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Crystallographic analysis of shear bands initiation and propagation in pure metals
Part II. Initiation and propagation of shear bands in pure ductile rolled polycrystals

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THE PAPER deals with an experimental analysis of advanced plastic deformation and shear band initiation in rolled polycrystals. Material microstructure evolution is investigated in the process of deformation and shear band initiation. The tests were performed on annealed pure copper polycrystal specimens. Application of an original experimental technique enabled the authors to study the subsequent stages of the process of plastic strain localization and to draw a number of novel conclusions.

Praca poświęcona jest doświadczalnej analizie zaawansowanych odkształceń plastycznych i tworzenia się pasm ścinania w polikryształach poddanych procesowi walcowania. Zbadano ewolucję mikrostruktury materiału podczas procesu deformacji i powstawania pasm ścinania. Badania wykonano na polikrystalicznych próbkach czystej miedzi po wyżarzeniu. Dzięki zastosowaniu oryginalnej metody badawczej autorzy mogli zbadać szczegółowo kolejne etapy procesu lokalizacji deformacji plastycznych i dokonać szeregu nowych obserwacji.

Работа посвящена экспериментальному анализу развернутых пластических деформаций и образованию полос сдвига в поликристаллах, подвергнутых процессу катания. Исследована эволюция микроструктуры материала во время процесса деформации и возникновения полос сдвига. Исследования проведены на поликристаллических образцах чистой меди после отжига. Благодаря применению оригинального исследовательского метода, авторы могли подробно исследовать последовательные этапы процесса локализации пластических деформаций и провести ряд новых наблюдений.

1. Introduction

SHEAR BANDS are now considered as a mode of deformation and failure of polycrystals submitted to highly constrained conditions such as rolling.

Previous experimental works have attempted to correlate the formation of shear bands with the involved pure metal or alloy microstructure. Shear bands can grow in rolled polycrystals as soon as the strain is about $\varepsilon = 1$. At this stage, polycrystals usually exhibit a crystallographical as well as a morphological texture, characterized by a lamellar structure with grains or twins stretched along the rolling direction [1, 2].

In previous works [1, 2, 3], shear bands are analysed as very thin (0.1 μm thick) layers showing a $\pm 35°$ tilt with regard to the rolling direction and parallel to the transverse direction. These macroscopical bands (composed of several shear bands) are reported to cross the grains of the polycrystals without misorientation. Consequently, it is generally pointed out that the shear planes are not the crystallographic ones.

When focusing to a more microscopical scale, previous observations through TEM [3, 4, 5] showed that about 0.1 μm thick shear bands were made of dislocation cells stretched in the shear direction. The misorientation between these cells could reach 30°.

As a matter of fact, the stacking fault energy as well as the grain size might be considered as outstanding features ruling the onset and the growth of shear bands.

This onset of shear bands corresponds to a threshold strain equal to about $\varepsilon = 1$ in alloys such as Cu—Zn, Cu—Si, Al—Mg with a low stacking fault energy (< 20 mJm^{-2}). As ε is increased to about $\varepsilon = 3$, 95% of the bulk is filled with shear bands [1]. Two kinds of shear bands (able to intersect each other) have been simultaneously observed in such materials and they might lead to the observed transition from copper texture to brass texture with increasing deformation [3].

In pure metals such as copper and aluminium, which have a higher stacking fault energy (> 40 mJm^{-2}), the shear bands onset corresponds to a threshold strain up to $\varepsilon = 2$ [1]. At $\varepsilon = 3$, the affected proportion of the bulk is only 5%. In this case, no intersection of the two kinds of shear bands has been observed [2].

Concerning the grain size effect, experiments [3] carried out on brass samples report that the threshold strain and the amount of volume containing shear bands are decreasing with increasing grain size.

Our purpose is to make clear how shear bands grow and propagate in polycrystals, especially in a given grain and its closest neighbours as the rolling strain is increased. As a first stage, the present work reports step by step observations carried out on rolled polycrystals. Such observations may be easier if a few shear-bands only are initiated in the samples. Consequently, pure copper polycrystals were chosen in our experiments.

2. Experimental procedure

In order to be able to observe the propagation of shear bands in polycrystals, an average grain size larger than 500 μm is required. Such polycrystals were obtained by annealing of a sheet of pure copper at 800°C during one hour under argon atmosphere.

