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The degradation of selected-area channelling patterns as a function of glide anisotropy

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The study of selected-area channelling pattern (SACP) degradation with deformation was performed using lines representing different sets of planes. It was established that the degradation of different lines on the SACP taken after a given deformation was not the same. It differs not only for lines from different sets of planes but also within the same type of line. The amount of relative line broadening depends on the position of a given plane with respect to the glide plane and direction. It tends toward a maximum for SACP lines from those planes perpendicular to the Burgers vector and a minimum for those parallel to that vector. It is proposed that at the beginning of the deformation process, while only a few systems operate, this phenomenon is most pronounced because of glide anisotropy.

1. Introduction

The selected area channelling pattern (SACP) technique is becoming a useful tool for the study of deformation in polycrystalline materials, even those with very fine grains [1]. This has been made possible by the ability to follow the strain developing in an area on the order of a few micrometres in diameter [2, 3]. Two types of information, such as slip traces observed on the surface of the specimen (topography contrast [4] or slip bands made visible using channelling contrast [5], together with SACPs providing crystallographic data, give a strong base for discussing details of the deformation process. In addition, SACP line broadening allows an evaluation of the strain level in the area being sampled. This assessment can be done simply by the comparison of the "quality" of the SACP with some standards obtained for a given deformation, or by using standard calibration curves.

Although the first method allows one to evaluate the strain with an accuracy of 1% [6] the second one is probably more often used [7]. Unfortunately, such calibration curves relating strain or dislocation density [8] with SACP line resolution are not universal. They are different not only for materials of different crystal structure, but also for materials exhibiting different dislocation arrangements after deformation [9]. Since the dislocation substructure is also a function of loading mode, these calibration curves also depend on the load history [10]. For example, the subcell structure developed by fatigue strongly influences the results obtained by SACP techniques compared to monotonic loading. Neglecting this fact may lead to an incorrect interpretation [11]. The characteristic feature of the calibration curves is a rather large scatter band for experimental data. We know that the deformation process of the crystal is not isotropic. Because of this anisotropy of deformation it should be expected that the SACP line degradation will proceed differently in the electron channelling pattern (ECP) bands possessing different Miller indices [7]. The purpose of this paper is to verify if and how much the degradation of SACP lines depends on the crystallography of slip in the case of b c c structures.

2. Experimental procedure

Miniature tensile samples with a diameter of 3 mm and gauge length of 10 mm were prepared from high strength, low alloy (HSLA) steel having a composition (wt %) of 0.07 C, 0.51 Mn, 0.03 Si, 0.01 Al and 0.014 Nb. The average grain size was approximately 120 μm. To ensure a constant position of the specimen with respect to the optical axis of the scanning electron microscope (SEM) a part of the thread crest was removed. After that, the central part of the sample was electropolished using the one-jet method. This removed any microroughness or deformed outer layer as might have been introduced by machining. The samples were then observed in the SEM in an undeformed state and a few grains lying in the plane perpendicular to the electron beam were studied. Both electron micrographs and SACPs were recorded. The specimens were then loaded by low-cycle fatigue in tension–tension at a frequency of 0.2 Hz. The average strain, ε, was equal to 6%. The same grains were observed in the SEM and the next set of micrographs was prepared. The surface strain for each particular grain was evaluated simply by measuring their elongation in the direction of pulling.

The resolution of SACP lines was determined on the basis of microdensitometer traces taken across the same lines before and after deformation. To compare the different line degradations, at least two lines representing planes of different hkl indices were chosen from each SACP. This provided a data set

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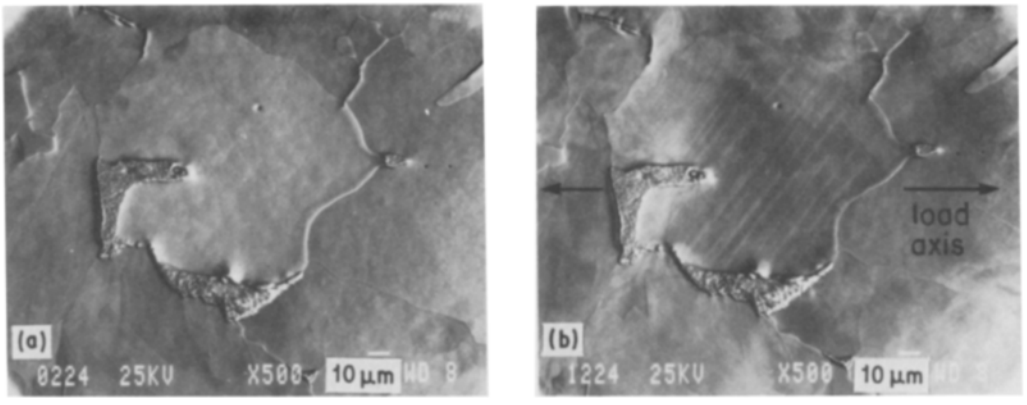

