity (dissipative structures) are formed under shear-induced displacements of the medium elements. In the course of time, their "multiplication" occurs: the entire medium is filled by interlayers with reduced viscosity; as a result, the sample-averaged (effective) viscosity decreases to a certain value $\mu_0 < \mu_{s*}$. The greater the values of μ_{s*}, $\dot{\varepsilon}_\tau$, and τ, the more intense this process. This scenario of the process evolution in the condensed medium satisfies the extreme principle of thermodynamics of irreversible processes [13]: the process variant that provides the maximum entropy production occurs in an open or closed system (in the case considered, entropy production is ensured by destruction of the ordered structure and, correspondingly, by the decrease in structural viscosity).

The time of the structural viscosity transition from the value μ_{s*} to the value μ_0 can be considered as the time of preparation of the medium structure to the beginning of its viscous destruction, because the medium passes to the fluid state at $\mu_s \simeq \mu_0$. Apparently, this time is similar to the lifetime of the loaded sample in the known Zhurkov's formula [2].

It does not seem possible to construct an exact analytical dependence $\mu_s(t)$ within the framework of mechanics of continuous media, because structural instability and, hence, structural viscosity instability are generated in the course of shear straining owing to fluctuations of the structural parameters at the microscopic and mesoscopic levels. Using the method of the dimension theory, however, and taking into account available experimental data, we can construct the dependence of μ_s on time in the form

$$\mu_s = \mu_0 + (\mu_{s*} - \mu_0) f(t). \tag{4}$$

Let us introduce a system of constitutive parameters μ_{s*}, μ_0, G, τ, τ_*, $\dot{\varepsilon}_\tau$, and t (G is the shear elasticity modulus and τ_* is the yield stress of the material). According to the π-theorem [14], we can form four independent combinations of these parameters:

$$(\mu_{s*}/\mu_0)^{\alpha_1}, \quad (\tau/\tau_*)^{\alpha_2}, \quad (\tau_*/G)^{\alpha_3}, \quad (\dot{\varepsilon}_\tau t)^{\alpha_4}, \qquad \alpha_i > 0, \quad i = 1, 2, 3, 4.$$

As the experimental data show that $\mu_s\Big|_{t=0} = \mu_{s*}$, and the value of μ_s with an increase in t decreases to μ_0, then we have $f\Big|_{t=0} = 1$ in Eq. (4); the greater the values of μ_{s*}, $\dot{\varepsilon}_\tau$, and τ, the faster its decrease with time. Therefore, it is reasonable to seek for the term $f(t)$ in Eq. (4) in the form

$$f(t) = \exp\Big\{ - \Big[(\mu_{s*}/\mu_0)^{\alpha_1} (\tau/\tau_*)^{\alpha_2} (\tau_*/G)^{\alpha_3} (\dot{\varepsilon}_\tau t)^{\alpha_4}\Big]\Big\}.$$

Let us denote

$$\xi = \frac{1}{(\mu_{s*}/\mu_0)^{\alpha_1/\alpha_4} (\tau/\tau_*)^{\alpha_2/\alpha_4} (\tau_*/\tau)^{\alpha_3/\alpha_4} \dot{\varepsilon}_\tau} = (\mu_0/\mu_{s*})^{\alpha_4/\alpha_1} (\tau_*/\tau)^{\alpha_4/\alpha_2} (G/\tau_*)^{\alpha_4/\alpha_3} \dot{\varepsilon}_\tau^{-1}.$$

Then, we obtain

$$f(t) = \exp\left[-(t/\xi)^{\alpha_4}\right]$$

and Eq. (4) takes the form

$$\mu_s(t) = \mu_0 + (\mu_{s*} - \mu_0) \exp\left[-(t/\xi)^{\alpha_4}\right]$$

or

$$\bar{\mu}_s(\bar{t}) = \bar{\mu}_0 + (1 - \bar{\mu}_0)\,\mathrm{e}^{-\bar{t}}, \tag{5}$$

