MESOSCALE LEVELS OF STRAIN AND FRACTURE OF COATED MATERIALS

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ABSTRACT

According to investigation on plastic deformation and failure within the framework of physical mesomechanics, surface layers of a loaded solid are an individual structural level of strain origin and development. If surface layers are treated or a protective (strengthening) coating is deposited, the pattern of strain origin and development is substantially changed. The restriction of dislocation plasticity results in increase of local stress concentrator level, while the character of strain development is governed by pattern of their occurrence and relaxation. Development of the considered processes depends on thickness and structure of a coating, relationship between mechanical properties of the coating and substrate, thickness ratio of the interfaced materials, presence of transient layers etc. Also, the basic factor is composition loading scheme, since the latter defines strain localization degree under applying external loading to a composition. In the present work investigations of plastic deformation origin and evolution in materials with protective coatings during their stretching, compression, 3-point static and cyclic bending were carried out using high-resolution television-optical technique TOMSC. It is shown, that incompatibility of strain development in a coating and substrate under tension results in occurrence of local bending-rotation-torsion zones in the vicinity of the interface. The size of such zones can vary from a scale of entire specimen cross-section down to areas comparable with thickness of the coating. During investigations carried out under cyclic bending the compositions, in which mechanical characteristics of the substrate significantly and insignificantly differed from those of the coating were studied. Complex pattern of localized plastic deformation evolution under friction and wear is related to extremely localized pattern of loading applying. On the basis of the results obtained some recommendations on coating and interface formation are formulated with the purpose of increasing their performance.

1 INTRODUCTION

Recently surface-strain mapping technique have found a wide application in experimental mechanics due to intensive development of image acquisition equipment (high–resolution TV- and photo–cameras) as well as possibility of fast and precise processing of experimental data with the use of personal computers. Most interesting and essential results on developing both experimental techniques and interpretation of results in terms of mechanics were achived in S.Corolina University in prof. M. Sutton's group [1]. In so doing most attention was paid to fatigue fracture of heterogenious materils. Interesting results on mathematical processing of experimental data obtained by surface–strain mapping were gained in Great Britain in Prof. P.Whithers' group [2].

In researches of Prof. V.Panin to carry out within the framework of physical mesomechanics, were shown that surface layers of a loaded solid are an individual structural level of strain origin and development. Prof. V.E. Panin [3,4] has shown that special state of surface layers causes fast shear stability loss under loading and gives rise to initial acts of plastic deformation there. In so doing the propagation of defect flows of a non-dislocation nature in surface layers plays the determining role. The development of the given processes is much pronounced in materials where dislocation plasticity is restrained by elements of internal structure.

If surface layers are subjected to various treatment procedures or a protective (strengthening) coating is deposited onto material surface, the pattern of strain origin and development is substantially changed. The restriction of dislocation plasticity results in increase of local stress concentration level, while the character of strain development is governed by pattern of their occurrence and relaxation.

The target of experimental study of coated materials being loaded under different schemes was associating shape and numerical parameters of loading diagram and characteristic patterns of strain development (localization). The estimation of strain localization can be obtained by calculating strain components (main plastic shear, strain rate intensity, shear and rotation component of distortion tensor) by numerical differentiation of data obtained by television–optical observation of surface of a loaded heterogeneous material.

Another important reason for carrying out the investigations is optimizing modes for coating deposition as well as structural and geometrical factors. Frequently cracking of coatings occurs under loading which does nor give rise to catastrophic failures of surface–hardened parts of machine. It is of importance to find out cracking pattern that diminishes the risk of strain localization while the estimation of the latter can be performed by processing optical images gained at the “coating–substrate” interface.

2 RESULTS AND DISCUSSION

2.1 Static tension

Uniaxial tension tests of low-carbon steel specimens with Ni-Cr-B-Si–coating deposited by electron–beam surfacing have shown that accumulation of local bending moment caused by hindering uniform strain development in the substrate precedes to next crack formation in the coating [5]. This gives rise to elastic stress concentration in this area. Unfortunately, it is impossible to get the estimation of such stresses directly from the results of television–optical observatios but calculation of strain components (particularly main plastic shear) makes possible to evaluate its distribution as well as localization degree just before crack nucleation. Comparison of images presented in fig. 1a and 1b shows that value of main plastic shear in the substrate in the vicinity of future crack nucleation (shown by an arrow in fig. 1b) has decreased by 2 times from $1{,}4 \cdot 10^3$ down to $0.7 \cdot 10^3$ while within entire region under observation integral localization degree has increased.

