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SOME FEATURES OF A METALLIC STRUCTURE AND MECHANISMS OF ITS DESTRUCTION AND JOINING UNDER THERMAL AND MECHANICAL ACTIONS

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We consider some known properties of metals, which are explained incompletely by the existing ideas or are contradictory. It is shown that the notion of a metallic bond involves three types of bonds with different energy regions of action. Based on the experimental data obtained at the initial stages of formation of a metallic structure from evaporated metals, we have drawn the conclusion on the existence of the smallest grains. The introduction of the notion of the deformation energy of metals has been substantiated, and formulas for its determination have been proposed. The intergranular binding energy has been determined. The probable mechanisms of destruction and binding of metals under mechanical and thermal actions are discussed.

At the present time, there are a number of contradictory ideas substantiating the consequences of mechanical action on metals, which, for example, lead to their destruction [1–3]. All these ideas are based on the identification of interatomic bonds with a metallic bond [2, 4], which is expressed in the fact that only the dependence of the atomic bonds on the distance, characteristic of the whole volume of the metal, is used in investigating the properties of metals [5–7]. Such an approach has led to uncertain ideas on the possibilities of movement of the atoms in metals. The attempts to use the features of a metallic structure in the above investigations, which are made not on the basis of consideration of sufficiently well investigated processes of production of such structures (these processes are described in [8]) but on consideration of certain consequences of the influence of the structure of metals on their properties [2], also do not clarify, for example, the physical nature of the destruction of metals. The conclusions on the uncertainty of the views on the possibilities of movement of atoms follow, in particular, from the generally accepted views of metals presented in [9], where it is reported that a metallic bond (the atomic bond in a solid or liquid metal which is based on the collectivization of outer electrons is one type of chemical bond) allows fairly large displacements of the atoms relative to each other without breaking the bond. The appearance of such a proposition in the physics of metals is explained by the fact that there are no explanations of the differences between the energy states of mono- and polycrystalline structures varying in the size of the grains and the differences between the latter for equal masses of the same metal. In this connection, based on the commonly known experimental data, we consider the energy states of a single-grain metallic structure and of a metallic structure formed from two grains and discuss the probable mechanisms of destruction of the latter.

By the above-indicated metallic structure is meant the structure typical of metals in their solid and liquid aggregative states; this structure simultaneously contains both neutral atoms and ionized atoms, i.e., atoms from which some of their valence electrons are separated. Since all the atoms of any given metal are identical, the transfer of an electron from a neutral atom to an ionized one can occur without expenditure of

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energy. As a result, in a metallic structure, the exchange by electrons is continuous and there is a certain number of free electrons at all times. These widely used ideas of a metallic structure are presented in [10].

The initial information on the energy state of a metallic structure can be obtained only from experimental results on its formation and joining but not from the conditions under which the crystalline structure of the metal forms or changes in any technological process involving mechanical and (or) thermal action [11–14], which influences the properties of the metal, such as strength and the grain size. Such information cannot be obtained on the basis of the notions of gradual formation of a structure from atoms [15], as for the remaining main structures of solid substances: atomic, molecular, and ionic [10]. The above experimental results are contained in the physics of thin films, which, in addition, gives ideas of the mechanisms of formation of structures from evaporated atoms. In accordance with these ideas presented in [8], the condensation of a metal vapor can bring about the formation of a crystal (grain) and a liquid drop (which transforms to a crystal as a result of cooling) and simultaneous formation of grains in the liquid and solid aggregative state, which have a metallic structure. This work also points to a commonly known feature, revealed in investigations of the initial stages of formation of metallic films and lying in the fact that either individual atoms or grains are fixed on the base. This suggests the discrete character of the growth of a metallic film owing to the increase in the number of grains formed in the liquid or solid aggregative states. The fact that the physical conditions have a great influence on the formation of a metallic structure allows us, in all probability, to speak of the physicochemical nature of this process. Taking into account the possibility of obtaining grains of different size in this process depending on the conditions of its realization [8], we may suggest that there exists the smallest grain that has a metallic structure and consists of a certain definite minimum number of atoms.

