SELF-ORGANIZATION OF SCALE LEVELS OF PLASTIC FLOW IN FRACTURE MESOMECANICS

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ABSTRACT

In the basic concept of physical mesomecanics, a deforming solid is viewed as a multilevel system in which the evolution of plastic flow and fracture occurs consistently on the micro-, meso- and macro-scale levels.

The self-organization of plastic flow, which takes place on the meso- and macro-scale levels in the deforming material at the prefracture stage, has been investigated using dual-phase pseudo-alloy Cu-25%Cr and high-strength construction martensitic steel (VKS-12). In the former case, material fracture involves shearing and in the latter, it is "cone-cap" type fracture.

It has been found that the fracture of the binary pseudo-alloy Cu-25%Cr occurs by three stages. At the first stage in the deforming material there forms a wide symmetric neck. At the second stage within of the neck along the "chromium particle-matrix" interface there occurs crack nucleation. As the self-organization of plastic flow, which involves the above two processes, a second system of U_x and U_y isolines characteristic of geometric stress concentrator (crack) appears on the background of U_x and U_y isoline pattern typical for a symmetric neck. At the third stage the self-organization of stress-strain state on the meso-scale level results in the formation of a extended local shear macro-band, with the line and shear components and strain-rate intensity along the latter macro-band having maximal values. Fracture in such specimens occurs by shearing along the same macro-band.

The deforming austenitic steel specimens at the pre-fracture stage form a symmetric neck. The maximal values of the principal line components, ε_1 and ε_2, and strain-rate intensity, ε_i, occur in the center of the neck region; the shear component, ε_{xy}, reaches a maximal value and reverses sign at every other quarter of the neck length. The above distribution of ε_1, ε_2 and ε_i values remains unchanged until the onset of fracture in the center of the neck where the strain-rate intensity, ε_i, reaches a maximal value.

An analysis of the results obtained suggests that the type of fracture is determined by the distinctive characteristics of plastic flow self-organization, which takes place within of the neck at different scale levels.

1 INTRODUCTION

According to the basic concept of physical mesomechanics [1], a deforming solid is thought to be a hierarchic system; therefore the underlying processes responsible for its plastic flow and fracture will occur in a self-consistent fashion on the micro-, meso- and macro-scale levels.

In the present investigation we consider the self-organization of plastic flow that occurs at the pre-fracture stage on the meso- and macro-scale levels. The investigation was performed using binary pseudo-alloy Cu-25%Cr whose fracture involves shearing and high-strength construction martensitic steel (VKS-12) which undergoes "cone-cup" type fracture.

Using television-optical method and a specially designed measuring complex (TOMSC) [2, 3], the evolution of local stress-strain state of a deforming material within a neck was examined in detail for flat specimens. Moreover, the processes involved in the self-organization of plastic flow on the above scale levels and their effect on material fracture were investigated. For quantitative specification of local stress-strain state, displacement vector fields and those of their longitudinal and transverse components were constructed. The distribution patterns derived for individual line and shear components and strain-rate intensity were matched against the strain-induced relief and the distinctive features of macro-fracture in the specimens tested.

2 EXPERIMENTAL TECHNIQUE AND MATERIALS

The flat specimens had dimensions 15×3×1 mm and a field of vision 1680×1250 μm for estimating stress-strain state. These were tested in tension on an IMASh-2078 testing machine, the rate of cross-head motion being about 10 mm/h.

For quantitative estimation of local stress-strain state, displacement vector fields were constructed. The technique intended for measuring of plastic strains at the mesoscale level was designed on the base of the TOMSC unit. This comprises (i) calculation of displacement vector fields; (ii) calculation of the fields of respective displacement vector components; (iii) finding out of isothetics to facilitate the search for displacement component functions U_i and (iv) subsequent differentiation of functions U_i. The Cartesian grid was superimposed on the region investigated. The grid step was 1/30 of the length of the entire field of vision. The values of line and shear deformation components, ε_x, ε_y and ε_{xy}, were calculated in the Cartesian co-ordinates per each grid node

$$\varepsilon_x = \frac{\partial U}{\partial x} \quad (1)$$

$$\varepsilon_y = \frac{\partial V}{\partial y} \quad (2)$$

$$\varepsilon_{xy} = \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \quad (3)$$

The deformation components, ε_1 and ε_2, along the principal axis were also obtained

$$\varepsilon_1 = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{1}{2}\sqrt{(\varepsilon_x - \varepsilon_y)^2 + \varepsilon_{xy}^2}, \quad (4)$$

$$\varepsilon_2 = \frac{\varepsilon_x + \varepsilon_y}{2} - \frac{1}{2}\sqrt{(\varepsilon_x - \varepsilon_y)^2 + \varepsilon_{xy}^2} \quad (5)$$

