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Laser-Induced Dislocation Structures in Copper Single Crystals

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Mechanical Stress fields of nearly radial symmetry are produced by focused laser irradiation on (111) surfaces of copper single crystals. The dislocation structures in the vicinity of the heat-affected zone can be revealed with the aid of an etch pit technique. The observed etch pit pattern is in very good agreement with calculations based on dislocation theory.

1. Introduction

A focused laser beam may be used for highly localised and rapid heating of metal surfaces. Because of the very fast temperature changes a mechanical stress field is formed in the vicinity of the heat-affected zone. In the present paper, the deformation structures caused by this stress field in copper single crystals are detected and analysed by an etch pit technique. The observed etch pit patterns can be explained by dislocation theory.

2. Experimental Procedure and Results

The investigations were carried out on melt-grown copper single crystals (nominal purity 99.9998 %) of a parallelepiped shape. The (1 1 1)-faces of these crystals were electropolished (30 % nitric acid, 70 % methyl alcohol, temperature $T = -30°$ C) after a short mechanical treatment. The radiation of a neodymium pulse laser (5 Joules max. output energy, 1 msec pulse duration, 1.06 μm wavelength of radiation, 6 mm beam diameter) was focused on to the (1 1 1)-surface by a lens of 16 mm focal length. The diameter of the heat-affected zone on the sample was about 100 μm. After irradiation the (1 1 1)-face was electropolished and etched with the aid of a technique reported by Livingston [1]. In this technique an etchant is used which produces small triangular etch pits at dislocation surface intersections.

The etch pit pattern developed by such a treatment is shown in fig. 1 and at a higher magnification in fig. 2. The dark region in the middle of fig. 1 consists of material melted by the laser beam, the irregularly spaced dark spots are particles which were molten and splashed out of the crater. The etch pit pattern on the (1 1 1)-face due to the laser irradiation is shown schematically in fig. 3. The arrows indicate the ⟨1 1 0⟩-directions as determined from Laue patterns. Examination of figs. 1 and 3 shows that the pits are alternatively arranged along $[10\bar{1}]$, $[\bar{1}10]$, and $[0\bar{1}1]$ slip traces in angular intervals of $\Delta\phi = 30°$ each.

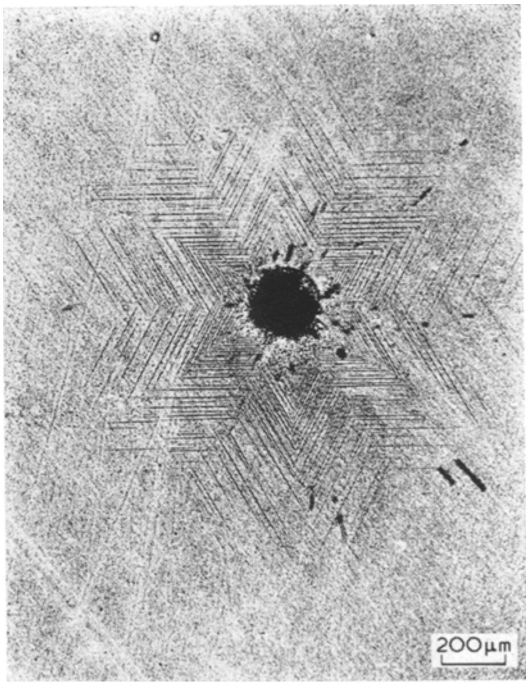

Figure 1 Etch pit pattern on (111)-surface of a copper single crystal after laser irradiation.

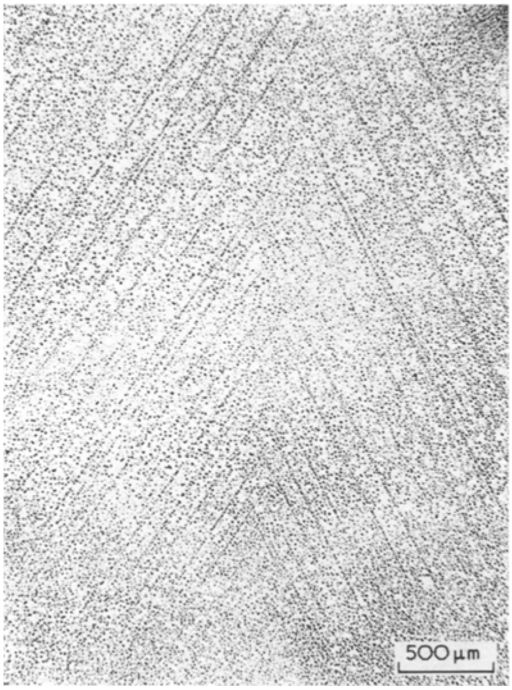

Figure 2 Region of fig. 1 at a higher magnification.