Figure 1 One grain in HSLA steel: (a) before deformation, (b) after deformation by fatigue up to $\varepsilon = 9\%$.

concerning the resolution change of given SACP lines at exactly the same deformation level. A problem in determining the position of the maximum and minimum, especially on microdensitometer traces taken after deformation, has forced us to very carefully investigate line shapes and how they change depending on their position. For this purpose a minimum of five microdensitometer traces spaced at approximately 0.5 mm intervals on the micrograph were taken across a relatively "clean" part of the line on the SACP. Eventually some "extra" maxima or minima had to be subtracted to find the position of the "real" one. A discussion of these "extra" maxima or minima is given in detail elsewhere [11]. This method, although time-consuming, was necessary to evaluate rather small differences. The quality of the channelling pattern is represented in terms of the line width ratio, m, which is the final line width after strain, $w(\varepsilon)$, normalized by the initial line width, $w(0)$, prior to straining.

3. Results and discussion

In Figs 1a and b, one of the grains before and after deformation is shown. In this case the strain measured parallel to the direction of loading was equal to 9%. Simultaneously, two sets of slip bands intersecting the free surface are visible. These slip lines form with the loading axis at angles of $\alpha_1 = 44.5°$ and $\alpha_2 = 55°$, which means that the angle between them is $\alpha \sim 99.5°$. The next two micrographs (Figs 2a and b) show SACPs taken from the grain in Figs 1a and b, respectively. These selected area channelling patterns, indexed according to a channelling map [4], exhibit three pronounced bands: (2 0 0), (1 2 $\bar{1}$) and (1 $\bar{2}$ 1) intersecting in an [0 2 4] pole. The [0 2 4] pole, being first situated approximately at the centre of the SACP, has shifted by about 2° after deformation. This means that the crystal lattice had to change its orientation with respect to the electron beam axis. The trace analysis based on these SACPs was performed using a stereographic projection and the assumption that the [0 1 2] pole lies in the centre of this projection. Taking into account the rotation [3, 12] between the SACP in Fig. 2b and the micrograph in Fig. 2a showed that the slip traces observed in Fig. 1b are intersections of the grain-free surface with ($\bar{2}$ 1 1) and (0 $\bar{1}$ 1) planes. This means that the operating slip systems are ($\bar{2}$ 1 1) [1 1 1] and (0 $\bar{1}$ 1) [1 1 1].

The deformation of the crystal structure causes lattice distortion which in turn brings about degradation of the SACP. The microdensitometer traces have been taken across the second-order lines of (2 0 0), (1 2 $\bar{1}$) and (1 $\bar{2}$ 1) at the places marked by the small squares. The results of these measurements are shown in Table I. It follows from the table that the average $\bar{m}$ values representing the degradation of the SACP line are different depending on the line being chosen. This effect can be partially explained by the different geometry of backscattering caused by the tilting of the grain. This tilting would mostly influence the (1 $\bar{2}$ 1) line broadening because its position is nearly perpendicular to the direction of tilting. The other lines connected with (2 0 0) and (1 2 1) bands have practically the same position with respect to that direction, and any

