INVESTIGATION OF THE PLASTIC DEFORMATION DURING CLEAVAGE FRACTURE

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In most cases no or very little plastic deformation accompany cleavage fracture and therefore cleavage fracture is generally classified as a brittle type of fracture. In this paper we present a way how small contributions of plasticity during that "brittle" fracture process can be measured and analysed. For that we carefully investigated both fracture halves of a specimen with the EBSD (Electron Back Scatter Diffraction) technique in the SEM (Scanning Electron Microscope). By comparing the orientations of homologue areas of one cleaved grain orientation relationships can be analysed. As a model material we used technically pure iron which has been cleaved at 77K. The misorientation found lies above the measurement inaccuracy and therefore the misorientation should be related to a plastic deformation during cleavage fracture.

INTRODUCTION

Metals can fail by cleavage under conditions where plastic flow is severely hindered, i.e. low temperature and/or a high deformation rate favour this mode of fracture. Under such conditions virtually no macroscopic plasticity accompany cleavage fracture and therefore this mode of fracture is generally seen as brittle[1-3]. The catastrophic results when engineering structures failed by cleavage is well documented in the literature and nowadays materials are not used for structural applications when there is even a slight risk of cleavage fracture. However, for the development of intermetallic materials for instance cleavage fracture is a severe problem. For these alloys cleavage fracture occurs already at ambient temperatures limiting their potential as structural materials so far [4]. Thus it is important to better understand the processes and mechanisms which occur during cleavage fracture. One of the technically most interesting questions is the role of plasticity and the amount that plasticity could contribute to that "brittle" fracture process. This paper reports on how to investigate the role of plasticity during celavage fracture and also how small amounts of plasticity during cleavage crack propagation can be measured.

When a polycrystalline material is cleaved the propagating cleavage crack separates individual grains along crystallographically low indexed planes. If the atomic bonds between the two fracture halves are broken in a fully brittle manner then the crack tip will be atomically sharp and the crack propagates without any plasticity. This is the case when crystals with covalent bonds are broken. In metals however, the conditions at the crack tip are more complex. As has been shown theoretically by Rice and Thompson {6} an atomically sharp crack tip can be blunted when dislocations are emitted from the crack tip.

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This blunting takes readily place for fcc metals explaining that those metals generally fail in a ductile manner. For bcc and hcp metals the amount of blunting occurs to a smaller extent, thus those metals are prone to cleavage fracture. In the past it has also been proofed experimentally by in-situ TEM studies that dislocations can be emitted from the crack tips [5]. Such studies are constrained by the time consuming specimen preparation and by the very small amount of material which can be investigated.

If dislocations are emitted or generated in the plastic zone in the vicinity of the crack tip then a change between the orientations of the two halves of the cleaved grain should be noted. This is shown schematically in Fig. 1. As this misorientation is a function of the number of dislocations it will be a measure for the amount of plasticity during the fracture process. So far this misorientation has never been measured and quantified for a polycrystalline material.

APPLIED METHODS

We have investigated the misorientation by carefully measuring orientations with the EBSD (Electron Back Scatter Diffraction) technique in the Scanning Electron Microscope (SEM). For such measurements the electron beam of the SEM is focussed on a cleaved grain and so called EBSPs (Electron Back Scattering Pattern) are recorded. These patterns are similar to Kikuchi lines known from TEM-studies but they are recorded in the back-scattering mode. By analysing the geometric arrangement of the poles (intersection between the bands) the orientation of the crystalline area of interest can be determined. As can be deduced from Fig. 1. Plastic deformation in the vicinity of the crack tip should give rise to a misorientation between the two fracture halves of one grain. Therefore the orientation of the same grain of both fracture halves must be determined. Then the misorientation can be calculated from the transformation matrix which relates the orientation matrixes of the two halves [7-9].

