Progress in the theory of strength and plasticity of solids (A review of A. V. Stepanov's works)

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The article presents a review of the ideas and works of corresponding member of the USSR Academy of Sciences A. V. Stepanov, one of the founders of the theory of strength and plasticity of solids, during his creative period from 1930 through 1972. The work by A. V. Stepanov and his school covers many problems, starting with the study of crystal-damage processes, the mechanism of crystal plastic deformation, and ending with the control of crystallization processes and the obtaining of complex-shaped articles directly from the melt. In the theoretical field, Stepanov has not only advanced ideas concerning the mechanical properties of crystalline materials, but formulated also general laws governing the failure of solids, including crystals, oriented polymers, fibrous materials (lumber, composites), and biological and geological structures.

CONTENTS

In this article we wish to review the work and ideas of one of the founders of the theory of strength and plasticity of solids, corresponding member of the USSR Academy of Sciences Aleksandr Vasil'evich Stepanov. During his creative period from 1930 through 1972, his experimental and theoretical investigations have made a large contribution to the development of solid-state physics.

His work and the work of his school cover a wide range of problems, starting with the study of crystal failure and the mechanism of plastic deformation of crystals, and ending with the control of crystallization processes and the obtaining of metallic articles with irregular shapes directly from the melt. In his theoretical investigations he developed concepts dealing not only with the mechanical properties of crystalline materials, but also formulated general laws governing the failure of crystals, oriented polymers, fibrous materials (lumber composites), and biological and geological structure.

1. ROLE OF PLASTIC DEFORMATION IN THE FAILURE OF CRYSTALLINE BODIES

One of the particularly important results obtained by A. V. Stepanov is the establishment of the general nature of defects that lead to the failure of crystalline bodies. The physical theory of failure of solids was originally developed by the British scientist Griffiths (1922)[1] and by the outstanding Soviet scientist Academician Abram Fedorovich Ioffe (1920–1925)[2]. Ioffe performed the first systematic investigations in this field, which determined to a considerable degree its development for many years. These researches were subsequently continued by numerous students and followers.

In a well known study of sodium-chloride crystals, Ioffe has established in 1923 a number of fundamental facts and has advanced basic premises concerning the nature of the strength of solids. Among the most important results pertaining to the nature of brittle failure the following should be included:

a) Establishment of the relation between brittle and plastic failure when the temperature is varied (known as the Ioffe scheme for brittle failure).

b) Establishment of the exclusive influence of the state of the surface on the character of the failure (the so-called Ioffe effect).

c) Experimental proof that the strength of crystals agrees with the theoretically predicted value (when the tests are performed under definite conditions).

From 1923 through 1933, the prevailing point of view was that cracks that lead to brittle failure are the result of the development of embryonic cracks present on the surface of the sample prior to its loading, and that the nature of failure of all crystals, and consequently also of metals, is the same as that of glass. However, studies made in Ioffe's laboratory after 1923 have shown that the initial concepts of brittle failure were not complete.

By 1933 there were accumulated a number of facts contradicting the point of view that failure is due only to cracks existing on the surface of the sample prior to the test; these facts were the results of detailed investigations of the Ioffe effect[3].

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A new important stage in the study of crystal failure started with the work of A. V. Stepanov[4-7]. He advanced a new point of view, which offered a way out of these contradictions. He proposed that the brittle-failure centers are produced in the crystal during the course of loading as a result of plastic deformation, which always precedes the fracture, albeit to a most negligible degree. By plastic deformation was taken to mean all possible manifestations of plastic changes in the shapes of the crystals, namely slip, twinning, etc. In all these processes, dangerous defects, including microcracks, are produced in the crystals and cause the failure.

Stepanov subsequently performed a number of clever, simple, but precise experiments aimed at verifying and justifying this hypothesis[8-10]. He has also shown that his point of view explains unambiguously all the known cases of observed changes in strength. He explained a number of phenomena accompanying crystal loading, including, the Ioffe effect[11].

These experiments have also clearly demonstrated the connection of a fracture crack with plastic deformation and with primary defects on the crystal surface.