Parallelepipedic samples ($30 \times 7 \times 3$ mm^3) were cut out (by spark machining) in the sheet and rolled at room temperature. The longitudinal sections were observed through a SEM at different stages of deformation. In order to point out the displacement induced by shear bands, the longitudinal sections were polished and the grain boundaries revealed by chemical etching. Fiducial grids were then set down by a photoresist technique using the electron beam of a SEM [6]. In this way, a lmm^2 square grid with a 100 μm mesh size and an average 2 μm grid width line was obtained.

As an example, a fiducial grid set at $\varepsilon = 1$ on a copper polycrystal, then deformed at $\varepsilon = 1.4$, is given in Figs. 1a and 1b. In Fig. 1b one can see simultaneously the grain boundaries, the activated slip systems and the shearing of the grid due to shear bands.

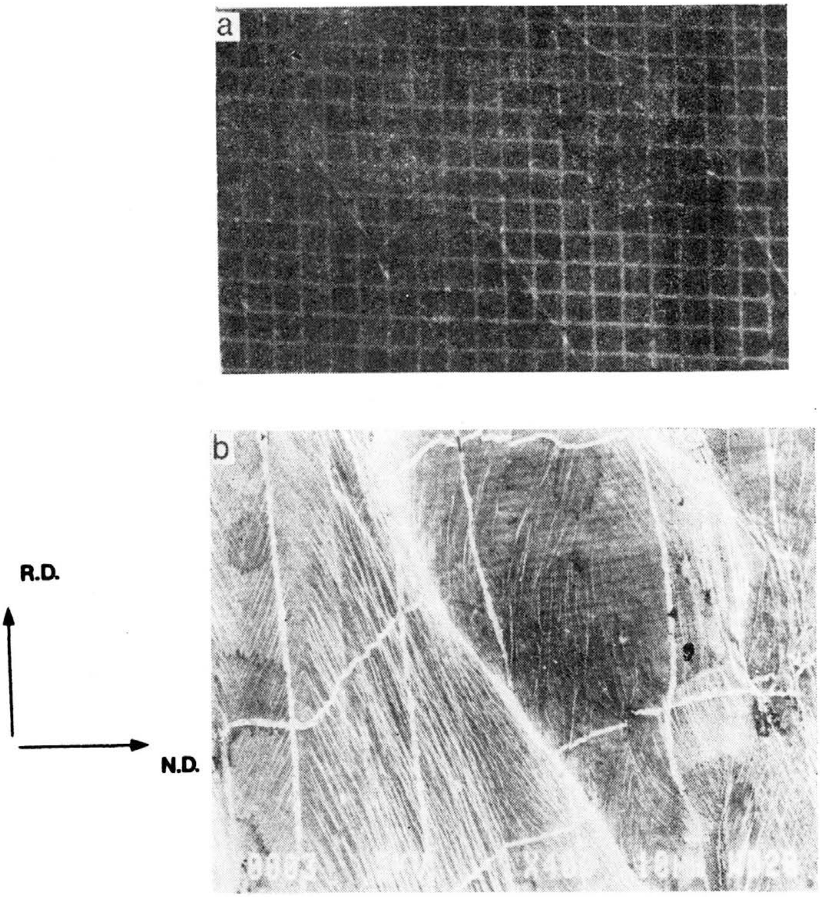

FIG. 1. a) Example of fiducial grid with 100 μm mesh size. b) Fiducial grid after cold rolling to $\varepsilon = 0.9$.

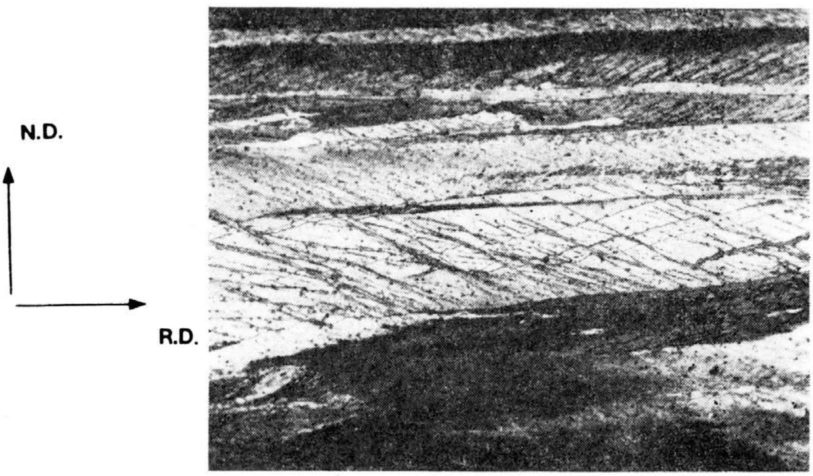

FIG. 2. Pattern of the observed copper polycrystal cold rolled to $\varepsilon = 1.4$.

