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## **THEORY AND APPLICATIONS OF MECHANOPLASMA EFFECT IN THE PROCESSES OF MACHINING INTENSIFICATION**

The results of studying the deformation and destruction of solids in the process of machining by cutting under the influence of various media are reviewed. Dependences of the specific features of the deformation and destruction processes in the metal on the set of mechanical factors, the properties of the investigated solid, and its physicochemical interaction with the environment are revealed. Experimental data and most important achievements in the related science fields enabled to propose a hypothesis on the initiation and self-acceleration of chemical transformations of the environment due to the positive feedback between the chemical and mechanical destructions. As shown, in this case, the growing crack plays the role of a trigger device that includes the processes of chemical transformations of the medium. The mechanism of these processes and phenomena is related to the contact interactions of the physical and chemical phenomena, which have a quantum nature and emerge, when the crack grows, with an electrically active new structure formed because of mechanical impact on the metal. As shown, the current views have not changed since the introduction of the well-known scientific point about the reduction of the material strength as a direct response on the reduction of free surface energy, when the material contacts with the medium. However, facilitation of the processes of deformation and destruction of the solid due to the adsorption medium is not the main cause for the decrease in the mechanical properties of solids. The facilitation of the metal destruction in media occurs because of contact interactions between the electrically active hydrogen particles with the electrically active real metal structure. As shown, the high temperature of the cutting zone, juvenile catalytically active surfaces of the gap space between the tool tip and the crack mouth and exoelectronic emission act as the ionizers of the hydrogen-containing media. The process of forming products in the media is suggested to be not as mechanical process but a mechanoplasma one. New ways of the shaping metal component parts with simultaneous diffusion saturation of the surface layer with alloying elements are

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justified that substantially increases the products' operational lifetime. A method for mechanoplasma processing of metals is proposed, and a serial production of lubricating-cooling technological equipment of a new generation is organized.

**Keywords:** mechanoplasma effect, mechanical properties, machining, diffusion process, strength, crack, dislocation.

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## **1. Introduction**

About 90 years ago, academician P.A. Rehbinder carried out the first remarkable studies of the effect of various media on the processes of deformation and destruction of solids [1]. Since then, a great experimental material has been accumulated in this field. Numerous attempts have been made to interpret theoretically the effects of mechanical factors, temperature, composition, and structure of the metals, alloys and solid solutions on their physicochemical properties, interatomic interactions, and interaction with environment (see, e.g., [2–7] and references therein). It turned out that the medium, first of all its nature, cannot only significantly reduce the mechanical properties of a solid, but also the features of the processes of deformation and destruction occurring in it. Analysis of the printed and electronic literature of numerous studies shows that now there is a clear idea of the mechanical properties of solids [1, 8–12]. At the same time, some regularities and mechanism of the physicochemical processes of their interaction with the medium still cause inadequate understanding and different interpretations. This is especially manifested in various cases of overcoming adhesion in solids, when the process dispersed work is carried out in extreme conditions with the direct participation of various technological tools, such as when machining a metal by cutting in lubricating-cooling technological fluids (LCTF). In this case, the improvement of workability is usually achieved by applying LCTF, and the physicochemical interactions of its components with the metal being processed increase the cutting tool durability, reduce cutting force, improve surface quality, etc. Therefore, at present, in domestic and foreign practice, great attention is paid to the development of new types of lubricating-cooling technological means (LCTM). At the same time, based on the analysis of experimental data and generalization of the results of LCTF in industry application, it follows that modern methods of LCTM creating and producing continue rely on outdated ideas about the mechanism of their influence on the processes of deformation and destruction during cutting. This does not allow timely meet continuously increasing demands on the accuracy and quality of processing and solve all new and more complex tasks put forward by researchers.

As is well known, the generally accepted point of view on the processes of facilitating the deformation and destruction of a solid under

the influence of various media is based on general thermodynamic ideas about the tendency of the free energy of the system to decrease, which manifests itself in the decrease form of the solid surface tension [12]. Hence the conclusion that the most effective ways to control the forces of solids interatomic cohesion is the optimal combination of mechanical effects and surface interactions controlled by the addition of surface-active substances to it. This is the group of phenomena, caused by a decrease in the strength of the solid under conditions of adsorption interaction with the medium (Rehbinder effect), was and still forms the basis of the developed LCTM.

At the same time, it is known that ideas about the strength of solids in the medium as a value proportional to their surface energy are true for simple splitting of a solid in a given medium [8]. When a quasi-brittle metal, mainly machined by cutting, is destroyed, a considerable plastic deformation occurs during the extension of a crack near it. In the process of concomitant deformation along the front of a developing crack, dislocations nucleate and move, bending and rotation of the grains occur, as well as the orientation of substructure elements in them [13]. In this case, the surface energy does not exceed one ten thousandth of the amount of work expended on fracture [14], and its overwhelming part is the work of plastic and elastic deformation of the layer being cut when it turns into chips [15, 16]. For example, it is considered that in the total work spent on the cutting process, the work on plastic deformation is about 60%, and when cutting some alloys, it reaches 90%.

Thus, on the one hand, there is an extensive evidence base illustrating a noticeable decrease in metal properties and operational durability of parts and metal structures due to the influence of the medium. On the other hand, the generally accepted mechanism of this effect, as a result of a decrease in the surface energy of the solid under conditions of reversible interaction with the medium, is not always adequate to the level of reduction of mechanical properties. This implies the practical conclusion that the classical model of the adsorption decrease in the strength of solids due to the influence of various medium s, in many cases, cannot satisfactorily describe their mechanical behaviour.

The first experiments carried out in this direction showed that some gases released during the destruction of organic substances that make up the LCTF, demonstrate tribological activity [16]. This activity was manifested in the reduction of torque that occurs when turning a steel billet in the atmosphere of the corresponding gas. The chain of pyrolytic transformations of the original hydrocarbon medium, which form the basis of the LCTF, leads to the formation of hydrogen and carbon in the atomic and other active forms. Therefore, a hypothesis was put forward about the permanent carbonization of the cutting edge of the instrument and the active participation of hydrogen in the mechanochemical process

during metal shape forming in the LCTF [16]. According to this model, diffuse elementary hydrogen particles with a positive electric charge are captured by traps in which proton recombination occurs, accompanied by the release of high thermal energy [16]. In this regard, the process of deformation and destruction of the solid should be considered as a result of the combined action of mechanical and thermal energy in ultra-microscopic regions, where impacts of restructuring and rupture of the forces of interatomic bonds of a solid occur. This circumstance gave reason to consider the process of removing chips from the workpiece using LCTF, as a process of mechanical and physicochemical processing — mechanoplasma (MPP).

Despite the fact that at the first stage of work in favour of this hypothesis, very different and very encouraging experimental data were obtained, it certainly needed and needs study and approbation.

Further studies showed [16] that a decrease in the surface energy of a solid due to the adsorption of the medium is only the first act initiating multi-stage chemical transformations of the medium. Herewith, there is the formation (at first) an intermediate product in the form of a nano-material and (then) electrically active elementary particles and hydrogen atoms that make up the organic medium. It also turned out that the effectiveness of the application of the medium to the processes of deformation and destruction depends not only on the speed of wave propagation of the chemical transformation of the initial medium and its timely arrival in the region of opening the new surface and the deformation of the adjacent layer. Most importantly, however, physical factors are of great importance in this case: heat release during a chemical reaction and heat fluxes in the chip formation zone, catalytic activity of the resulting surfaces, exoelectronic emission, etc.

These considerations suggested that, in order to increase the effectiveness of existing LCTM, additives to them should not be sought among surfactants, which do not give a high concentration of radical-active products in the cutting zone that can timely enter directly into the bonding zone between atoms and interfere with deformation and destruction processes. Ideally, for this, there must be substances capable of producing, at high speed, nanometric objects and elementary particles with a high speed, whose properties differ not only from the properties of free atoms by their minimum size and electric charge, but also from the bulk properties of the substance consisting of these atoms. High-molecular weight compounds, for example polyethylene and polyvinyl chloride, are known to have such properties.

Thus, the first experiments confirmed some of the hypothesis. In particular, the main thesis was confirmed that the various physicochemical phenomena accompanying the process of destruction during metal cutting do not leave the properties of the initial surface-active medium unchanged.

Hydrocarbon substances contained in it are destroyed due to the high temperature in the chip formation zone, first with the formation of two or more elementary substances, and then elementary particles. Further wave propagation of the process of chemical transformation of the resulting hydrocarbon gas mixture under extreme cutting conditions is accompanied by its gradual transformation into a radically active medium, at the nanometric and atomic level. At the same time, the chemical transformations of the medium are accompanied by the release of a huge amount of radiant energy (approximately 100 kcal/mol). The emitted thermal energy due to the contact interactions of the formed electrically active particles with the new electrically active real structure, complementing the mechanical, will facilitate the processes of deformation and destruction.

The simplest practical value that followed from the data obtained is that a fundamentally new way appears this should lead to the creation of such a technology of forming metal products, which would combine the complex processes of optimal mechanical, physicochemical and thermo-chemical processing. The complexity of solving such a problem is because the nature of physicochemical and mechanical processes and phenomena at destruction lies on the border of various fields of science and a number of technology industries. Nevertheless, even a brief and incomplete analysis of the problems that are studied in related scientific fields clearly demonstrates that the accumulated experimental materials and established regularities open up new possibilities for studying in detail the rearrangement and rupture of bonding forces, and can explain empirical and commonly physicochemical and mechanical properties.

In connection with the foregoing, it becomes clear that to substantiate new, more efficient ways of shaping metal products, a more complete understanding of the mechanism of metal destruction is needed. This is a set of processes related to the wave propagation of chemical transformations of substances included in the LCTM, as well as knowledge of the properties of individual atoms and simple molecules of the technological medium and their interaction between themselves and the structure of the material.

Although much work has been already done in this area so far, it is still important to carry out further study of a number of interacting systems and perform quantitative measurements for them.

## **2. Formulation of Research Directions**

The first obtained research results show that the hypothesis underlying the point of view about the effect of surface-active medium on the processes of deformation and fracture deserves attention and points to the possibility of formulating directions for further research related to intramolecular rearrangements of atoms of the medium under mechanical,

thermal, electrical, and magnetic effects, and the use of the resulting product in the processes of deformation and fracture. It was taken into account that the objects of the nanoscale range and elementary particles formed as a result of chemical transformations can represent the environment for high-speed thermal diffusion saturation of a deformable metal with chemical elements [16]. In general, thus, carrying out of research in this direction should open up the possibility to carry out a complex process of effective mechanical and optimal strengthening technology in one technological cycle of forming metal parts.

Below there are some formally constructed proposed processes and phenomena that make up the overall picture of the mechanism of environmental influence associated with interactions of an electrically active structure with an electrically active surrounding hydrocarbon medium and their transformations during the mechanical process, as well as the conditions necessary for its occurrence. An attempt to, at least, qualitatively link the macro- and microviews, as well as the analysis of numerous studies in related fields of science, served as the basis for the formulation of the task and objectives of the research, the main results of which are discussed in this article.