When first advanced by Stepanov, his hypothesis was not accepted, and his research seemed to most workers to be insufficiently convincing. He had to fight hard, inasmuch as the idea that plastic deformation, which strengthens crystalline materials, lays the ground work for brittle failure contradicted the then existing concepts and opinions. Further experimental study of the conditions of brittle failure unequivocally confirmed its close connection with the preceding microplasticity[12,13].

In essence, each new investigation devoted to the conditions under which brittle and plastic failure are realized, provides us at present with a new confirmation of Stepanov's hypothesis (see e.g.,[14,15]). This premise, revolutionary in its time, can now be regarded as proved and accepted by the world's science.

The next (third) important stage in the theory of brittleness was the development of dislocation theories and their application to the problem of crystal failure. Without entering into a discussion of the dislocation theories of failure, we note that all accept the general premises advanced by Stepanov concerning the role of plastic deformation in crystal failure. Thus, it is stated in a review by V. L. Indenbom and A. N. Orlov[16] that "in dislocation theory are considered a number of atomic mechanisms of crack nucleation, which are in essence a concretization of the general idea of A. V. Stepanov, concerning the appearance of failure centers as a result of the inhomogeneous course of the plastic deformation."

In his review, Gilman[17] notes (referring only to a 1937 paper[18] by Stepanov) that "Stepanov was the first who understood that plastic deformation can cause nucleation of cracks in ionic crystals;" his conclusions were unequivocally confirmed by recent studies" etc.[19,20].

In the later course of investigations aimed at establishing the connection between the primary defects present prior to the experiment on the crystal surface and the secondary resulting from plastic deformation, Stepanov has discovered, using polarization-optical methods (which were applied to the study of crystal plasticity by I. V. Obreimov and L. V. Shubnikov[21]), an important phenomenon pertaining to the nature of plasticity and which has become of independent interest.

2. CAUSES OF SHEAR IN CRYSTALS

When discussing these studies, one should bear in mind the state of our knowledge of the nature of plasticity of crystals 35 years ago. It was then known that plastic changes in crystal shapes are possible as a result of slip, but the cause of the slip was still unclear. It was impossible to control this phenomenon. At the same time, Stepanov has observed a very important fact. It turned out that if the surface of the crystal is damaged in such a way that the damage is oriented relative to its crystallographic axes, then shear can propagate from such a fault when the sample is subsequently loaded to a certain value (which coincides approximately with the elastic limit)[22-28]. Thus, he discovered, on a "macroscopic scale" for the time being, the cause of shear in crystals. Investigations of this phenomenon, carried out in 1937—1939, led to the establishment of the following fundamental facts:

The presence of a two-stage shear-formation process. The first stage is the formation of the "nucleus" of the shear, which in accordance with Stepanov's concepts call for large (theoretically) local stresses. The second stage is the growth of the "nucleus" of the shear. It was established that the growth of the nucleus begins at stresses that coincide with the real elastic limit. By the same token, he explained the physical meaning of the elastic limit as the stress at which the growth of shear nuclei becomes possible[27].

3. SHEAR NUCLEI. ARTIFICIAL SHEAR PRODUCTION

The possibility of shear growth on "locally case hardened" or "strengthened" region was far from obvious. All these phenomena were at that time new and unexpected, and served as a basis for further study of the plasticity process. The concept of the nucleus at that stage of research was quite arbitrary in character. It was necessary to clarify the nature of this region of the crystal. Stepanov performed to this end a number of experiments, in which he strived to localize the position of the nuclei, and also to determine the condition for their onset.

Stepanov investigated exhaustively the phenomenon observed by him and found a number of important regularities pertaining to the process of shear formation. He traced the process of the growth of the shear nuclei and their transformation into macroscopic shears. He discovered the existence of "left-hand" and "right-hand" shears, i.e., according to modern terminology, of dislocations of opposite signs. He observed interference of shears. He traced the influence of dissolution on the condition of shear formation, etc.[28,29].

Only in 1956, i.e., 20 years following the work by Stepanov, did Gilman[30,31] publish interesting papers that constitute, as it were, a natural continuation of the just-cited papers by Stepanov.

Gilman's experiments were analogous to those of Stepanov, but performed by the more subtle and more universal method of observing local deformations, rather than use the polarization-optical method. He employed selective etching[32].