A way how to infer from the misorientation to a plastic deformation in one cleaved grain is shown in the schematic in Fig. 2. In which the vertical lines shall symbolise lattice planes. The first line shows a crystal (half A), the third line shows the other fracture half. The fracture half B is in a mirror position to its location in space before the crystal was separated by cleavage. This measurement arrangement shows how the two fractures halves are surveyed on the specimen stage of the SEM. Now, three different cases can be distinguished. The first column shows a fully brittle cleavage along a {001} plane of a crystal in ideal position. The pole figure (last line in Fig. 2) shows no deviation from the central position for both fracture halves. (For simplicity, only *the* [001] direction is shown which is closest to the centre of the stereographic projection. The latter points in the direction of the specimen normal). The second column shows the same brittle cleavage of a crystal in arbitrary position. In that case, the central [001] poles are symmetric to the specimen normal. Finally, the third column shows a crystal in arbitrary position where plasticity leads to a small misfit between the crystallographic cleavage planes. This misfit can be seen in the pole figure because the central [001] poles do not lie symmetrically to the specimen normal.

EXPERIMENTAL PROCEDURE

As a model material we used technically pure iron (Armco®) with a grain size between 700 µm and 800 µm. Standard fracture mechanics tests were performed according to ASTM E399 on pre-fatigued CT (Compact Tension) specimens at 77 K. The loading of the specimens were stopped after the first crack initiation was detected with a back-face strain technique. Then the specimens were unloaded and fractured by post-fatigue.

As the EBSD technique yields the orientation of a crystal with respect to a fixed SEM co-ordinate system it is important that the specimen is built into the stage such that the edges of the specimen coincide with the fixed reference co-ordinate system of the SEM. To minimise a possible misalignment between the two specimen halves a special sample holder was built to guarantee a good parallel alignment. To check that the measured mis-orientation is not due to a misalignment between the two specimen halves we did several measurements where the specimens were taken off the specimen stage before we did new measurements. The misorientation between homologue cleaved areas is determined in the following way: First the orientations of the fracture grain is measured on both specimen halves. Then the misorientation is determined taking the relative position of the two halves into account. This is done by multiplying the results of one half with a matrix which transforms one specimen co-ordinate system into the other one. To determine that matrix a general equation for co-ordinate systems transformation was used [12]. If both halves are aligned as has been shown in Fig. 2, the matrix describes a rotation around the mirror axis of 180°.

RESULTS AND DISCUSSION

In the following the way how cleavage facets are analysed is described on one example. In Fig. 3 (a+b) both halves of a fractured specimen are shown. As can be seen the two fracture halves fit very well together (i.e. protrusions on one side correspond with intrusions on the other half) and *one* cleaved grain can be easily identified by finding the same fracto-graphic features. It should be noted that both halves are highly tilted.

When EBSPs are recorded from one cleavage facet it has to be taken care of that the area of the measurement is flat and yields an orientation which correctly describes the orientation of the cleaved grain. Often cleavage facets contain macroscopic ligaments which are not broken by cleavage. These ligaments hold the propagating crack together and provide a ductile contribution to the fracture. As we unloaded the specimens after the first crack initiation has been detected several ligaments were still present and they were bridging the cleavage crack together. These were sheared off when the specimens were post-fatigued. This process often bends up the broken ligament thus changing the orien-tation of the cleavage surface in the vicinity of the ligament. Therefore measurements very close to broken ligaments could yield a "wrong" orientation and must be avoided. Another possibility for "wrong" measurements is that a secondary cleavage crack undermines a cleavage facet. Thus the orientation of the cleavage facet concerned can be changed with respect to the other specimens half and an "abnormal" misorientation will be measured.