(i) A special additive to LCTM should ensure the formation in the cutting zone the optimum concentration of electrically active hydrogen particles. Such additives should also have high functional properties, belong to the class of low-hazard substances, dissolve or give a stable emulsion in an aqueous or oil-based LCTM. High molecular weight compounds of chain-chain aliphatic saturated hydrocarbons (for example, polyethylene or polyvinyl chloride) have such properties as additives for LCTM. Possessing a low energy of breaking bonds, the destruction of which flows through a chain-free-radical mechanism, these polymers, under the influence of the high temperature of the cutting zone, provide a high rate of formation of hydrocarbon gas in the chip formation area.

As is known, the cutting process is accompanied by thermal phenomena, which are one of the main physical indicators of the machining process, and with increasing heat generation; the rate of chemical transformations of the polymer additive to the LCTM will increase. In this connection, as the technological parameters of processing increase, the temperature of the chips will increase, as well as the entire surface of the contacting working edges of the tool with the medium, which will increase the rate of chemical transformations of the medium, which will increase the efficiency of LCTF.

(ii) In this mechanical process, a growing crack plays the role of a triggering device that activates ionizers (catalytically active crack surfaces, exoelectronic and thermoelectronic emission), which ionize the hydrocarbon gas to a plasma state (a mixture of electrons, positively charged ions and neutral molecules). Most provide a positive feedback

mechanism of the mechanical and chemical process. Thus, the advancement of a crack initiates a chemical reaction, the products of which accelerate the growth of this crack.

Ionization of the medium can also occur in the event of a break in the electrical connection 'machine-tool-workpiece' between the cutting edge of the tool and the workpiece. The resulting electrical discharges are able to ionize some organic substances that are part of the LCTF.

(iii) Hydrocarbon environment for active intervention in the process of destruction must timely arrive in the area of opening a new surface. From the chip formation zone to the reaction gap, hydrogen-containing gas diffuses mainly through a network of microcracks. Further, hydrogen particles of positive charge diffuse along the slit to the crack tip under the action of an electric field, and then their movement through the surface into the depth of the metal proceeds due to ambipolar diffusion with conduction electrons (the effect of the electronic 'wind'). In the process of such diffusion, one part of hydrogen is bound by material defects, and the other is moved freely between the lattice sites.

It was also taken into account that simultaneously with the kinetic process of material destruction, the interacting metal-medium system also changes, and as a result, new kinetic processes of chemical activation of the medium are initiated, continuously deepening chemical transformations of hydrocarbon compounds, various hydrocarbon molecules, and hydrogen atoms along the mechanical process before the formation of hydrogen plasma. It was assumed that the speed and concentration of the formation of the final product primarily depends (*ceteris paribus*) on the various contact interactions of new electrically active metal structures with electrically active and electrically passive elements of the activated medium.

The results of the first experimental data showed that the effects associated with the interactions of electrically active hydrogen particles with an electrically active real metal structure are diverse in their final manifestations, but all of them contribute to facilitating the processes of deformation and destruction of the material.

Among them, the thermal effect resulting from recombination of hydrogen protons both on surfaces near the crack tip and in ultramicroscopic areas directly in the overcoming adhesion zone between atoms [16, 22] can have the greatest effect on the reduction of the mechanical properties of the solid.

Thus, the first results made it possible not only to evaluate the proposed hypothesis, but also to clarify its main points.

Assuming that the experiment in the future will confirm the above provisions, some of which are hypothetical in nature, the task of this study primarily included the need to penetrate and study the physical essence of only some complex and diverse processes and phenomena

accompanying the destruction of the material and initiating and accelerating the chemical transformations of the original medium to the level of hydrogen plasma. This is also adjacent to the very important problem of contact interactions of electrically active elementary particles of hydrogen plasma, with the electrically active real structure of the material arising at the time of its destruction under the influence of mechanical action. From our point of view, such a group of phenomena is central to the processes of facilitating deformation and destruction.

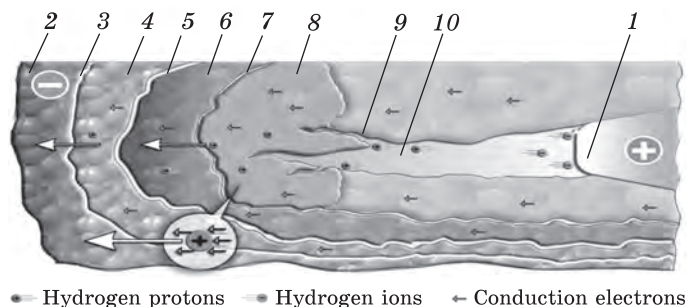
While planning research from a large, complex and multifaceted problem, three aspects were identified. On the one hand, this is the initiation and acceleration of chemical transformations of the initial surface-active medium as a result of using the thermal energy of the chip formation zone and the stored energy on the surfaces newly formed during the destruction. On the other hand, the kinetics of moving electrically active hydrogen plasma particles in the narrow gap space of a fracture crack to its top, and in another direction, to the cutting tool was very important. The problem of moving protons across the surface of the crack tip and their diffusion into the deformable region of the solid in front of the crack tip also ends here. And finally, the third aspect is an important problem of the interactions of electrically active hydrogen particles with a new electrically active structure formed during the mechanical process. At the same time, special attention was paid in planning the experiment to bringing the interpretation of each studied phenomenon to the atomic-molecular level.

The formulation of the research task was carried out not only on the basis of the results of the first assessment experiments, but also an analysis of the results of studies carried out in various fields of physical and chemical science related to the phenomena accompanying the cutting process (plastic deformation of metal, friction, wear, electromagnetic fields and other physical phenomena), as well as to the phenomena associated with the wave propagation of the process of chemical transformation of the initial medium.

In this regard, the mechanical process of destruction of the solid, occurring in extreme cutting conditions and accompanied by numerous physicochemical phenomena, was conventionally divided into a series of successive stages, which allowed the search to be more specific: the parameters of the sophisticated models of individual deformation stages were associated with its possible effect on activation the environment. Then, the feedback between the product formed and the real structure of the material arising at the time of its destruction was investigated. It is this technology of studying the problem that allowed, though in many respects and in hypothetical outlines, to move in the right direction.

It is important to note that the elucidation of the patterns and mechanism of the physicochemical processes of medium activation was





*Fig. 1.* The schematic view of reaction zone [16]: 1 — the cutting tool edge; 2 — base metal; 3 — transition area; 4 — elastic range; 5 — the input motion of dislocations; 6 — plastic range; 7 — subcritical region of the crack growth; 8 — damage area, subcritical crack-growth stage; 9 — the juvenile crack hollows; 10 — the main crack

carried out at two fundamentally different levels. At the microscopic level of the modern theory of the structure of atoms and molecules, their interaction with each other and with the actual structure of the material, which can give a conclusion about the possibility and speed of elementary acts of chemical interaction. For the formation of ideas about the reality of the processes of initiation and self-acceleration of chemical reactions during metal destruction, it is necessary to take into account the physical factors of great importance associated with the specific conditions of reactions in the narrow gap between the tool wedge and the tip of the fracture crack (Fig. 1). Thus, in the work it was planned to consider only individual, but very important issues of a major problem.

The objects of investigation of the chemical transformations of the initial medium were organic substances, which are usually part of the LCTF, first of all the products of oil refining (hydrocarbons) and their derivatives, as well as numerous additives.

As already noted, the first studies showed that there is always hydrogen in the chips and in the treated metal surface, as well as in samples after mechanical tensile tests. From this, it follows that additives to the coolants should be sought not among the surfactants, but among the high-molecular compounds that give the active forms of hydrogen in high concentrations in the chains of thermo-mechanical transformations. This conclusion further allowed the development and organization of serial production of coolant-cutting fluxes [16, 22, 23], and also gave grounds to consider the processes of shaping metal products by cutting into such coolants as the result of mechanoplasma processing (MPP).

From all the above, it follows that successful solution of practical problems of improving the workability of products requires a more complete understanding of the complex and diverse physical essence of the phenomena accompanying the destruction process in various environments, which is feasible at the level of ideas about the real laws of

interaction between atoms dependent on their electronic structure. While some macroscopic characteristics of the workability of the material provide only empirical information about the microscopic processes of interaction and can be fully explained later, using the quantum-mechanical theory of the structure of the atom.

The paper summarizes and substantiates the results of many years of research by the authors, in which microscopic approaches to the study of the mechanisms observed at the macroscale and causing changes in the properties of a solid under the joint influence of the medium and mechanical load were brought to the fore. Moreover, macroscopic changes in material properties are studied as a result of the interactions of a new electrically active structure of a solid with electrically active hydrogen particles formed as a result of the chemical activation of the initial medium, which change adequately along the mechanical process. For this purpose, not only the results of own research, but also some provisions of modern physics, physics of destruction, physical chemistry, materials science were used.

### **3. Facilitation of the Processes of Restructuring and Breaking the Interatomic Bond Forces under the Conditions of the Reversible (Adsorption) Interaction of the Solid and Medium**

Existing views on the general problem of the influence of the active medium on the mechanical properties of solids have not been changed in principle since the time when P. Rehbinder advanced a well-known proposition on the responsibility of the reversible (adsorption) interaction of the solid with the medium for facilitating the processes of restructuring and breaking of interatomic bonds [1, 12, 17–20].

Theoretically-based and confirmed by practice notions of the physical nature of the reduction in the mechanical properties of materials under the influence of surface active medium made it possible to determine the ways of finding seemingly the most effective methods of controlling the cohesion forces in solids with the optimal combination of mechanical interactions and physicochemical factors created by the surface active medium or by small adsorbing additives [19]. To the present time, these representations underlie the reduction of the power parameters of the machining of the developed LCTF. At the same time, even a cursory and, naturally, incomplete list of works on the problem under consideration shows that in most cases the adsorption effect is not decisive in facilitating deformation and fracture processes. Accumulated over a long period experimental data show that the adsorption of the medium on a deformable solid is likely to be only the first act in the chain of further chemical transformations of the initial medium.

Indeed, it has been shown that lubricating-cooling fluids, mostly consisting mainly of two elements — hydrogen and carbon, are activated in the fracture zone to a new phase state — hydrogen plasma [21]. Therefore, the main changes in the mechanical properties of a solid under the conditions of interaction of the solid with the medium should be associated with the effect of the emerging radically active medium, and not with the initial surface active.

Ambiguity in assessing the causes that facilitate the deformation and destruction of solids, deformable in various medium, has led to the formation of system studies on the problem under consideration. We present an analysis of the results of some of them below.

