PLASTIC DEFORMATION OF POLYCRYSTALS.

REPORT I. THE DEFORMATION MODEL OF GRAIN BOUNDARY STRENGTHENING

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Introduction. Grain size is one of the fundamental structural parameters by means of which one can effectively change the mechanical properties of polycrystalline materials. For some time now this effect has received both scientific and engineering acceptance.

This study consists of two parts, the first of which concerns the nature of grain boundary strengthening at the yield point, and the second, the role of grain size in strain hardening of polycrystals beyond the yield point.

The first part includes a short review of current theories of grain boundary strengthening, a critical review of which will logically reveal the necessity of developing a new deformation model of such strengthening.

A Review of Theories Concerning Grain Boundary Strengthening. The first to study the dependency of the yield point \( \sigma_y \) on the grain size were Hall [1], Petch [2], and Low [3], who independently arrived at a relationship of the type

\[
\sigma_y = \sigma_0 + K_y D^{-1/2},
\]

where \( \sigma_0 \) and \( K_y \) are constants. After a relatively short period of time, equation (1) was experimentally verified on a large number of metals and alloys, which necessitated a physical interpretation.

The physical meaning of the first component of equation (1) is relatively clear since the structural independence of \( \sigma_0 \) immediately shows that it is associated with the properties of the crystallographic lattice, and in particular, its resistance to plastic flow. Therefore, the value of \( \sigma_0 \) is called the resistance of the crystallographic lattice to the movement of dislocations, or the friction stress. Occasionally \( \sigma_0 \) is expressed through the properties of a monocrystal as

\[
\sigma_0 = \tau_0 M,
\]

where \( \tau_0 \) is the critical shear stress for the monocrystal, and \( M \) is the Taylor orientation factor [4].

Interpretation of the coefficient \( K_y \) is somewhat more complicated. Among the various models which attempt to explain such strengthening, the most widely spread are the following:

1) the barrier effect theories of Cottrell [5, 6], Armstrong, Cold, and others [7] which are based on the notion that plane dislocation pile-ups occur around the grain boundaries which give rise to shear stress concentrations at their fronts. These stress concentrations are required for transfer of slip into the next grain (Fig. 1a),

2) the Conrad deformation model [8], in which the density of dislocations in a deforming polycrystal should be inversely proportional to the grain size (Fig. 1b),

3) the Li model [9] which explains the initial stage of flow by the operation of grain boundary dislocation sources whose number in each grain is proportional to the ratio of the grain boundary area to the grain volume (Fig. 1c),

4) the Ashby model [10] which isolates the so-called "geometrically critical" dislocations from the overall dislocation population. It is these dislocations which are responsible for localized deformation around the grain boundaries, and their density is inversely proportional to the grain size (Fig. 1d).
Table 1. Fundamental Equations of the Grain Boundary Strengthening Theories

<table>
<thead>
<tr>
<th>Authors</th>
<th>Equation</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Cottrell, 1958</td>
<td>$K_Y = 2 \sigma d^{1/2}$</td>
<td>(3) [5, 6]</td>
</tr>
<tr>
<td>Armstrong, Cold, et al., 1962</td>
<td>$K_Y = 2m \tau_0^{1/2}$</td>
<td>(4) [7]</td>
</tr>
<tr>
<td>Conrad, 1961, 1963</td>
<td>$p = (C_1/D)e$</td>
<td>(5) [8]</td>
</tr>
<tr>
<td>Li, 1961</td>
<td>$K_Y = \alpha G b V/V$</td>
<td>(6) [9]</td>
</tr>
<tr>
<td>Ashby, 1970</td>
<td>$\rho_G = (1/bL_G) e$</td>
<td>(7)</td>
</tr>
</tbody>
</table>

Note. $\sigma_0$ and $\tau_0$ are the critical stresses required for the operation of a dislocation source at some distance $t$ (or $r$) from the head of a plane dislocation pile-up; $\lambda$ is the length of a grain boundary dislocation being emitted from a unit area of the grain boundary; $F$ is the grain boundary area; $V$ is the grain volume; $\rho_G$ is the density of geometrically critical dislocations; $L_G$ is the length of the mean free path of the geometrically critical dislocations; and $C_1$ and $C_2$ are constants.

Also worth mentioning are the models of Thompson [11] and of Margolin-Gaguschi [12] which are further developments of Ashby's model [10] concerning geometrically critical dislocations.

The fundamental equations of these theories are presented in Table 1. An analysis of these theories leads to a number of generalizations and conclusions.

1. The above theories and their initial experimental results reveal several parameters (stress concentration, dislocation density, density of dislocation sources, mean free path of the dislocations, etc.) each of which may cause grain boundary strengthening.

2. Simultaneous deformation is the main condition for macroflow of polycrystals according to which the grain aggregate can deform without the formation of cracks and discontinuities only when each grain deforms in the same manner as the whole aggregate [13, 14]. One form of simultaneous deformation is taken into consideration by the well-known Mizes condition [4, 11] which assumes macroflow in a polycrystal only in the presence of five independent slip systems in each grain.

3. The occurrence of plastic flow in polycrystals has the following characteristics: