STRAIN SOFTENING EFFECTS DURING CROSS-ROLLING OF ALUMINUM

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Abstract

The change of the deformation path during plastic deformation of metals leads to destabilization of the dislocation substructure and in consequence, causes transgranular strain localization in the form of shear bands. Such a dramatic evolution of the mode of plastic flow must obviously influence the mechanical performance of the material during straining and its post-deformation properties.

In the present work it is experimentally shown that during secondary deformation in the cross-rolling experiment, shear banding becomes a dominating mode of the plastic flow. This effect is accompanied by much smaller strain hardening than that caused by the equivalent strain increment during monotonic rolling. Such a response of the materials to the change of the deformation path opens new perspectives in design of the energy efficient metal forming operations.

Introduction

The results of the studies of features of the heterogeneous deformation and conditions under which it becomes competitive or alternative form of plastic flow in metals [1-3] seem to provide sufficient arguments, that the technological operations of metal forming are to be reconsidered from the point of view of the mode of the plastic deformation of metals. These arguments led us to the conclusion that there is possible, in a very practical way, to reduce the energy needed for forming a metallic material and to improve the final properties of the product. Let us , therefore, recall the most fundamental observations and discuss the physical backgrounds which stand behind our understanding of the nature of strain localization.

The observations of the topological features of shear bands reveal that they concentrate very large deformation within a very narrow plate (micro shear band) of the material which extends across many grains, often throughout the material. When several micro shear bands stack, forming a macroscopic shear band, than the global deformation reveals the features of pure shear [4]. Deformation within the micro shear band shows, therefore, the same property as the slip in a crystal, except that now plane of shear does not need to be the plane of easy slip (dislocation glide plane) in the crystal lattice. Although the crystal symmetry discriminates slip in non-easy systems it does not, however, exclude such a possibility, provided that the characteristic for non-easy system critical shear stress is attained. Examples of slip in non-easy systems are well known from the experiments on hexagonal crystals.

From the experiments we have also learned that the change of the mode of deformation from a homogeneous multi system slip into shear banding may be easily induced by the change in the set of operative (easy) slip systems [5]. The physical motivation to this effect, regardless whether a particular dislocation-dislocation interaction or destabilization of the existing substructure (obstacles network) due to the secondary slip caused reorientation in the crystal is considered, consists itself in the formation of a softer path (locally softened plane) along which a catastrophic, highly collective glide of dislocations develops (transsubstructural coarse slip). Such a collective glide of dislocations (dynamic pile-up [6]) may generate sufficient stress concentration that the slip (shear) in non-easy system of the neighboring grain is to be activated [7]. Another words, the energy of the pile-up configuration does not disperse at the grain boundary but gives rise to the transgranular shear in the common for neighboring grains system.

Finally, if we invoke the energy argument like that used by Taylor [8] it becomes obvious that deformation due to shear banding needs less energy than equivalent deformation due to homogeneous multi system slip. This is because a transgranular shear does not generate the internal constraints (incompatible deformation from grain to grain), as the displacement field is uniform across several grains. There is no need, therefore, to activate slip in five systems in every grain and to spend the energy in each of them. In particular, under the plane-strain conditions (the case of rolling) one shear system (one family of shear bands) can carry an imposed rolling deformation.

The energy argument may be also considered in terms of the change of the free energy of the material. The amount (density) of the stored dislocations is much smaller in the case of shear banding (one system, very large free path of the dislocation movement). Hence the increase of the crystal free energy is also smaller than that during equivalent homogeneous deformation. Both these arguments lead to the conclusion that shear banding is the energy saving mode of deformation. It also accumulates less energy within the material and from this point of view is thermodynamically preferred. In a very practical sense this means that, if we can replace a homogeneous multi system slip by shear banding, we may expect a significant reduction of the work done during deformation. We may expect also that then the material will shown a different mechanical properties because of the different spatial arrangement and density of the stored dislocations.

The purpose of this work is to provide the experimental information about the magnitude of the expected effects in the case of the industry important rolling deformation.