The foregoing allows us to introduce the notion of binding energy for the smallest system of atoms in the form of a grain in the liquid or solid aggregative state, considering it as the work necessary to break this bond. In this case, the separation of even one atom from such a system of the smallest size must lead to its destruction, i.e., the destruction of the metallic structure. Although such a notion of the smallest grain is probable, it is inconsistent with the experimental data on the possibility of the metals having different crystal lattices [7] and on the nonmultiplicity of the size of grains produced from evaporated metals by vacuum technologies [8]. Thus, *by the smallest grain is meant a grain in which no intergranular boundary will be formed or which will not break down, under mechanical action, into parts having a metallic structure.*

In the smallest grain, there are also other bonds determined by the structure of the atoms and dependent on the distance between them (we will call them interatomic bonds), since the atoms can change their position within the limits of the grain volume, which is supported by the possibility of changing the aggregative state of the smallest grain and accordingly of deforming it. In the case of the above changes in the positions of the atoms in the grain, the interatomic bonds will break and be replaced by new ones. Consequently, the smallest grain represents a system which contains smaller subsystems characterized by interatomic bonds that do not determine or determine only partially the formation and destruction of the metallic structure. Here it is pertinent to note the presence of one more bond typical of metals, namely, the bond (intergranular bond) that arises as a result of joining of the metallic structures formed (for example, being in the molten state).

The foregoing allows the conclusion that *the destruction of metals means the disruption of the metallic structure in a certain volume of the metals, while the binding (joining) of metals means the formation of the above structure at the boundaries dividing them before.*

Thus, for metals, the commonly known notion of binding energy involves three types of binding energies. When mechanical action on a metal is considered, the energy regions of action of such bonds are not separated and their influence on its mechanical properties is not taken into account, since there is no need to do this within the framework of only the chemical concepts of the nature of formation of a metallic structure. Such a concept can be applied with certain assumptions to alkaline metals in which, in all probability, the smallest grains contain a small number of atoms and the intergranular bond is broken for energies differing only slightly from the energies of breakdown of these grains. The use of these concepts for explanation of the strength properties of any metals has led to the notion of theoretical strength, the disagreement of which with the actual values was explained by the existence of dislocation defects in the crystal structure [16, 17]. Since these defects are formed for energies corresponding to elastoplastic deformations or temperatures lower than the melting temperature, the fact of their existence gives a qualitative (but not substantiated) explanation for the decrease in the strength of materials relative to the theoretically expected value. The possibility of explaining this disagreement on the basis of the known results on the separation of metals in the molten state practically without expenditure of energy was considered as inconsistent with the existing views. Relation of the dislocation defects to the disruption of the metallic structure leads to the idea of the unimportance of the influence of the energies for which the metallic structure is formed on its mechanical properties, which does not comply with experimental data and has, thus, escaped the attention of researchers. To obviate these errors, any structural defects should be considered only as probable zones of localization of deformations (regions in which one observes the most intense plastic deformation and the maximum manifestation of the thermal effect [11]). As for dislocations, because of the imperfection of the crystal lattice of the grain, they, in all probability, determine one realization of the possibility of its breakdown or another, and the observed traces of them are centers of the probable formation of future intergranular boundaries.

To characterize the energy of the smallest grain, which gives an idea of the existence of two types of bonds, it makes sense to introduce a notion that would differ from the notion used of the metallic energy of the bond. There is also another reason, for which we should do away with the notion of binding energy for the characteristic considered. As has been mentioned above, the smallest grain can be plastically deformed, but the expenditure of energy required for realization of this process in different directions of the grain will be different, which is due to both the absence of symmetry in the grain shape and the right order of arrangement of the atoms in the metallic crystal. Because of this, the binding energy will be a variable quantity unsuitable for characterizing the energy of the smallest grain.

One of the characteristics of the new notion of the energy of the smallest grain in the liquid or solid aggregative state must be the maximum value of the energy determining the boundary of its existence as a system of atoms with a metallic structure. *As such a characteristic of the smallest grain, we will use the notion of the critical energy determining the unstable state of the number of atoms forming it, which are found in a confined space and are capable of being a single whole or escaping from this space when, respectively, their energy decreases or increases.* The critical energy E_{crit} is determined from the equality

$$E_{\text{crit}} = n\,(E_{\text{evap}} - E_{\text{p}} - \delta E)\,. \tag{1}$$

The base, on which the atoms are deposited, is usually positioned under the evaporated metal. To take this into account, we used the notion of the potential energy E_{p}. The energy required for disruption of a metallic structure is higher than the energy at which it is formed; therefore; we have introduced the quantity δE into (1).