3. Experimental results

Eight grains hereafter named A, B ... H separated by nearly "parallel" grain boundaries were chosen in the polycrystal and observed at three stages of rolling deformation ($\varepsilon_1 = 1.47$, $\varepsilon_2 = 1.54$, $\varepsilon_3 > 1.61$, respectively).

The fiducial grid laid on the sample at $\varepsilon = 1.4$ helped us to point out the localized shearing and therefore the progression of the shear bands. The pattern of the studied sample can be seen at $\varepsilon = 1.4$ in Fig. 2.

Stage $\varepsilon = 1.47$ (Fig. 3)

No shear band was observed in grains B, C, G and H. In grains A, shear bands stopped at some distance to the grain boundary (A/B). On the contrary, shear bands began (or

a

b

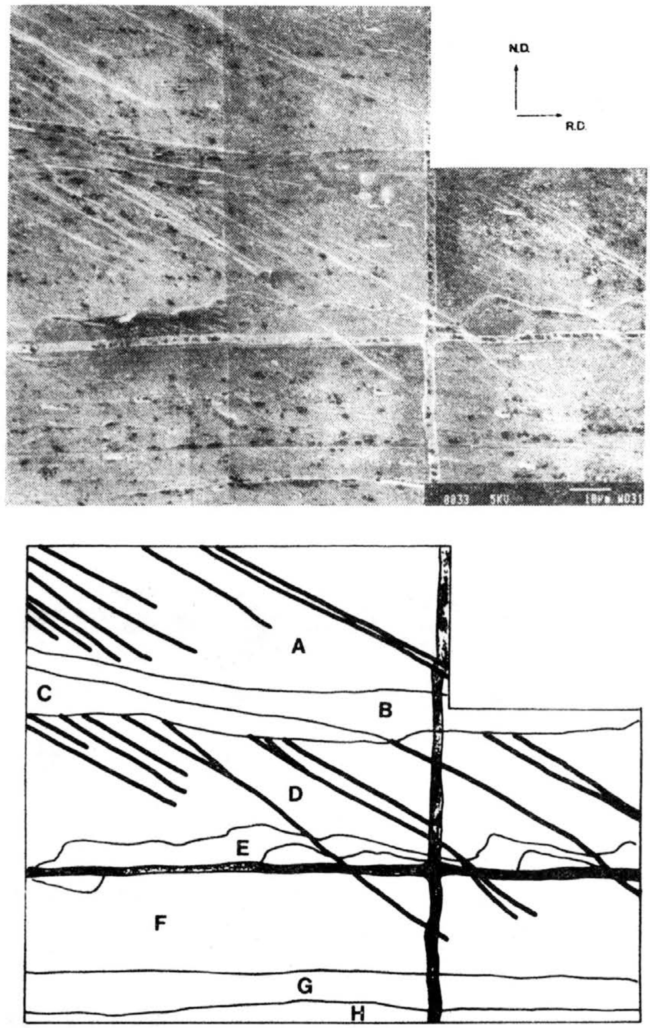

FIG. 3. a) Shear bands in copper rolled to $\varepsilon = 1.47$. b) Sketch of the observed shear bands in the different grains of the copper polycrystal.

stopped) on the C/D grain boundary and some of them crossed D/E and E/F boundaries. Shear bands induced an offset of the grid in grains D and F, but the grain boundaries D/E and E/F did not exhibit any shearing. In this last case it can be considered that the intersection of shear bands and grain boundaries occurred after the grid was laid on. The angle between the observed shear bands and the rolling axis was nearly 35°.

Stage $\varepsilon = 1.54$ (Fig. 4)

New shear bands parallel to the former ones were observed. Some of them contributed to widen the already existing macroscopical bands in a given area whereas others crossed the grain boundaries so that they penetrated the B, C grains.

