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FLOW WEAR BY SHEAR INSTABILITY IN SLIDING

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ABSTRACT: Inhomogeneous character of deformation in subsurface layers of metals in sliding resulted in generation of a nanocrystalline layer. Specificity of its deformation behavior is a hydrodynamic flow pattern developing due to shear instability under conditions of thermal softening. Macroscopic analysis of plastic deformation carried out on the assumption that deformation behavior of the nanocrystalline subsurface layer is similar to that of the parallel-plane viscous Newtonian flow. It was shown that velocity tangential discontinuity surfaces may exist inside the deforming subsurface layer. These surfaces are particular cases of Helmholtz instability and may serve as potential sites where turbulences may nucleate.

KEYWORDS: shear instability, nanocrystalline layer, sliding, wear

INTRODUCTION

Now there is an interest in studying high-strain deformation behavior of nanocrystalline materials. The well-known fact is that inhomogeneous deformation in subsurface layers of metals in high-load sliding results in generation and flow of a nanocrystalline layer [1]. Specificity of its deformation behavior is a hydrodynamic flow pattern developing due to shear instability under conditions of thermal softening. The nature of shear instability here is a crossover from common shear deformation mode to the grain rotation governed either by grain boundary slipping mechanism (GBS) or rotational recrystallization mechanism [2] or disclination mechanism [3] under condition of submicron size grain structure formation and dynamic recrystallization. All these proposed deformation mechanisms might be discussed in studying deformation in nanocrystalline materials. However, GBS is the most studied and well-documented mechanism, which may serve a basis for analyzing the shear instability. Phenomenon of the shear instability in sliding is considered as a product of deep structure modification, which is a common finding in metals subjected to high strain rate impact test when adiabatic shear bands are generated [4].

Shear instability of a special type described as a Kelvin-Helmholtz instability is observed when metal (copper, beryllium or aluminum) plates collide each other in a glancing manner at 2 to 8 mm/μs velocity and small angle [5, 6]. Wave-like patterns or eddies are often found at the interface between the plates and are inherent in the said instability. Generation of this pattern may be suppressed by depositing either galvanic or electron beam coatings on the surface of samples. Such an effect of stabilization is explained by suppression of shear band generation due to refining source metal grains [6]. Judging by this explanation we may suggest that the developments of shear instability and shear bands are interrelated.

It is reported [7] that generation of eddy-like structures during high velocity impact might be by strain localization zones formed at the previous deformation stages. Once generated these zones become then involved in a vortex-like flow [7]. In our opinion these zones are the results of shear instability like those observed in impact welding, i.e. under high-velocity impact shear deformation.

Eddy-like structures of another nature may be found on the worn surfaces of soft Al–Sn and Cu–Pb alloys after testing at low sliding speeds [8]. It was suggested [8] that they might nucleate and grow under thermodynamic instability conditions with their axes being parallel to the sliding direction. However, the most feasible mechanism for formation of these structures may be mechanical mixing as follows from pioneering works of D.A. Rigney.

Dynamic high-speed sliding of aluminum/steel pair was reported [9]. It was shown that both eddy-like flow and intermixing occurred at the worn surfaces and resulted in formation of a mechanically mixed nanocrystalline layer (MML).

The objective of this work is to estimate macroscopic conditions for generation of the eddy-like flow instability in sliding on the basis of hydrodynamic approach including previously obtained both experimental and numerical simulation results.

EXPERIMENTAL CONDITIONS

Modern literature sources offer models for gradual formation of nanocrystalline layer in sliding test [9]. These models are based traditionally either on deformation rate or wear debris intermixing within the contact zone.

However, the nanocrystalline layer structure is very much alike the structure of adiabatic shear bands obtained in explosion loading [10]. It is possible with the tribological experiment to simulate conditions close to both approaches depending on the sliding speed and the size of a real contact area. In connection with this, we carried out tribological experiments under conditions when friction coefficient changed sharply due to adhesive interaction between the samples' surfaces'.

Such an approach allowed obtaining fast changes in the contact geometry and thus provoked the occurrence of shear instability. Preliminary experiments allowed us to determine needed test regimes and sample dimensions.