Taking into account this fact as well as the fact that in the case of destruction of a metal by evaporation, predominantly neutral atoms separate from it (the vapor of atoms of the majority of metals consists partially of ions, whose quantity can account for up to 0.1% of the evaporated neutral atoms [8]), and the above-mentioned notion of a metallic structure, in accordance with which the transfer of an electron from a neutral atom to an ionized one occurs without expenditure of energy, we introduce the notion of the *deformation energy of the smallest grain, which must include the existence of the system of atoms as well as their relative position and oscillations.* The deformation energy of a grain could be represented as a sum of the kinetic and potential energies of interaction of the atoms, which must not exceed the above critical energy. With such a notion, all its components would have to include the mutual influence of all the atoms of the grain. At the present time, such mathematical formalism is developed insufficiently; therefore, using the above notion of deformation energy, we will confine ourselves to only the relative values fitting the existing notions and experimental data.

When the total energy of the atoms of the grain or its deformation energy exceeds the above critical energy, the grain breaks down into individual atoms with energies gained by the time of breakdown. However, since the potential energy of interaction of the atoms of the grain can increase nonuniformly under mechanical action, it can break down not only into individual atoms, but also into groups of atoms linked by interatomic bonds. In this case, the assumed equivalence of the change in the deformation energy, which leads to the breakdown of the smallest grain as a result of a change in the kinetic or potential energy of interaction of atoms or a simultaneous change in these energies, is supported by the fact that, as has been mentioned above, the grain formed can be in two aggregative states simultaneously.

In principle, for the smallest grain we could use the commonly known thermodynamic notion of internal energy. While on the subject of the internal energy of a system of grains being a single whole, it is necessary to specify the existence of the internal energies of the smallest grains in it, which will lead to certain terminological difficulties in presenting the problems considered.

It should be noted that the notion of the internal energy of a body, used in thermodynamics, mainly suggests the consideration of the change in the kinetic energy of its atoms. A replica of the cycle of increasing this energy to a value higher than the energy at which the molten state is attained and which, in all probability, is equal to the energy responsible for the plastic deformations, and subsequently decreasing it to the initial value under the same cooling conditions does not cause changes in the energy state of the body, whereas an analogous change in the potential energy of interaction of the atoms, caused by mechanical action, will invariably lead to a change in the energy state of the metallic body. This situation is explained by the fact that in repeated cycles of heating and cooling, the atoms of the metal will repeat their motion, whereas the mechanical action causing the potential energy of interaction of the atoms to increase leads to a change in their position and corresponding expenditure of energy on changing the above three types of bonds. Moreover, a change in the position of atoms, which is caused by their displacement relative to each other, leads to a change in the kinetic energy, which is accompanied by heating of the body.

The notion of a triple point at which three different phases of a substance are observed, used in molecular physics for solid bodies [18], is not quite suitable for metals, since for the latter, the vapor phase having a metallic structure is absent. Instantaneous transitions from the liquid phase to the solid one and conversely are also not observed. Because of this, for metallic bodies *the triple point is the state attained when both the total kinetic energy of all the atoms and the potential energy of their interaction change to a value equal to half the total critical energies of all the smallest grains in the metal volume considered.* In this state, the disruption and formation of a metallic structure will occur at one time, and the deformation energy of the smallest grains will change from negative values to positive ones near zero.

As a result of cooling, the smallest metallic drop obtained in the process of evaporation of a metal transforms into a new aggregative state. In this case, a portion of its energy E_g will be lost to the environment, and the other portion will be transformed to the deformation energy. Consequently, we may write that

$$E_{def} = E_g - E_1 - E_2 \,. \tag{2}$$

As a result of transformation of the drop considered from the liquid phase to the solid one and subsequent cooling of the drop transformed into the crystal, the structure will be deformed; therefore, we introduced the quantity E_2 into (2).

