

## DEVELOPMENT OF TEXTURE AND MICROSTRUCTURE DURING ROLLING OF THE COPPER - 8 WT PCT GERMANIUM ALLOY

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### INTRODUCTION

A comprehensive description of processes occurring during the plastic deformation requires confrontation of the variation of texture with the accompanying changes in microstructure and physical properties. However, the variation of texture and microstructure in low stacking fault energy f.c.c. metals and alloys has not been till now well recognized as investigations were generally limited to texture analysis at high rolling reductions e.g. 1. Not enough attention has also been paid to the effect of initial texture and grain size, and to the influence of geometry of the rolling gap on inhomogeneity of texture and microstructure. Equally, the commonly used method of series expansion for the quantitative description of texture does not allow a satisfactory identification of texture details, especially in lower levels of orientation density. The orientation distribution function is then burdened with truncation errors and those ensuing from the phenomenon of ghosts; the ghosts are observed in the ODF in the positions which are in twin relations with the pronounced components, and mechanical twinning is a very important process in the deformation of low stacking fault energy metals and alloys.

In the present research the rolling has been carried on with unit draughts generally not much smaller than 0.5 and not greater than 5. In these conditions the texture does not exhibit the through-thickness inhomogeneity<sup>2</sup>. Texture analysis has been carried out on samples from the central layer of the rolled material when applying the direct ADC method based on discretization, in which the above described errors do not appear<sup>3,4</sup>.

For all experiments the copper - 8 wt pct germanium alloy was used, rolled from the annealed state up to 98 pct reduction. In the initial state the alloy was characterized by a rather sharp texture, and the mean grain size was 95  $\mu\text{m}$ . The stacking fault energy determined by the dislocation nodes method was equal to 10 mJ/m<sup>2</sup>.

### EXPERIMENTAL PROCEDURE

The copper with 8 wt% Ge alloy was prepared by melting of components of 99.99% purity in vacuum. The cast ingot was hot extruded to obtain the flat bar with 20mm×9mm cross-section. After annealing in argon at 973K for two hours the grain size was 95  $\mu\text{m}$ . The annealed bar was unidirectionally cold rolled on a 60 mm diam. two-high mill at a speed of 1.33 m min<sup>-1</sup>. Samples for the microscope examination and texture analysis were removed at various reductions in the ranges 0 to 98 pct reduction. The rolling reductions in examined samples and the

respective draughts (l/h) in several passes are presented in Table 1.

Table 1. The rolling parameters of the Cu8wt%Ge alloy

No	1	2	3	4	5	6	7	8	9	10	11
red.%	00.0	10.0	19.6	29.8	39.4	50.0	70.0	80.0	90.0	95.0	98.0
l/h		0.36	0.38	0.45	0.49	0.64	0.87	1.53	2.85	3.46	7.04
J	3.57	3.61	3.47	3.38	2.50	2.46	2.43	3.12	3.37	4.35	5.35

Optical and transmission electron microscopy was used to examine longitudinal sections (perpendicular to TD). For each specimen three texture pole figures were measured in the reflection mode while the tilt angle was limited to 75°. The pole figures were obtained from the mid-plane of the central part of the rolled sheet.

The discrete ADC method of the ODF calculation<sup>3,4</sup> was applied which allows to avoid the appearance of ghost.

From the ODF the average sharpness of texture (texture index J) has been calculated from the formula

$$J = \oint f^2(g)dg$$

the respective data are plotted in Table 1.

#### VARIATION OF TEXTURE DURING ROLLING

The recrystallized sample is characterized by the appearance of strong components at cube position and in the vicinity of typical rolling components S = (213)[364] and B = (101)[121] with considerable zones of irregular scatter. However, after small deformation (10%) a significant ordering of scatter around the positions of the rolling components C = (112)[111], S and B can be observed. On the other hand, first clearly marked symptoms of twinning appear at about 20% reduction: considerable diminishing of orientation density in a large zone around the C position (observed at  $40^\circ \leq \varphi_2 \leq 55^\circ$ ) with a simultaneous increase in density in twin orientations in the zone of scatter of the B component. No twinning is noticed in zones of scatter of S and B components while in the ODF the density rises according to changes accompanying the glide mechanism.

At 29.8% reduction the twinning front moves and embraces the S position (this is seen in  $60^\circ \leq \varphi_2 \leq 75^\circ$  sections). At the same time in the wide zone around the C position the beginning of the rotation of the twinning plane into alignment with the rolling plane is observed. This tendency is more pronounced at further rolling (39.4–90% reduction) as well as the rotation towards the Goss orientation.