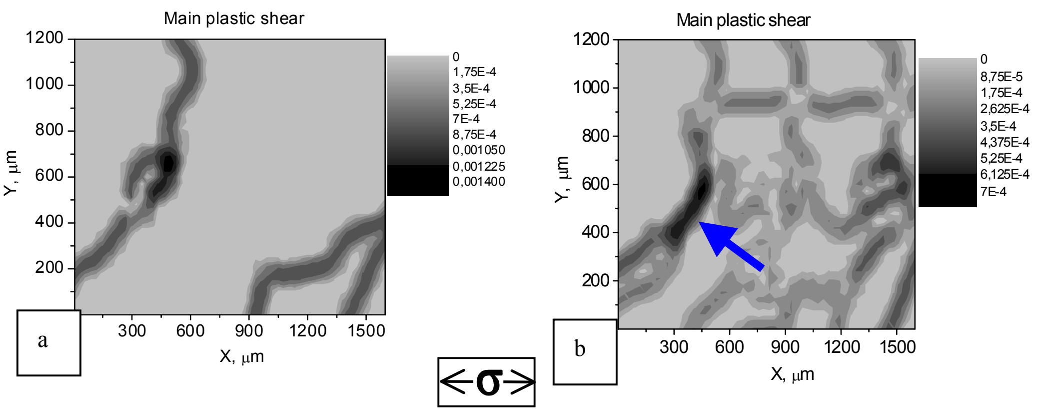

Figure 1: Distribution of main plastic shear in low-carbon steel specimen with coating (on the top) before crack nucleation; arrows show direction of applied load; ε = 4.5%; Δε = 0.3%. Image size 1685×1260 µm

2.2 Static compression

We investigated deformation behaviour of low–carbon steel specimens surface–hardened by diffusion boronizing and having either transient layer between coating and substrate (fig. 2a) or thin intermediate layer (fig. 2b). Specimens of the first type were subjected to preliminary carbonizing that ensured formation of more strength coating containing boranized cementite dirung subsequent boronizing. Varying temperature of diffusion treatment allowed to prepare specimens for compression tests having a) high–strength boronized layer of 250 μm with nearly flat "coating–substrate" interface geometry; b) multi–layer composition: high–strength boronized layer had thicknes of 70 μm and toothed interface with lower transient laeyr. The latter was of 150 μm thickness and characterized by flat interface between the layer and substrate (fig. 2a). The total thickness of specimens for compression tests made 2 mm. Loading was applied parallel to the interface. Also specimens with boronized layers of 70 and 100 μm thickness not subjected to preliminary carbonizing were researched. These specimens had thin intermediate pearlite layer filling space between boride needles (fig. 2b). Though such layer exerted substantial influence on cracking pattern under tension [6] it could not be called as gradient transient one in common sense of its functional destination.

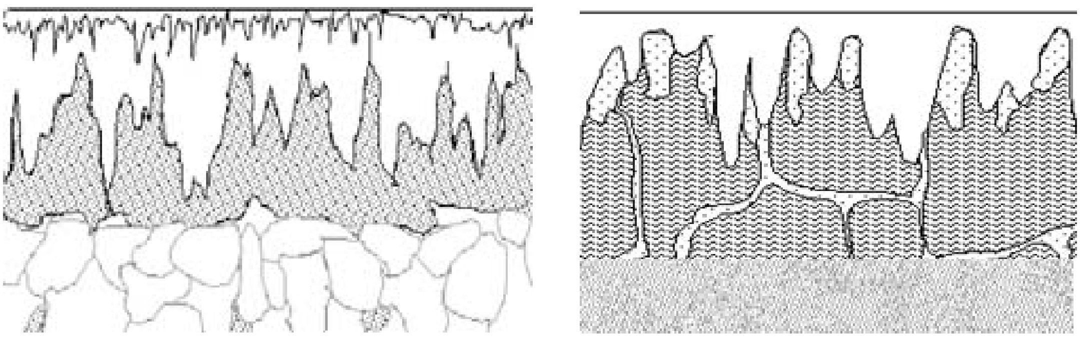

Figure 2: Schematics of boronized surface layers of 70 μm a) with toothed interface and transient layer of 150 μm; b) with needled interface and intermediate sublayer

The governing role of the transient laeyr between the coating and substrate becames evident at analysis of stress-strain curves shown in fig. 3a. If Fe_2B layer thickness is 70 μm, presence of the transient gradient layer influences mainly the value of strain hardening coefficient (fig. 3a, curve 1 and curve 2 correspondently). Increasing thickness of the coating exerts more substantial influence.