When an aggregation of evaporated atoms found in the above-mentioned critical state and located in a confined space on the surface of the base transforms into a crystal (grain), the kinetic energy of the atoms is converted to the potential energy of their interaction. After such a conversion, the potential energy of interaction of the atoms will be maximum, which causes deformation of the grain and decreases its deformation energy at later instants of time. Because of this, we may state that equality (2) will also determine the deformation energy of the grain formed in the solid aggregative state, but the relation between E_1 and E_2 will be the same at each instant of formation of two different aggregative states of the grain to the point of establishment of a certain equilibrium state for these grains. These equilibrium states for grains obtained from different aggregative states will be, in all probability, characterized by different deformation energies.

By increasing the energy of a cooled drop after its formation by the above-mentioned method, owing to heating one can make its atoms free again, i.e., not bound by the metallic structure. But a grain can break down under mechanical action. In this case, the expenditure of energy to do work will increase the deformation energy (it will be spent on elastic and plastic deformations) and the temperature of the grain. In this case, the influence of the thermal action on the energy state of the grain can be reduced to a minimum or eliminated completely by decreasing the rate of deformation and increasing the removal of this energy to the environment. Since in the case of plastic deformation, a grain cannot withstand loads with an energy exceeding the energy at which it was formed, the grain will break down, as in the case where the temperature of a drop increases to the boiling or sublimation temperature [19]. In this case, its parts — atoms and their groups — will fly apart in accordance with the energy gained at the instant of disruption of the metallic structure. Since the atoms of certain metals can form stable diatomic molecules [20], it may also be assumed that in the case of breakdown of a grain, which occurs with a great release of energy, a portion of this energy can be expended in forming atomic and molecular structures in the fragments of the grain. It should be noted that the breakdown of a grain by mechanical action will occur like an explosion, and if the grain was surrounded by other grains prior to the explosion, a cavity can be formed at the site where it was positioned, and its parts can become interatomic defects. Since the fractions of the grain surrounded by other grains are limited in their movement, the energy of breakdown of this grain will be released in the form of heat.

When metals are joined by mechanical action, for example, as has been carried out in [21], in the zone of localization of deformations, which is positioned near the boundaries of the joined metals, the grains of the metal also break down, and the released energy of their fragments is expended in connecting to the new metal.

If two smallest grains obtained by evaporation of a metal in vacuum through the mechanism vapor → liquid [8] will be heated to the temperature of their melting, their total energy $E_{2\mathrm{d}}$ will be

$$E_{2\mathrm{d}} = 2\,(E_{\mathrm{def}} + E_{\mathrm{m}})\,. \tag{3}$$

If we link two analogous grains and heat them to the melting temperature, the grains will coalesce into one drop having a metallic structure. The energy of such a drop $E_{1\mathrm{d}}$ must differ from the energy given by equality (3) by some value that will be called the intergranular binding energy E_{bond}, i.e.,

$$E_{1\mathrm{d}} = 2\,(E_{\mathrm{def}} + E_{\mathrm{m}}) + E_{\mathrm{bond}}\,. \tag{4}$$

The introduction of the term E_{bond} into (4) eliminates difficulties in the perception and representation of processes occurring in a metallic structure subjected to mechanical action, as in the case of using the new notion of the energy of a two-grain or a multigrain structure. In (4), before the term E_{bond} we put a plus sign, because the intergranular binding energy has a negative value. This reflects the fact that the expenditure of energy to do work on the disruption of a two-grain structure will increase as compared to the expenditure of energy required for the breakdown of two individual grains.

After cooling of two individual heated grains, their total energy $E'_{2\mathrm{d}}$ can be represented in the form

$$E'_{2\mathrm{d}} = 2\,(E_{\mathrm{def}} + E_{\mathrm{m}}) - E'\,. \tag{5}$$

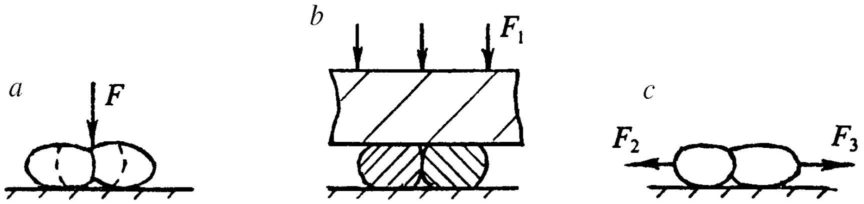

Fig. 1. Schemes of mechanical actions on a two-grain structure, which cause the disruption of the intergranular bond (dashed lines separate a certain volume of the smallest grain, which includes the intergranular boundary).

The energy E' lost to the environment is apparently equal to $2E_m$. This completely corresponds to the above property of metals, which implies that the energy state of the grains does not change in repeated cycles of increasing the kinetic energy of the grain atoms to a value higher than the energy at which the molten state is attained and subsequently decreasing it under the same cooling conditions.

Let us assume that after the coalescence of grains and cooling of them under certain special cooling conditions, the structure of the grains coalesced together remains unchanged and there is a boundary between them. The energy of such a cooled drop E'_{1d} can be represented in the form

$$E'_{1d} = 2\,(E_{def} + E_m) + E'_{bond} - E'' . \tag{6}$$

The situation where the intergranular boundary between the grains coalesced together is absent upon change in the conditions of their cooling is no less real. Different conditions of cooling of a metal must cause different motions of atoms and different arrangements of them relative to each other. In this case, the deformation energy of the initial grains must change to certain values of E'_{def} and E''_{def} and the quantity of heat E''' lost to the environment must also change. The energy of such a cooled drop E''_{1d} will be

$$E''_{1d} = E'_{def} + E''_{def} + 2E_m + E'_{bond} - E''' . \tag{7}$$

Having done some work on plastic deformation of a grain without an intergranular boundary, we can obtain a structure with such a boundary. In this case, a grain with the energy E'_{1d} can be obtained.

Heating of a body leads to practically the same increase in the kinetic energy of all the atoms, while mechanical action brings about the formation of zones of the so-called regions of localization of deformations, in which the atoms have values of the potential energy of interaction, which differ significantly from those in other parts of the deformed body. Since the smallest grain can be deformed, we may speak of the realization of the state of localization of deformations in the volume of the smallest grain in a two-grain structure (Fig. 1a). Having increased the energy in the above volume of the two-grain structure, containing the intergranular boundary, by mechanical action to a value insignificantly higher than the energy required for melting of the smallest grain, we break down the grain into two initial grains. As a result of such a breakdown, we obtain two individual grains having a metallic structure. In this case, the energy $E_m/2$ will be given to identical grains, and the fragments of the earlier whole body will fly apart in different directions with this energy.

Acting on the two-grain structure by a plane instrument, as is shown in Fig. 1b, we will deform it plastically. Under this action, the structure considered will also undergo stretching deformation. As the deformation energy increases to a value exceeding $2E_m$, the intergranular boundary must break down, since in accordance with (4) the energy of a two-grain structure must not exceed E_{1d}. In this case, it may also be assumed that the energy