The characteristic feature of texture, to be seen in the ODF within the medium reductions (39.4 to 70%), is connected with very intensive twinning: the drop in density in the wide zone around the B position. The density of Goss component increases; its height at 29.8% reductions is 1.5, then 5.3 at 50%, 6.5 at 70%, 7.8 at 80% and 9.3 at 90% rolling reduction. In the  $\varphi_2 = 45^\circ$  section there appears the locus of orientations of all twins parallel to the rolling plane. We observe in this section ( $\varphi_2 = 45^\circ$ ), in the vicinity of the line for which  $\langle 111 \rangle \parallel \text{ND}$ , the irregular spread of zones with not very great orientation density which evidence the decomposition of twin structure after arriving at the state  $\langle 111 \rangle \parallel \text{ND}$ ; this would be also attributed to the developing of shear bands. It should be stressed that within the range of rolling reductions 39.4 to 70% the texture index J assumes the lowest values, and remains almost constant (Table 1).

At 80–90% deformation the decomposition of twin structure is more

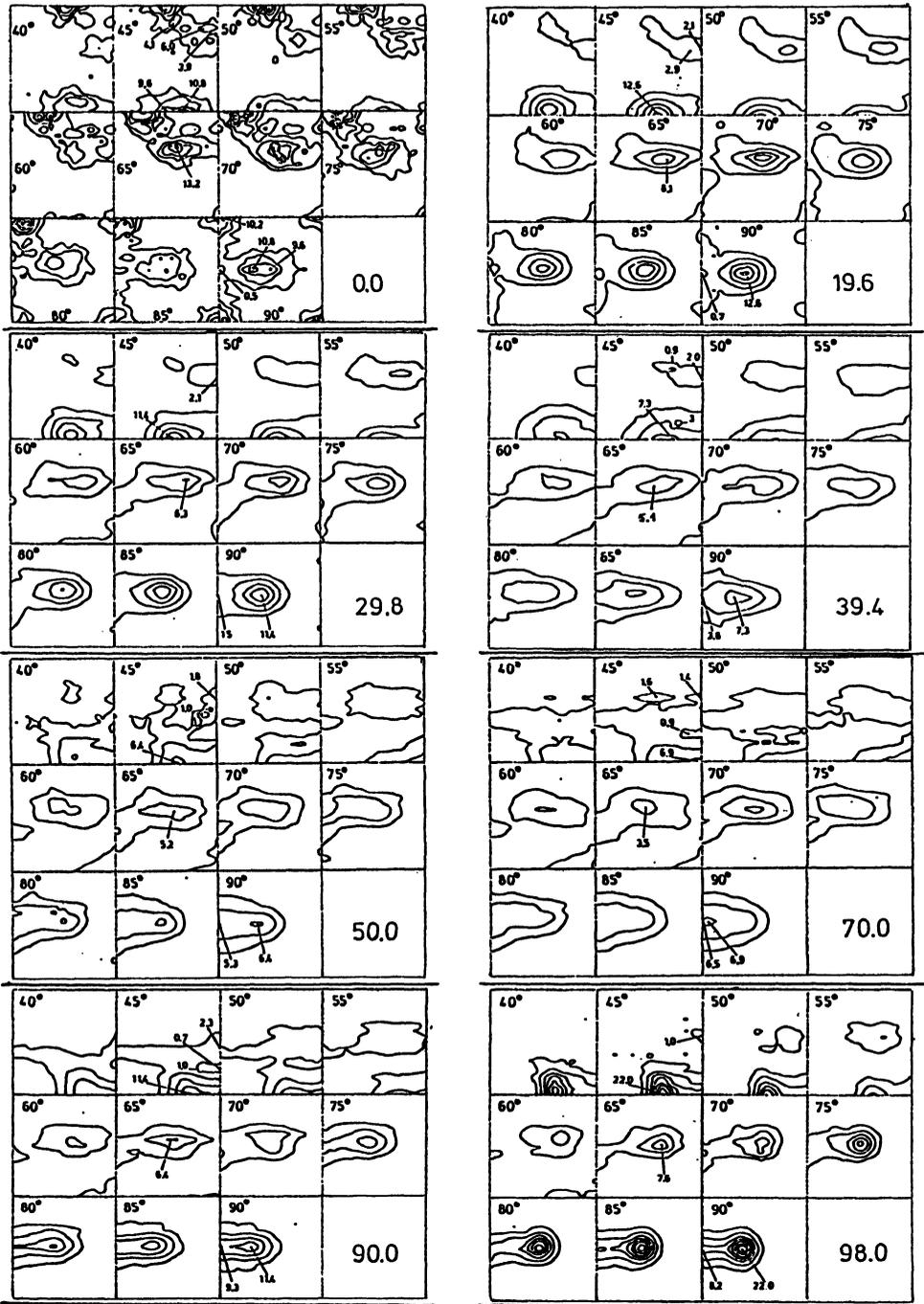


Fig.1 ODFs ( $\varphi$ , sections) of the rolled Cu-8 wt%Ge alloy; levels 1,3,6,9,12,15,18

pronounced; the increase of the orientation density may be observed, especially at the B position, its spread reaching the Goss orientation.