Note that when evaluating the influence of the medium on the processes of elastoplastic destruction of a solid during the machining of metal by cutting, we will take into account not only the possible interactions of the chemical elements of the fracture formed in the composition of the medium with the surfaces of the crack tip formed by the inhomogeneous part of the material, but also with the part at longer distances from the crack tip. Considering these interacting systems, we will also take into account the extreme conditions that are created in the zone of destruction. Among them, in the first place, is the high rate of metal deformation, the value of which reaches  $10^3$ – $10^6$  s<sup>-1</sup> or more, and also a narrow crack descending at the apex to the size of the lattice parameter through which, in order to influence the destruction, the medium have to migrate.

In view of the foregoing, let us evaluate the result of possible contact interactions of the medium with the metal at the time of opening new surfaces near the crack tip.

(1) It is known that up to 90–95% of cutting work is wasted for the work of plastic deformation, for example, when turning heat-resistant alloys [14]. In this case, the total work on plastic deformation consists of plastic deformation work in the immediate vicinity of the tool cutting edge, where the separation of the metal begins, i.e. immediately starting from the surface and adjacent to the surface layer, as well as plastic deformation, flowing in the zone of advanced hardening and covering a large volume of metal. For example, the dimensions of the total plastically deformable zone when turning in the air HN77TYUR (DIN — German analogy) steel before the cutting pick reached more than 6 mm, and under the cutting pick — more than 3 mm. In this case, it is generally accepted that the work expended during cutting on elastic deformation is secondary and in the overall balance of energy costs is close to zero.

It is also known that during mechanical processing of polycrystalline metals, when elastoplastic failure occurs, the free surface energy in the balance with the total expended energy is usually only  $10^{-3}$ – $10^{-4}$  [14]. Consequently, in the case of a hypothetical contact of the medium with

the material directly in the source of destruction, the share of the decrease in free surface energy due to adsorption may amount only a small part of the total energy costs. For example, the thermal effect of physical adsorption of hydrogen on steel, one of the most active chemical elements reducing the mechanical properties of metal, is small and usually causes a decrease in surface energy by  $900 \text{ erg/cm}^2$ . At the same time, the actual energy costs in this case are  $2 \cdot 10^5 \text{ erg/cm}^2$  [29, 30]. Therefore, even if we admit that adsorption layers of surfactants from the environment manage to penetrate into rapidly developing defects covering their new surfaces, in the total balance of energy costs for deformation, fracture and friction, the fraction of the decrease in strength due to adsorption of the medium on the surfaces of the crack tip will not have a significant value.

Nevertheless, for example, when turning an alloy of HN77TYUR or 10H14T14N4T, depending on the composition of the surface-active LCTF, the power consumption can decrease from 25 to 36%, the tool life is increased by an average of 8 times, the roughness of the treated surface is reduced by 1.5 classes. Similar results were obtained in the machining of other high-temperature alloys at various operations and processing regimes [21].

Let us cite one more demonstrative example, when the adsorption activity of the medium does not change, and its efficiency is significantly increased.

Drilling of steel 40H (HRC 50) under different processing conditions was carried out in two media: heptane ( $\text{C}_7\text{H}_{16}$ ) and in heptane, which contained 1.5% of the low-molecular-weight polyethylene with molecular weight 150000 dissolved in it. Molecules of one and the other medium consist of the same carbon and hydrogen atoms, but the second medium is an equalized solution of polyethylene in heptane whose macromolecules differ only from the first medium by a huge molecular mass.

We have to stress here that, generally, polymolecular adsorption should be considered as the adsorption of separated phases. In this case, more configurations of macromolecules are possible on the 'solid-solution' interface. Probably, therefore, adsorption equilibrium can be established very slowly, only after exposure for hours and even many days [28]. In addition, it was found that not energy but entropy factors are dominated during the adsorption of the polymer [31]. It should also be taken into account [29] that as the molecular chain lengthens (i.e., the molecular weight increases), the molecular chain bends in the solution increasingly bring the molecule closer to the folded form, so that the bends of the chains screen the internal parts of the molecule more and more and, finally form a model of an infinitely folded coil. Consequently, the presence of polyethylene in heptane cannot affect its adsorption activity because the polymer coils will be filtered by a crack,

since their size overcomes the distance between the crack edges by several times.

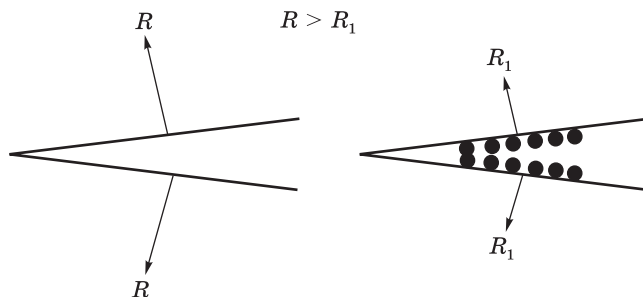
Thus, the addition of polyethylene to heptane does not change its adsorption activity, and therefore, according to the adsorption theory, it should not affect the power parameters of cutting. Nevertheless, in fact, the drilling torque in the medium with the addition of polyethylene on average decreased compared to the processing in a medium without polymer by 40%.

Similar results were obtained during other types of machining. For example, when honing steel parts with the same diamond honbrusks in heptane with a polymer as compared to pure heptane, the following results were obtained: the average value of the layer removed by diameter increased by 40%, the roughness of the treated surface decreased by 30%, and the average specific consumption of diamonds decreased by 55%.

(2) At present, oil liquids with additives for cutting at relatively low speed and water-based fluids (emulsions or chemical solutions) for cutting with medium and high speeds are most widely used in practice. All of them are organic compounds, including a large group of compounds consisting of atoms of only two elements — carbon and hydrogen. The effectiveness and stability of modern water-based LCTFs depend significantly on the nature of the surface-active emulsifier. The most widely used are anionic surfactants, the distinguishing feature of which is their ability to form strong adsorption layers on the metal surface. It is important to note that surfactants in the composition of LCTF are prone to micelle formation and such a smallest particle (consisting of 20–30 molecules) with which the deformation and fracture facilitation bounds has diameter of 10–60 Å. However, the microcracks converge to the mouth of an interatomic distance [1]; much less than the geometric dimensions of the substances that make up the surfactant. The smallest of the chemical elements is the hydrogen ion, which can be in the aqueous solution (the diameter of the hydrogen proton is thousands of times smaller than the diameter of the ions of other elements), not in the free state, but in the form of a very strong hydrate — hydroxonium  $H_3O^+$ , whose concentration in water is extremely low. For example, pure water contains hydroxonium ions at a concentration of only  $1 \cdot 10^{-7}$  mole per litre, and even with the addition of acid the concentration of hydrogen ions increases insignificantly. This means that although there is a hypothetical probability of influencing the course of the mechanical process of hydrogen contained in water, however, its low concentration in the medium practically cannot have a significant effect on strength.

Thus, the geometric dimensions of the substances that make up the LCTF are an obstacle to their direct contact interaction not only with the metal in the path of the growing crack, i.e. where there is a res-

Fig. 2. The microcrack model:  $R$  — the surface tension force causing the crack growth on the juvenile surface;  $R_1$  — the surface tension force equilibrated due to adsorption



structuring and breaking of the bond forces, but also with the structure of the material formed at the time of destruction.

As for the kinetic factor, here one can assert a priori; that at huge speeds of metal deformation at cutting its realization is impossible. For example, the fastest spreading rate for steel has oleic acid, which is the part of LCTF. Its spreading rate is 20 cm/s, while the cutting speed is higher for several times.

(3) Assuming that the medium manages to diffuse in the cavity of the formed cracks and is adsorbed on their surfaces, and then in this case its effect reduces not to relief, but to a slowing of the growth of the crack. This is because the atoms located on the surface of the crack cavities are affected by forces from only one side, i.e. on the part of atoms of the solid under the surface layer. The developed resultant force is directed inward from the crack surface, because of which the surfaces tend to decrease, which will promote the expansion of the fracture cavities and its growth (Fig. 2). When adsorption of media in one way or another, there will be a compensation of the broken bonding forces of surface atoms and a decrease in the forces that draw atoms into the depth of the material, as well as a decrease in the surface tension. In this case, the stresses at the crack tip developed by the surface forces will decrease, and the obstacles to destruction will increase, which will help to collapse of the crack cavities and provide greater resistance to its growth. Consequently, proceeding from this model, the adsorption of the medium, although it reduces the free surface energy of the fracture cavities, however, the stresses developed by the surface forces at the crack tip will increase and provide additional resistance to fracture.

As a result, on the basis of the above analysis of the experimental data, the following conclusions can be drawn.

(a) The limitations of the generally accepted theory of the adsorption decrease in the strength of a deformable metal in a medium active surface are shown.

(b) In the hope that the experiment will confirm the positions stated here in the future, we note that, obviously, parallel to the adsorption processes of the initial medium, there are other deeper radical processes

having a quantum basis, and causing various changes in the properties of the deformed solid.

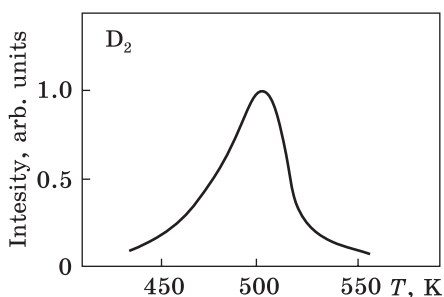
(c) Due to chemical transformations of the initial medium to the level of formation of electrically active hydrogen particles, it becomes possible for them to interact with ions and free electrons of the metal, amplified by the electric field existing in the ‘machine-tool-workpiece’ system. It is precisely the interactions of the electrically active metal structure, arising as a result of mechanical action, with electrically charged hydrogen particles, i.e. electron–electron, electron–ion, and ion–ion interactions can radically change the physical and mechanical properties of the metal.

#### 4. Hydrogen Effect on the Destruction and Deformation Processes

The conclusion about the proposed hypothesis was given by the results of investigation of surface and near-surface layers of the treated metal in various media and chips for the content of hydrogen in them. In the study of such poorly studied processes, hydrogen is usually recorded either directly, by the content of metal hydrides in the surface layers, or indirectly by gas evolution from the sample when it is heated. The scope of the first of these methods is limited by the capability of metals to form stable compounds with hydrogen, for example, titanium, nickel [33], etc. The second method usually determines the total content of hydrogen in the sample, and not its depth distribution or energy characteristics [34].

In this study, the method of temperature-programmable heating (TPH) of a sample placed in a vacuum volume with simultaneous mass spectrometric recording of evolved hydrogen was used to detect hydrogen [34]. The experimental data obtained in this case represent the dependence of the mass spectrometer signal on a given mass (in our case proportional to the rate of hydrogen or deuterium evolution) on the sample temperature, which, as a rule, rose at a rate of 0.5 K/sec.