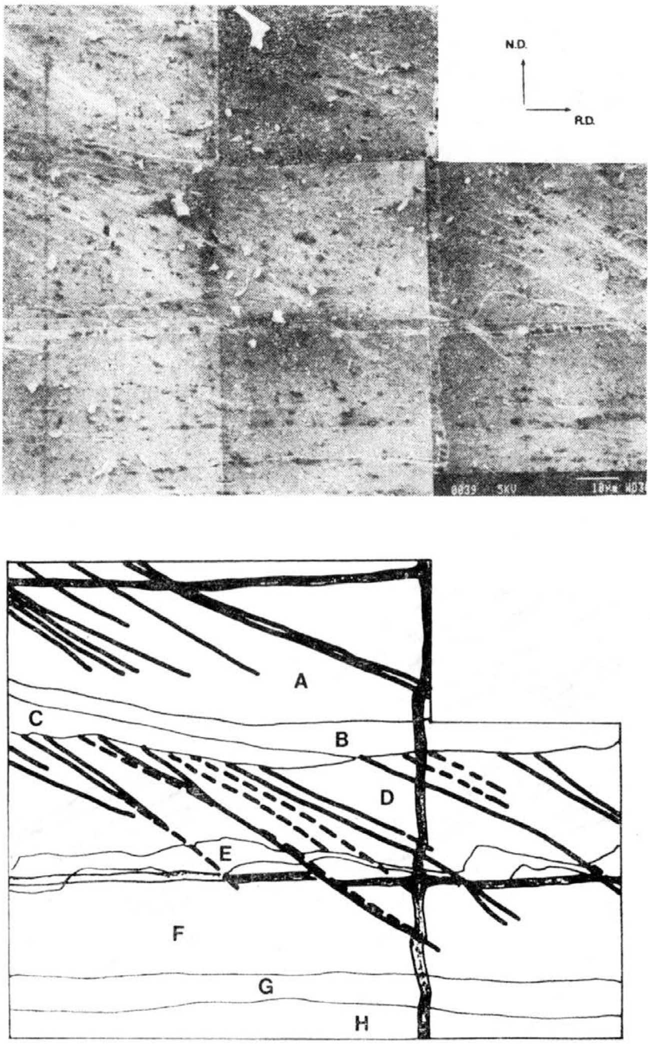

FIG. 4. Shear bands in copper cold rolled to $\varepsilon = 1.54$. The dashed lines represented the new activated shear bands compared to Fig. 3.

In both cases, the new shear bands induced a shearing of the fiducial grid. A qualitative evaluation of the shear intensity γ assuming a 0.1 μm width of shear band leads to about $\gamma \simeq 5$. These observations supported the following assumption: the shearing intensity depends on the number of shear bands gathered in the macroscopical band, the width of each individual microscopical shear bands being constant.

Stages $\varepsilon > 1.61$ **(Figs.** 5, 6)

At latter stages of deformation, junctions of shear bands in grains B, C and D were observed. The junctions were constituted by shear bands presenting a slight variation of orientation as compared to the former ones.

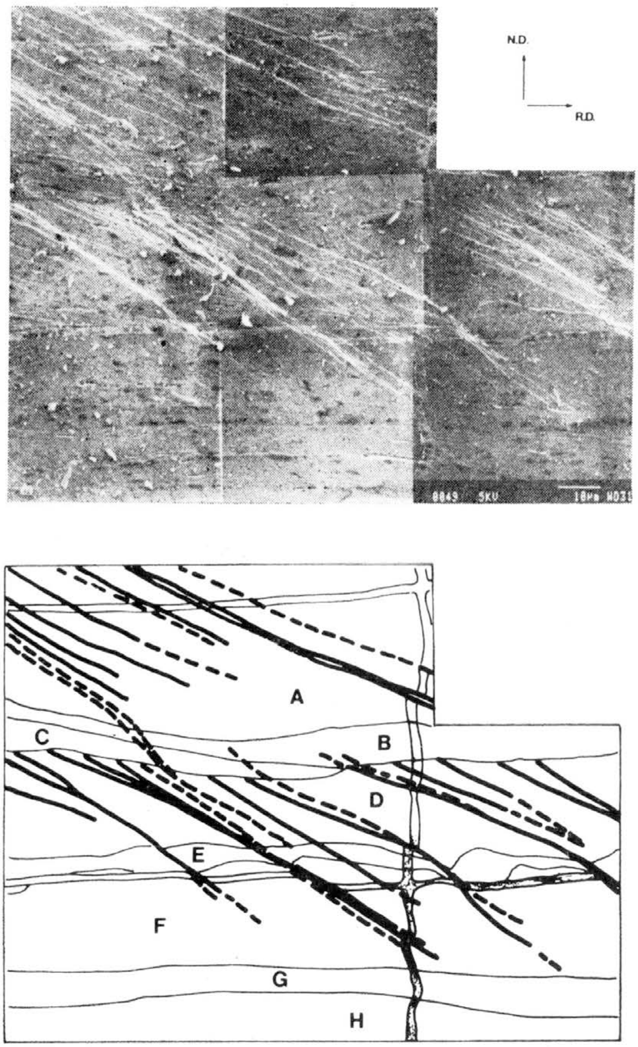

FIG. 5. Shear bands in copper cold rolled to $\varepsilon = 1.61$.

