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SIMPLE SHEAR AND TURBULENCE IN THE METALS

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The paper shows that metal in microvolumes behaves as turbulent flow during large plastic deformation under simple shear scheme. This gives a unified explanation of the following effects: saturation of strain hardening; abnormally fast diffusion in the metals under large plastic deformation; specimen lengthening in free end torsion test (known as the Swift effect); equalization of metal properties in different directions after sufficiently many passes of Twist Extrusion.

Keywords: Simple shear, Severe plastic deformation, Swift effect, Turbulence, mixing

Introduction

Simple shear test are done by twisting cylindrical specimen and are widely used for determining metal flow lines. There are two problems with transferring the results of these experiments to other types of deformation. The first problem is choosing a measure for equivalent strain that would let one combine the results of shear and tension experiments into a single «unified flow curve». There is no unequivocal solution in the literature. A short but comprehensive survey of this subject appears in [1].

The second, more serious problem was revealed by Bridgeman [2] in his high pressure experiments. He discovered that in large deformations, the stress-strain curves for tension and shear diverge sharply: the first one continually increases while the second one saturates. The same saturation effect in metal strengthening during deformation according to simple shear scheme was also observed in High Pressure Torsion (HPT) [3], Equal Channel Angular Pressing (ECAP) [4] and Twist Extrusion (TE) [5].

In this work, we give an explanation of this effect based on a hypothesis that metal in microvolumes behaves as turbulent flow [6,7]. This concept allows us to give a unified explanation of the following effects related to deformation according to simple shear scheme: saturation of strain hardening [2]; abnormally fast diffusion in the metals under large plastic deformation [5,8]; specimen lengthening in free end torsion test (known as the Swift effect) [9]; equalization of metal properties in different directions after sufficiently many passes of TE [10].

Note that we consider cold deformation, i.e., we assume that once loading stops all processes in the metal stop as well.

1. External and internal vorticity

Simple shear is defined using the following velocity field **V**:

$$V_x = \dot{\gamma} y\,,\ V_y = V_z = 0\,, \tag{1}$$

where $\dot{\gamma}$ is the shear strain rate, the axis x is the shear direction, the axis y is normal to the shear plane xz. Every material point of this field has a non-zero vorticity with absolute value $\dot{\gamma}$. A non-zero vorticity can be either due to the curvature of the point's trajectory (we called external vorticity), or due to a vortex motion inside the material point (we called internal vorticity). In order to picture internal vorticity, recall that each material point is the representative volume element (RVE) of a polycrystal, which contains a great number of structural elements [11]. There are regions of polycrystal where dislocations get plugged during plastic deformation. Such regions cause bending of the crystalline lattice. Its relaxation implies rotation, grains refinement and growth of the misorientation angle [12,13]. The transformations above can be described using a random vortex velocity field **v**, existing inside a representative volume element. As a quantitative measure of this internal vorticity we take the average value of the velocity curl inside the RVE:

$$\left\langle \left|\mathrm{curl}\mathbf{v}\right| \right\rangle = \frac{1}{S}\left| \iint\limits_S \mathrm{curl}\mathbf{v}\cdot\mathbf{n}\mathrm{d}S \right|.$$

Here angle brackets denote the average with respect to the RVE, integration is done along the cross-section of the RVE, **n** is the unit normal vector of the cross-section, and S is the area of the cross-section.

In [6,7], we establish an analogy between velocity field **v** and a velocity field of a turbulent liquid flow. The two velocity fields have the same structure since they are formed via gradual self-similar fragmentation of larger curls into increasingly smaller curls. Furthermore, both fields have a limiting curl size when fragmentation stops. In metals, this phenomenon is caused by grain boundary sliding, while in liquids it is caused by viscous friction [14].

Under simple shear, according to Eq. (1), trajectories of material points are rectilinear. This leads to two important conclusions: (a) under simple shear, vorticity is only internal; (b) to realize simple shear, a material must be able to support an internal vorticity equal to shear strain rate. We argue that under internal vorticity constraints, solid bodies cannot be deformed via simple shear. Internal vortex is replaced with external vortex. This curves the trajectory of material points. As a result, deformation becomes complex and non-homogenous. Thus we will distinguish between «simple shear» and «deformation according to the simple shear scheme».

