A COMPARISON BETWEEN DIFFERENT THEORIES PREDICTING THE STACKING FAULT ENERGY FROM EXTENDED NODES

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The stacking fault energy $\gamma$ is the principal factor determining the unidirectional work hardening behaviour of various f.c.c. metals and alloys. More precisely, the dimensionless parameter $\gamma/Gb$, where $G$ is the shear modulus and $b$ the slip distance, gives a measure of the ease of cross slip of screw dislocations and therefore determines the work hardening behaviour in stage III of deformation. There are several methods to determine the value of the stacking fault energy $(1)$. It has well been established in f.c.c. metals and alloys that ordinary dislocations can split up into two Shockley partials bounded by a stacking fault. Materials with a low value for the stacking fault energy have large separations between the Shockley partials and a reliable value for $\gamma$ can be deduced from these separations using anisotropic elasticity theory $(2)$. Materials with a medium value for the stacking fault energy have separations too small to provide a reliable value for $\gamma$. However, using the node method originated by Whelan $(3)$ and improved by others, a reliable value for $\gamma$ can be obtained for the latter materials. In this article attention will be focused on three different analyses of extended nodes in Cu$_2$NiZn based on the theory of Brown and Thölen $(4)$, of Siems $(5)$ and of Jössang et al. $(6)$.

An extended dislocation node is the result of a reaction between two extended dislocations on different slip planes. One of the extended dislocations is cross slipping into the plane of the other. The reaction is described in detail by Whelan $(3)$. A schematic drawing of an extended node is shown in Fig. 1.

The models $(4-6)$ provide different values for the equilibrium configuration of a symmetrical extended node using isotropic elasticity theory. These differences can be related to different approximations made for the dislocation line energy and the dislocation interactions. For more details the reader is referred to the original papers. Comparison of the three theories shows that for extended nodes of screw character ($\alpha=0^\circ$) all three theories result into almost the same value for the stacking fault energy. The difference between the theories is more pronounced for larger values of $\alpha$. Measuring the stacking fault energy from nodes with a large value of $\alpha$ will therefore provide a critical test on the different models. However, only a few extended nodes with $\alpha > 50^\circ$ were observed.

Strips of Cu$_2$NiZn are cold-rolled to a thickness of about 100 $\mu$m. Previously, thicknesses of 35 $\mu$m were used $(7)$. However, it seems that with a thickness of 100 $\mu$m a better electro-chemical polish of the specimen can be obtained as effects of surface roughness and grain boundaries on the polishing process are less pronounced. An increase in transparent area by a factor of 5 is achieved. A more extended sample is also a better representation of the bulk material. Samples, 5 mm wide and 120 mm long, are produced from these strips. They are encapsulated under vacuum in a narrow tube of fused quartz and annealed at 1123 K for 4 days to provide specimens, which are free from internal stresses and have a large grain size. These strips are annealed at 838 K (which is 70 K above the critical temperature for the order-disorder transformation of Cu$_2$NiZn) for 10 minutes and subsequently quenched in water. Therefore no long-range order is present. After these thermal treatments the composition of the strip is 51,1 at% Cu, 24,7 at% Ni and 24,2 at% Zn. The dislocations are introduced by a 5% elongation, using a strain rate of 5 $10^{-5}$ (sec$^{-1}$). The final average grain size measured by random linear intersection is 100 $\mu$m. A disc-type specimen is electro-chemically thinned in a polishing equipment at room temperature in a 33 vol% solution of concentrated orthophosphoric acid in water. The electron microscope is a Philips EM 300 with a side-entry goniometer stage operated at 100 kV.
In f.c.c. materials extended nodes consist of an intrinsic stacking fault, with fault vector of type $\frac{1}{6} a_{0}<211>$, bounded by Shockley partials with Burgers vector of type $\frac{1}{6} a_{0}<211>$, lying in slip planes of type $\{111\}$. The characterization of the slip plane can be done by tilting the foil and observing the projected dislocation spacing. The Burgers vector of the partials can be determined using the invisibility criterion. Partial imaged with $|g.b_p|=1/3$ are effectively invisible, where $g$ is the diffraction vector and $b_p$ is the Burgers vector of the partial dislocation. Stacking fault contrast occurs when $\delta = 2g.f_{\rho}$, where $n$ is an integer. All nodes are imaged in the dark field weak-beam mode. The position of the dislocation image in this mode is less than 0.7 nm apart from the dislocation core position under condition that $|s_g| \geq 0.2$ nm$^{-1}$ and $|\omega| \geq 1.2$ nm. Here $s_g$ is the deviation parameter from exact Bragg position and $\epsilon_g$ is the extinction distance. Since the image of the partials of an extended node lies on the same side of the cores, the measured dimensions of the extended node differ less than 0.7 nm from the actual dimensions, when the above values of $s_g$ and $\omega$ are applied. The nodes are imaged in the EM 300 at a magnification of about 75,000 x. After a further photographic enlargement of the electron micrograph, a series of circular annuli is superimposed onto the final picture and the ones which fit the inner and outer radii of the extended node are chosen. For all extended nodes in this paper the projection plane makes a small angle with the slip plane and thus one has to take into account a small geometric distortion. In the case of symmetric extended nodes, Ruff (1) provides a correction formula which deduces the true circle radius from the projected (elliptical) figure by measuring the values of $y$ in the direction opposite to a node arm. By doing this for all three node arms he determines the true $y$ from the average of those three calculated $y$'s. As the dimensions of the extended nodes measured in Cu$_2$NiZn are too small an alternative procedure had to be applied also using Table XII of reference (1). The average of the correcting factors corresponding to the angle between projection plane and slip plane is used to correct the radius of the circle which best fitted the projected node image. Figs. 2a and 2b show the extended nodes as part of a network in dislocation line and in stacking fault contrast, respectively. All nodes in the network have the same character, which is to be expected because the network is formed by the intersection of an extended dislocation with a pile-up of dislocations. Isolated and symmetrical nodes will provide the most reliable results for the stacking fault energy. However, most extended nodes appear in networks.