Usually, the curve (TPH spectrum) has one or several peaks of bell shape with peaks corresponding to the outlet temperature of a certain hydrogen ‘species’. The position of the maxima on the curve, as well as the shape of the peaks, reflects a complex process occurring under conditions of linear temperature rise,



*Fig. 3.* The dependence of the mass-spectrometric analyzer signal on the sample temperature after compressive deformation in  $D_2O$  [21]

the main components of which are the diffusion of hydrogen atoms in the metal, their yield and recombination on the surface, with the release of molecular hydrogen. It is obvious that the distribution of hydrogen along the depth of the sample before the rise in temperature, as well as its amount, affects the shape and position of the peaks.

The paper studied the diffusion of hydrogen in the process of plastic deformation, observed, respectively, during compression and cutting in hydrogen-containing media: water, hydrocarbons, etc. The objects of investigation were Armco iron and steel 20.

#### **4.1. Compression-Induced Plastic Deformation**

The fact of penetration of hydrogen into the metal was established in an experiment with the compression of Armco iron in a D<sub>2</sub>O medium.

A sample of the cubic form ( $l = 3$  mm) was placed between plane-parallel surfaces inside the D<sub>2</sub>O drop. After applying the load (20 tons), the sample was compressed to a thickness of 0.5 mm (relative compression deformation of 80%). Then a 30 μm thick layer was grounded on both sides of the sample to remove surface deuterium-containing compounds. The use of marked water is due to the need to exclude the registration of 'extraneous' hydrogen present in the initial sample or introduced onto its surface as a result of adsorption of atmospheric moisture during grinding.

In the TPH spectrum of the deformed sample, after the removal of the surface layer, a deuterium depletion peak with a maximum of about 540 K was detected (Fig. 3), which proves its penetration into iron.

#### **4.2. Cutting-Induced Plastic Deformation**

Most of the data was obtained in experiments with cutting (drilling), which, as is known, is accompanied by considerable plastic deformation of the material being processed. Samples were drilled both from steel 20 and iron from Armco. Cutting parameters: speed — 450 rpm, feed — 5 mm/min, drill — steel P6M5. Drilling was carried out in the following mediums: H<sub>2</sub>O, D<sub>2</sub>O, atmospheric air, dry nitrogen, heptane, vaseline oil, ethanol, ethanol–water mixtures, vaseline oil–water emulsions and water–polyethylene emulsions. In addition, a sample of steel preliminarily saturated with hydrogen by an electrolytic method was drilled [21].

In the experiments on drilling with the object, TPH was chips, and always took the same sample (50 mg). All drilling experiments were carried out with steel and iron samples pre-annealed at 700 K for 10 hours. Such heat processing of the samples is because residual metallurgical hydrogen is possible in the initial metal preforms. Thus, in the steel 20 bars used as raw workpieces, residual hydrogen was found, the maximum of the peak in the TPH spectrum of the unannealed steel



was at 500 K, and the peak intensity corresponded to the usual concentration of metallurgical hydrogen  $1-5 \cdot 10^{-6}$  [35].

Table 1 shows the results of determining the position of the maxima ( $T_{\max}$ ) on the TPH curves, as well as the soaking times ( $t$ ) of the chip samples from the time of the drilling start to the time of the TPH spectrum measurement at room temperature.

*Drilling in water.* Figure 4 shows the TPH spectra of the chips obtained during drilling in water, measured, respectively, in 0.5, 2, 23, and 300 hours after drilling. The peak in the TPH spectrum of freshly prepared chips is observed at the lowest temperature and has the greatest integral intensity.

The magnitude of the intensity indicates that when drilling in water, the total amount of hydrogen penetrates into the chips,  $1-10 \times 10^{-6}$ , i.e. comparable to the content of metallurgical hydrogen.

As the time for soaking the shavings increases until the spectrum is removed, the peak shifts to the high-temperature region with a simultaneous decrease in intensity. At a sufficiently long soaking time (several

**Table 1. Position of hydrogen peaks in TPH spectra based on the results of drilling steel 20 [21]. (Here, 0.5 hours is the minimum time required to prepare a test for the measurement of the TPH spectrum. Molecular weight of polyethylene is 100000)**

No.	Medium	$t$	$T_{\max}^0$ , K
1	Air	0.5	480
2	Dry nitrogen	0.5	—
3	H <sub>2</sub> O	0.5	425
4	H <sub>2</sub> O	2	445
5	H <sub>2</sub> O	23	493
6	H <sub>2</sub> O	300	—
7	H <sub>2</sub> O	1.0 ( $T = 70$ °C)	490
8	D <sub>2</sub> O	0.5	425
9	D <sub>2</sub> O (coarse fraction)	7	480
10	D <sub>2</sub> O (small fraction)	7	490
11	D <sub>2</sub> O (coarse fraction)	50	505
12	D <sub>2</sub> O (small fraction)	50	505
13	Electrolysis	0.5	475
14	Electrolysis	29	480
15	Ethanol	0.5	480
16	Ethanol + water	0.5	443
17	H-heptane	0.5	455, 505
18	Vaseline oil	0.5	455, 505
19	Oleic acid	0.5	500
20	Vaseline oil + water	0.5	425, 480
21	Polyethylene emulsion + water	0.5	425, 475

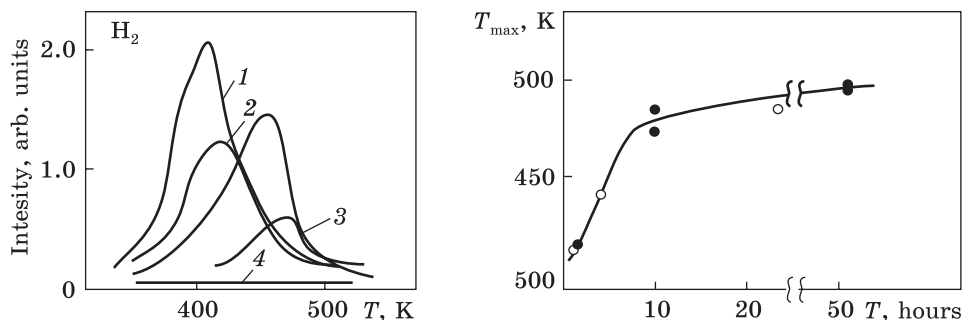


Fig. 4. The dependence of the mass-spectrometric analyzer signal on the sample temperature after drilling in H<sub>2</sub>O [21]. The soaking time is 0.5 (1), 2 (2), 23 (3), and 300 (4) hours

Fig. 5. The dependence of the mass-spectrometric analyzer signal on the sample temperature after drilling (○ — H<sub>2</sub>O, ● — D<sub>2</sub>O) [21]

days), the intensity drops to zero. In the case of an increase in the chip soaking temperature before the removal of the TPH spectrum, the process of hydrogen redistribution is accelerated, and the peak is mixed into the high-temperature region in a shorter time (Table 1).

In order to exclude the possibility of manifestation of ‘extraneous’ hydrogen in the TPH spectrum, experiments with drilling in D<sub>2</sub>O were also carried out. Its results are identical to the results after drilling in H<sub>2</sub>O.

To determine the possible spread in the position of the maxima on the TPH curve due to the non-reproducibility of the chip size from the experiment to the experiment, the size fractionation of the chips on the sieves (0.3 mm) was carried out followed by the removal of TPH spectra. From the results given in the table it follows that the particles size obtained in the drilling experiments has practically no effect on the position of the peaks in the TPH spectra of the chips soak for 7 and 50 hours.

To assess the depth of hydrogen penetration into the workpiece after the first pass through the drill in D<sub>2</sub>O medium, the hole was drilled in the air with a drill of a larger diameter. With an increase in the diameter of the second pass drill by 1 mm, a deuterium peak with an intensity of 10% of the initial value was detected in the TPH spectrum of the workpiece, which qualitatively indicates the depth of deuterium penetration into the metal during the cutting process of the order of one mm.

The data on the maximum position on the TPH curve for chips obtained after drilling in water, depending on the time of their preliminary soaking, is convenient to represent graphically (Fig. 5). It can be seen from the figure that the dependence is asymptotic, and the maximum temperature reaches a limit with a time soaking of about 6 hours.

The results obtained can easily be interpreted if we assume that, as in the above experiments with metal compression, the plastic deformation

of the metal during cutting is accompanied by the transport of hydrogen to the surface layer. Indeed, penetrating into the process of cutting into the chips, hydrogen concentrates mainly near the surface. When chips are soaked at room temperature, hydrogen in it is gradually redistributed due to diffusion from the surface layer into the material, which leads to equalization of the concentration in depth. Subsequently, hydrogen adsorbs to the surface on which its recombination passes with the formation of hydrogen-containing surface compounds, and then their removal into the gas phase.

Redistribution of hydrogen in the metal with a simultaneous decrease in its total content in the sample leads to the observed high-temperature shift of the peak in the TPH spectrum and a fall in the integrated intensity, as the chips are soaked before the TPH.

To test the proposed interpretation, an experiment of drilling electrolytically-hydrogenated steel was performed. Electrolysis was carried out in 0.2N  $H_2SO_4$  solution with a current density of 300 mA/cm<sup>2</sup> for 2 hours. To exclude the ingress of 'extraneous' hydrogen drilling was carried out in dry conditions (nitrogen), and the portion of chips obtained when removing 1–2 mm of the surface layer was separated and subsequently was not used.

The data obtained indicate that electrolytic saturation leads to 'pumping' large amounts of hydrogen into the sample. In this case, the intensity of the TPH spectrum corresponded to 10 conventional units. Therefore, the hydrogen content in the same amount of chips of the mild sample when drilling in water and the previously hydrogenated sample is related approximately as 1/5.

The mechanism of hydrogen transport in general terms can be presented in the following form. In the course of plastic deformation, both during compression and during cutting, a chemically pure (juvenile) metal surface, with which the molecules of the medium react, is continuously formed. As known, the reaction with pure iron of such hydrogen-containing molecules as water, limiting and unsaturated hydrocarbons, alcohols and ketones is accompanied by their dehydrogenation and the appearance of chemically bonded hydrogen atoms on the surface. We know that for the transition of hydrogen atoms to the volume it is required to overcome a high activation barrier, and the transition itself is endothermic. In other words, the processes of penetration of hydrogen into iron proceed with appreciable rates only at sufficiently high temperatures of the metal and considerable concentrations (pressures) of hydrogen. The chip temperature at the time of its separation from the workpiece does not usually exceed 600–700 °C. At such temperatures, the diffusion rate of hydrogen in iron, as well as the partial pressure of hydrogen near the surface, is too small to penetrate deep enough into the near-surface layers of the metal.