Experimental

The rods of commercial purity aluminum of 12.6 x 9 mm cross-section and 20 μm average grain size were subjected to the equivalent rolling deformation in room temperature in two different schemes of straining: monotonic and cross-rolling. In both cases the final shape of the test piece was the same and total deformation in terms of the relative cross-section reduction was about

37%. The deformation was imposing in two rolling passes. The first, common for both variants of straining, caused the change of the shape of the rod from rectangular into 10 x 10mm square. The subsequent (secondary) monotonic rolling caused farther the reduction of the sample height. The cross rolling, which was due to the rotation of the sample by 90° around the rolling direction, caused in turn, the reduction of the sample width.

The experiments were conducting by using specially designed device (Fig.1) which was driven by the tensile machine (Instron). This allowed to use the machine load cell and recording system to make the direct measurements of the "rolling force" in each stage of the rolling experiment and to quantify the effect of scheme of straining on the rolling force. The tensile tests of the samples were used, in turn, to evaluate the effect the scheme of straining upon the material properties. The information about the mode of plastic flow was drawn from the micro structural observation.

Results and discussion

The records of the rolling force versus time of rolling are shown in Fig.1.

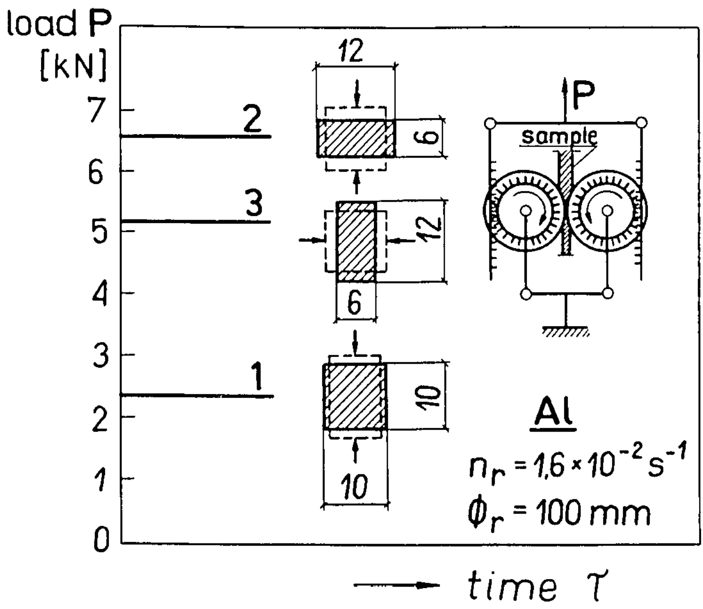
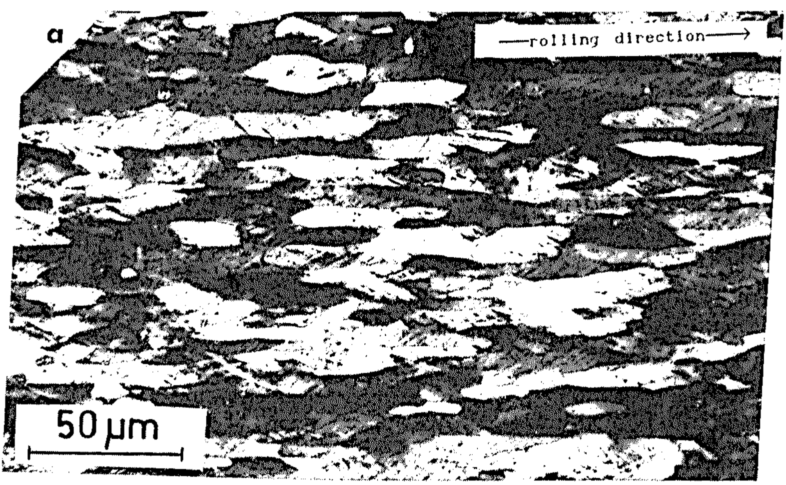


Figure 1. Mechanical characteristics of aluminum during monotonic and cross-rolling. Dimensions of the roll pass designs, scheme of the testing and measuring device are also shown.