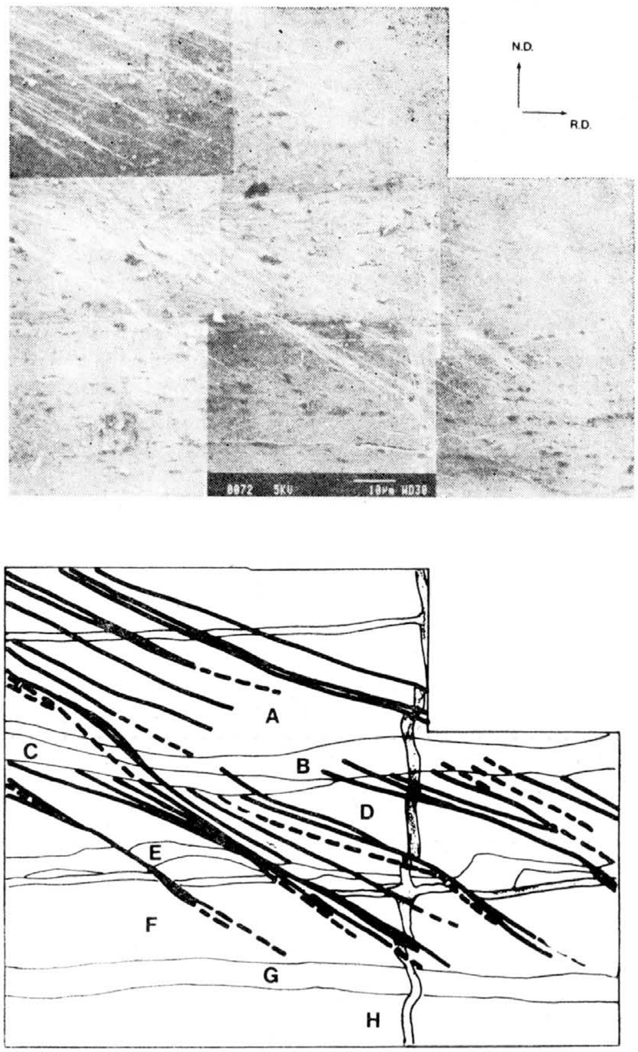

FIG. 6. Shear bands in copper cold rolled to $\varepsilon = 1.70$.

At this stage of strain, slip bands could be seen in all the grains, but their weak intensity led to assume that the whole deformation was due to the shear bands activation. This last assumption was confirmed by the following experimental result: large increment of strain equal to about $\Delta\varepsilon = 0.3$ was necessary to give rise to new visible slip bands after a chemical polishing of the sample surface.

The analysis of shear bands propagation showed that they grew only in a few grains of the studied polycrystal. No checking of the orientation of such grains could be possible here, owing to the small average grain size, but, according to the single crystal behaviour deformed by rolling [7], we may assume that these "first" shear bands appeared in some especially "well" oriented grains and had crystallographic shear planes. On the other hand, it was not necessarily the case for shear bands activated in the neighbouring grains for higher deformation. As a matter of fact, though the polycrystals presented morphologic and crystallographic textures, the observed misorientation of the activated slip planes pointed out a large crystallographic misorientation of the grains. Consequently, the subsequent parallel shear planes of the shear bands activated in the whole polycrystal could not be crystallographical ones. Nevertheless the deformation inside the shear bands may have a crystallographic nature depending on the activated slip systems.

4. Conclusion

Our observations of microscopical shear bands by means of fiducial grids at different stages of rolling pointed out that the shearing intensity is proportional to the number of microscopical shear bands activated inside macroscopical ones, considering that the width of the microscopical shear bands is constant [4].

According to our observations, it may be assumed that the first shear bands appeared in some especially oriented grains and then activated near the grain boundaries of the adjacent grains new parallel shear bands with increasing deformation. These latter shear bands may be activated by the internal stresses induced by the impingement of the former ones by a grain boundary.

In order to check this hypothesis, we have undertaken a calculation of the internal stresses for such a situation. Moreover, to make clear the onset and the propagation of shear bands in the grains of polycrystals, the deformation by rolling of plane boundary bicrystals is now under investigation. According to Morii's previous work on single crystals [7], one grain is oriented in order to allow an observation of the onset of shear bands and the other one in order to make the analysis of the propagation possible.

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