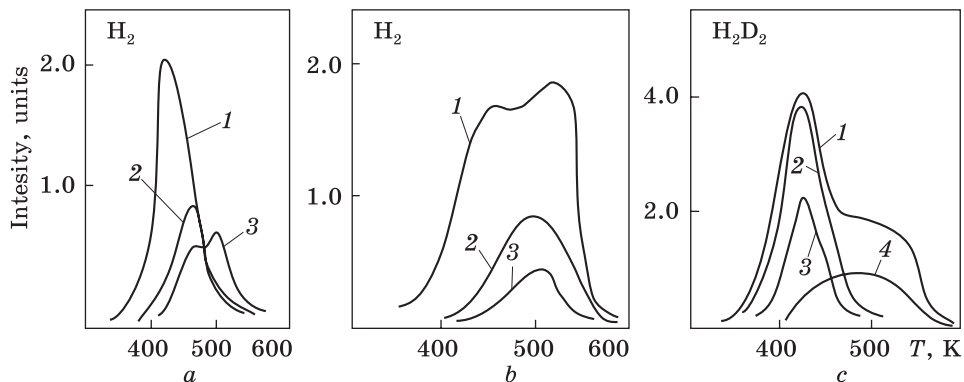


Fig. 6. The dependence of the mass-spectrometric analyzer signal on the sample temperature after drilling in  $\text{H}_2\text{O}$  (1),  $\text{H}_2\text{O} + \text{C}_2\text{H}_5\text{OH}$  (2),  $\text{C}_2\text{H}_5\text{OH}$  (3) (a). The dependence of the mass-spectrometric analyzer signal on the sample temperature after drilling in N-heptane (1), liquefied petrolatum (2), oleic acid (3) (b). The dependence of the mass-spectrometric analyzer signal on the sample temperature after drilling in  $\text{H}_2\text{O} + \text{vaseline oil}$  (1),  $\text{D}_2\text{O} + \text{vaseline oil}$  (2),  $\text{H}_2\text{O}$  (3),  $\text{D}_2\text{O} + \text{H}_2\text{O}$  [21] (c)

Indeed, the typical penetration depth of hydrogen ( $R$ ) can be estimated from the formula  $R^2 = Dt$ , where  $D$  is the diffusion coefficient,  $t = l/V$ ,  $V$  is the cutting speed,  $l$  and  $t$  are the typical size of the physical contact area of the cutting tool and the treated material, and the contact time during which plastic deformation proceeds. We take the size of the physical contact area, according to [24], equal to 1 mm. Since in our case  $V = 0.1$  m/s, then the contact time will be of the order of  $10^{-2}$  s. As known [32], the diffusion coefficient of hydrogen in metals is limited to  $10^{-4}$   $\text{cm}^2/\text{s}$ , therefore, even by a greatly high estimate, the penetration depth of hydrogen cannot exceed  $10^{-3}$  cm. However, since hydrogen penetrates into the metal under the specified conditions into the depth of 1 mm, we assume that the high rate of hydrogen transfer to the surface layers during the plastic deformation can be due to two reasons. They are a very strong instantaneous ‘heating’ of those degrees of freedom in the crystal lattice that are responsible for the transfer of hydrogen or transport positively charged hydrogen particles (protons). The possibility of electrical transport is due to the presence of an electric field in the interacting system, which always arises from the presence of a thermoelectromotive force (TEMF) in the cutting zone, and due to a local negative charge of the plastically deformable material in front of the crack tip.

*Drilling in ethanol.* The TPH spectrum of chips obtained by drilling in ethanol is shown in Fig. 6, a. We can see that the position of the peak maximum is substantially shifted to the high-temperature region in comparison with the corresponding value for water. As for the intensities

of peaks in the case of alcohol and water, then, although they are generally of the same order, but for alcohol, the intensity is always somewhat lower. The same figure shows the TPH curve for drilling in 1:1 ethanol-water solution and for comparison the TPH spectrum for drilling in water. As seen, the peak maximum during drilling in the solution is in the intermediate position. Looking ahead, we note that drilling in organic media, as experience shows, always leads to a high-temperature shift of the maximum in comparison with water. This can be explained as follows.

When drilling in water due to the special thermophysical properties of water, the chips are cooled considerably faster than in the case of other solvents. Consequently, in the case of organic media chips are in a heated state for a longer time and during this time hydrogen can distribute more evenly over its volume than in the case of water. This explanation is confirmed by the fact that when drilling in air (containing water vapour), the peak leaves at a temperature higher than when drilling in water (Table 1). Although in both cases the hydrogen-containing substance (source of hydrogen) is water, however, in the air the chips are cooled longer than in water and, consequently, hydrogen has time to diffuse into the interior of the sample. Water-alcohol mixtures have intermediate thermophysical properties, which leads to an intermediate position of the maximum on the TPH curve.

*Drilling in saturated hydrocarbons and in oleic acid.* Figure 6, *b*, shows the TPH spectrum of chips obtained by drilling in heptane, vaseline oil and oleic acid. The spectra for the first two substances are almost identical. They have two maxima (or maximum and shoulder). The high -temperature maximum, in all cases is more intense, most likely refers to hydrogen diffusing into the surface layers during the cutting process. This conclusion is also confirmed by the fact that the corresponding maximum for oleic acid is at the same temperature. As for the low-temperature shoulder, its origin is not entirely clear. It is possible that it refers to hydrogen desorption, which is a part of surface compounds, but this explanation needs additional verification. As in the case of alcohol, the shift of the maximum to the high-temperature region is due to the worst conditions of heat transfer from chips to the medium for hydrocarbons in comparison with water.

*Drilling in the emulsion of vaseline oil in water.* The carrying out of this experiment was caused by the sharp increase in the efficiency of lubricating-cooling liquids observed in practice using aqueous emulsions or suspensions of polymers, in particular polyethylene [21]. Figure 6c shows the TPH curves of chips obtained when drilling in emulsions of vaseline oil in  $H_2O$  and  $D_2O$ . The spectrum for chips obtained during drilling in water is given there for comparison. The mass spectrometer was tuned to register both  $H_2$  and  $D_2$ . The figure shows, first, that of

the two peaks observed in the emulsion spectrum, the low-temperature refers to hydrogen that absorbs metal from water, and high-temperature refers to hydrogen from organic substances. This is evidenced by the fact that when drilling an emulsion of vaseline oil in  $D_2O$ , the high-temperature peak is mainly  $H_2$ , and the low-temperature peak is  $D_2$ . The presence of two peaks in the spectrum simultaneously indicates that two types of regions are added to the chip material. The field of the first type arises due to the cutting in the water medium, and the field of the second type in the hydrocarbon. Secondly, the figure shows that when adding an emulsifier and, especially, a polymer, the peak corresponding to hydrogen sharply increases. The formation of a high concentration of hydrogen relates to the fact that because of addition of the polymer to water during catalysis on the juvenile surface of the metal, the hydrogen concentration and the rate of its formation with such chemical reaction will be higher as compared to the analogous conditions for the chemical reaction of water. The high concentration of hydrogen resulting from the addition of polymer (polyethylene) to the water in which the mechanical processing takes place appears to be related to the low activation energy of the macrochain of the polymer and its specific mechanism of thermal destruction.

In general, therefore, the most important conclusion, which, it seems to us, needs to be made on the basis of the results obtained, is the conclusion that plastic deformation, both during compression and when cutting metal in hydrogen-containing media, is carried out with the participation of hydrogen in process of destruction.

The obtained data, as well as the results of the already studied 'metal-hydrogen' systems, carried out in related fields of research, allow us to conclude the following.

(a) Opening of a new surface and deformation of the adjacent layer of iron and steel in hydrogen-containing media is accompanied by chemical transformations of the initial medium with the formation of hydrogen.

(b) Since hydrogen diffuses during deformation into a metal in the proton state, therefore, such a form of hydrogen state can be achieved due to its dissociation on juvenile catalytically active surfaces, and also due to collisions with mechanoemission electrons.

(c) Adding small amounts of organic emulsifier and especially the polymer to water results in a sharp increase in the efficiency of the transfer to the interior of the metal of hydrogen, the source of which are molecules containing hydrogen atoms in their composition.

(d) The contact interaction of active forms of hydrogen with metal plays a decisive role in facilitating the processes of metal destruction and deformation in surface-active media.

(e) Transport of hydrogen into the metal during its plastic deformation cannot be described within the framework of the equilibrium

thermodynamics of the diffusion process and requires other theoretical approaches and experimental studies.

(f) A weakly ionized gas in the crack space apparently represents a mixture of at least three types of particles: the electrons, charged positive ions, and neutral molecules. In connection with this distinctive feature of the radical-active products of the nanometric and atomic scale formed during the chemical activation of the medium is a qualitative change in their physicochemical properties and a unique reactivity. Consequently, the investigation of the quantum nature of phenomena and processes in the destruction zone and their use as a natural way of obtaining nanomaterials and electrically active hydrogen particles from the surface-active medium makes it possible to approach the justification of new ways of machining solids.

## **5. Influence of Hydrogen State on the Deformation and Destruction**

The study of the phenomena occurring during the interaction of active forms of hydrogen with a deformable metal is of interest not only in connection with the mechanical processing, but also for the scientifically grounded use of the effect of this interaction in order to obtain the necessary positive result in protecting metals from undesirable consequences of processes arising from the operation structures that come into contact with different media.

It is known that hydrogen can be in the molecular, atomic and ionic states in nature. It is clear that in connection with the various forms of hydrogen state, a variety of phenomena of its interaction with the deformed metal also appears. Usually, changes in the process of deformation and destruction of iron alloys are attributed to their interaction with hydrogen in the atomic or ionic state, while hydrogen in the molecular state has practically no effect on these processes [36, 37]. At the same time, these conclusions ground on phenomenological reasoning, which is in a connection with the experimental difficulties of modelling such processes.

We developed a technique, created special equipment and hardware that allowed the predicted transfer of molecular hydrogen to the atomic or ionic state, to monitor and evaluate the influence of such hydrogen state forms on the strength characteristics of the steel.

### **5.1. Mechanical Properties**

*Test procedure.* As known [38] that when waves and corpuscular radiation are affected on molecular hydrogen, the energy state of hydrogen molecules changes with the formation of electrically charged particles. In this case, the form and energy of radiation affect the degree of the gas medium ionization.

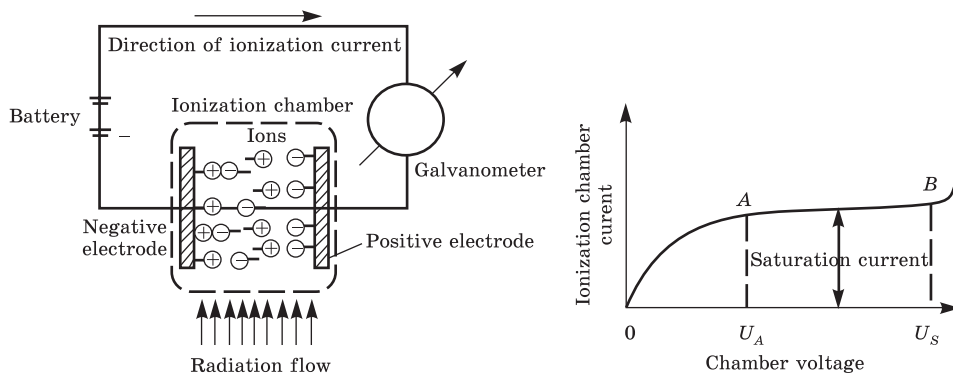


Fig. 7. The schematic view of ionization chamber and measuring unit: A — the working theory of the ionization chamber; B — the volt-ampere characteristic of the ionization chamber [16]

As a result of changes in the physical and chemical state of the gas medium, the nature of the interaction of the gas with the surface of the solid changes. In this case, it is very important to quantify the state of the gas medium (the number of ionized atoms or molecules), as well as the nature and quantitative changes in the physicomechanical properties of the materials.