Samples in the form of ∅5 mm and 20 mm length pins were cut off the ∅5 mm commercial copper rods using a lathe tool. End surfaces were ground manually and gently to remove lathe grooves and then used in wear test. After testing, the sample was fixed inside a steel nut using Wood's metal. The abrasive wheel rotating at1000 RPM with water cooling was used only for initial rough metal removal in the longitudinal cross-section so that it in no way could produce any artifact nanocrystalline layer at the end surface of the pin. All further polishing was carried out manually. A cross-section of a typical pin after preparation but before sliding looked like as having no plastic deformation traces.

Vertical pin-on-disk sliding tester 2169 UMT-1 (Tochpribor, Ivanovo) was used to test three samples simultaneously against a counterface of ∅320 mm 64 HRc tool steel disk. These samples were brought in an unlubricated sliding contact and then tested at 0.5 MPa, 0.6 m/s and 0.1 MPa, 1 m/s. It was shown by preliminary experiments that combination of low sliding speed and high contact stress is the most severe wear test mode for copper samples.

Microstructure of the worn samples was characterized using both an optical and a differential-interferential (DIC) contrast microscope Axiovert 200 MAT (Carl Zeiss). More details on the experiment and characterization are given in [15].

RESULTS

The result of experimenting was a realization of shear instability conditions (0.6 m/s, 0.5 MPa) and generation of a nanocrystalline layer having a clear boundary with the low-lying plastically deformed material (see Fig.1). This clear boundary may be evidence of shear mechanism of the nanocrystalline layer formation, which is similar to that of a shear band formation. Structurally, this layer may be divided into four zones as follows:

- plastic deformation and texturized grain zone I;
- intense fragmentation zone II;
- "turbulent" flow zone III and finally,
- "laminar" flow zone IV.

Zones I and II may be called also by usual deformation zones whereas both III and IV are the viscous flow zones [15]. One may see that both strain and fragmentation gradually grow starting from the deepest layers of zone I to the fragmentation zone II until an interface between zones II and IV (III) is formed as a result of shear instability.

Zone I is characterized by crystallographic rotation of the grains with respect to shear stress while zone II is a place of intense structural fragmentation.

More details on structure and mechanical characteristics of this layer are given elsewhere [15].

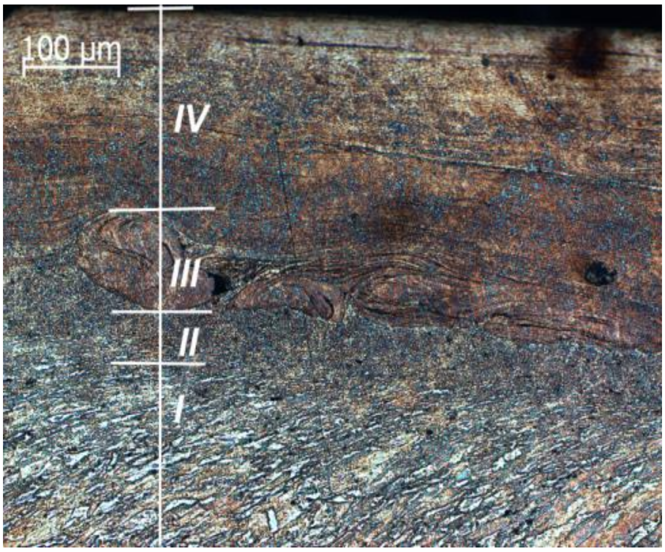

Figure 1. Microstructure of plastic deformation zones in a copper sample after sliding test at 0,6 m/s, 0,5 MPa). I – plastic deformation and texture zone ; II – fragmentation zone; III- flow instability zone; IV – stability low zone.

Figure 2. Turbulent flow zone III.

Morphological specificity of zones III and IV is that they are composed mainly of fine grains arranged in ~1 μm thickness sublayers which are elongated with the sliding direction.

Another important morphological feature is zone III within which one may see eddy-like flow of material which is very much alike the fluid turbulent flow patterns (see Fig.2). It is necessary to note here that those eddies are often found on the worn surfaces [8] as a result of mechanical intermixing. In our case, we found them generated at some depth below the worn surface, which may be related to the specificity of shear instability mechanism of nanocrystalline layer formation. Furthermore, the vortex flow may be found within zone IV which is composed of 1 μm thick sublayers [15].