We believe that the length changes during free end torsion test (Swift effect) [9] is caused by annealed metals not being able to realize simple shear. As a result, twisting the material produces a velocity field with an axial component, which changes the length of the specimen.

2. The main idea

We are making the following hypothesis. Under «deformation according to the simple shear scheme», metals successively go through two stages: (a) Development of Turbulence when there are constraints on the internal vorticity, $\langle|\mathrm{curl}\mathbf{v}|\rangle = k\dot{\gamma}\sqrt{2}$, $k < 1$; (b) Fully Developed Turbulence when internal vorticity is unconstrained, $\langle|\mathrm{curl}\mathbf{v}|\rangle = \dot{\gamma}$, $k = 1$.

Parameter k is a coefficient characterizing the degree of rotational freedom in the RVE. The value of k is determined by defects enabling rotations of the crystalline lattice (e.g., disclinations or non-equilibrium grain boundaries). Before grain refinement starts, there are no such defects and thus $k = 0$. Once grain refinement starts, such defects start to appear, and their number grows as strain increases. When k reaches 1, grain refinement stop, turbulence reaches the second stage, initiating simple shear.

In liquids, the fully developed turbulence stage is stationary [14]. By analogy, the velocity field of simple shear Eq. (1) and the random vortex velocity field $\mathbf{v}$ are independent of strain during this stage, where strain acts as an analog of time. This means that under constant axial pressure P, metals do not harden under simple shear, since flow stress should also be independent of strain [6].

Strain rate hardening is possible, as in viscous liquid. Moreover, if there is no strain rate hardening, the material loses its stability under simple shear, and the deformation gets localized in a thin layer [15].

The hypothesis about the two stages of deformation naturally explain results of classical experiments of Henri Tresca about hole punching [16]. The first stage corresponds to the hardening phase, while the second stage – to the liquid-like flow of metals without strain hardening. The fate of the two stages discovered by Tresca about 150 years ago turned out to be very different. The first stage is scrupulously studied to this day, while the second stage was immediately overlooked and was rediscovered only relatively recently, when studying severe plastic deformation (SPD) processes.

3. The two stages of deformation under the simple shear scheme

Strain hardening was investigated for different loading processes. Paul Ludvik was the first to propose and experimentally justify a hypothesis about the equivalence of hardening via pure and simple shear. This is how the notion of equivalent strain came into existence. We give a different explanation for the experimental results observed by Henri Tresca and Paul Ludvik. When deforming a metal specimen according to the simple shear scheme, there are two consecutive stages:

(a) a complex, inhomogeneous strained state that is not simple shear, and (b) simple shear. Stage (a) exists due to constraints on internal vorticity. A given total curl is composed of internal vorticity plus external vorticity, which curves the trajectory of material points making deformation complex and non-uniform. These ideas explain the emergence of macroswirls during the early stages of HPT, an interesting effect recently observed in [17]. Deformation during stage (a) creates additional degrees of rotational freedom, causing a gradual transition from pure to simple shear. This explanation is in agreement with the experiments in [17], which show that as the number of HPT revolutions increases, macroswirls gradually disappear and a uniform simple shear strain pattern settles throughout the disk.

The appearance of this «gradually disappearing» pure shear is mistakenly taken as experimental evidence that simple and pure shear affect metals in the same way. In fact, they do not. Therefore, such notions as «single stress-strain curve» and «the equivalent strain» make sense only when strain is relatively small. Since the seeming equivalence of different loading schemes is explained by the gradually disappearing pure shear, a good candidate for the role of equivalent strain during stage (a) are Eichinger's relations based on nonlinear mechanics [1]. They take into account the lengthening and rotations of material fibers. When the shear strain is in the range $0 \le \gamma \le 2$, we can substitute Eichinger's relations for $\varepsilon = \gamma/\sqrt{3}$, obtained via integrating strain rate $\dot{\gamma}/\sqrt{3}$ over time. Since the obtained results are very similar, this relation can also be used to compute the equivalent strain in this interval. During simple shear (b), its strain γ is analogous to time in the theory of turbulence in liquids.