where $\bar{\mu}_s(\bar{t}) = \mu_s/\mu_{s*}$, $\bar{\mu}_0 = \mu_0/\mu_{s*}$, and $\bar{t} = (t/\xi)^{\alpha_4}$. According to Eq. (5), at $\tau = 0$ or $\dot{\varepsilon}_\tau = 0$, we have $\bar{\mu}_s = 1$, whereas the value of $\bar{\mu}_s$ at $\tau \neq 0$ and $\dot{\varepsilon}_\tau \neq 0$ decreases monotonically down to $\bar{\mu}_0$ with increasing $\bar{t}$; the smaller the value of ξ (i.e., the greater the value of μ_{s*}, τ, or $\dot{\varepsilon}_\tau$), the faster this decrease, which agrees qualitatively with experimental results. To reach quantitative agreement between Eq. (5) and experimental results, it is necessary to determine the power index α_i depending on the structural features of the medium in each case on the basis of experimental data. Nevertheless, the value of $\bar{\mu}_s(\bar{t})$ can be roughly estimated by Eq. (5) as follows. It is known that solid–plastic materials have $\mu_0/\mu_{s*} \leqslant 10^{-6}$ (under intense shock-wave loading, the viscosity of metals decreases to values typical for viscosity of liquids [1, 2]) and $\tau_*/G \leqslant 10^{-3}$. For viscous polar fluids, we have $\mu_0/\mu_{s*} \sim 10$ [9] and $\tau_*/G \sim 1$ [15, 16]. A comparative analysis of results obtained by formula (5) and data of experiments on studying the viscosity kinetics in condensed media under shear loading shows that it is reasonable to use the following values of parameters in Eq. (5): $\alpha_1 = 10$, $\alpha_2 = 4/10$, $\alpha_3 = 1$, and $\alpha_4 = 1$. Then, Eq. (5) takes the following form:

— for solid–plastic media,

$$\xi = (\mu_0/\mu_{s*})^{0.1}(G/\tau)(\tau_*/\tau)^{2.5}\dot{\varepsilon}_\tau^{-1} \approx 251(\tau_*/\tau)^{2.5}\dot{\varepsilon}_\tau^{-1}; \tag{6}$$

— for liquids,

$$\xi = (\mu_0/\mu_{s*})^{0.1}(\tau_*/\tau)^{2.5}\dot{\varepsilon}_\tau^{-1} = 0.794(\tau_*/\tau)^{2.5}\dot{\varepsilon}_\tau^{-1}. \tag{7}$$

Let us consider several examples of using the estimate of $\bar{\mu}_s(\bar{t})$.

If the solid–plastic medium is loaded by a weak shear stress $\tau = 0.2\tau_*$ at $\dot{\varepsilon}_\tau = 0.01$ sec^{-1}, then, Eqs. (6) and (5) predict that $\xi = 389$ days, and $\bar{\mu}_s\Big|_{t=\xi} = 0.368 + 0.632\bar{\mu}_0 \approx 0.368$, i.e., the process of medium structure destruction can proceed during several hundreds of days. Under intense shock-wave loading of a metal sample, however, the experimental data [17] show that the destruction of structural viscosity and the transition of the medium to the fluid state occur during a time shorter than the pulsed loading duration (less than 10^{-6} sec). For shock-loaded aluminum, Eqs. (6) and (5) with $\dot{\varepsilon}_\tau = 10^4$ sec^{-1} and $\tau \approx 10^{10}$ Pa and with allowance that $\tau_* \approx 10^8$ Pa predict the value $\xi = 2.5 \cdot 10^{-7}$ sec. Therefore, during the time $t = 10^{-6}$ sec (i.e., $\bar{t} = 4$), the value of $\bar{\mu}_s$ decreases almost to the value of $\bar{\mu}_0$.

For liquid media, based on the experimental data cited in Sec. 1 for glycerin, we have $\mu_0 = 0.3$ Pa·sec at $\mu_{s*} = 2.1$ Pa·sec and $\dot{\varepsilon}_\tau = 0.24$ sec^{-1}. It follows from the equation $\tau = 2\mu_{s*}\dot{\varepsilon}_\tau$ that $\tau = 1.008$ Pa and (as we have $\tau_* = 1$ Pa for glycerin) $\tau_*/\tau \approx 1$. Substituting these values into Eq. (7), we obtain the estimate $\xi = 3.43$ sec. In the experiments, the local decrease in viscosity (in the dark regions in Fig. 3) becomes essential at $t = t^0 = 6$ sec, when viscosity is expected, in accordance with Eq. (5), to decrease from the value $\mu_{s*} = 2.1$ Pa·sec to the value $\mu_s = 0.87$ Pa·sec at $t = 6$ sec, i.e., by a factor of 2.4.