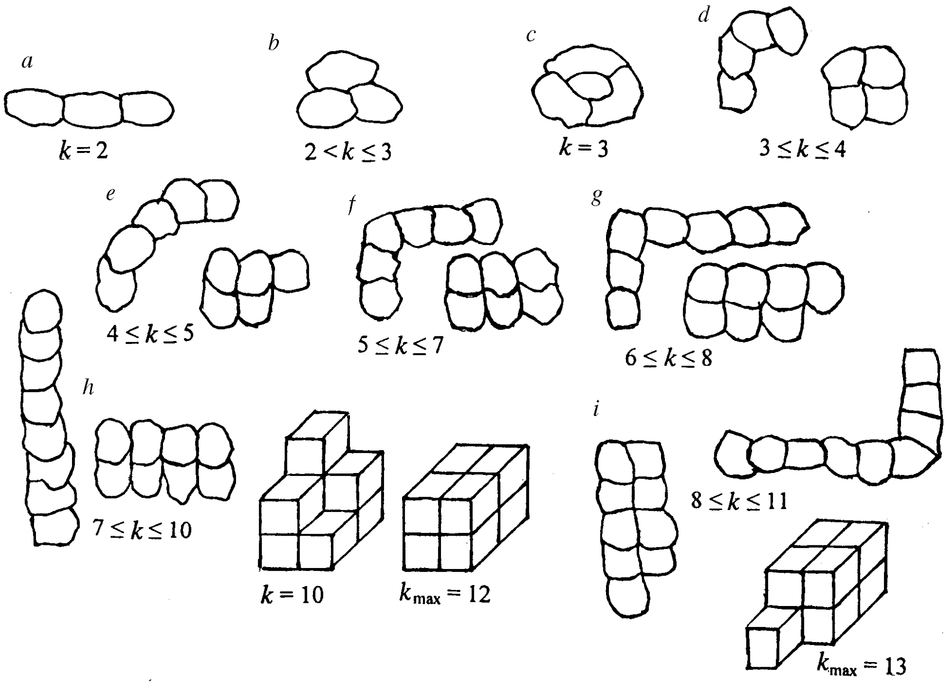

Fig. 2. Possible cases of linking of multigrain structures.

TABLE 1. Maximum Numbers of Intergranular Bonds in the Case of Three-Dimensional Linking of *n* Grains

n	8	9	10	11	12	13	14	15	16
k	12	13	15	17	20	21	23	25	28
$k_{n+1}-k_n$		1	2	2	3	1	2	2	3

$$E_{\rm pl}=E_{\rm m} \tag{8}$$

was spent on the deformation of two grains.

In the case of stretching of the two-grain structure (Fig. 1c), because of the localization of deformations, the energy ΔE of the two-grain structure, at which the intergranular boundary breaks, will increase in the range between $E_{\rm m}$ and $2E_{\rm m}$.

Taking into account that the intergranular energy of binding is equal to $-E_{\rm m}$ and using (6), we can write

$$E'_{\rm 1d}=2E_{\rm def}+E_{\rm m}-E'' . \tag{9}$$

It is evident that after the melting of the grains, the energy lost to the environment will differ insignificantly from the energy transferred to the grains for their heating, i.e.,

$$E''\approx 2E_{\rm m} . \tag{10}$$

Substitution of this value of E'' into (9) gives

$$E'_{\rm 1d}\approx 2E_{\rm def}-E_{\rm m} . \tag{11}$$

We now determine the deformation energies for bodies having different crystalline structures. Let us assume that the body of mass m has a monocrystalline structure and the mass of the smallest grain of average diameter d_0 is equal to m_0. In this case, in accordance with the foregoing, taking into account the possibility

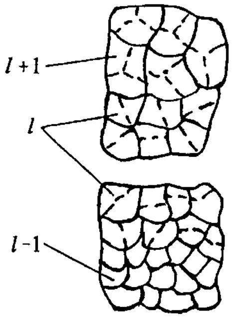

Fig. 3. Possible arrangement of grains of different size in a certain *l*th region of a deformed body and in the neighboring regions (dashed lines denote the possible intergranular boundaries).

of further destruction of all the bonds and grains of such a body, we can represent its deformation energy E_Σ as follows:

$$E_\Sigma = \frac{m}{m_0} E_{\mathrm{def}} - kE_{\mathrm{m}} \,. \tag{12}$$

Preparatory to determining the quantity k for a body having an arbitrary number of grains, we consider the case where the body consists of three smallest grains. In such a body, the grains can be positioned relative to each other in the manner shown in Fig. 2a–c. In the case where the grains are arranged so as in Fig. 2a, the number of intergranular bonds is equal to two, while the linkage of grains shown in Fig. 2c has three intergranular bonds. Because of this, it may be suggested that in the situation shown in Fig. 2b, the number of intergranular bonds can be arbitrary in the range between the values two and three. Representation of the possible linkages on the plane for a larger number of grains (Fig. 2d–i) shows that with increase in the number of the latter, the difference between the maximum and the minimum number of intergranular bonds increases. For eight grains or a larger number of them, the quantity determining the number of intergranular bonds will fit the inequality

$$N_i - 1 \le k \le N_i + i + 2 \,. \tag{13}$$

Different relations between the maximum number of intergranular bonds and the number of smallest grains will be observed in the case of three-dimensional linking of the latter (Fig. 2h, i and Table 1), but the above relationship will hold. Such views of the number of intergranular bonds and of the possibilities of changing them for the same mass of the metal agree with the experimental data on the possibilities of changing the shape of a body in the case of plastic deformation.