In these investigations, Gilman observed a number of regularities previously established by Stepanov concerning the onset and development of shears in crystals. On the other hand, his work yielded essentially new data, which made it possible to make considerable progress towards the knowledge of plasticity, In particular, it follows from Gilman's work that Stepanov's "shear nuclei" are groups of dislocation loops. The experimental study of the mechanism of plasticity by shear production thus followed the path indicated by Stepanov back in the Thirties.

The method introduced by Stepanov for studying the plasticity mechanism by investigating regions of local faults in the crystal, (regions near scratches, pricks, scratches, pits, etc.) found wide application[32,33]. In spite of the fact that Stepanov's papers are frequently not listed in bibliography, his priority was in this case recognized. Thus, Gilman's review[17] states that "surface finish influences the slope of the stress-strain diagram in the region of strain hardening. It is probable that this is likewise not the principal effect in hardening. It is more likely that the hardening is due to the fact that the distribution of the slip (and consequently of the dislocation density) in the crystal depends on the surface finish." The main features of this phenomenon were investigated long ago by A. V. Stepanov (references are made to Stepanov's papers[1,22,23]). He found that pairs of slip bands originate from surface defects, and he was able to detect these bands by the birefringence they produce. However, the extreme subtleness of the influence of the surface was understood only when it was observed that an individual half-loop at the surface can generate a large slip band containing thousands of dislocations. Thus, the residual dislocation loops are very small defects capable of generating a dislocation loop under the influence of stress can exert a significant influence on the course of the "stress-strain" diagram.

In his further studies of the conditions of failure in "brittle orientations" of crystals, Stepanov observed in sodium-chloride crystals slip along the cube planes $\{100\}$ in the $\langle 110\rangle$ directions[25,34]. He investigated a number of features of slip along this plane in comparison with slip along the $\{110\}$ planes in the $\langle 110\rangle$ directions. He also investigated the influence of surface faults among the shear-formation conditions. It was found that the two-stage shear-formation process is indeed the general process in this case. At the same time, he established a very important new circumstance, namely that the condition for the growth of the nucleus is not only the attainment of a definite stress, but also of a definite temperature.

4. CONNECTION BETWEEN MECHANICAL CHARACTERISTICS AND OTHER PHYSICAL PROPERTIES OF CRYSTALS

Among the results of that time notice should be taken of the following:

a) Establishment of a connection between the melting heat and the work of the deformation[35,36]. This connection has enabled Stepanov to predict in 1932 the then-unknown mechanical properties of beryllium.

b) Discovery of the effect of electrification of slip bands in plastic deformation of ionic crystals[4], or of charged dislocation in modern terminology. Recently this phenomenon has attracted much attention and has been called in the literature the Stepanov effect[36,37].

c) Investigations of the influence of plastic deformation on the electric conductivity of ionic crystals (this phenomenon is now called the Gyulai-Hartli effect[38]), on the basis of which Stepanov proved his hypothesis of deformation of narrow regions of the crystal during the slip process[5,36].

5. "TRANSPARENT METALS." CONNECTION BETWEEN MECHANICAL PROPERTIES AND THE PROPERTIES OF ATOMS. PHOTOELASTICITY. PHOTOPLASTICITY

Attempting to determine the connection between the character of the failure and the mechanical properties of crystals, on the one hand, and the properties of atoms making up the crystals, on the other[39], Stepanov discovered that a definite group of crystals (halide compounds of silver and thallium as well as alloys on their basis) have mechanical properties that are unusual for ionic and atomic crystals. In this respect, they behave like metals, and this gave grounds for calling them "transparent metals"[40-45].

Stepanov was the first to grow large single crystals of these substances; he investigated in detail their properties and explained their peculiar behavior by establishing the connection between the mechanical properties and the polarizability of the atoms, indicating that the mutual polarization of the ions, by decreasing their electric repulsion, should strongly influence the plasticity of ionic crystals. These results played an important role in the development and in the understanding of the mechanism of process of plasticity and failure of crystals. In addition, it turned out that the special properties of these crystals have numerous practical applications (for example, TlBr—TlI = KPC-5). Subsequently, Stepanov has developed, on the basis of these materials, a number of new methods of investigating stress stages in crystalline, polycrystalline, and anisotropic media[29,42-47]. Various investigations and applications of these methods have subsequently been greatly expanded.