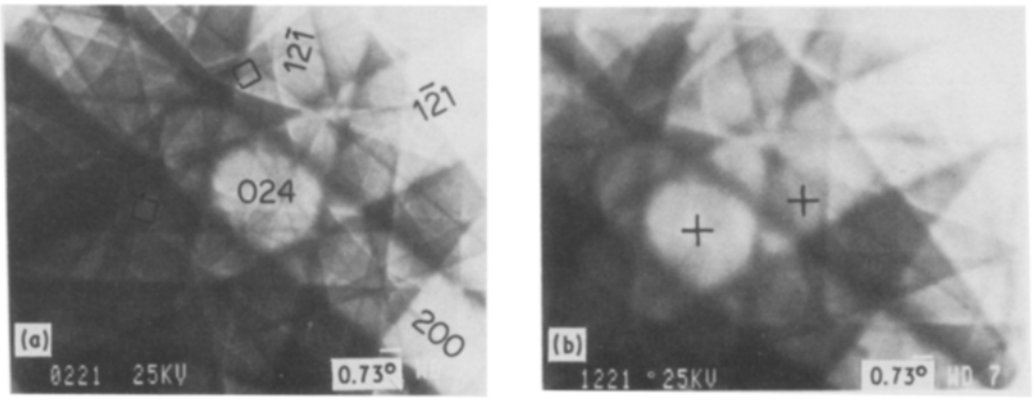

Figure 2 SACPs from the same grain of the HSLA specimen (a) before deformation and (b) after deformation up to $\varepsilon = 9\%$.

TABLE I Measurements of SACP degradation for different $h\,k\,l$ values

Sample No.	(2 0 0)			(1 $\bar{2}$ 1)			(1 2 $\bar{1}$)		
	w(mrad)		$m = \frac{w(\varepsilon)}{w(0)}$	w(mrad)		$m = \frac{w(\varepsilon)}{w(0)}$	w(mrad)		$m = \frac{w(\varepsilon)}{w(0)}$
	$\varepsilon = 0\%$	$\bar{\varepsilon} \sim 9\%$		$\varepsilon = 0\%$	$\bar{\varepsilon} \sim 9\%$		$\varepsilon = 0\%$	$\bar{\varepsilon} \sim 9\%$	
1	1.91	2.93	1.53	1.72	2.8	1.63	3.44	4.84	1.41
2	1.94	2.93	1.51	1.53	2.36	1.54	3.44	4.78	1.39
3	2.3	2.87	1.25	1.74	2.99	1.72	3.5	5.1	1.46
4	1.91	2.67	1.40	1.78	2.99	1.68	3.38	5.73	1.69
5	2.04	2.8	1.37	1.78	2.8	1.57	3.44	5.1	1.48
6	–	–	–	–	–	–	2.8	5.1	1.82
	$\bar{m} = 1.41 \pm 0.11$*			$\bar{m} = 1.63 \pm 0.07$*			$\bar{m} = 1.54 \pm 0.17$*		

*Standard deviation.

additional broadening should be the same or even a little larger for the (2 0 0) band. As is known, dislocations have a small core region of heavy atomic distortion (~ 1 nm) and a much larger region of elastic distortion. These cause bending of the lattice planes which in turn decollimates the electron beam.

From the geometry of slip, it appears that the deformation caused throughout, e.g. the bending of planes, will not be the same for different crystallographic planes. It should depend on the relative position of a particular set of planes with respect to the slip system, being maximum for those planes perpendicular to the Burgers vector and zero for the planes which include this vector. The sketch in fig. 3 shows a simplified situation with two sets of planes being perpendicular to each other and only one of these an active slip system. It is easily seen that an appropriately large number of such dislocations sliding on the same glide plane will cause bending of the crystal lattice in the plane perpendicular to the dislocation line. On the other hand the second set of planes perpendicular to the first one will not experience any lattice bending except perhaps at the termination points of dislocation lines, i.e. at some network. It follows that the maximum SACP line broadening should be observed across the lines representing crystal planes perpendicular to the Burgers vector. This broadening should decrease with deviation from that "critical" position. If β denotes the angle between the Burgers vector and a given set of planes, then line broadening $\Delta w = f(\varepsilon)$ can be described as follows:

$$\Delta w = \Delta w_{\max} f(\beta)$$

being

$$\Delta w = \Delta w_{\max} \quad \text{for } \beta = \frac{\pi}{2}$$

$$\Delta w = 0 \quad \text{for } \beta = 0$$

where

$$\Delta w_{\max} = \Delta w\left(\varepsilon, \beta = \frac{\pi}{2}\right)$$

An example shown in Fig. 4 presents the SACP taken from the grain cyclically deformed up to $\varepsilon = 15\%$. It is very easy to see that the lines representing the same family of planes like (1 0 $\bar{1}$) and (0 1 $\bar{1}$) exhibit different acuity. In the case of the first one even the fourth-order lines are still visible while in the case of the (0 1 $\bar{1}$) band, only the second-order lines are clear. The