Also very informative are results on comparison of stress–strain curves of preliminary carbonized a) specimen with a thick coating (fig. 3a, curve 3) and b) specimen with a transient gradient layer (fig. 3a, curve 3). It is easily seen that for the specimen with a thick coating under strain less than 4% a portion is formed with a descending stress level. With further loading presence of cracks in the coating substantially localized strain development within individual macro shear bands that eliminates most of the specimen volume from the resistance to plastic deformation. As a result the stress–strain curve fir such specimen is characterized by low strain–hardening coefficient (fig. 3a, curve 3).

From the other hand, absence of transient gradient layer in a specimen with boronized coating of 100 μm caueses decreasing yeild stress down to 400 MPa. Under further loading the stress level does not exceeds 475 MPa (fig. 3a, curve 4).

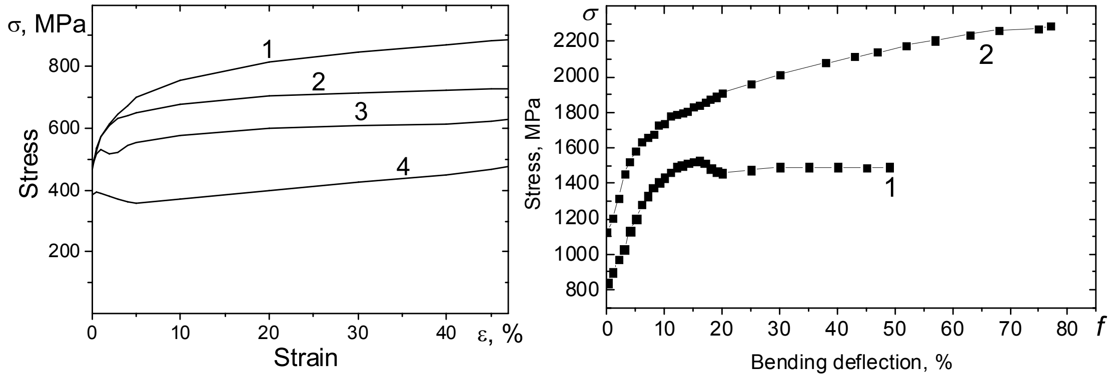

Figure 3: a) Stress–strain curves for boronized low–carbon steel specimens: preliminary carbonized (boronized layer thickness 70 μm (1) and 250 μm (3): non–carbonized (boronized layer thickness 70 μm (2) and 100 μm (4)).
b) 3point bending loading diagrams of 40Cr13 steel specimens surface–modificated by nitrogen ion at temperature of 500 experiencing (2) and not experiencing cracking in the notch tip.

Three point bending

The role of surface–hardened layer and and its cracking onto behaviour of entire specimen is most pronounced under three–point bending tests. We investigated structural 40Cr13 steel specimens subjected to irradiation by nitrogen ions that allowed to form a high–strength layer of 30÷40 μm. For the sake of strain localization a V–shape notch was made on flat surface of specimen before the treatment. After implantation that was performed at temperature of 500°C strain development was determined by fact of coating cracking in the notch region (fig. 3b, curve 2) or absence of this process (fig. 3b, curve 2).
When loading was applied to the substrate the notch governs localized strain development being pronounced in formation of rather large region of localized plastic deformation from the very onset of loading. High level of substrate ductility allows to avoid vortex pattern of plastic flow to be ensured, mainly, by microscale mechanisms of its development. With further loading the strain localization in the notch region governs noncompensated character of rotational modes development. In doing so within one of the mesobands strain develops more intensively. This determines plastic deformation to develop at the macroscale with subsequent specimen failure at rather low strain.
Plastic deformation development in a specimen with a cracked implanted layer is determined by partial macrostress concentrator relaxation at the expence of cracking of the surface–hardened layer. With increase of bending deflection the stress concentration level in the tip of the notch is increased but it is compensated by formation of a mesoband system developing from cracks in the surface–hardened layer. Such pattern of mesoscale plastic deformation development makes possible to avoid substantial deformation localization for rather long time (up to strain corresponding to bending deflection of *f*~79%).
Gradually, difference in strain development intensity within adjacent mesobands gives rise to non–compensated rotational moments which become evident on the patterns of main plastic shear distribution. Before fracture strain localization level in the notch tip region reaches some critical value while substrate relaxational ability becomes exhausted. Fracture takes place along one of the

mesobands which just before the fracture is transformed into the macro shear band developing over the cross section of the substrate.
The results obtained testify the fact that fine cracking of the coating allows to effectively relax macro–stress concentrator (to occur due to specimen bending because of non–uniform applying of the loading) that provides increasing ductility of the surface hardened material. Absence of coating cracking under three–point bending gives rise to substantial strain localization, lowering of flow stress and decreasing of plasticity.