In this paper, we present a technique for studying the effect of radiation (as the source of electrons, thallium-204 with an energy of 0.765 MeV and activity of 600 mCi was chosen) for the degree of inoculation of the gaseous medium (hydrogen) and its effect on the deformation and fracture processes of steel.

To carry out the work, a tensile machine with an ionization chamber and an ionization current measuring device was designed and manufactured.

The ionization chamber is a closed volume of a cylindrical shape ( $d = 80$  mm,  $l = 100$  mm), inside which two electrically isolated from each other electrodes are located. In the working position, a constant voltage is applied to the electrodes, due to which one of them is charged positively, the other is charged negatively. A positive electrode in this construction is the current-carrying layer that covered the inner cylindrical part of the chamber, and the negative is a sample isolated from the rods of the machine (Fig. 7).

Under normal conditions, in the absence of radiation, the gas between the electrodes serves as an insulator, and there is no current in the chamber circuit. When exposed to radiation, the gas is ionized, and an ionization current arises in the chamber circuit, which is recorded by a special device.

The magnitude of the ionization current for a given volume and the geometry of the chamber depends on the composition of the gas medium,



the magnitude of the voltage applied to the electrodes of the chamber, and the dose rate of the radiation.

At a sufficiently high voltage ( $U_A$ ), all the formed ions reach the chamber electrodes and a further increase in voltage does not lead to an increase in the ionization current (section *AB*); the magnitude of the ionization current is directly proportional to the radiation dose rate. The recombination of ions in the inter-electrode gap during the operation of the chamber in the saturation regime is zero. The magnitude of the applied voltage for the saturation regime was in the range  $U_A = 800$  V,  $U_B = 1800$  V. The operating voltage during the experiment was  $U = 1200$  V. The measuring device has 6 ranges, which allow measuring current from  $2.12 \cdot 10^{-11}$  to  $2.12 \cdot 10^{-6}$  A. Due to a wide range of measurements, the device allows fixing the ionization currents with the activity of radioactive emitters from 1 to 1000 mCi.

To reduce ionization losses, radioactive  $\beta$ -emitter Tl = 204 emitters were placed inside the chamber on its end caps. The investigated gas medium was supplied to the chamber through a gasholder. The chamber was purged during the time necessary to obtain a homogeneous gaseous medium. During the experiment, an excess pressure was maintained in the tight chamber ( $P_{\text{excess}} = 15$  mm H).

The samples were deformed in a gas medium on a tensile machine specially designed for experiments and installed in a protective chamber, which made it possible to work with preparations up to 1000 mCi.

The tensile machine, due to safety requirements, is designed with remote control of the loading device and with the automatic recording of the 'load-deformation' diagram. It makes it possible to investigate samples with a flat and circular cross section, a cross-sectional area of 1–3 mm<sup>2</sup> and a tensile strength of up to 1000 n/mm<sup>2</sup>. Samples and preparations are installed in the ionization chamber remotely, with the help of sword manipulators.

The results of the experimental data are contained in Table 2. An important parameter that estimates the order of the number of ionized atoms is the magnitude of the ionization current. The use of ionization chambers for radiation study has difficulties because the current produced in the chamber depends on the energy distribution-particles. In addition, it is difficult to estimate the average path of particles within the chamber due to the scattering they experience in the gas filling the chamber and on its walls [36]. The calculation shows that the values of the ionization current, obtained experimentally and theoret-

Table 2. Calculation of the number of ionisable molecules [16]

Ionized environment	$(dE/dx)_{\text{ion}}$ , eV/cm	$\epsilon$ , eV	$I_{\text{exp}}$ , $10^{-7}$	$I_{\text{theor}}$ , $10^{-7}$	The number of ionized molecules, %
Hydrogen ...	350	38.5	0.34	1.15	0.0000055

tically, are comparable and, in our opinion, confirm the correctness of the chosen scheme and experimental procedure.

The calculation took into account that all primary electrons have an energy equal to 0.765 MeV, although some electrons emerge from the inner layers of the isotope and decelerate by the source material itself. However, this braking will be insignificant due to the small thickness of the source (0.5 mm) and the relatively large value of the half attenuation layer (4.2 mm) for  $Tl = 204$ , which will not lead to large errors in the calculation. As believed, all electrons move in a straight line and, having reached the inner surface of the chamber, are completely absorbed. When determining the ionization current, we will not take into account the interaction of electrons and positive gas ions obtained because of ionization with the surface of the chamber and the sample.

The ionization losses of the primary electrons were determined from the formula [35]:

$$-\left(\frac{dE}{dx}\right)_{\text{ion}} = \frac{2\pi n y^4}{m\beta^2 c^2} \times \left[ \ln \frac{m\beta^2 c^2 E}{2(1-\beta^2)I^2(z)} + 1 - \beta^2 - 2(\sqrt{1-\beta^2} - 1 + \beta^2) \ln 2 + \frac{1}{8} \left(1 - \sqrt{1-\beta^2}\right)^2 \right],$$

where  $-(dE/dx)_{\text{ion}}$  is an average ionization loss per centimetre,  $n$  — number of electrons per  $1 \text{ cm}^3$  of medium;  $I(z) = 13.5$ ,  $z$  is an average ionization potential of medium atoms in electron-volts.

According to the studies carried out [41] for electrons with an energy of 0.765 MeV  $-(dE/dx)_{\text{ion}}$  of air is  $1,3 \text{ MeV}\cdot\text{cm}^2/\text{g}$ ,  $-(dE/dx)_{\text{ion}}$  for  $\text{H}_2$  is  $4.2 \text{ MeV}\cdot\text{cm}^2/\text{g}$ .

Multiplying these values by the hydrogen density, we obtain  $-(dE/dx)_{\text{ion}}$  for  $\text{H}_2$ :  $350 \text{ eV}/\text{cm}$ . Dividing  $-(dE/dx)_{\text{ion}}$  for ionization  $\varepsilon$  of hydrogen, we obtain the number of pairs of ions  $N$ , which creates an electron when the path is 1 cm in the gas. According to [39, 40], the work of ionization of electrons of a given energy for hydrogen is 38.5 eV. Part of the energy expended by the electron on the excitation of molecules, as well as additional ionization of molecules due to secondary electrons, is taken into account by a change in accordance with the change in the energy of the primary electrons [41]. Knowing the volume of the ionization chamber ( $V = 502.4 \text{ cm}^3$ ), we determine the number of molecules of gas in a given volume, which is  $n = 135 \cdot 10^{20}$ . Dividing the number of pairs of ions in the chamber, equal to  $NCl/2$  for  $n$  and multiplying by 100, we get the percentage of ionization molecules of gas in the chamber;  $l$  is the middle free path of the primary electron in the chamber, and  $C$  is the total activity of the sources in the chamber. The result is exhibited in Table 2.

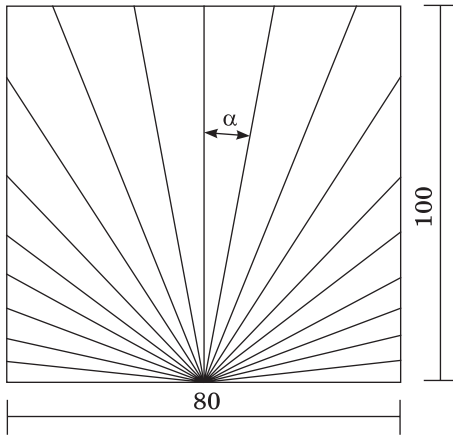


Fig. 8. On the calculation of the electron's average path in the chamber [16]

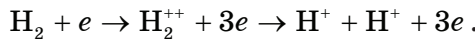
As the electron beam of a radioactive isotope propagates in a solid angle, then taking into account the fixation of isotopes in the chamber, it can be assumed that half of the electrons do not directly participate in the ionization of the gas, but are immediately absorbed by the chamber wall. In this case, the motion of electrons is symmetric

in a circle (the radioactive isotopes are located in the center of the bases of the cylindrical chamber), therefore, to determine the average value of  $l$ , we can consider the projection of the chamber on the plane (Fig. 8). Dividing the resulting rectangle by the rays emanating from the point O into 20 parts, we determine the range of the electron in each part of the rectangle and, averaging the results obtained over the entire rectangle, we obtain the middle range, and the electron in the ionization chamber is 6.7 cm. Thus, the ionization current, obtained as a result of irradiation of gas molecules by electrons, is equal to

$$I = \frac{(dE/dx)_{\text{ion}} l C p \cdot 1.6 \cdot 10^{-19}}{\varepsilon} a ,$$

where  $l$  represents value of the electron mean free path in the chamber (cm),  $C$  is an activity of the source (decay/sec),  $p$  is a multiplicity of ion charge,  $1.6 \cdot 10^{-19}$  is a factor determining the electron charge coulombs, and  $\varepsilon$  is a gas ionization work (eV).

We determine the multiplicity of ion charges. According to [23], the following reactions occur mainly in the ionization of hydrogen:

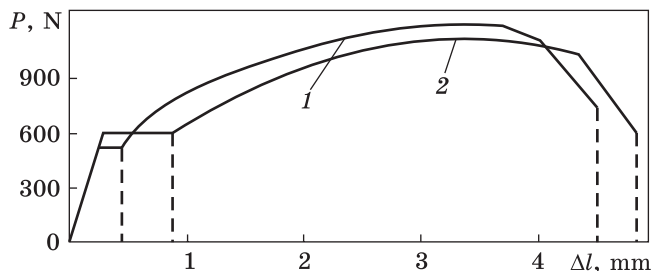


The first reaction clearly dominates in case of the interaction of electron with the molecule [30], therefore hydrogen ions formed as a result of interaction with electrons are charged once.

On the basis of the foregoing, let us formulate an equation that makes it possible to determine the ionization current. In our case, the equation will have the form

$$I = \frac{(dE/dx)_{\text{ion}} l C \cdot 1.6 \cdot 10^{-19}}{2\varepsilon} a .$$

Fig. 9. The 'intensification-extension' diagram for testing in  $H^+$  (1) and  $H_2$  (2) [21]



The experimental and calculated data presented in Table 2 confirm with accuracy the correctness of the measuring device.