As is well known, the general theory of photoelasticity of crystals was developed by Pickels. Stepanov and coworkers have developed the theory of the photoelastic effect in cubic crystals in a planar loaded case[43-47]. Prior to Stepanov's studies, the stressed state of metallic structures was investigated with models made of amorphous materials, glass, or plastics. Stepanov has proposed and developed a new optical method of studying the stressed state of metals, using silver and thallium halides as models, "Using models of these materials it is possible to assess not only the distribution of the stresses, but also the structural changes that occur under plastic deformation."

6. FAILURE OF PERIODICALLY INHOMOGENEOUS ANISOTROPIC MEDIA

As already mentioned, prior to Stepanov's work, the theory of failure of solids was based on the opinions of Griffiths and Ioffe. According to these opinions, the presence of cracks and pores, which concentrate the stresses, should weaken materials, "yet wood and bone, in spite of their inhomogeneous porous structure, have high mechanical strength," noted A. V. Stepanov (1950). "The high mechanical strength of wood and bone is due not only to their composition but precisely to their unique very fine structure, which gives rise to the anisotropy of the elasticity and strength. The anisotropy of the mechanical properties prevents failure from developing in certain directions, and by the same token creates conditions for higher strength''[48]. From 1948 through 1950, Stepanov developed the principles of the physical theory of failure of periodically-inhomogeneous and anisotropic media. He has demonstrated the possibility of establishing general failure laws for substances as different as crystals, oriented polymers, fibers, and biological and geological structures, since these laws are determined only by the inhomogeneities and their spatial distribution[48-53]. These ideas of Stepanov acquire at the present time a particular practical interest in connection with the development of commercial applications of composite materials that are macroscopically periodically-inhomogeneous media[54]. Stepanov has predicted and verified the existence of a special group of phenomena, which he called ''mechano-orientational phenomena,'' and which play the fundamental role in different structural transformations of crystals under the influence of external mechanical forces. He includes among these phenomena, for example, mechanical twinning of crystals and cleavage[55,56].

7. ELASTIC PROPERTIES AND THEIR TEMPERATURE DEPENDENCE

Stepanov was one of the first to emphasize the need for studying the elastic properties of crystals as properties that are determined directly by the binding forces and are connected with all the properties of crystals. Under his leadership, new methods were developed for the measurement of elastic constants of crystals, and extensive research was done on the temperature dependence, especially near the melting point[57,62]. The crystals investigated were mainly those of alkali-metal halides. It was shown, in particular, that the character of the temperature dependence is determined by the form of the metallic ion. The contribution of the thermal expansion and of the lattice vibration to the temperature coefficients of the elastic constants was determined[62].

A number of discrepancies between the atomic theory of elastic properties and the experimental data was established. It was shown that the theory of Leibfried and Giep gives good results only when the temperature influences are calculated for those elastic constants of solid solutions, which depend little on the temperature[62]. Stepanov's laboratory is one of the renowned centers in the field of the physics of elasticity.

8. MECHANICAL PROPERTIES OF POLYCRYSTAL AND SINGLE CRYSTALS AT HELIUM TEMPERATURES

The very first investigations of the mechanical properties of different metals at very low temperatures (4.2–1.6°K) were initiated in the same laboratory (1955)[63-69]. Several original instruments were developed for the study of the mechanical properties of metals at helium temperatures. A number of new phenomena were discovered (nonstationary character of the tension diagram, changes in the character of the failure). These investigations are now of practical importance in connection with the exploration of space. To develop a theory of crystal plasticity, the mechanical properties of ionic crystals were investigated at helium temperatures. The presence of plasticity and a number of features of shear formation were observed at these temperatures[70,71]. These investigations are progressing successfully at present and yield information on the development of the dislocation theory of plasticity.