The third component, ε_3, was derived from the incompressibility condition

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \quad (6)$$

The intensity of deformation was calculated as

$$\varepsilon_i = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2} \quad (7)$$

The strain rate components, $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$ and $\dot{\varepsilon}_3$, were obtained by division of the respective deformation component by the time equal to the time interval between two metallographic pictures compared. The strain-rate intensity, $\dot{\varepsilon}_i$, was calculated as follows

$$\dot{\varepsilon}_i = \frac{\sqrt{2}}{3}\sqrt{(\dot{\varepsilon}_1 - \dot{\varepsilon}_2)^2 + (\dot{\varepsilon}_2 - \dot{\varepsilon}_3)^2 + (\dot{\varepsilon}_3 - \dot{\varepsilon}_1)^2} \quad (8).$$

Figure 1a illustrates the typical microstructure of polished metallographic section surface of Cu-25%Cr, which incorporates irregular multi-facet chromium particles having sizes of 50 - 100μm. At larger magnification uniformly distributed 1-μm particles could be seen in an optical microscope. According to the X-ray analysis data [4], the original phase composition of pseudo-alloy Cu-25%Cr is preserved (see Fig. 2).

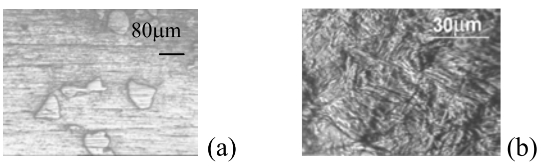


Figure 1: The microstructure of pseudo-alloy Cu-25%Cr (a) and martensitic steel VKS-12 (b).

Thus, owing to the poor solubility of chromium in copper, the structure of dual-phase pseudo-alloy is copper matrix with bimodal chromium particle size distribution.

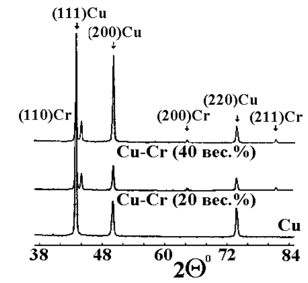


Figure 2: An X-ray pattern of Cu and Cu-Cr overlayer.

The tensile loading diagram obtained for pseudo-alloy Cu-25%Cr illustrated in Fig.3.

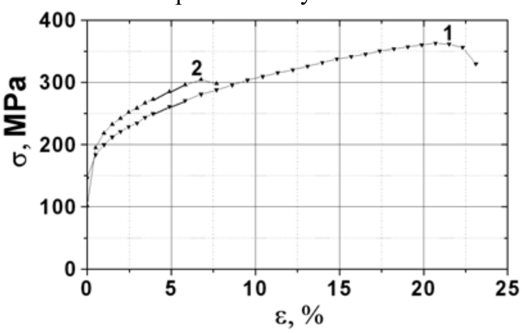


Figure 3:The tensile loading diagram for pseudo-alloy Cu-25%Cr

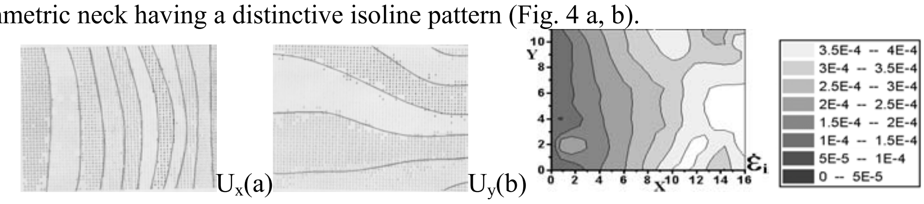
Martensitic steel (Fig. 1b) is widely used in industry (steel composition is presented in the Table).

Table: Steel composition.

wt. %	C	Cr	Si	Co	W	Mo	Ni	Fe
	0.4	2.0	3.0	2.0	2.0	1.0	4.0	85.6

3 ANALYSIS OF STRESS-STRAIN STATE AT THE PRE-FRACTURE STAGE

The results of a metallographic study and the examination of the stress-strain state of pseudo-alloy Cu-25%Cr reveal that its fracture occurs by stages. At the first stage in the material there forms a symmetric neck having a distinctive isoline pattern (Fig. 4 a, b).



U_x(a) U_y(b) (c)

Figure 4: Isolines in the neck at ε = 19%.

Then along the chromium particle-matrix interfase there occurs crack nucleation, which disrupts the symmetry of isoline configuration in the neck region (Fig. 5 a, b) and results in the emergence of another isoline picture that is typical for geometric stress concentrator (crack).