It is only at rolling reduction above 95% that the effect of progressing stabilization of the rolling texture, typical of f.c.c. metals with low stacking fault energy, may be noticed. The C component disappears together with a large zone around it (including S component). There is a considerable rise in density of B at the cost of Goss orientation; the latter markedly falls down.

#### METALLOGRAPHY AND STRENGTH

The initial structure of copper - 8wt% germanium alloy is characterized by equiaxial grains with a great number of annealing twins (fig.2a). There are stacking faults while density of dislocations is relatively small (fig.2b). At low rolling reductions (10%), plastic deformation is realized chiefly by glide; the structure is inhomogeneous and, besides zones with a uniform distribution of dislocations, there appear weak cell structure and several twins in one crystallographic plane (fig.2c). At 19.6% reduction a considerable number of twins in the form of thin plates can be found as well as some shear bands (fig.2d); the amount of twins and shear bands increases with deformation, though well shaped cell structure (fig.2e) can be noticed. The deflection of twins is observed which is caused by the intersecting shear bands (fig.2f). The appearance of cell structure is accompanied by the relaxation of stress.

At 60-70% reduction the second family of shear bands is observed; they are symmetrical to the rolling direction and inclined at  $\pm 40^\circ$  to RD. The progressing rolling causes that intersecting shear bands comprise still larger volume of material, leading to the formation of entanglement (fig.2g). Zones with marked density of twins become lesser, and acquire the form of lenses elongated in the rolling direction (fig.2h). This process is associated with a continuous increase in strengthening of the material.

Finally, above 95% rolling reduction, the effect of dynamic recovery is visible as well in mechanical properties as in microstructure.

#### DISCUSSION

A simultaneous observation of the variation of texture, microstructure and mechanical properties has led to the following sequence of changes.

At first, dislocation glide dominates with a weak participation of twinning in one crystallographic plane. At 20 pct rolling reduction there appear occasional microbands. As the rolling is continued, the mechanical twinning intensifies - the process is observed both by X-ray and microscopy techniques. The twins are formed in two intersecting planes what is accompanied by the increase of dislocation density and the appearance of a well shaped cell structure ( notwithstanding the small stacking fault energy). Above 50 pct deformation, in regions of great density of mechanical twins, the intensive shear banding is seen as well as the intense fragmentation and sharp deflection of twins. The setting in motion of the second family of shear bands is observed at higher rolling reduction (60-70 pct). At further increase of deformation (above 80 pct) a very inhomogeneous structure appears in the form of intersecting shear bands, and the rise of their intensity provokes the formation of the entanglement.