Values of the elastic constants and $b_p$ for the alloy Cu$_2$NiZn are obtained by de Groot et al. (11). From the measured radii ($y$ and $R$) of the extended nodes and the effective (12) values of $C$, $\nu$ and $b_p$, stacking fault energies are calculated using the three theories. The results are compiled in Table I. Using the theories of Brown and Thóln and of Siems the stacking fault energy is calculated from the inner radius ($y(y)$) and from the outer radius ($y(R)$). Using the theory of Jøssang et al. the stacking fault energy is calculated from the inner radius taking $E_1=b_p$ and $E_2=b_p/4$.

<table>
<thead>
<tr>
<th>No.</th>
<th>$\alpha$</th>
<th>$y$ (nm)</th>
<th>$R$ (nm)</th>
<th>Siems</th>
<th>Brown and Thóln</th>
<th>Jøssang et al.</th>
<th>$\epsilon_2$</th>
<th>$\epsilon_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60°</td>
<td>6.5</td>
<td>36.2</td>
<td>31</td>
<td>18</td>
<td>25</td>
<td>34</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td>30°</td>
<td>8.4</td>
<td>29.9</td>
<td>29</td>
<td>29</td>
<td>30</td>
<td>37</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>30°</td>
<td>6.4</td>
<td>33.3</td>
<td>37</td>
<td>30</td>
<td>38</td>
<td>33</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>30°</td>
<td>7.3</td>
<td>25.0</td>
<td>33</td>
<td>38</td>
<td>34</td>
<td>42</td>
<td>32</td>
</tr>
</tbody>
</table>

In Table I nodes 1 and 4 are embedded in a network, whereas nodes 2 and 3 are isolated. The assumption of Ruff (1) that nodes in a network can be used for the determination of the stacking fault energy, provided that the network mesh size is larger than the outer radius of the extended node, seems to be justified because the average value of the stacking fault energy calculated from the network of extended nodes is not different from the value obtained from the two isolated nodes. Systematic errors are present in the calculated values of the stacking fault energy. First, local ordering may exist in the specimen, which enhances the internal energy of the faulted area, resulting in an over-estimate of the stacking fault energy. Secondly, due to image forces the dimensions of the extended node increase, resulting in an under-estimate of the stacking fault energy. Random errors are present due to magnification (< 2%), image formation (< 10%) and measuring technique (< 3%). A stacking fault energy for Cu$_2$NiZn of $32 \pm 7$ mJ/m$^2$ can be obtained from Table I.
The stacking fault energy is independent of the character of the node. Hence, the theory which results in the same value of the stacking fault energy for the 30° and 60° extended node is the most appropriate one. Only stacking fault energies calculated from the inner radius ($\gamma(y)$) are compared because they are more reliable than those obtained from the outer radius ($\gamma(R)$). Comparison of the average value of the 30° nodes with the 60° node results in the conclusion that the theory of Siems provides good agreement among the stacking fault energies ($33 \text{ mJ/m}^2$ and $31 \text{ mJ/m}^2$, respectively). The theory of Jøssang et al. also provides good agreement ($c_1: 28 \text{ mJ/m}^2$ and $31 \text{ mJ/m}^2$, $c_2: 32 \text{ mJ/m}^2$ and $34 \text{ mJ/m}^2$, respectively). The theory of Brown and Thölén exhibits intrinsic discrepancy ($34 \text{ mJ/m}^2$ and $41 \text{ mJ/m}^2$, respectively). More conclusive information has to be obtained from extended nodes of edge (90°) character, however, up to now none of these nodes have been observed.

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REFERENCES


FIG. 1
A schematic drawing of an extended dislocation node. Burgers vectors of the Shockley partials are indicated in Thompson's notation.
FIG. 2a
A network of extended nodes imaged in dislocation line contrast. Dark field weak-beam image using diffraction vector \( \vec{g} = [113] \); \( s_g = -0.2(\text{nm}^{-1}) \); \( \alpha = 30^\circ \); (111) slip plane; (211) projection plane.

FIG. 2b
Same network of extended nodes as in Fig. 2a imaged in stacking fault contrast. Dark field weak-beam image using diffraction vector \( \vec{g} = [111] \); \( s_g = +0.1(\text{nm}^{-1}) \); \( \alpha = 30^\circ \); (111) slip plane; (211) projection plane.