In the case of mechanical action on a single crystal by loads exceeding the loads that cause elastic deformations of a body, we will do work on the formation of intergranular boundaries, on plastic deformation of grains, and on the displacement of them relative to each other. In this case, in the deformed metal, because of the existence of localization zones, one will observe regions with grains of different size (Fig. 3). The work on the formation of intergranular boundaries and on plastic deformation of grains will constantly increase the deformation energy of the body, whereas the work on the displacement of grains will increase this energy only in the case where the number of intergranular bonds is decreased, which can be taken into account in relation (12) in the following way:

$$E'_\Sigma = \frac{m}{m_0} E_{\mathrm{def}} - (k - k_1)\, E_{\mathrm{m}} + \frac{1}{2}\left(k - \sum_{l=1}^{L} \frac{m_l d_l}{m_{lg} d_0} \right)(E_{\mathrm{b}} - E_{\mathrm{el}}) + \sum_{j=1}^{N} \frac{m_j}{2m_0}\,(E_{\mathrm{pl}} - E_{\mathrm{el}}) \,. \tag{14}$$

Since the number of intergranular bonds is determined by the shape of the body (see, for example, Fig. 2h), the quantity k_1 can be determined as the difference between the number of bonds for the body before the deformation and for the body after the deformation. For E_{def} in (12) and (14) we can use, without a high error, the quantity opposite in sign, which is determined by the energy at which the boiling or sublimation of one smallest grain of average diameter begins. In rough determinations of the deformation energy of a body, for E_{b} we can use the half-sum of the energies at which the crystallization and recrystallization of the two-grain mass of the metal studied occurs, since it is in this range of energies that the intergranular boundary is formed. Since the same elastic deformations of a metallic body can be attained by both mechanical and thermal action [18], the quantity E_{el} can be determined as the expenditure of energy required to attain the maximum elastic change in the volume in the case of heating a two-grain structure. In the majority of processes used in press forging, the molding of products is made in a volume closed partially by the instrument, which, as for most metallic products meant for different purposes, is exposed to different actions and has only partially closed portions at the sites of transfer of force loads. It may be assumed without a high error that the value of the energy $E_{\text{pl}}/2$, at which the smallest grains in the lth regions of such bodies are deformed, is equal to $E_{\text{m}}/2$, because, as has been indicated above, after attainment of this energy in the neighboring grains, the intergranular bonds between them begin to break in the case of existence of stretching deformation.

Thermal action on a single crystal will also increase its deformation energy, which can be taken into account in relation (13) in the following way:

$$E''_{\Sigma} = \frac{m}{m_0}\,(E_{\text{def}} + E_{\text{h}}) - kE''_{\text{bond}}\,. \tag{15}$$

Thus, *the atoms of a metallic structure can change their position within the limits of a grain, and the grains can move relative to each other in the volume of the entire body. When the smallest grains in a body subjected to mechanical action break down, their atoms cease to be bound by the metallic structure and can move under the action of internal stresses throughout its volume as defects of the metallic structure and escape from it on emergence.*

When the kinetic energy of the atoms of a metallic body exceeds a certain value, recrystallization occurs in it, whereas the increase in the potential energy of their interaction to a value higher than the energy at which the Hooke law is fulfilled leads to the formation of localization zones and the breakdown of grains in them. Further increase in the kinetic energy of the atoms owing to the heating of the body will lead to boiling and sublimation and, apparently, to free movement of the atoms throughout the volume of the body. An analogous change in the potential energy of interaction of the atoms will cause expansion of the volumes in which the breakdown of grains occurs, whereas in the zones of localization of deformations the disruption of the metallic structure of the grains will occur upon attainment of the minimum size of the grains and using their entire plastic resource and the possibilities of changing the positions of the boundaries (the probability of realization of any mechanism of destruction of the metal will be determined by the scheme of deforming forces acting in the localization zone). Simultaneous change in the kinetic energy of the atoms of a metallic body and increase in the potential energy of their interaction will lead to a change in the dimensions of the zone of localization of deformations, as compared to the mechanical action on an analogous body. Thus, with increase in the kinetic energy of the atoms, the plastic properties of the grains will increase and the zone of localization of deformations will decrease and disappear completely when these energies reach the values at which the molten state occurs. At the same time, a decrease in this energy leads to a decrease in the plastic properties of the grains, causing the localization of the extremum values of the deformations in a smaller region. This is responsible for the increase in the probability of disruption, first of all, of intergranular bonds, which explains the sharp decrease in the strength properties of metals at decreased temperatures. The process of joining of metals by mechanical action, which is the reverse of destruction, will also be realized in two ways at the above considered absolute values of the energies characterizing the smallest grain and the intergranular bond, because it is impossible to localize the extremum energies in a narrow region including only boundary grains or their parts.