The examination of texture exhibits that with rising of the

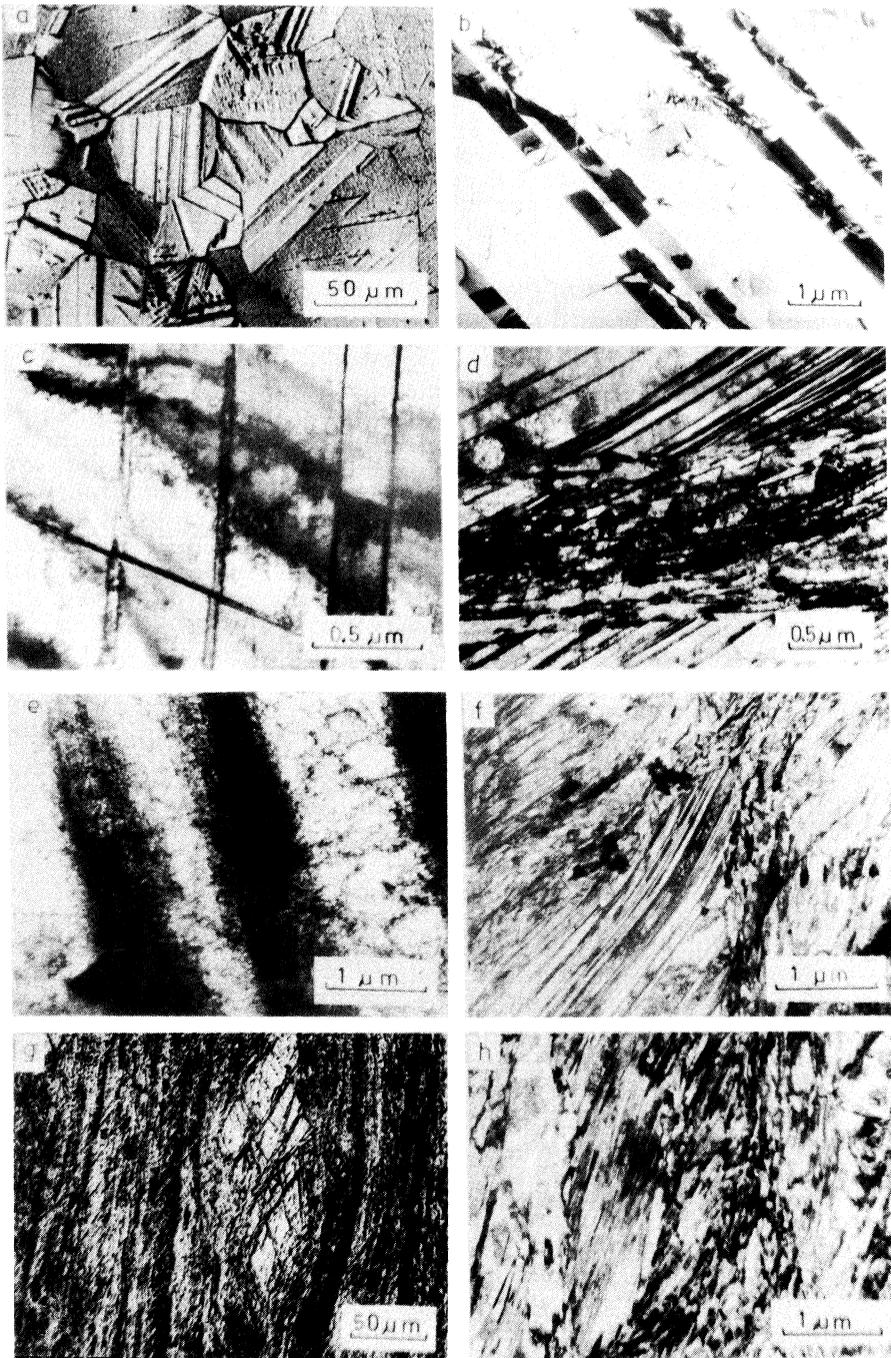


Fig.2 Microstructure of the rolled Cu-8wt%Ge alloy; reductions: a,b - 0%, c - 10%, d - 19.6%, e - 39.4%, f - 50%, g,h - 90%

rolling reduction, twinning intensifies embracing all the components of texture except the  $\{110\}\langle 001\rangle$  the density of which constantly increases up to about 90% reduction. The TEM observations of two samples deformed up to 50 and 70 pct rolling reduction have shown that isolated small regions free from deformation twins have the  $\{110\}\langle 001\rangle$  orientation. Similar observations have been made by several authors on low s.f.e. austenitic steel<sup>6</sup> and copper-silicon alloy<sup>7</sup>.

The characteristic feature of the observed changes in the rolling texture is that after initial tendency to the concentration of orientations in copper type position, in the medium range of the rolling reduction, the spreading of texture causes the drop in sharpness of texture, and this is due to the superposition of many above described mechanisms of deformation. It is only above 90 pct rolling reduction that the typical rolling texture appears, this process being accompanied by the diminishing of density in the  $\{110\}\langle 001\rangle$  position. Similar results have been obtained in our previous research into the formation of texture in rolled silver<sup>8</sup>. The quantitative analysis of the volume fraction and sharpness of several texture components appearing and vanishing during the rolling made possible the assumption of a sequence of orientations from  $\{112\}\langle 111\rangle$  to  $\{4\ 4\ 11\}\langle 11\ 11\ 8\rangle$ , the latter disappears gradually, undergoing a twin transformation into  $\{552\}\langle 115\rangle$ . In further rolling this component is being transformed into  $\{110\}\langle 001\rangle$  which sharpens gradually but at maximal deformations passes continuously into  $\{110\}\langle 112\rangle$ .

If, however, in case of silver it was possible to separate components of texture and describe them univocally, in copper-germanium alloy characterized by the still lower stacking fault energy a great frequency of twinning during the rolling induces superposition of components leading to a large scattering, not allowing the quantitative description of texture. It was only above 90% rolling reduction that separation of components became possible.

It follows from the above described mechanism of formation of the rolling texture in the Cu-Ge alloy that any description of the texture in low stacking fault energy f.c.c. metal, on the basis of freely chosen degree of deformation (as many authors do, e.g. Malin et al.), is ambiguous. Several texture components appear and vanish during the rolling and the frequency of changes is the higher the smaller the stacking fault energy is. Therefore, the full characteristics of the rolling texture can be obtained from the analysis of the whole process, the number of rolling reductions necessary to be examined being larger, the smaller is the stacking fault energy.

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