The developed technique and equipment for detection of the effect of ionized gas media on the mechanical characteristics of 08 кп carbon steel allowed to perform experiments with flat samples (working section of  $3 \times 1$  mm). Annealing of the samples was carried out at the temperature of  $875^\circ C$  for 1.5 hours in a vacuum of  $2 \cdot 10^{-4}$  mm Hg.

When the radiation was absorbed, ionization of molecular hydrogen, which previously filled the sealed chamber, occurred. Simultaneously with the ionization process, recombination of ions continuously occurs—the process of the reduction of ions of the opposite sign into a neutral atom or molecule. Using an external DC source, a potential difference was created between the chamber wall and the central electrode (test sample). The motion of ions becomes directional: positive ions tend to the cathode (sample), and negative to the anode (chamber wall). A measuring device recorded the resulting ionization current. The voltage applied to the electrodes, equal to 1200 V, corresponded to the saturation current, i.e., almost all ions are collected on the electrodes with this voltage.

*Test results.* Figure 9 shows the 'force-elongation' diagram, which indicates that the mechanical properties of steel change only when tested in ionized hydrogen with a positive electric charge. In this case, the yield strength and elongation decrease, the length of the yield pad and the time to failure of the specimen are reduced at a constant strain rate.

Generally, we can thus establish that the change in the mechanical properties of a metal during its deformation in a gaseous medium consisting of hydrogen in its active forms is caused by interaction with a metal of electrically active hydrogen particles having a positive charge. This happens if the metal has a negative potential.

## 5.2. Effective Surface energy

In the glow discharge of air, hydrogen, and helium, the effective surface energy of the U8A sheet steel with a pre-introduced crack was determined by the known method [42]. The degree of influence of the gas medium on the effective surface energy was calculated by the formula:  $\Delta\gamma =$

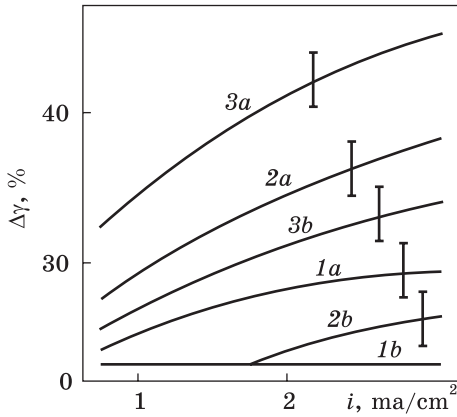


Fig. 10. The dependence of the effective surface energy variation value on the ionization current density when the sample has negative (a) and positive (b) potential; 1 — Helium, 2 — air, 3 — Hydrogen [42]

$= (\gamma_1 - \gamma_2) / \gamma_1 \cdot 100\%$ , where  $\gamma_1$  and  $\gamma_2$  are the effective surface energy in the vacuum and test gas, respectively.

The investigations were carried out in a specially manufactured apparatus that allowed loading the sample, monitoring the development

of a crack in the glow discharge of various gases. Between the sample and the electrodes, the potential difference necessary for obtaining a glow discharge in the range  $\pm 0.9$  kV. In the working chamber, under the action of an ionizer, a gas mixture consisting of positively and negatively charged ions was formed. This process proceeds in two stages. First, under the influence of an external ionization source, when its energy reaches the ionization potential, for example hydrogen, an ionized hydrogen gas, which is a mixture of electrons, positively- and negatively-charged ions and neutral molecules (atoms) are formed. At the same time, energy is not required for the proton recombination process, but, on the contrary, energy is released. As the temperature increases, more and more particles, which have kinetic energy exceeding the ionization energy, appear in the system, and thus can lead to ionization in collisions with other particles. As a result, a rapid increase in the degree of ionization occurs. Such processes of ionization to a certain extent model the processes of ionization of hydrogen flowing in the gap space that occurs when cutting (Fig. 1).

The obtained results (Figs. 10 and 11) confirm the test data presented in Fig. 10 and all this allows us to draw some conclusions. (a) The reduction of the effective surface energy of steel occurs only in the gas, consisted of charged particles. (b) The change in the effective surface energy of steel occurs only in that case when in the ‘metal-gas’ system, the electrically charged particles of a gas interact with a metal having an electric charge of the opposite sign. (c) The maximum effective surface reduction is achieved when negative potential of the sample. A much smaller decrease in the effective surface energy of steel occurs with a positive potential of the sample. This difference is apparently because the concentration of negative ions in the system is much less than that of positive ions (at 180 eV there is a negative for each positive ion  $0.1 \times 10^{-4}$ ), and their geometric dimensions are much larger ( $10^{-5}$  Å for  $H^+$  and more

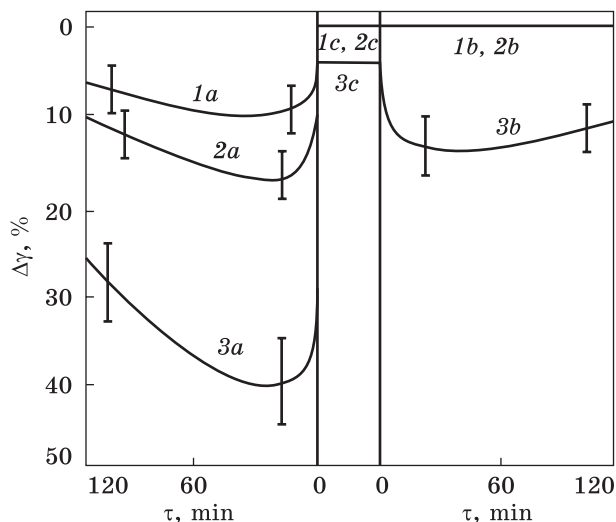


Fig. 11. The time-dependent variation of the effective surface energy in the ionized gases for negative (a) and positive (b) potential of the sample as well as for the sample without charging (c); 1 — Helium, 2 — air, 3 — Hydrogen [42]

than 1 Å for H). Apparently, a practical lack of H<sup>-</sup> influence on mechanical characteristics (Fig. 9) relates to such a difference of positively and negatively charged ions. (d) Adsorption processes can cause a slight change in the effective surface energy of the metal in hydrogen without polarization of the sample, when dispersion forces carry out the attraction between the adsorbent and the adsorbent.

Thus, it is clear that the phenomenon of facilitating the deformation and fracture of a metal under conditions of its interaction with hydrogen in the process of cutting in a surface-active LCTF is the interaction of hydrogen-charged particles with real electrically active material structure, formed as a result of a mechanical process.

## 6. Initiation and Self-Acceleration of Chemical Transformations of the Surface-Active LCTF during Mechanical Process

Due to obtained data on the presence of hydrogen in the chips and in the treated metal surface by cutting in various hydrogen-containing media, it follows that chemical transformations of the initial hydrocarbon surface-active medium (LCTF) really takes place in the metal destruction zone. At that, there is a formation of active forms of hydrogen — a chemical element which strongly affect the metal changing its physical and mechanical properties. This conclusion is of great practical importance. This recommends us to seek effective additives for LCTF not among surfactants having a high adsorption capacity, but giving an insignificant

concentration of hydrogen due to activation, and among polymer compounds, which (due to their pyrolysis) capable to form in the cutting zone a large yield of a mixture of gaseous substances containing hydrogen in active forms [43].

In order to establish at least qualitative linkage between various processes and phenomena in ultramicroscopic regions, where the acts of restructuring and rupture of the forces of interatomic bonds occur due to the combined effect of mechanical energy and hydrogen, and results of the material workability, let us consider some of the main aspects of this problem.

### **6.1. Polymer in the Composition of LCTF as a Contributor to the Plasma Effect Formation and Improver of the Machinability of Metal**

In the overwhelming majority all modern LCTF, without which it is impossible to carry out the process of manufacturing parts with specified accuracy and surface quality, are hydrocarbons whose molecules consist of atoms of only two elements: carbon and hydrogen. Other classes of organic compounds commonly used in producing LCTF molecules also consist of carbon; however, one or more hydrogen atoms can be substituted for other atomic groups. Unlike low-molecular substances, polymers, recommended for using as an additive to increase the efficiency of LCTF, are also organic compounds. However, their macromolecular chains consist of molecules of their low-molecular analogues, connected to each other in a macrochain, the molecular mass of which can reach several million.

Currently, the global assortment of LCTF has about a thousand items, which are multicomponent system containing a combination of additives of different chemical composition that determine their various functional purposes. The basis of LCTF (water, oil or oil in water emulsion), as well as the chemicals in its composition, are adsorbed by various surfaces of the metal and the tool which are processed.

The metal surfaces on which the LCTF is condensed have a different temperature, which varies depending on the type and parameters of the machining, as well as the properties of the metal being processed, and can reach the melting point of the material being processed. As the temperature rises, the intensity of all types of molecular motion increases, which can lead to the breakdown of the substances composing the LCTF.

The temperature at which the substance disintegrates depends on their chemical composition, building and structure (molecular weight). A substance with a large molecular weight, but of a single chemical composition loses its stability at a lower temperature. For example, high-pressure polyethylene is thermally stable up to a temperature of

290 °C, followed by the liberation of significant amounts of volatile products, and low-molecular-weight linear hydrocarbons lose their stability only at temperatures above 600 °C. (Note that polyethylene (PE) and polyvinyl chloride (PVC) are used as polymer additives to LCTF. Therefore, the study of the 'metal-polymer' system can act as 'model substances' and prototypes for studying a number of physicochemical phenomena [43].)

If we compare the detachment energy of a hydrogen atom in a series of saturated hydrocarbons, then in comparative units it will be for heptane 11, and for a polymer, for example, polyethylene 3, polyisobutylene, 2 units [32]. The main reason for this difference is that thermolabile structural anomalies often occur in polymer molecules, on which both typical reactions and other completely unexpected processes can be easily initiated.

In addition, many reactions, typical for low-molecular compounds, are converted into polymers in chain processes, which is also conditioned by their specific structure.

A significant difference in the mechanism of chemical reactions of low-molecular and high-molecular compounds leads to an increase in the efficiency of LCTF when polymer is introduced into its composition.

As already noted, the stability of polymers to heat, the rate of thermal decomposition and the nature of the formation of products depends on the chemical structure of the polymer chain. However, the first stage of the process is always the formation of macroradicals as a result of the rupture of the most strained and weakened bonds in the macromolecule. In the second stage, macroradicals are involved in the chain transfer reaction, i.e. transfer of an unpaired electron with the formation of a new free radical and a macromolecule with a reduced molecular weight. For PVC, the reaction proceeds in the direction of elimination of the side group (Cl) from the main chain with the formation of double bonds in the chain and the evolution of hydrogen. It has been established that each radical is able to initiate a radical reaction, leading to the rupture of about 10 000 polymer chains, and further chemical activation can acquire self-accelerating character, which leads to the avalanche-like growth of new active particles, including ionized hydrogen [32, 43].

It should be noted that the established presence of hydrogen in the chips and in the treated surface is recorded by cutting the metal in any hydrogen-containing medium, even in water. However, the concentration of hydrogen in the metal after processing in a low-molecular liquid is always significantly lower than in a medium with a polymer additive, sometimes even more than two orders of magnitude. Naturally, due to this, the effect of the environment containing the polymer is also significantly increased.

