Strain hardening and features of slowing down the movement of dislocations in single crystals

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Abstract. The study of deformation hardening of single crystals for modern engineering is an important task due to the emergence of new promising methods of processing metal materials. Although in practice we usually deal with polycrystalline metals and alloys, it is advisable to start the analysis with simpler objects – single crystals of pure metals, where you can most clearly and fully identify the main patterns of deformation hardening. The article considers the temperature range limited by the interval of intensive thermal return.

1. Introduction
When studying the mechanical properties of metal from the beginning of deformation to the moment of destruction, an increase in the resistance force of the sample is observed as the degree of deformation increases. Primary tension diagrams may show areas of load drop, but after the primary diagram is rearranged in the true stress-strain coordinates, these areas disappear.

Among the many unclear questions in the problem of plasticity of single crystals is the question of the nature of strain hardening, which consists in increasing the resistance of the crystal to plastic deformation under active loading, is one of the most difficult. According to modern concepts of plasticity physics, the main reason for hardening is the difficulty of dislocations moving through the crystal due to an increase in their number in the crystal and the associated increase in the interaction of dislocations with each other[1-3].

To build a physical theory of the strain hardening it is necessary to describe the evolution of dislocation structure: dislocation density, character of their location and interaction in the crystal with increasing external voltage, and to associate these changes with the increase of plastic deformation of the crystal.

2. Features of studying the movement of dislocations in single crystals
The greatest success in the study of the theory of deformation hardening was achieved for single crystals of metals with a face-centered cubic lattice, in which the plastic deformation process has a pronounced stage. Several theories of strain hardening have been developed for each individual stage. Without giving a complete overview of all the theories, we will focus mainly on Zeger's theory, which is the most reasonable both in terms of comparison with experimental data and in terms of logical sequence [4-7].

However, let's start with a review of the very first theories of deformation hardening by Taylor and Mott, in order to carefully trace the development of the theory from its first steps to its current state. The essence of plastic deformation is a shift, as a result of which one part of the crystal is displaced in relation to another part. For a shift in an ideal crystal, in which all the atoms on the plane of the shift immediately
move one interatomic distance, it is necessary, as shown by calculations, a certain tangent. In real crystals, the shift occurs at fairly small stresses of everything.

The mechanism of shift of one part of the crystal relative to another can be represented as the result of a dislocation run through it, for example, a boundary, with a length equal to the width of the crystal. The greater the number of moving dislocations and the longer the total path of their movements, the greater the amount of macroplastic deformation. There are two types of shift: sliding and the appearance of «doubles». In both cases, plastic deformation is associated with certain planes and directions in the lattice [8-10].

In single crystals and amorphous substances, a special structure with special properties is formed. Single crystals can be obtained if conditions are created for the growth of a crystal from only one crystallization center. There are several technological methods that use this principle. For example, such a structure is formed when a single crystal is pulled out of the melt, due to directed crystallization from a single center, which uses a single-crystal seed with a given crystallographic orientation.

In real metals and alloys, as a rule, there are many dislocations of different types even before the deformation begins. Under the influence of applied stresses, various sources of them begin to work, generating new dislocations. Moving dislocations come to the surface of the sample, interact with each other inside it: they react, slow down, annihilate, and form plexuses. Therefore, the real picture of plastic deformation of metal materials is complex and in many cases is still far from clear. It is determined by the structure, composition of the material and the conditions of its deformation. Plastic deformation is experimentally studied by microscopic analysis of the polished surface of samples, on which special «lines» and «slip bands» appear as a result of deformation, and by diffraction electron microscopy of thin foils cut from deformed samples.

3. Methods for studying strain hardening in single crystals

Sliding lines are steps formed on the surface as a result of dislocations. By analyzing the location of sliding lines, the distance between them, and their height, you can make not only a qualitative, but also a quantitative representation of the picture and the amount of plastic deformation. Having learned the crystallographic orientation of the analyzed sample surface using x-ray diffraction analysis, the planes and sliding directions are determined by the direction of the sliding lines.