The line "1" shows the rolling force during primary rolling (first pass). Lines "2" and "3" give the values of the rolling force during secondary monotonic and cross-rolling respectively. The difference between P_2 and P_3 forces is about 23% what means that the cross-rolling, which brings to the geometrically equivalent final shape (equivalent strain) of the test piece as the monotonic rolling needs about 23% less energy. This effect results from a much smaller strain hardening of the metal during secondary cross-rolling. If we take as a measure of the metal strain hardening the relative difference of the rolling forces: $(P_2 - P_3) / P_1$ than, at the fixed value of the secondary strain $\varepsilon_s = 0.28$, it appears that cross-rolling reduces the hardening rate to the level of about 60% of that during monotonic rolling. An alternative measure of the strain hardening are the ratios : $(P_2-P_1)/\varepsilon_s$ and $(P_3-P_1)/\varepsilon_s$. Under the experimental conditions they assume the value of 15.4kN and 10.2kN respectively. And again, when compared with one another, they show that the strain hardening during the cross-rolling variant of the secondary deformation is about 34% less than during monotonic straining.

Such a large difference in the metal behavior during geometrically equivalent deformation imposed with the same rate in the same (room) temperature must be motivated by the difference in the mechanism of plastic flow. The structural observations allowed to distinguish in the structure pattern of the metal the features which reflects the difference in the mechanism of the plastic flow. In particular, the cross-rolling generates shear banding which becomes a dominating mode of the deformation.

This may be seen in figures 2 and 3 which are show the micro structures of aluminum, revealed in the section parallel to the secondary rolling direction after secondary monotonic (Fig.2) and cross-rolling (Fig.3).



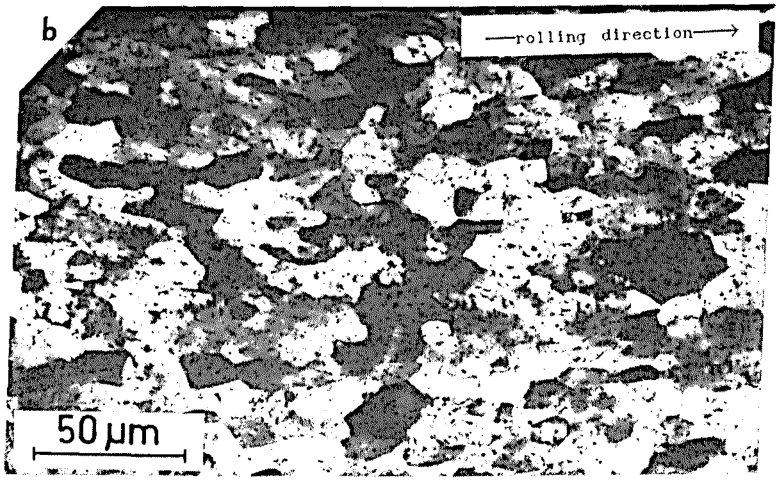
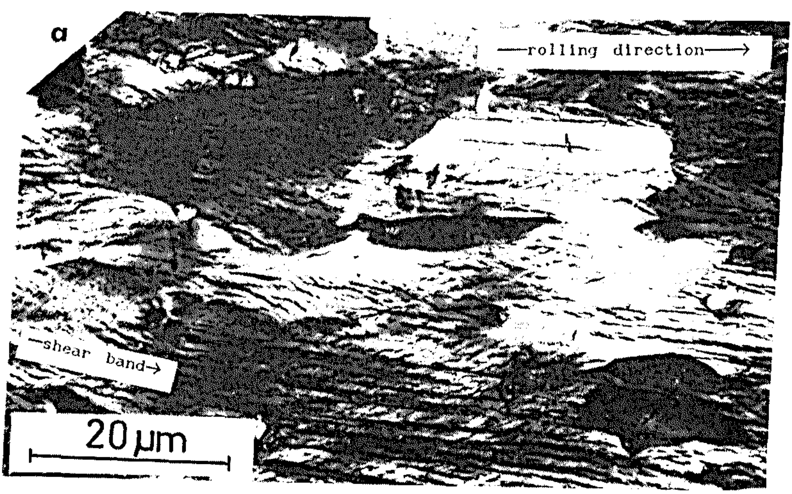


Figure 2. Optical micrograph of monotonically rolled aluminum revealed by etching. View of a section parallel to lateral surface of the test piece (a) and a section parallel to the rolling plain (b).



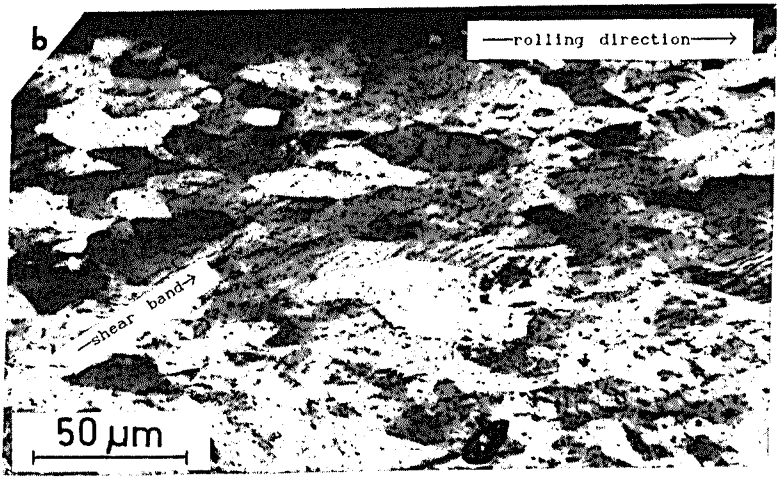


Figure 3. Shear bands in aluminum after cross-rolling, revealed by etching in section as in Fig. 2.

Fig. 3 shows that deformation concentrates within shear bands, which reveal the property of transgranular spreading. Only very few and weakly marked shear bands were observed in the sample after monotonic deformation (Fig.2).

The results of the tensile test performed on samples of the metal taken from every variant of the secondary rolling are shown in Fig.4.

The difference in the tensile curves clearly reflects the significant effect of the history of straining on the mechanical properties of the metal.

The observations confirmed, therefore, that the change of the scheme of straining causes a substantial change of the mode of plastic flow from a homogeneous fine slip in several systems into shear banding in the one (Fig.3) but the most often in two symmetrical systems. Such a change is accompanied by significant decrease of the global strain hardening of the metal during the forming operation.

The results of the experiments seem to be important because of two reasons. First of all they well support the predictions based upon some physical arguments and understanding of the nature of shear bands in metals. Secondly, they prove that there is possible to control the mode of deformation and through this technological parameters of the process (load, energy, material properties). They also point to an urgent need to redesign the metal forming operations in terms of the energy saving modes of the plastic flow.

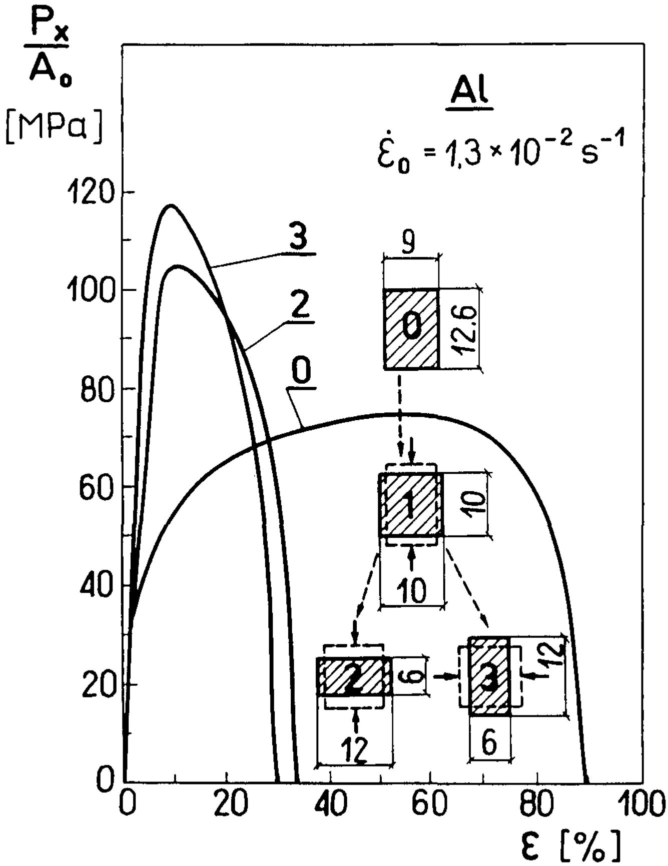


Figure 4. Tensile curves of monotonically (line 2), cross-rolled (line 3) and virgin aluminum.

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