THE EFFECT OF SOLUTE AND DISLOCATION INTERACTIONS ON THE STRAIN RATE SENSITIVITY AND FLOW STRESS OF METALLIC ALLOYS

by

Renge Li

An Abstract of a Thesis Submitted to the Graduate

Faculty of Rensselaer Polytechnic Institute

in Partial Fulfillment of the

Requirements for the degree of

DOCTOR OF PHILOSOPHY

Major Subject: Mechanical Engineering

The original of the complete thesis is on file
In the Rensselaer Polytechnic Institute Library

Examining Committee:

Catalin Picu, Thesis Adviser

Antoinette Maniatty, Member

Lucy Zhang, Member

Liping Huang, Member

Rensselaer Polytechnic Institute
Troy, New York

April, 2010
(For Graduation May 2010)

ABSTRACT

Dislocations are line defects in crystalline materials, and microscopic carriers of plastic deformation. Dislocation motion is controlled by both dislocation-obstacle and dislocation-dislocation long-range interactions; understanding the collective motion of dislocations is the essential step in studying the underlying physical mechanisms of plasticity. This thesis presents several fundamental aspects of small-scale plasticity, with emphasis on thermally activated processes. Contributions are made with respect to both method development and understanding fundamental physics.

Solute is added to pure metals to improve strength, while alloying may also lead to reduced ductility and cause plastic instabilities, which both limit material formability. The (negative) strain rate sensitivity (SRS) is one of the factors causing plastic instabilities and reduced formability. The strain rate sensitivity has an instantaneous component (always positive), which is associated with the thermally activated motion of dislocations, and a transient component (which may be either positive or negative), associated with the correlated motion of dislocations and solute. One of the issues studied in this thesis is the contribution of various obstacle sub-populations to defining the instantaneous component of strain rate sensitivity.

We further study the Cottrell-Stokes (CS) law, which requires that the ratio of the thermal to the athermal components of the flow stress remains constant during straining. Most single and polycrystals of pure metals obey this law. The common method for testing the validity of the CS law is performing strain rate jump experiments and monitoring the Haasen plot (strain rate sensitivity coefficient versus flow stress). If the plot is a straight line passing through the origin, it is considered that the law applies. In this thesis it is shown that the relation between the Haasen plot and the CS law is not bijective and multiple types of Haasen plots may be obtained at constant CS ratio.

The third issue studied is related to the superposition law of effects of multiple strengthening mechanisms, superposition which is at the base of all mechanism-inspired constitutive equations for plasticity. We provide an analytical proof for the functional form of the superposition law and determine the conditions under which it can be extended to finite temperatures (i.e. to situations in which thermal activation applies). A

“superposition” law for strain rate sensitivity (i.e. of contributions to strain rate sensitivity of the various mechanisms producing strength) is also derived.

Plastic deformation involves a large number of dislocations, and dislocation motion has a scale-free intermittent plastic activity characterized by power law distributions of dislocation avalanche size, time correlations and aftershock triggering. In the last part of the thesis, we present numerical simulations of dislocations that generate scale-free avalanches and power-law behavior by means of 2D computer simulations of thermally activated dislocation motion through a field of point obstacles. The behavior has been studied with the system being driven below its critical point. The goal is to investigate the effect of the field-mediated dislocation interaction, and that of the presence of randomly distributed obstacles, on the dynamics of the system. It is shown that the elastic interaction of dislocations is the essential process leading to unsteady dynamics and intermittency.

In summary, the contributions of this thesis are related to: a) the effect of various types of sub-populations of obstacles on the strain rate sensitivity and flow stress; b) the nature of the CS law and its relation with the strain rate sensitivity; c) the functional form of the superposition law of various strengthening mechanisms defining the flow stress at zero Kelvin and finite temperatures and d) the collective dislocation motion (avalanches) and the effect of long-range dislocation-dislocation interaction on plastic flow.