Cyclic bending

It is well known that fatigue fracture possesses certain stage pattern. For "coating–substrate" compositions the pattern of such stages is different that is determined by physical–mechanical properties of coating and substrtate. We study evolution of stress–strain state in "NiCrBSi–surfaced coating–structural 20Cr13 steel" in the case when coating strength substantially exceedes substrate one and has low ductility. As we have shown earlier [7] crack propagation in coated specimen has three pronounced stages. With the use of surface–strain mapping we evaluate stages of strain development under fatigue crack growth.

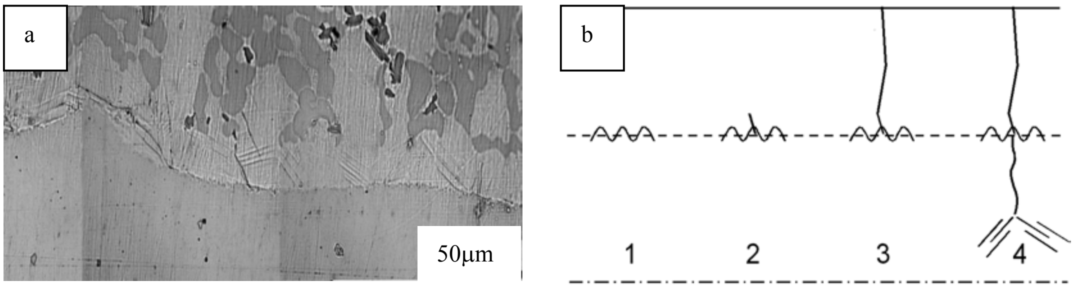

Figure 4: a) Optical image, illustrating nucleation of adhesion and cohesion cracks at the stage I. "NiCrBSi–coating–20Cr13 steel" composition. Image size 330×110 μm; N=0,45 N_f; b) schematic of nucleation and growth of fatigue crack.

First stage on the curves of growth and openning of fatigue crack is related to its nucleation at the interface with further failure of the coating. Within loading interval of ~0,2÷0,4 N_f (where N_f – number of cycles before failure) there appear sign of plastic deformation development in the region adjacent to "coating–substrtate interface" (fig. 4, case 1). With the use of displacement vector field construction we revealed displacements of surface regions mainly in the interfacial coating and substrate layers with thickness up to 30 μm. The values of displacements, which mainly have stochastical orientations, are increased with the loading. The width of the region where displacement are registered is also grown up. This becomes evident on the distributions of main plastic shear γ. With further cyclic loading at ~0,45÷0,5 N_f sliding traces appear in the coating grains being adjacent to substrate. At number of loading cycles of ~0,5÷0,55 N_f adhesion and cohesion cracks emerge in this region (fig. 4, case 2).
The experimental data obtained proved that they are cracks at the "coating–substrtate" interface which initiate subsequent coating failure. At ~0,55 N_f fast formation of through crack in the coating happen (fig. 4, case 3). In doing so the crack propagates both along phase coating components and along interphase boundaries.

Stages II–III (crack propagation in the substrate). Straight away after coating cracking (at ~0,55 N_f) the crack starts to grow into the substrate (fig. 4, case 4). The propagation of fatigue crack into the substrate in the composition with a cracked coating differs but slightly from that of the specimen without coating and is similar to second and third stages of fatigue fracture of non–coated specimens: kinetics of growth and opening of the crack, patterns of plastic deformation development and fractographic fracture signs are nearly identical. During cyclic loading interval of ~0,55÷0,94 N_f stabilized crack growth takes place while during ~0,94÷1 N_f – accelerated growth is observed.

3 SUMMARY

The most optimal from the point of view of behaviour under mechanical loading is formation of coatings with nonflat "coating-substrate" interface and presence of a gradient transient layer. The latter hinders crack propagation into lower substrate layers and increasing composition strength by the additivity law.

Fine cracking of the coating allow to avoid substantial strain localizations that can keep exploitational properties of surface–hardened parts of machine that does not completed with catastrophic consequences (fast failure).

In materials with high-strength low-ductile coatings the interface is the site of fatigue crack origin. The decrease in distinction of elastic moduli of a coating and substrate results in nucleation of the crack on surface of the coating.

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