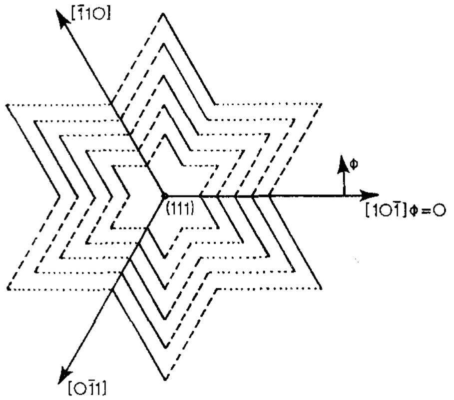

Figure 3 Schematic representation of the etch pit pattern on (1 1 1)-surface following laser irradiation. (. . . . . . . Rows of etch pits from dislocations D_1; - - - - - - Rows of etch pits from dislocations D_2; ——— Rows of etch pits from dislocations D_3).

3. Discussion

The observed etch pit pattern is considerably more detailed than that found by Meyer and Meier [2] on antimony single crystals. Its symmetry rather strongly suggests that in each angular interval $\Delta\phi = 30°$ only one slip system was operative, causing accumulations of dislocations on $(\bar{1}\,1\,\bar{1})$, $(1\,\bar{1}\,\bar{1})$, and $(\bar{1}\,\bar{1}\,1)$ planes. To explain this we have assumed that the observed etch pit pattern is due to the influence of the laser-induced stress field on the formation and motion of dislocations. It should be possible to derive this effect quantitatively from the component

$$\mathbf{K} = [\mathbf{F} \times \mathbf{n}] \times \mathbf{n}$$

of the force

$$\mathbf{F} = \boldsymbol{\sigma}\,.\,\mathbf{b} \times \mathbf{L} \tag{1}$$

which acts on a dislocation (Burgers vector **b**, dislocation line **L**) in its slip plane (unit vector **n**) when an external stress field (tensor $\boldsymbol{\sigma}$) is applied.

In order to simplify the following interpretation of the observed deformation structure we assume that in each particular angular interval only those dislocations are formed or moved for which the magnitude of the force **K** is largest.

The stress field σ can be taken from a paper published by Bailey [3]. For a simple model Bayley has calculated the thermal stresses, which are produced by suddenly increasing the temperature of a circular area on the surface of a semi-infinite solid by ΔT. These assumptions correspond quite well to the case of laser irradiation because in this case a nearly circular zone is heated to the melting point within a very short span of time ($\leqq 1$ msec). Bayley's calculations yield a stress field of radial symmetry, if it is assumed that Young's modulus, E, and the linear expansion coefficient, β, are isotropic. For the surface ($z = 0$) we obtain in cylindrical co-ordinates (origin of co-ordinates in the centre of the heat-affected zone):

$$\begin{aligned} \sigma_{\mathrm{rr}} &= -\,\tfrac{1}{2}E.\beta.\Delta T.\left(\frac{R}{r}\right)^2 \text{ for } r > R \\ \boldsymbol{\sigma}_{\phi\phi} &= +\,\tfrac{1}{2}E.\beta.\Delta T\left(\frac{R}{r}\right)^2 \text{ for } r > R \\ \sigma_{\mathrm{rz}} &= \sigma_{\mathrm{zz}} = 0 \end{aligned} \tag{2}$$

where r, ϕ, z are the cylindrical co-ordinates and R is the radius of the heat-affected zone.

Altogether there are edge dislocations of nine different orientations (D_1 to D_9) and screw dislocations of three different orientations (D_{10} to D_{12}) which intersect the (1 1 1)-surface and therefore may lead to the formation of etch pits. The Burgers vectors, dislocation lines and slip plane orientations of these dislocations are listed in table I; some of them are illustrated in fig. 4. The application of equation 1 for these dislocations yields in cylindrical co-ordinates ($z = 0$: (1 1 1)-surface; $r = 0$: centre of the heat

TABLE I Forces on dislocations ($D_1 - D_{12}$) due to the stress field referred to in equation 2.