As it is rather difficult to determine the exact values of G and τ_* in experiments (the orders of magnitude of these quantities are usually estimated), Eqs. (6) and (7) yield only approximate estimates for ξ. These estimates, however, allow at least a qualitative analysis of the structural viscosity kinetics in condensed media (liquid, liquid-type, and solid–plastic media) under shear loading.

4. Conclusions. The experiments performed with a high-viscosity polar fluid (glycerin) and a polymer material (PMMA) show that arbitrary (however weak) shear loading of these media leads to destruction of their structural viscosity; under a long-time application of the shear load, the structural viscosity decreases to a certain limiting value. The lower the shear stress level, the longer the duration of this process. This response of the condensed medium structure to shear loading is consistent with Ziegler's principle of the maximum entropy production.

The experimental results obtained do not agree with the dependences of the structural viscosity on the shear strain rate (Powell–Eyring formula) and on the shear stress intensity (Mikhailov–Lichtheim formula). Therefore, another dependence is derived in the present work by the method of the dimension theory. At least, this dependence provides a correct qualitative description of the viscosity kinetics of condensed media under shear loading.

This work was supported by Program No. 14.3 of the Department of Power Engineering, Machine Building, Mechanics, and Control Processes of the Russian Academy of Sciences.

REFERENCES

1. M. A. Lavrent'ev and B. V. Shabat, *Hydrodynamics Problems and Their Mathematical Models* [in Russian], Nauka, Moscow (1977).
2. G. M. Bartenev and Yu. V. Zelenov, *Physics and Mechanics of Polymers* [in Russian], Vysshaya Shkola, Moscow (1983).
3. V. V. Rybin, *High Plastic Strains and Failure of Metals* [in Russian], Metallurgiya, Moscow (1986).
4. S. V. Stebnovskii, "Fragmentation of liquid and liquid-plastic media under steady strains," *J. Appl. Mech. Tech. Phys.*, **48**, No. 4, 519–524 (2007).
5. S. V. Stebnovskii, "Shear instability of the structure of media possessing viscous fluidity," *J. Appl. Mech. Tech. Phys.*, **47**, No. 2, 208–213 (2006).
6. G. Astarita and G. Marrucci, *Principles of Non-Newtonian Fluid Mechanics*, McGraw-Hill, New York (1974).
7. N. V. MIkhailov and A. M. Lichtheim, "Study of total rheological curves and formulas for calculating the effective viscosity of structured fluids with molecular-kinetic interpretation of terms involved," *Kolloid. Zh.*, **17**, No. 5, 364–378 (1955).
8. V. E. Panin, V. A. Likhachev, and Yu. V. Grinyaev, *Structural Levels of Deformation of Solids* [in Russian], Nauka, Novosibirsk (1985).
9. S. V. Stebnovskii, "Tangential discontinuities of parameters of a polar fluid under shear strain," *J. Appl. Mech. Tech. Phys.*, **46**, No. 3, 339–345 (2005).
10. S. V. Stebnovskii, "Generalized rheological model of shear deformation of structured condensed media," *J. Appl. Mech. Tech. Phys.*, **48**, No. 5, 694–700 (2007).
11. T. Alfrey, *Mechanical Behavior of High Polymers*, Wiley, New York–London (1948).
12. R. P. Kambour, "Refractive indices and compositions of crazes in several glassy polymers," *J. Polymer Sci., Part A*, **2**, 4159–4163 (1964).
13. H. Ziegler, *Some Extremum Principles in Irreversible Thermodynamics with Application to Continuum Mechanics*, Amsterdam (1963).
14. L. I. Sedov, *Mechanics of Continuous Media* [in Russian], Nauka, Moscow (1970).
15. R. A. Apakashev and V. V. Pavlov, "Determination of ultimate strength and shear modulus for water at low velocities of the flow," *Izv. Ross. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 1, 3–7 (1997).
16. S. V. Stebnovskii, "Shear strength in structured water," *Zh. Tekh. Fiz.*, **74**, No. 1, 21–23 (2004).
17. V. I. Mali, "Study of jet flows of metals under explosive loading," Candidate's Dissertation in Phys.-Math. Sci., Novosibirsk (1974).