The method of diffraction electron microscopy allows you to directly observe individual dislocations, determine their burgers vector and slide crystallography, and evaluate the characteristics of the dislocation structure at different stages of deformation [11-13].

Both of these methods have their advantages and disadvantages and complement each other. The method of sliding lines is much simpler, especially when using a light microscope, and provides more integrated information. However, it is used to study only the surface structure and, indirectly, the movement of dislocations in near-surface layers, which has some specific features [14-17].

The method of sliding lines is known and has been used for a long time. With its help, it was found that sliding and shifting in crystals under low-temperature deformation go along certain crystallographic planes and directions for each type of lattice. The sliding direction always lies in its sliding plane. Their totality is a sliding system. In metals, one or more sliding systems may operate, but all these systems usually belong to one or two crystallographic orientations characteristic of each metal and determined by the type of lattice [18-22]. The directions and planes of preferential sliding are the most densely Packed in each lattice (figure 1). Planes with maximum atomic density have the largest interplane distance. Therefore, the shift along them is particularly easy. The sliding directions correspond to the direction of the burgers vector of individual dislocations characteristic of each lattice, which is also quite natural.
Figure 1. Examples of the planes and directions of the most dense installation in typical metal grids: a - face-centered cubic lattice (HCC); b – hexagonal densely Packed crystal lattice (GP); c - volume-centered cubic lattice (BCC).

Plastic deformation in a crystal depends significantly on its orientation relative to the direction of action of external stresses [23-27]. The most obvious and generally accepted way to image the orientation of the crystal and, consequently, its sliding systems is a stereographic projection, which is a geometric flat construction that conveys the angular relations between the planes and directions in the crystal (figure 2).

Figure 2. Scheme for determining the reduced shear stress.

In densely Packed lattices – HCC and GP – sliding occurs mainly in planes of the same type: the octahedron {111} – in HCC and the basic {0001} - in GP. Sliding in the predominantly basic plane is observed, for example, in magnesium and zinc [28-33].

The packing of atoms in crystals with a BCC lattice is not the most dense. There are several types of planes here – {110},{211},{321} – with a close packing density. In each of the BCC metals, dislocations can slide along all these three types of planes, but at low temperatures, the {110} and {111} systems
most often «work». Due to the large number of sliding planes, the number of possible sliding systems for metals with a BCC lattice is usually much higher than for metals with densely packed lattices [30-34].

There are such types of crystallographic planes and sliding directions, each of which has a set of specific planes and directions. When establishing a separate sliding system, which is a combination of the plane and the direction, it is necessary to remember the crystallographic condition of belonging to the direction of this plane [30-35]. The product of cosines determines the orientation factor (the Schmid factor): the smaller it is, the lower the tangent stresses in a given sliding system at a given tensile force.

4. Conclusion

Low-temperature plastic deformation from its very beginning to the moment of destruction is accompanied by an increase in the resistance of the sample material to deformation as its degree increases. In other words, a constant increase in the applied stress is required to continue the strain. This phenomenon is called strain hardening. It manifests itself not only in the process of deformation. It is known, for example, that after preliminary cold deformation, the strength characteristics of the material increase (the phenomenon of hardening) [36-40].

Deformation hardening is caused by inhibition of dislocations. The more difficult it is to move dislocations in the material, the greater the coefficient of strain hardening-the derivative of strain stress that characterizes the slope of the deformation curve. During the test, this coefficient changes, and its changes ultimately determine the geometry of the strain diagram. For a strict analysis of the regularities of strain hardening, it is necessary to use strain diagrams in the true stress-strain coordinates [41-46].

Since plastic sliding deformation in metals is carried out due to the movement of dislocations in certain planes under the action of tangent, rather than normal stresses, in practice, these coordinates are used to build single crystal stretching diagrams used in theoretical work to clarify the fundamental issues of deformation hardening. Single crystals have minimal structural imperfections. Obtaining single crystals allows us to study the properties of metals, excluding the influence of grain boundaries. Most theories of strain hardening are based on the effect of elastic interaction between dislocations. These theories, based on a number of simplifying assumptions, are often based on experimental data of structural analysis, and allow us to obtain empirical equations for the relationship of internal stress with deformation.

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