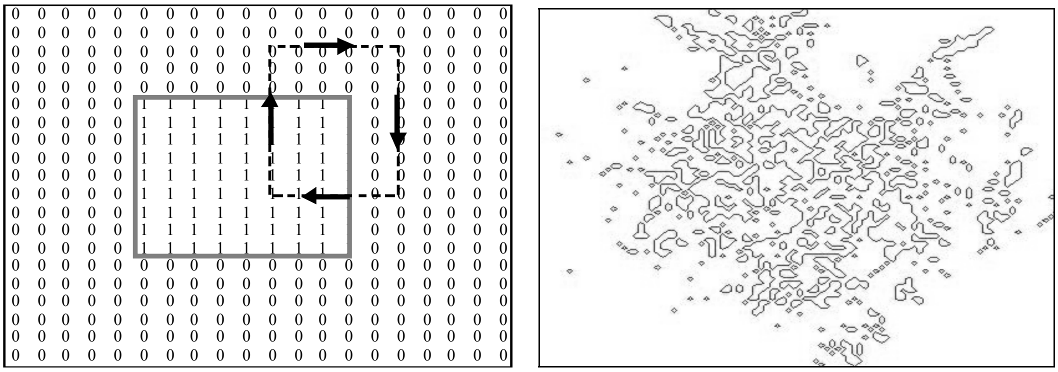
4. Deformation-induced intermixing

Strong evidence in support of the analogy is the deformation-induced intermixing of different phases and inclusions [5,8]. This effect is one of the most important manifestations of a turbulent flow and is explained by active mixing [14]. We hypothesize that it is turbulent motion, rather than a large increase in the diffusion coefficient, that causes rapid mixing during large plastic deformation.

We propose a simple computer model for investigating turbulent mixing. Suppose that we have a polycrystal with an inclusion. We will represent the polycrystal by a matrix of zeros, with the inclusion corresponding to the set of ones in the matrix (Fig. 1,*a*). Turbulent velocity field is represented as a sequence of random curls superimposed on this figure. Each curl rotates the region under it by a random angle. The Fig. 1,*b* shows how the matrix looks after 100 steps. It's easy to see that such motion mixes the material quite rapidly.

5. Several implications of the proposed model related to SPD processes

Let's analyze several implications of the proposed model related to SPD processes based on simple shear (HPT, ECAP, TE). It's well known that strain hardening has a limit in these processes. Here is why. Deformation according to the



a *b*

Fig. 1. A two-dimensional model for investigating turbulent mixing in the metals: *a* – polycrystal with an inclusion (shown as a block of 1s) and a curl (the boundary of a curl shown as dashed line with arrows); *b* – inclusion after 100 successive curls

simple shear scheme gradually creates a turbulent motion inside the RVE. Rotational freedom increases and the material gradually transitions from the first stage to the stage of Fully Developed Turbulence. The deformation gradually transforms into simple shear, under which there is no strain hardening.

If the answer is correct then the ultrafine grained (UFG) materials obtained with SPD processes should showcase two interesting effects.

Effect 1: Materials with a structure corresponding to the Fully Developed Turbulence stage must be isotropic.

It has been convincingly shown that the velocity field of the Fully Developed Turbulence stage must be locally isotropic [12]. If the proposed analogy is valid, metals under SPD will eventually become isotropic (under very large strain). We noted the isotropy tendencies on Al in [10]. Fig. 2 shows how the hardness of CP titanium specimen in two orthogonal directions experimentally depends on number of TE passes. Fig. 2 shows the flattening of hardness in the two directions, strongly supporting the hypothesis we made above.

Effect 2: The Swift effect should disappear in UFG materials

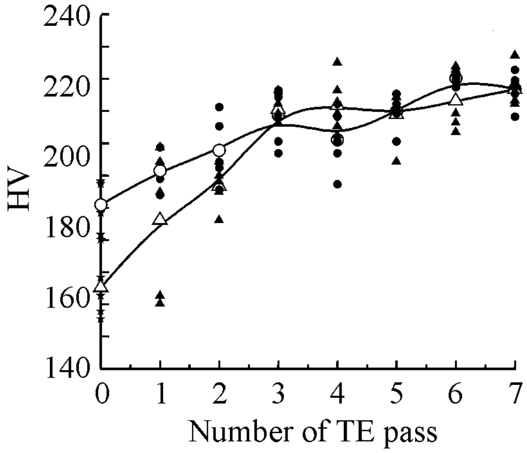
Indeed, by gaining a UFG structure via deformation according to the simple shear scheme, metals transition into the stage of Fully Developed Turbulence. Rotations are localized inside the material points, streamlines straighten during free end torsion test, and the swift effect should disappear.

