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Physical Patterns of Dislocation Structure Kinetics in Friction Loaded Surface Layers

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ABSTRACT *This paper analyzes characteristic dislocation mechanism of metallic (nickel) surface layer destruction under friction. The authors define the effective role in formation of uniformity rupture of slipping strips of material, large angle borders of block and crystalline structure disorientation.*

KEYWORDS : dislocation structure, wear intensity, ferromagnetic resonance, friction loading

Introduction.

Deformation dispersion and the consequent destruction of surface metal layers under friction layers are multi-level processes defined mainly by the dislocation structure kinetics and the formations corresponding to it. Papers [1-4] analyse the microstructure characteristics of hardening and destruction in the surface layers of polycrystalline nickel specimens under friction and identify several stages in these processes. In contrast with conventional methods of contact loading (such as rolling or compression), changes in the strength properties follow a cyclical pattern. This pattern has been established by ferromagnetic resonance (FMR) [1 - 4], electron microscopy and electron diffraction [1 - 3], X-ray diffraction [3], and intensity of wear analysis [4].

The physical processes underlying the cyclicality of the lasting characteristic are explained with reference to the dislocation conjectures consistent with the lamellar theory of wear and destruction under friction. It has been established with certainty that the decline in the cyclic function is related to relaxation of elastic stresses in the crystal lattice through intensive cracking and cell formation around the crack tips, and through secondary crystallisation in the shear bands. It was found that the growth and migration of the cracks, and the formation of closed boundaries was causing selective peeling of the deformation layer at this phase of the experiment.

Investigation results and their discussion.

In stage 1, the observed monotonous rise of the oscillating curve uniquely reflects the increase in dislocation density [1]. The peak of the curve coincides with a critical level of elastic stress energy (fig. 1, point A). At each subsequent cycle, the monotonous rise of the curve Δ H = f(t) occurs from a minimum that corresponds to residual deformation of the underlying material and peaks at progressively higher absolute values of the strength characteristics. As the strengthening and microdestruction processes affect one layer at a time, the low and high points in each subsequent cycle are coincide progressively higher values of dislocation density.

The second stage in the strength property kinetics is reached at the point of maximum dispersion (fig. 1, curve 1, point A). A succession of deep declines in dislocation density is observed at points M, N and K.

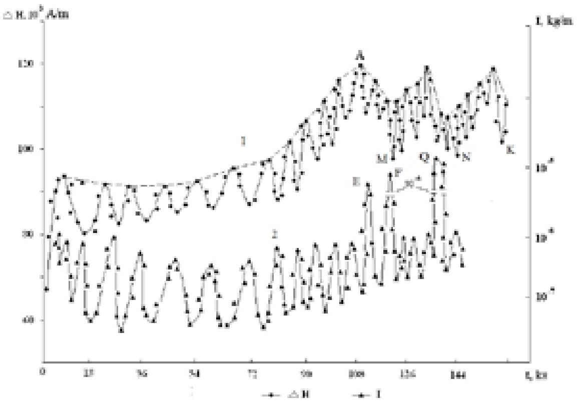

Fig. 1 – Relationship between the ferromagnetic resonance line width ΔH, wear intensity I (1) and time of exposure to friction loading (2) [4]

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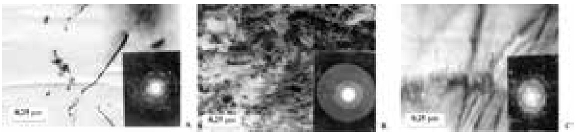

Fig. 2 – Evolution of nickel structure at different times of friction exposure (ks): a) = 0 (original sample); b) - 5,4; c) - 10,8 [1]

Microstructure studies of the initial stages of friction loading indicate the presence of a highly dispersed crystal structure with blocks of ≈ 10^{-2} mkm distributed quasi-regularly throughout the surface layer (fig. 3). This nano-structuring of the thin surface layer significantly alters the mechanism of strengthening within it, In addition to a high levels of surface layer strengthening, extended block boundaries and boundary slippage create a certain degree of material plasticity. This is facilitated by the presence of high temperatures during the friction contact. The accompanying dispersion of the block microstructure increases the macroscopic elastic limit and resistance to fatigue fracture through reduction in crack formation at grain boundaries. Uniform distribution of dislocation complexes eliminates formation of local destruction nuclei.

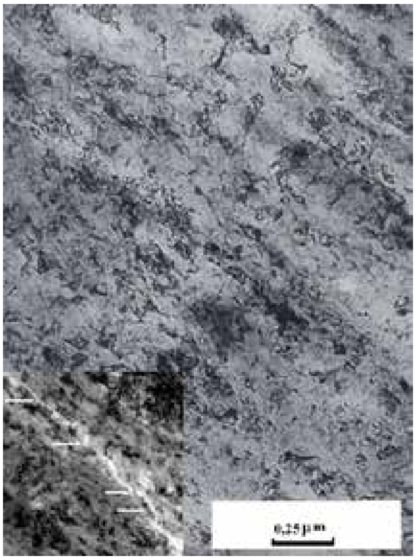

Fig. 3 – Nickel surface layer microstructure: a) nanostructure (insertion – destruction of the highly dispersed structure (t=5,4 ks))

Continued loading increases the trend towards dislocation structure texturing and accelerates formation of localised plastic deformation microbands. The microcracks appearing within this microstructure with typical sizes of 0,01 mkm in diameter and 0,1 mkm in length (fig. 3, insertion). These minuscule cracks will have emerged through the dislocation mechanism [9], which must be true even for singular slide strips, where no activation from adjacent lines or the entire strip is required for the process.

As extruded material, these stripes become the nuclei of localised deformation under extended loading. The presence of stable slide stripes defines the kinetics of the surface layer's subsequent strengthening and destruction. As concluded in [8], these stripes are transformed into fragments of a plate-like structure with stacking faults at the boundaries (fig. 4, a, arrows); large elastic stresses are concentrated at these faults, which represent elements of crystal face non-alignment. Within a highly fragmented band structure, microcracks form mainly along the boundaries (fig. 4, b, arrows). Localised disintegration and slide band shears increase elastic stress gradients and result in main crack formation.

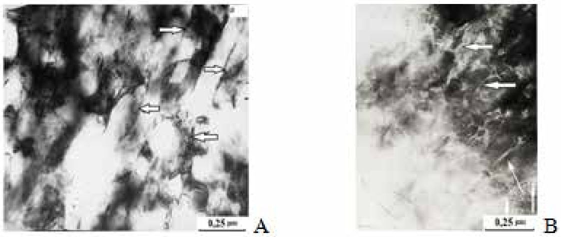

Fig. 4 – Slide bands (t = 21,6 ks): a) plate-like structure; b) crevices along the band boundaries

Remarkably, the process of material destruction is affected by progressive growth in porosity. The thermal cycling at the friction points, accompanied by vacancy mobility and coagulation create multiple micropores within the plate-like structure and at its boundaries in the presence of large numbers of stacking faults (fig. 5, a, b) at the friction loading stage. Under the action of applied stress, the micropores themselves become stress concentrators, which may result in transgranular and intergranular fracture (fig. 5, b). The ratio of porosity reaches 15% of the entire surface area covered by the observation.

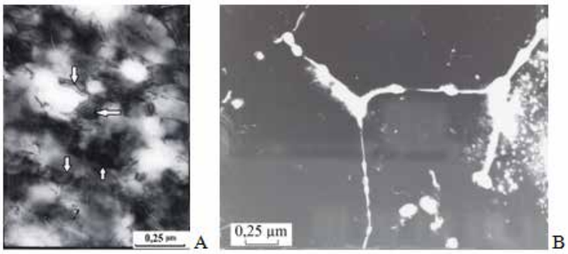

Fig. 5 – Pores within the plate –like structure (the defects of puck up – arrows); a, b – pores within the plate-like structure and at its boundaries

At the maximum strengthening stage (fig. 1, pos. A), highly dispersed areas of mesosubstructure are observed in majority granules, resulting from the rotational shifts and microcracks along the texturised formations (fig. 6, a, b, arrows). The formation of these defect-rich microstructures, as represented by the small plates within meso-band, is related to effective suppression of dislocation microshears. This determines the presence of high elastic stress gradients; relaxation of these stresses may take place at the expense of plastic deformation rotational modes [10].

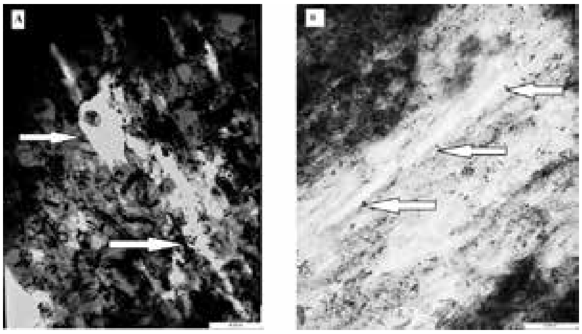

Fig. 6 – Mesosubstructure at maximum dispersion (t = 113,4 kc). Combina-tion of cracks and pores (arrows)

As stated in the works cited, this structure evolves into a highly dispersed polycrystalline structure with extreme strength properties. Consistent with the concept of physical mesomechanics scale levels, the strengthening and destruction of the surface layers at maximum dispersion may be interpreted as global loss of shear resilience by the surface layer following nucleation and migration of the localised plastic deformation mesobands [11-13]. As concluded in [13], formation of a fragmented layer, which extends with time to a depth up to tens of micrometers, is the defining factor behind the destruction process under friction loading. Surface layer destruction results in catastrophic wear, as reported in [4]. Authors established that destruction of this surface layer happens by means of association of the main cracks (Fig. 6, a, b, arrows), pores (fig. 5, b) and other volume defects [4, 6].

Analysis of the relationships presented in fig. 1, curve 2 confirms correspondence of peak wear intensity to each minimum in the cyclic function $\Delta H = f(t)$. As follows from this observation, the process of wear product formation must be limited in time.

For convenience, the following terms and definitions will be utilised in the remained of the paper for the discussion of wear kinetics. Microdestruction will refer to the intensity of wear observed during layered material destruction at the running inclusive of the peak point E ($I = 10^{-7}$-10^{-6} kg/м), while abnormal peaks in wear intensity corresponding to drastic drops in the strength parameters at points F and Q (I = 10^{-4} kg/м) will be referred to as macrodestruction peaks. Anomalous peaks in wear intensity at macrodestruction exceed the wear intensity peaks observed at the running-in stage by two orders of magnitude.

The presence of the intensity lows Δ H and the corresponding abnormal peaks in wear intensity (I) are indications that progressively deeper layers of materials may be affected by embrittlement, enabled by absorption of latent strain energy. In this process, strain energy is accumulated during thin layer destruction (and peeling at the end of each cycle), preparing the ground for the eventual peeling of a thicker layer of up to tens of micrometres in a process of intensive destruction [4, 13].

Conclusion.

A comprehensive study of the physical processes of plastic deformation in metals under friction has confirmed that variations in the strength properties are cyclical.

Several stages in the evolution of the dislocation structure have been identified. During the first stage, the oscillating curve rises monotonously to a peak that coincides with a critical level of elastic stress energy, followed by destabilisation of the crystal lattice.

Peak dispersion at the end of this stage ultimately results in substantial brittling of the material and is the primary cause of the ensuing deep disruptions in the monotonously ascending cyclic curve. Such disruptions are characteristic of the later stages in the course of the strengthening and disruption processes in the surface layers.

A mutual relationship has been established between the dislocation structure kinetic and wear intensity. It has been shown that the recurrent peaks of wear intensity are synchronous with the low points in the dislocation density curve.

A comprehensive study of the hardening and wearing processes has been performed after sufficiently long periods of friction loading to track the structural transformations of the crystalline lattice up until the critical point and to relate the results to the intensity of wear. It has been established strong peaks of wear intensity are synchronous with the deep declines in dislocation density and occur during the phase of maximum dispersion during each cycle of variation in the strength properties.

Based on the comprehensive investigation of the strength and tribotechnical properties of metals under friction, it has been concluded that the cyclic destruction of dispersed surface layers follows a lamellar layered pattern.

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