In the following the analyses of three different grains of the fracture surfaces shown in Fig. 8 (a+b) are presented and discussed. By tracing river patterns we determined that in the first grain (grain A of Fig. 3) the cleavage crack initiated. From that grain 16 local EBSD measurements have been recorded. The EBSPs have been taken in the direction of the crack propagation covering the whole diameter of the grain. The measurements on the two other grains have been chosen in such a way that again the measurements follow the direction of the crack propagation. From "Grain B" 6 measurements have been taken and from "Grain C" 12. In terms of local crack propagation these measurements covered a length of several hundred μm's. The results of all the misorientation measurements is plotted in Fig. 4. It is interesting to see that the amount of the misorientation is fairly high, lying on average between 5° and 10°. In terms of "local crack propagation" a small increase in the amount of the misorientation can be found. Whether or not this is a result of an increasing plastic deformation during cleavage fracture can not be decided yet. On the one hand it is possible that the plastic deformation increases a little with the distance from the cleavage crack initiation, on the other hand it is possible that the higher misorientation was caused by the fact that the loading was stopped after the first crack initiation leading to a higher plastic deformation of the crack tip when the crack stopped. However, other causes are also conceivable such as an orientation dependence of the plastic deformation, a local variation of the amount of plastic deformation with crack propagation velocity etc.

CONCLUSION

We showed that careful orientation analyses of cleavage fracture surfaces yield a misorientation between homologue areas in cleaved grains of metals. This misorientation lies above the measurement inaccuracy of the EBSD technique and therefore that misorientation should be a result of a plastic deformation during the crack propagation process. Further studies will show how this misorientation varies with other important parameters such as the temperature or the orientation of cleaved grains.

REFERENCES

[1] Ushik, G.W. Deutscher Verlag für Grundstoffindustrie, Leipzig, DDR 1961.

[2] Hahn, G.T., Metallurgical Transactions 15A (1984) pp.947-959.

[3] Thompson, A.W., Knott, J.F., Metallurgical Transactions 24A (1993) pp.523-534.

[4] Hebesberger, T., Semprimoschnig, C.O.A., et al, Crystallographic fractometry of TiAl fracture surfaces, same proceedings ECF 12.

[5] Rice, J.R., Thompson, R., Phil. Mag. 29, pp 73-97, 1974.

[6] Ohr, S.M., Mat. Sc. Eng. 72, (1985) pp.1-35.

[7] Boersch, H., Uber Bänder bei Elektronenbeugung, Z. f. techn. Phyik (1937) pp. 574-578.

[8] Venables, J.A., Bin-Jaya, R., Phil. Mag. Vol 35, 5 (1977) pp 1317-1332.

[9] Dingley, D.J., Randle, V., J. of Mat. Sci. 27 (1992) pp.4545-4566.

[10] Semprimoschnig, C.O.A., Pippan, R., Kolednik, O., Dingley, D.J., ECF 11. Poitiers, France. 1996, pp.753-758

[11] Semprimoschnig, C.O.A., Die kristallographische Fraktometrie-Entwicklung einer Methode zur quantitativen Analyse von Spaltbruchflächen, Ph.D. Thesis, 1996, Montanuniversität Leoben, Austria.

[12] Bartsch, H.-J., Mathematische Formeln, VEB Fachbuchverlag Leipzig, 20. Aufl. (1984) DDR 280 ff.

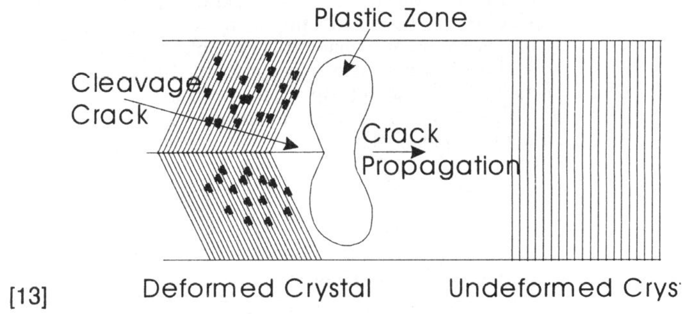


Fig. 1: Model about the change in orientation when a crystal is cleaved.

