DISLOCATION MECHANICS AT HIGH STRAIN RATES

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ABSTRACT

In this paper a high strain rate is defined as high if the dislocations that produce the plastic strain must move at velocities of the order of, or larger than the shear wave velocity $a_2$. Except possibly in the initial portions of stress strain curves dislocation velocities are much smaller than $a_2$. Only in shock loaded specimens should very fast dislocation velocities exist. An approximate analysis is made to show how supersonic dislocations in a shock wave interface (the Smith interface) can produce a hydrostatic stress behind the interface.

WHAT IS A HIGH VALUE FOR A PLASTIC STRAIN RATE?

Crystalline material is deformed plastically at strain rates in the range $10^{-18}$ to $10^{-13}$ s$^{-1}$ (geologic strain rates); $10^{-12}$ to $10^{-8}$ s$^{-1}$ (glacier flow strain rates); $10^{-8}$ to 1 s$^{-1}$ (ordinary stress-strain and creep tests); 10 to $10^3$ s$^{-1}$ (impulse loading tests); and at virtually infinite strain rates (shock wave tests). The plastic strain rate $\dot{\varepsilon}$ is given by the well known equation

$$\dot{\varepsilon} = \alpha \rho b v$$

(1)

where $b$ is the magnitude of the Burgers vector of a dislocation, $\rho$ is the density of the mobile dislocations, $v$ is the average velocity of the dislocation, and $\alpha$ is a dimensionless constant ($\alpha \sim 1$). The average velocity $v$ of a dislocation thus is of the order of
The stress field of a dislocation is essentially independent of the value of the dislocation velocity if \( v \) is much smaller than the shear wave velocity \( a_2 \). Only if \( v \) is of the order of, or larger than \( a_2 \) is the stress field of a moving dislocation radically different from the stress field of a stationary dislocation\(^1\). Because the properties of a dislocation change markedly at \( v \sim a_2 \) it is reasonable to expect that the dislocation mechanics of plastic deformation may be qualitatively different at high strain rates. A plastic strain rate thus reasonably can be defined to be "high" if it satisfies the inequality

\[
\varepsilon > \alpha \rho a_2
\]  

The dislocation density in a metal can be expected to be of the order of or larger than \( 10^{10} \text{ m}^{-2} \). A high strain rate thus is greater than about \( 10^4 \text{ s}^{-1} \) since \( b \approx 3 \times 10^{-10} \text{ m}, a_2 \approx 3 \text{ km s}^{-1} \), and \( \alpha \approx 1 \).

The strain rates that are produced in various impulse type loading tests are not larger than about \( 10^3 \text{ s}^{-1} \) (see, for example, the papers of Hockett and coworkers\(^2\)–\(^6\) or of Nagata and Yoshida\(^7\),\(^8\)). Such tests are considered in the literature, with justification, to be high strain rate tests because the strain rates are orders of magnitude larger than those employed in ordinary stress-strain tests. However by the criterion given by Ineq. \([3]\) these are not high strain rate tests. Dislocation theories developed to account for the results obtained at relatively small strain rates can be applied to tests in which the strain rate does not exceed \( 10^3 \text{ s}^{-1} \). The properties of the dislocations have not changed qualitatively in such tests because \( v \) is small compared with \( a_2 \). At strain rates in which Ineq. \([3]\) is satisfied the properties of a fast moving dislocation in a test specimen are qualitatively different from the properties of a slowly moving dislocation in a low strain rate test. Dislocation theories of plastic deformation developed for low strain rate tests obviously must break down when dislocations move at velocities compared to \( a_2 \).

Transient Effect

It should be noted that dislocations may have to move at a fast velocity at the start of even a low strain rate test if the initial mobile dislocation density \( \rho \) is relatively small. Only