DISCUSSION

It was shown in the first part of this work that plastic deformation patterns of nanocrystalline layer are similar to those of a flowing fluid. The zone IV sublayer interfaces denote shear direction in the materials and look similar to the flowing fluid laminar layers, whereas zone III rotation mode zones look like eddies initiated in turbulent mode flow. Let us assume that the basic deformation mechanism for nanocrystalline metals is by grain boundary slipping. Then, the nanocrystalline layer generated in sliding wear tests becomes even more alike a fluid since its structural elements are nanograins which are capable both of translational and rotational movements.

As noted [11], the polycrystalline material grains deforming in accordance with the diffusion accommodated grain boundary slipping mechanism reveal a behavior patterns very much alike if they possessed the Newtonian viscosity. Therefore, we can numerically evaluate a possibility of turbulent mode occurrence in a subsurface layer from a standpoint of hydrodynamics by drawing an analogy with a viscous fluid flowing in a space between two parallel plates, one of which is fixed while the other is moving relative to the first one (Couette flow) (see Fig.3).

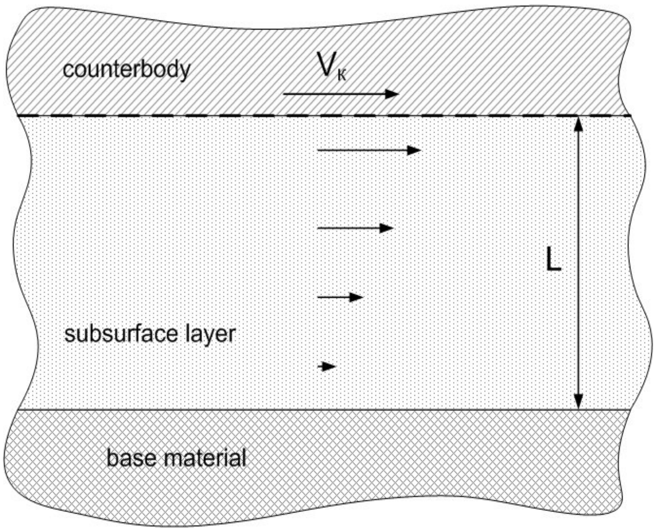

Figure 3. Plastic deformation of subsurface layer in the form of Couette flow.

The type of a flow regime is characterized by the Reynolds number:

$$Re = \frac{\rho L V_m}{\eta} \qquad (1)$$

*where ρ is density, L is characteristic size, Vm is mean flow velocity , η - viscosity. In theory, the Couette flow is assumed to be absolutely stable against infinitesimal perturbances [12] whereas in practice a crossover from laminar to turbulent regime may be observed for Reynolds number in the order 10^3. To estimate the Reynolds number, we assume that the maximum mean flow velocity V_m is equal to the counterbody's velocity $V_c \approx 1$ m/s and the characteristic size coincides with the experimentally obtained nanocrystalline layer's thickness **L**$\approx$500 μm [15].*

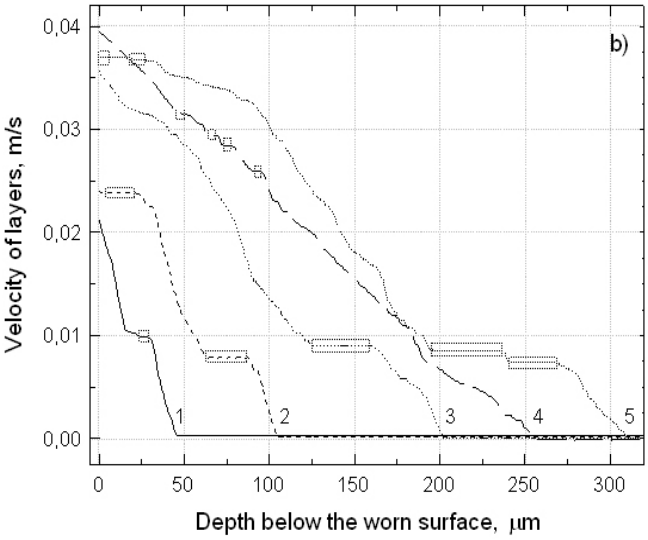

Figure 4. Subsurface layer velocity distribution vs. depth below the worn surface. Curves 1 to 5 correspond to different moments of time [15].