9. DISLOCATION CONCEPTS

Stepanov's school has made an undisputed contribution to the development of dislocation concepts[72-74], which are being developed along the path marked by him even in his earliest papers. One cannot fail to mention that Stepanov at one time opposed gullibility with respect to dislocation concept[75] and subsequently expanded cleverly the experimental premises of this theory. Investigations of the dynamics of dislocations in ionic crystals were initiated in his laboratory and were successfully continued by E. M. Nadgornyĭ. These investigations have cast light on the following: the mechanisms of dislocation motion under different conditions, the role of the resistance of the crystal lattice, the role of point defects, of elementary excitations, of interaction between dislocations; they also made it possible to compare the basic dynamic characteristics of microplasticity with the characteristics of macroplasticity.

10. WHISKER CRYSTALS

The laboratory headed by Stepanov made an appreciable contribution to extensive research on the properties of whisker crystals[76]. In this field, the laboratory served as a sort of school for many young workers in other institutes. The members of the laboratory[76] investigated the strength and elasticity of whisker crystals of many substances.

11. STUDY OF CAPILLARY AND THERMAL CONDITIONS OF CRYSTALLIZATION, DIRECT PRODUCTION OF ARTICLES FROM MOLTEN METALS

The initiative, ideas, and works of Stepanov in the science and practice of crystal growth can hardly be overestimated. Most materials and alloys are transformed into finished articles (sheets, tubes, rods, wire, etc.) are prepared by pressure working (rolling, pressing, extrusion). Stepanov obtained various metal articles directly from the melt[77-84]. He has developed for this purpose a number of original installations. The gist of Stepanov's method is the following: ''A plate of a material that interacts little with the melt is placed on the horizontal surface of the molten metal. In the plate there is a cut or slit, the shape and dimensions of which are the same as those of the article. The plate is called a float or a shaping tool. A primer having the same shape as the article is dropped into the melt through the slit of the shaping tool. The melt adheres to the primer. When the primer moves upward, the adhered melt is drawn by it. Entering into a region of lower temperature, the melt cools and is transformed into the article.''[84]

It should be noted that attempts to obtain articles with a given profile from a melt were made even earlier. These attempts, however, were confined to particular technological developments and were not theoretically thought out. Stepanov's method is based on a special and original principle of shaping, consisting in the fact that the liquid can be caused to assume a definite shape in the free state. This principle is formulated by Stepanov as follows: "The desired shape or element of shape is produced in the liquid state by various effects that permit the liquid to retain (the required) shape, and then this shape or its element are transformed to the solid state by creating suitable crystallization conditions[83]." Many variants of Stepanov's method are possible. A number of them have already been tested successfully, others still await their solution. The most advanced is the variant of capillary shaping, which uses the surface properties of the liquid—its wetting ability. Stepanov's method is therefore frequently called in the literature capillary shaping. Stepanov's method was tested on aluminum, copper, their alloys, cast iron, alkali-halide salts, and semiconducting materials. Stepanov and co-workers investigated the main properties of these finished articles. The surface of the article is nearly polished, and the tolerances are close to those established by the government for analogous articles obtained by extrusion or oppressing. Stepanov investigated theoretically the thermal conditions of the process, and has developed experimentally and theoretically the science of capillary phenomena[82,84]. The use of shaping devices in crystallizations uncovered new possibilities for the control and monitoring of crystallization processes. It has become possible to grow single crystals of specified shape[84]. This decreases the material waste, decreases the labor required for finishing, and uncovers new technological possibilities for designers of devices in which single crystals are used. Soviet industry is presently mastering the technique of obtaining semiconducting single crystals of specified shape by Stepanov's method.

In most recent years, many papers have been published abroad on the production of finished articles and single crystals of specified shape. There are many patents and papers on this problem. In essence, however, all the proposed methods are based on Stepanov's fundamental research.

Stepanov paid much attention to the organization of annual conferences devoted to obtaining commercially important single crystals by the crystallization methods proposed and developed by him, and also to the prospects of using single crystals in Soviet instrument construction[84].

In his concluding remarks at one of the conferences on the physics of strength of crystals in Leningrad, Stepanov said: "We all think and discuss how to raise the real strength of solids to their theoretical values. It is now time to start thinking of producing new materials with strengths exceeding the theoretical strengths of existing substances."

Stepanov died on 16 May 1972 and many of his ideas and the works, as well as the works of his students, have not yet been completed.

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