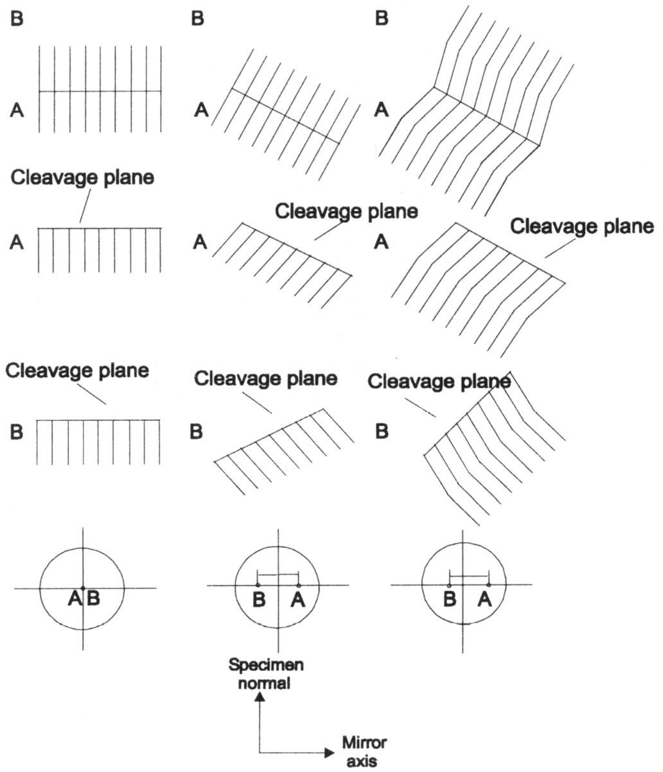
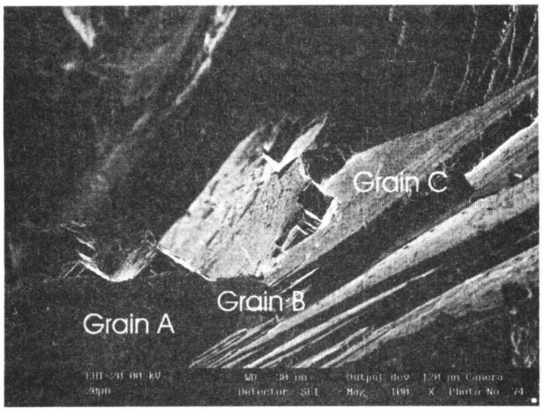
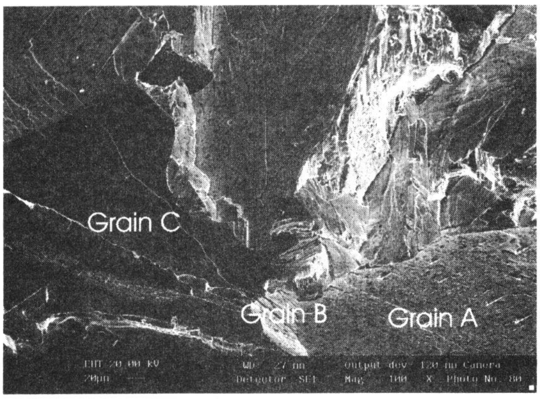


Fig. 2.: Schematic model about misorientation measurements due to plastic deformation.



(a)



(b)

Fig. 3 (a+b) : SEM-images of both specimen halves.

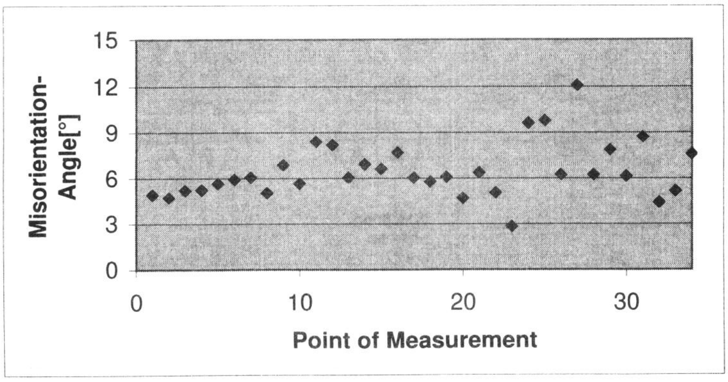


Fig. 4.: Misorientation-plot of local EBSD-measurements