Both CBS deformation and, therefore, the viscosity of the nanocrystaline layer are controlled by the grain boundary diffusion. We are going to estimate the nanocrystalline layer's viscosity on the assumption that the nanocrystalline layer suffers a through-thickness flow. Assuming this, we can use the Coble's diffusion creep equation considered in details elsewhere [11] to determine the viscosity as follows:

$$\eta_B = \frac{1}{C_1}\frac{d^3 kT}{\delta D_B \Omega}, \qquad (2)$$

where d is a mean grain size, k is the Boltzmann constant, T is temperature, δ is a grain boundary width, Ω is atomic volume, D_B is a grain boundary diffusion coefficient, C_1 is a dimensionless coefficient which is $\approx 10^2$ for equiaxial grains [11].

The mean grain size is assumed to be $\approx$100 nm. The grain boundary width was 0.5 to 10 nm to estimate both maximum and minimum viscosity levels.

It is difficult to determine temperature in the vicinity of worn surface; therefore, we believe it is not below 200 ℃ since we found it experimentally to be at the level of $\approx$160 ℃ at the 1 mm depth below the worn surface [13]. Also, we believe the temperature was in the range of 300 to 400 ℃.

The grain boundary diffusion coefficient D_B determined by the Arrhenius equation both from diffusivity factor and activation energy [14] for nanocrystalline copper in the 200 to 400 ℃ temperature interval of interest is in the range 10^{-12} to 10^{-10} m^2/s. Substituting corresponding temperature as well as diffusion coefficient in expression (2), we obtain the viscosity to be within $1 \cdot 10^6$ to $5 \cdot 10^4$ Pa·s range.

The result of dry sliding wear process simulation on a copper sample showed that plastic strain rate $\dot{\gamma}$ reached $10^3 s^{-1}$ for applied shear stress $\tau \approx 200$ MPa [15]. Using this result, we can determine the viscosity of a Newtonian fluid from a ratio between the shear stress and shear strain rate:

$$\eta = \frac{\tau}{\dot{\gamma}} \qquad (3)$$

Substituting the above found values of both τ and $\dot{\gamma}$ in (3) we obtain the viscosity $\approx 2 \cdot 10^5$ Pa·s, which falls within the above determined range $1 \cdot 10^6$ to $5 \cdot 10^4$ Pa·s. The Reynolds number determined using expression (1) from these viscosities will be in the order of 10^{-5}. From the standpoint of hydrodynamics, that low Reynolds numbers correspond only to nonperturbed laminar plastic flow of the nanocrystalline subsurface layer [12].

The Reynolds theory works correctly only for infinitesimal perturbances whereas the polycrystalline structure of materials implies the inhomogeneity of its characteristics in itself. Moreover, sliding test conditions serve to produce extra mechanical and thermal inhomogeneities in the material. It was shown by numerical simulations on a macroscopic one-dimension model that plastic shear in subsurface layer of copper sample is developed nonstationary in time and inhomogeneously through the depth below the worn surface [15]. This process generates a velocity field characterized by its non-linear profile contrastingly to that of the Couette flow (see Fig.4). It follows from Fig.4 those two types of velocity zones could exist in the deforming material. High velocity gradient zones (slope curve portions) correspond to shear instability zones developing under plastic deformation. Other zones of zero velocity gradients (horizontal curve portions shown in rectangles) are moving in parallel to the worn surface at the same velocity and carrying only elastic deformation. Therefore, the surfaces with the velocity tangential discontinuities may exist inside the subsurface layer in different moments of time and different depths below the worn surface. From the hydrodynamics standpoint, the absolute instability is of occurrence on these surfaces. This instability may be interpreted as a simplest case of the Helmholtz instability which is a special type of an instability occurring at the interfaces between the flows of either the same or different fluids but under condition of having different flow rates [12].

Another example of a surface on which the Helmholtz instability may develop is a boundary between the subsurface layer and elastically deforming low-lying base metal.

Taking into account the results of numerical simulations, we may describe the process of deformation in the subsurface layer as follows. During any moment of time elastic deformation zones are generated together with one or even several shear instability zones where intense plastic shear occurs (see Fig.5), i.e. there is at least one interface on which the turbulence may develop.

To evaluate the feasibility of such a case, we invoke again the Reynolds number but now we apply it to some smaller structure scale of the subsurface layer, namely, to relative movement of 1 μm- thick sublayers which compose the subsurface layer [15].

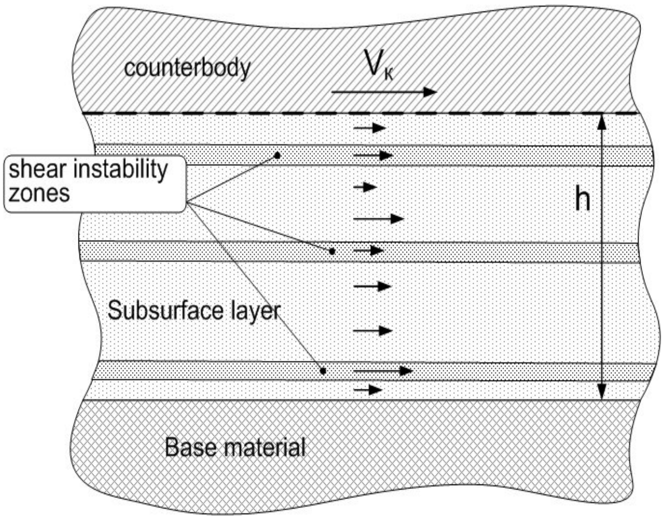

Figure 5. Schematic of the subsurface layer deformation in sliding

Reynolds himself defined his criterion as follows [16]:

$$Re = \frac{Vh}{c\lambda} \qquad (4)$$

where V is the flow velocity, h is the characteristic size of flow, c is the mean velocity of molecules, λ is the mean run of molecules. In our situation, V and h is the mean velocity of movement and the subsurface layer thickness, respectively.

Within the framework of our model [15], an elementary strain carrier is a 1 μm- thickness sublayer of material, therefore, parameters c and λ may be interpreted respectively as the velocity and displacement of this sublayer for a time during which it stays in the shear instability zone. Numerical modeling enabled the values of these parameters to be as follows: $V \approx 2 \cdot 10^{-2}$m/s, $h \approx 3 \cdot 10^{-4}$m, $c \approx 1 \cdot 10^{-2} - 4 \cdot 10^{-2}$m/s, $\lambda \approx 1 \cdot 10^{-8} - 8 \cdot 10^{-8}$m [15]. Substituting this numbers in expression (4), we obtain the Reynolds number to be in the range 1875 to 30000.

The system of parallel-plane flows as simulated in [15] and which describes deformation in a subsurface layer of metal in sliding becomes instable at that high Reynolds numbers and any infinitesimal perturbance may bring it to the turbulence regime.

CONCLUSIONS

Shear instability conditions were realized in the course of tribological experiment. A nanocrystalline 500 μm thickness subsurface layer was obtained as a result of shear instability (see Figs. 1, 2). Plastic deformation pattern of this layer gives evidence of a deformation mechanism much alike a viscous fluid flow. One of distinctive structural features of this layer is the occurrence of eddies both inside the layer and at the interface with the base low-lying material.

Macroscopic analysis of plastic deformation was carried out on assumption that the deformation behavior of the nanocrystalline subsurface layer is similar to that of the parallel-plane viscous Newtonian flow. Specificity of deformation mechanisms was not considered explicitly. From the standpoint of hydrodynamics, plastic flow of copper subsurface layer under existing experimental conditions should be absolutely stable, i.e laminar.

Situation becomes quite opposite when we take into consideration earlier revealed nonstationary and inhomogeneous shear deformation pattern. In this case, one or more velocity tangential discontinuity surfaces may exist inside the deforming subsurface layer at different moments of time and depths below the worn surface. These surfaces are particular cases of Helmholtz instability and may serve as potential sites where turbulences may nucleate. The feasibility of eddy-like structure in such zones was supported by estimating Reynolds number values.

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