Dislocations	D	Direction of Burgers vector **b**	Direction of dislocation line **L**	Slip plane	Slip trace parallel to	Normalised values of | **K** |
Edge	D_1	$10\bar{1}$	$\bar{1}\bar{2}\bar{1}$	$\bar{1}1\bar{1}$	$10\bar{1}$	$\sqrt{3} . \vert\sin 2\phi\vert$
	D_2	$0\bar{1}1$	$\bar{2}\bar{1}\bar{1}$	$1\bar{1}\bar{1}$	$0\bar{1}1$	$\sqrt{3} . \vert\sin(2\phi + 240°)\vert$
	D_3	$\bar{1}10$	$\bar{1}\bar{1}\bar{2}$	$\bar{1}\bar{1}1$	$\bar{1}10$	$\sqrt{3} . \vert\sin(2\phi - 240°)\vert$
	D_4	110	$1\bar{1}2$	$\bar{1}11$	$0\bar{1}1$	$\vert\cos 2\phi\vert$
	D_5	011	$21\bar{1}$	$1\bar{1}1$	$10\bar{1}$	$\vert\cos(2\phi - 240°)\vert$
	D_6	101	$\bar{1}21$	$11\bar{1}$	$\bar{1}10$	$\vert\cos(2\phi + 240°)\vert$
	D_7	110	$\bar{1}12$	$1\bar{1}1$	$10\bar{1}$	$\vert\sin(2\phi - 30°)\vert$
	D_8	011	$2\bar{1}1$	$11\bar{1}$	$\bar{1}10$	$\vert\sin(2\phi - 270°)\vert$
	D_9	101	$12\bar{1}$	$\bar{1}11$	$0\bar{1}1$	$\vert\sin(2\phi + 270°)\vert$
Screw	D_{10}	110	$\bar{1}\bar{1}0$	$\bar{1}11$	$0\bar{1}1$	$\vert\cos 2\phi\vert$
				$1\bar{1}1$	$10\bar{1}$	$\vert\sin(2\phi - 30°)\vert$
	D_{11}	011	$0\bar{1}\bar{1}$	$1\bar{1}1$	$10\bar{1}$	$\vert\cos(2\phi - 240°)\vert$
				$11\bar{1}$	$\bar{1}10$	$\vert\sin(2\phi - 270°)\vert$
	D_{12}	101	$\bar{1}0\bar{1}$	$11\bar{1}$	$\bar{1}10$	$\vert\cos(2\phi + 240°)\vert$
				$\bar{1}11$	$0\bar{1}1$	$\vert\sin(2\phi + 210°)\vert$

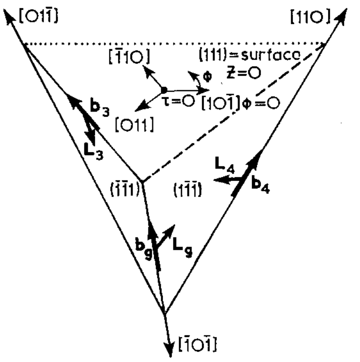

Figure 4 Orientations of some of the dislocations listed in table I.

affected zone; $\phi = 0$: $[10\bar{1}]$-direction) the magnitudes of the components | **K** | of the forces on these dislocations as listed in table I. The values of | **K** | are normalised here by r^2/c, where c is a constant.

Thus the largest forces act on the edge dislocations D_1, D_2, and D_3. The magnitudes of the components | **K** | of these forces have maxima for the angles

$$D_1 : \phi_1 = 45° + n . 90°$$
$$D_2 : \phi_2 = 15° + n . 90°$$
$$D_3 : \phi_3 = 75° + n . 90°; n = 0, 1, 2, 3.$$

If for each angle ρ we draw the traces only of those slip systems for which the acting forces are largest, we obtain parallel patterns of traces within angular intervals of $\Delta\phi = 30°$ which is in exact agreement with our experimental results (figs. 1 and 3).

A condition for the etch pits to arrange themselves in a small number of slip bands is that there exist a sufficiently high dislocation density before laser action; in the present case this was found to be of the order of $10^7/cm^2$. The effect of the original dislocation density on the etch pit pattern will be discussed in a further publication.

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