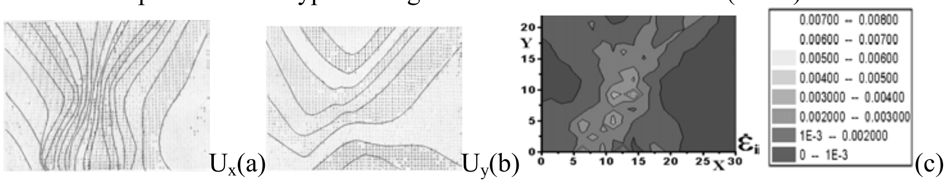


Figure 5: Isolines in the neck at ε = 21%.

As a result, the U_x isolines are drawn together and another maximum appears on the U_y isolines (Fig. 5b). A typical strain-rate intensity pattern obtained for a symmetric neck has a maximum in its center (see Fig. 4). As soon as crack nucleates in the material, a second intensity maximum appears at the crack tip. Apparently, the self-organization of stress-strain state causes the formation of parallel U_x and U_y lines traversing the entire specimen cross-section.

All the line and shear components are located in the same direction, which results in the emergence of a prominent local shear macro-band having a maximal value of strain-rate intensity (Fig. 6c). It is along this band that fracture by shearing is bound to occur (Fig.7).

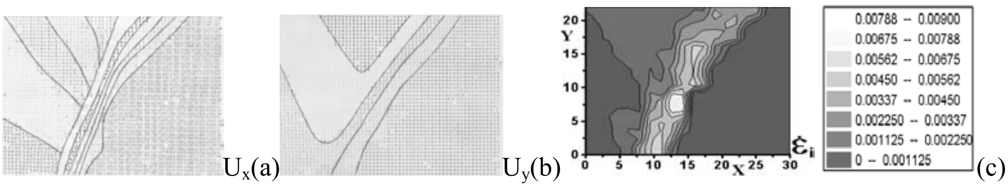


Figure 6: Isolines in the neck at ε = 22%.

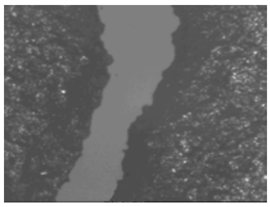
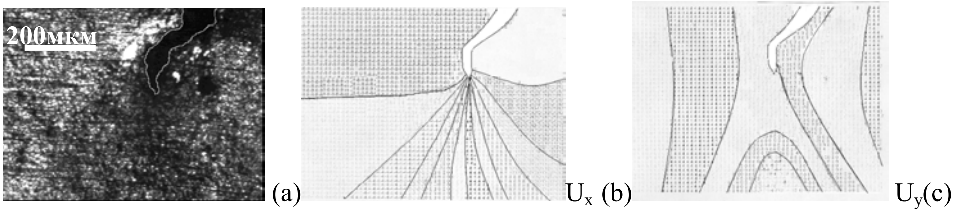


Figure 7: Fracture by shearing.

Fracture of low-ductility specimens has certain distinctive features. Thus a forerunner of fracture in such materials is crack nucleation which occurs in the material long before the onset of necking. The chromium particle-matrix interface is the most likely region in which nucleation and propagation of crack may occur. Figure 8 exemplifies a U_x and U_y isoline pattern typical for geometric stress concentrators. As is seen from the figure, the maximal strain intensity, which favors crack propagation, corresponds with the crack tip.



(a) U_x (b) U_y(c)

Figure 8: A metallographic picture of a region in the neck (a); isolines (b, c) at ε = 8.5%.

The fracture of martensitic steel specimens is different in character. Illustrated in Fig. 9 is the metallographic picture obtained for the steel specimens tested (a); the displacement vector fields (b); the fields of longitudinal, U_x, and transverse displacement vector components, U_y, (c) and (d), respectively.

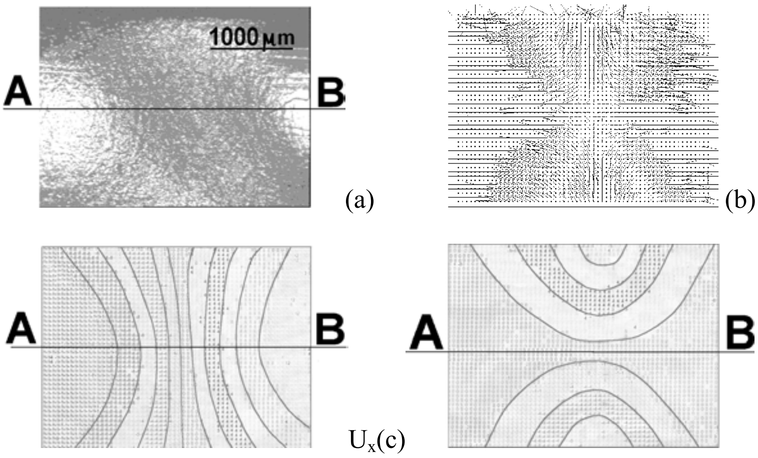


Figure 9: A metallographic picture (a); displacement vector fields (b); isolines of the longitudinal , U_x, (c) and the transverse displacement vector component, U_y, (d) in the neck of martensitic steel specimen.