The mechanisms considered of destruction and formation of a metallic structure allow one not only to explain a number of known experimental data from the field of treatment of metals by pressure, such as a high release of heat in experiments on high-speed impact joining [22] and destruction of metallic products in the zones adjacent to the newly formed boundaries, but also make it possible to predict new results that can be obtained in this field of knowledge, for example, for heterogeneous metallic materials with such characteristics as adhesion, thickness of the coating, and so on.

NOTATION

$\mathrm{E}_{\mathrm{crit}}$, critical value of the energy of evaporated atoms; n, number of atoms forming the smallest grain; E_{evap}, energy of the atoms in evaporation; E_{p}, change in the potential energy of the atoms, caused by a change in the height of the base relative to the position of the metal surface, from which the atoms evaporate; δE, energy given by the atoms to the environment or to the base before the realization of the unstable state; E_{g}, energy of the grain formed in the liquid or solid aggregative state; E_1 and E_2, energy lost to the medium surrounding a cooled drop and then a grain and energy expended in removing or producing stresses in the grain formed and in deforming it; E_{def}, E'_{def}, and E''_{def}, deformation energies of the grain; E_{2d} and E_{1d}, total energies of the two smallest grains heated to the melting temperatures, respectively, singly and together; E_{m}, energy given to the grain to bring it to the molten state; E_{bond}, intergranular binding energy; E'_{2d}, E'_{1d}, and E_{1d}, energy of cooled grains after heating to the molten state; E', E'', and E''', energies lost to the environment as a result of cooling of grains brought to the molten state; E'_{bond}, binding energy after cooling of a melt drop; ΔE, increase in the energy of the two-grain structure as a result of its deformation; E_{Σ}, E'_{Σ}, and E''_{Σ} deformation energies of the body; d_0, average diameter of the smallest grains; m_0, mass of the grain of diameter d_0; m, mass of the body; m/m_0, number of smallest grains in the body; k, number of intergranular bonds between the smallest grains; k_{max}, maximum number of such bonds; $N_i = n'_i$, respectively, for the even or odd number of grains; $n_0 = 8$, $n'_0 = 9$, $n_1 = 10$, $n'_1 = 11$, $n_2 = 12$, $n'_2 = 13$, ..., $i = 0, 1, 2, ...$; k_1, number of broken but not restored intergranular bonds; m_l, mass of the lth region of the body; d_l, average diameter of the grain for the lth region of the body; m_{l3}, mass of the grain of diameter d_l; l, number of the region of the body, which includes grains of the same size d_l larger than the size of the smallest grain by a factor of two or more; $l = 1, 2, 3, ..., L$; m_l/m_{l3}, number of grains in the lth region; d_l/d_0, number of the smallest grains or intergranular bonds in the grain of diameter d_l; m_j, mass of the jth region of the body, which includes only the smallest grains; m_j/m_0, number of smallest grains in the jth region; $j = 1, 2, 3, ..., N$; E_{b}, E_{el}, and E_{pl}, energies expended, respectively, in forming the intergranular boundary for a two-grain structure and in producing the maximum elastic and plastic deformations of the smallest grains in it; E_{h}, energy transferred to the body in the form of heat; E''_{bond}, binding energy in the heated body; F, F_1, F_2, and F_3, forces acting on a two-grain structure. Subscripts: crit, critical; evap, evaporation; p, potential; g, grain; def, deformation; d, drop; m, melt; bond, bond; h, heat.

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