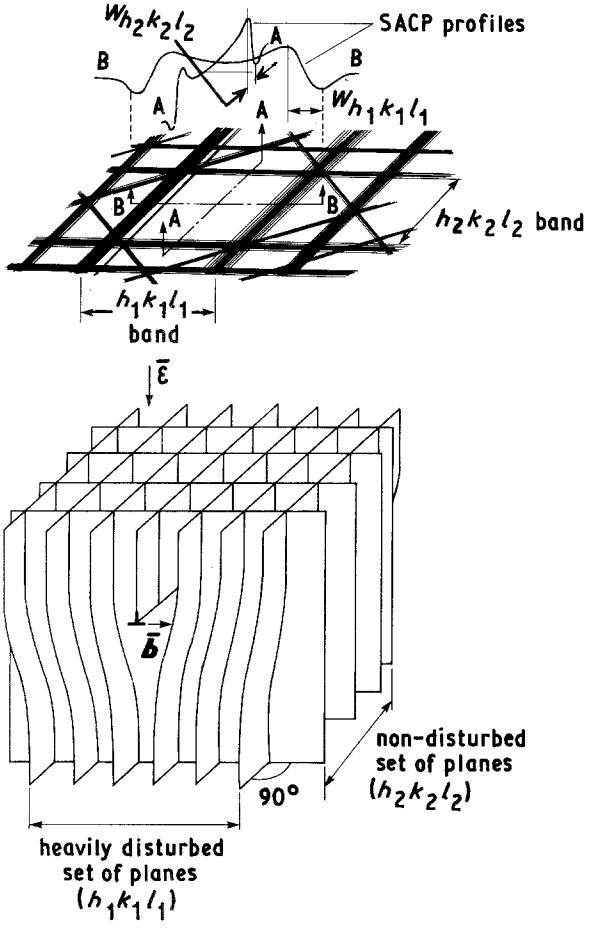

Figure 3 Sketch illustrating the deformation of two sets of planes caused by an edge dislocation; $w_{h_1k_1l_1} > w_{h_2k_2l_2}$.

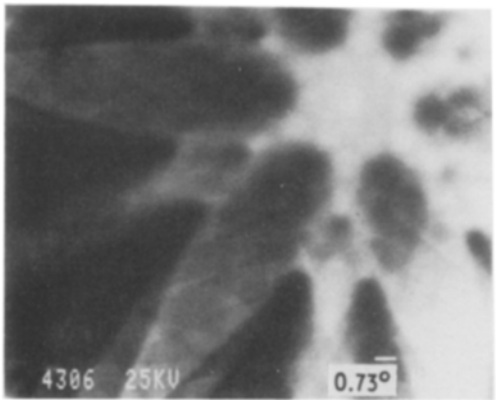

Figure 4 An SACP from a [1 1 1] pole showing differences in acuity of ECP lines from planes of the same family {1 1 0}.

third-order line is very diffuse as seen in the lower left corner of Fig. 4. The geometry shown in Fig. 3 is oversimplified, since in reality several slip systems usually operate.

Let us calculate the angles, β, and their respective cosines between the planes represented on the SACP (Fig. 2) and the Burgers vector [1 1 1]. These are as follows:

$$\cos \beta^{111}_{200} = 0.577 \quad \beta^{111}_{200} = 54.7°$$
$$(m = 1.41 \pm 0.11)$$
$$\cos \beta^{111}_{12\bar{1}} = 0.471 \quad \beta^{111}_{12\bar{1}} = 61.9°$$
$$(m = 1.54 \pm 0.17)$$
$$\cos \beta^{111}_{12\bar{1}} = 0.00 \quad \beta^{111}_{12\bar{1}} = 90.0°$$
$$(m = 1.63 \pm 0.07)$$

The comparison of how the angles are changing with the ratio m given in Table I shows the right tendency as proposed above. Consequently, this quantitatively confirms the hypothesis that the SACP line broadening depends on the position of a particular crystal plane with respect to the glide system.

It should be mentioned that if a previously developed calibration curve were now utilized [10], the apparent strain represented by the furthest disparate lines would be 9.7% compared with 17.9%. Thus, one should be careful to use similar line types or an average of lines from selected planes, particularly in the early stages of deformation.

4. Summary

The study of SACP degradation with deformation was performed using lines representing different sets of planes. It was established that different lines degraded more or less for the same deformation level. The amount depends on the position of each plane with respect to the glide plane. It is proposed that, at the beginning of the deformation process where only one or at most a few systems operate, this phenomenon is pronounced because of anisotropy of glide. At higher deformation levels where many systems start to operate, the deformation becomes more uniform and, consequently, the lines on SACPs degrade in nearly the same way.

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