Fig. 3 shows free end torsion test results for Al alloy specimen after two passes of twist extrusion. As we can see, the increase in gauge length ΔL is much weaker here than in control, annealed specimen.

The arguments above lead to the following conclusion.

Conclusion

Due to constraints on internal vorticity, a complex stress-strain state is realized in the specimen volume during early stages of deformation according to the simple shear scheme; this is not simple shear. A given total curl is composed of internal



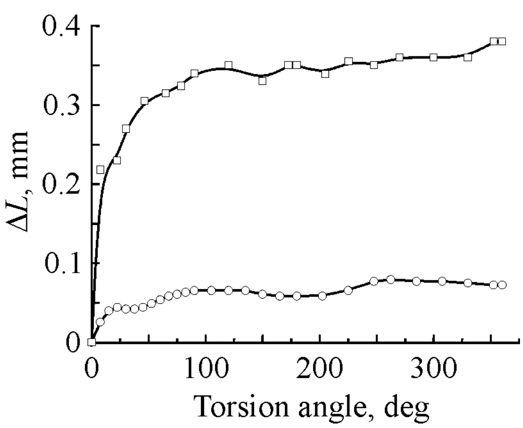


Fig. 2. A hardness of CP titanium specimen in two orthogonal directions depends on number of TE passes: ★ – initial state, ● – axis direction, ▲ – cross-section direction. Twist extrusion temperature – 100°C

Fig. 3. Free end torsion test results for Al–3 wt.% Mg–0.3 wt.% Sc alloy: –□– – initial, –○– – after TE. Twist extrusion temperature – 100°C. Gauge length – 38 mm, diameter – 5 mm

vorticity plus external vorticity, which curves the trajectory of material points making deformation complex and non-uniform. Increasing strain when deforming according to the simple shear scheme creates new degrees of rotational freedom. This creates a flow in the material, a process similar to the development of turbulence in liquids. When strain is sufficiently large, constraints on internal vorticity disappear, leading to simple shear and the formation of a stationary UFG structure. Deformation hardening disappears, and the movement of metal in the RVE becomes analogous to fully developed turbulence. UFG structures thus represent «turbulence snapshots» of solid bodies. A turbulent motion can quickly transfer a substance inside a solid body, much more efficiently than diffusion. This is of both practical and theoretical interest.

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ПРОСТИЙ ЗСУВ ТА ТУРБУЛЕНТНІСТЬ В МЕТАЛАХ

Висунуто гіпотезу про вихрову течію металів при великій пластичній деформації за схемою простого зсуву. На її основі з єдиної точки зору подано трактування наступних ефектів: межі деформаційного зміцнення в процесах інтенсивної пластичної деформації; так званої аномально швидкої дифузії при пластичній деформації; подовження зразків при крученні з вільними кінцями (Swift effect); вирівнювання властивостей металів за різними напрямками при великій кількості проходів методом гвинтової екструзії. Наведено результати експериментів, що свідчать на користь висунутій гіпотезі.

Ключові слова: простий зсув, інтенсивна пластична деформація, свіфт-ефект, турбулентність, перемішування

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ПРОСТОЙ СДВИГ И ТУРБУЛЕНТНОСТЬ В МЕТАЛЛАХ

Изложена гипотеза о вихревом течении металлов при большой пластической деформации по схеме простого сдвига. На ее основе с единой точки зрения дана трактовка следующих эффектов: предела деформационного упрочнения в процессах интенсивной пластической деформации; так называемой аномально быстрой диффузии в пластически деформируемых металлах; удлинения образцов при кручении со свободными концами (Swift effect); выравнивания свойств металлов по различным направлениям при большом числе проходов методом винтовой экструзии. Приведены результаты экспериментов, свидетельствующие в пользу выдвинутой гипотезы.

Ключевые слова: простой сдвиг, интенсивная пластическая деформация, свифт-эффект, турбулентность, перемешивание