Figure 10 presents the patterns of equal-value isolines calculated per second for $\dot{\varepsilon}_x$ (a), $\dot{\varepsilon}_y$ (b), $\dot{\varepsilon}_{xy}$ (c), $\dot{\varepsilon}_1$ (d), $\dot{\varepsilon}_2$ (e) and $\dot{\varepsilon}_i$ (f).

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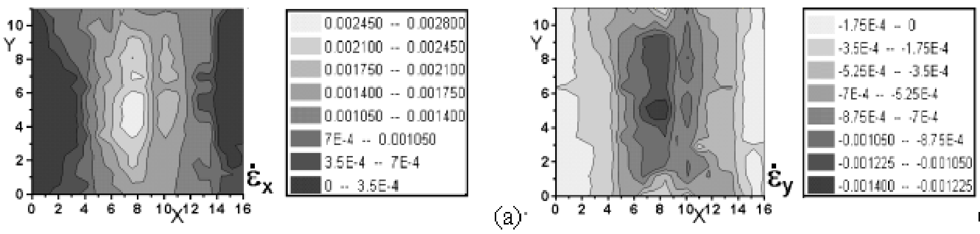

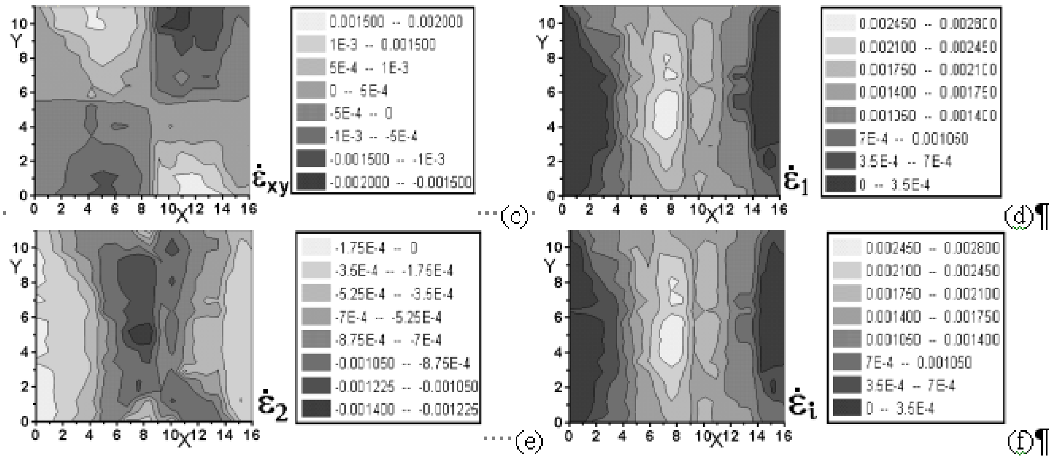

Figure 10: Equal-value isolines of $\dot{\varepsilon}_x$ (a), $\dot{\varepsilon}_y$ (b), $\dot{\varepsilon}_{xy}$ (c), $\dot{\varepsilon}_1$ (d), $\dot{\varepsilon}_2$ (e) and $\dot{\varepsilon}_i$ (f).

In the case of symmetric neck, tension and compression strain, ε_1 and ε_2 respectively, have maximum values in the center of the specimen. On going from one quarter of the neck to the next the shear component reaches a maximum with simultaneous change of sign. The patterns of equal-value strain isolines along the principal axes, ε_i, are similar to those of strain-rate intensity isolines, ε_i.

Fracture of such a specimen begins in the center of the neck, where the strain-rate intensity reaches the highest value. A picture of a steel specimen, which has undergone “cone-cup” type fracture, is shown in Fig. 11.

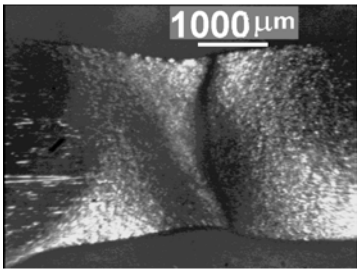

Figure 11: "Cone-cup" type fracture of martensitic steel specimen.

Thus, the results obtained suggest that fracture type is determined by the distinctive features of plastic flow self-organization within a neck, with the meso- and macro-levels being involved.

Literature

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