Thus, the specific mechanism of thermal decomposition of the polymer macrochain is used in this case to produce a weakly ionized gas



consisting of molecular and atomic hydrogen, as well as ions, ion radicals, radicals. As an intermediate product, the hydrogen-containing gas mixture subsequently penetrates into the slit, where its chemical transformations continue (Fig. 1).

Another important difference between the medium and the polymer additive is that during the pyrolysis of the polymer, a solid phase — polyconjugate polycyclic system consisting of graphitized aromatic rings is formed and accumulates on the cutting surfaces of the instrument [21].

In the proposed hypothesis, it was also assumed that during the cutting process, such a pyrolytic residue, firstly, could be a good lubricant that facilitates the separation of friction surfaces, and secondly, a medium for the permanent carbonization of the cutting edges of the tool. As the first feature of the polymer additive to LCTF, and the second, is that both of them will contribute to a significant increase in wear resistance of the tool, as well as reduce the work spent on friction along the front and back surfaces of the tool.

It is important to note that generally, the purpose of the polymer additive is also to affect not only the main energy costs of the cutting process (plastic deformation and friction), but also contribute to the reaching the main goal of machining — obtaining parts with specified accuracy and surface quality with the simultaneous achievement of certain economic results.

The mechanical characteristics of a metal have been changed under the action of hydrogen in active forms but not because of the decrease in the surface energy of the solid due to reversible adsorption of the medium. This is also because kinetic process of metal destruction is accompanied with changing the interacting systems. The initial system ‘the surface of the workpiece—the adsorption of the initial medium’ was followed by the system of interaction in a narrow zone ‘the outer and inner surfaces of the crack tip material—electrically active hydrogen particles’. In this case, the final activation processes take place in a narrow gap space with an expressed polar effect at the crack tip.

Thus, the process of polymer-containing surface-active medium activation, i.e. its transformation into radically active hydrogen plasma, includes several stages. (i) Adsorption of hydrocarbon molecules of a liquid and its chemical compounds on hot surfaces of the cutting zone. (ii) Dissociation of adsorbed molecules and thermal destruction high-molecular compounds. (iii) Chain reaction of macrochain initiated by pyrolysis of macrochain by the active products. (iv) Desorption from hot surfaces of reaction products: gas mixture consisting of atoms and molecules of hydrogen, as well as a homologous series of aliphatic saturated hydrocarbons. (v) Diffusion of activated products into the reaction gap. (vi) Heterogeneous and homogeneous catalytic reactions in juvenile freshly formed surfaces in the space of the reaction gap. (vii) Desorption

of reaction products (item 6) and formation of a weakly ionized hydrogen-containing gas. (viii) Recombination of protons in the space between the cavities of a crack and, as consequently, the temperature increases and the degree of ionization increases rapidly. (ix) Shock ionization of a hydrogen-containing gas by an electron avalanche and formation of hydrogen plasma.

Radically active, electrically charged products of nanoscale and atomic scale formed due to multistage transformations of the initial medium affect the processes of deformation and destruction, which is the main factor in the energy balance of the total costs of the cutting process.

Generally, therefore, in the cutting zone with a polymer-containing LCTF, two different processes run in parallel. First is the process of activation of the initial medium with the formation at the last stage of the plasma effect and its influence on the processes of deformation and destruction. The second process is the accumulation of a pyro-polymer residue on the cutting edges of the tool, which contributes to an increase in the wear resistance of the tool and a decrease in the coefficient of friction. Moreover, both processes contribute to the improvement of the machinability of the metal, which is an important technological characteristic.

## **6.2. Thermal Decomposition in the Cutting Zone of Chemical Compounds Composing LCTF**

Summarizing results of earlier works, we point out the features of the formation of active forms of hydrogen from a medium that does not contain and contains a polymer component.

Chemical reactions, as a result of which the initial surface-active media transform into radically active plasma, that is a complex, multi-stage physicochemical process taking place under conditions of high local mechanical stresses and temperatures. In other words, the manifestation of the environment chemical activation is connected with such thermally and mechanically activated processes in the cutting zone, which in other conditions are not mandatory at all.

Heat is one of the main physical indicators of the cutting process. Its main sources are plastic deformation, occurring primarily in the area of maximum shear and friction in the areas of tool contact with chips and workpiece.

The fact that the polymer component of LCTF in the cutting zone under the influence of high temperatures undergoes chemical transformations is unquestionable. Indeed, experimental data show that during the mechanical metalworking, the molecular weight of the polymer additive is continuously reduced, and gaseous products are released in the cutting zone [21].

The analysis of gaseous pyrolysis products of polymers was carried out under ordinary conditions, the results of which were compared with products formed directly in the cutting zone. Polyethylene and polyvinyl chloride emulsion as well as 100 000 molecular weight polyethylene and polyvinylchloride were used as the polymer.

Pyrolysis was carried out in quartz ampoules. A polymer sample was placed on the ampoule bottom, and slightly heated up to 50 °C, and evacuated. The pumped ampoule was placed in a preheated (800 °C) muffle furnace and incubated until the polymer sample was completely carbonized (1 minute). The resulting pyrolysis products condensed in the cold part of the ampoule. After pyrolysis, the ampoule was filled with helium to atmospheric pressure in order to further enter its components into the syringe chamber of the chromatograph.

The gas phase formed in the cutting zone during the drilling of 1X18H9T steel in an appropriate medium was also analyzed. The selection of the gases to be tested was standardized by means of a calibrator into a volume (1 L) for 1.5 min. All volatile products were collected first at a liquid nitrogen temperature in a one-litre volume. The condensed fraction (condensation time 30 min) was concentrated by freezing it to a small volume (10 cm<sup>3</sup>), followed by filling the ampoules with helium for chromatographic analysis. The gas fraction, which did not condense at a temperature of -196 °C, was not analyzed.

The results of the studies showed (Table 3) that the polymer additive in LCTF is actually destructing in the cutting zone, as evidenced by the

*Table 3. Comparative data of the gas fraction formed during the pyrolysis and drilling [21]*

No.	Pyrolysis		Drilling		Retention time, s	Pyrolysis products
	Emulsion polyethylene	Polyethylene + water	Emulsion polyethylene	Polyethylene + water		
1	17	16	16	17	17	Methane
2	–	29	28	–	30	Ethylene
3	30	33	33	34	34	Ethane
4	99	100	96	105	96	Propylene
5	145	–	–	–	105	Propane
6	263	260	257	264	–	–
7	400	400	400	410	400	Isobutene
8	575	–	–	–	–	–
9	1260	–	1280	1200	1290	Acetone
10	1650	1620	–	–	1620	Pentene
11	4380	4350	–	–	4350	Hexene
12	–	6690	–	–	6630	Hexane

formation of gaseous products of aliphatic saturated hydrocarbons from CH<sub>4</sub> to C<sub>7</sub>H<sub>16</sub>, hydrogen and liquid hydrocarbons. It should be noted that the composition of the gaseous products formed in the cutting zone does not differ from the substances contained in the heating of the same polymer under ordinary laboratory conditions.

Similar data were obtained in experiments on pyrolysis and drilling in a polyvinylchloride emulsion (PVC) medium, the only difference is in the presence of chlorine-containing hydrocarbons in gas fractions.

Thus, the obtained results demonstrate that in the cutting zone, under the influence of high temperature, the polymer additive is degraded, which can be conventionally divided into depolymerization reactions, or the sequential detachment of the monomer units from the end of the chain, and the destruction reaction causing the substitution of the substituents [43]. In the first case, during the cleavage of the main chain, the monomer units remain, and in the second case, the substituents in the polymer backbone are completely cleaved to form volatile products. In the resulting gas phase at a temperature of 230–250 °C, the amount of hydrogen molecules can reach 99.5% [44]. At this temperature, the process of pyrolysis of the polymer additive acquires an autocatalytic character with the formation of ionized hydrogen (or hydrogen chloride, if the polymer additive is PVC), as well as free radicals and ion radicals [43–45].

The well-studied mechanism of decomposition of macromolecules at heating does not differ from the mechanism on hot surfaces of the cutting zone [21]. Therefore, here it seems inappropriate to bring the mechanisms of the disintegration reaction of polymers macrochains, information on which can be obtained from special literature [43].

When chemical bonds of low-molecular organic compounds break, it is also possible to form ionized hydrogen; however, firstly, such a reaction can occur only at temperatures much higher than the temperature of thermal destruction of their high-molecular analogues; secondly, the reactions in this case proceed without radical formation and, therefore, do not contain the character of self-accelerating [46]. In this regard, the concentration of hydrogen that can be formed in the cutting zone during the breakdown of low molecular weight organic compounds is much less than in the thermal destruction of macromolecular chains of polymers.

The intermediate radical products, which are formed at the first stage of the decomposition of the macrochain of the polymer, are an additional source of the formation of new radical active substances [47]. Their further reaction may acquire self-accelerating character, which leads to an avalanche-like growth of active particles [48], including hydrogen in its active forms. Because of self-accelerating chain reaction, which takes place even under isothermal conditions, large concentrations of active particles forming the hydrocarbon gas mixture are formed.

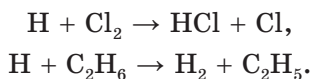
The N. Semenov's calculations [49] show that the number of protons,

atoms, and radicals, and hence the reaction rate exponentially increases,  $e^{\phi t}$ , where  $\phi$  is the branching factor determined by the difference between the branching probability of the chain and its breakage on the surface of the heated metal with which the macrochain of the polymer contacts. In a number of cases, the reaction rate in the appearance of groups that have already reacted can exceed  $10^3$ – $10^4$  times [43].

At the same time, in the case of the polymer chain decomposition, the intermediate substances do not lead to unlimited development of the chain reaction. This is because at a certain stage it terminates due to the destruction of the active sites as a result of their adsorption on the metal or collisions among themselves in the volume of the mixture.

Most importantly, however, that the first acts of rupture of polymer molecules with a length of hundreds of angstroms, in addition to initiating chemical free radical processes, most of the energy fragment stored in the ‘halves’ of the fragmented energy is released as heat [47, 48]. Taking into account the chain nature of destructive processes mentioned above, when, following the disintegration of the first molecule, the transfer of free radicals leads to a rapid disintegration of hundreds of neighbouring ones, and, consequently, to ‘group’ heat release, we can conclude that the system has its own kind of thermal micro-explosions.

As an example, let us show the reaction of molecules of hydrocarbons with an excited atom or radicals, when the released energy exceeds by more than an order of magnitude the energy expended on the reaction:



For the first reaction, it is necessary to expend 2 kcal/mol, and 57 kcal/mol is released. For the second reaction, it is necessary to spend 9.5 kcal/mol, and 98 kcal/mol is released. At the same time, interaction between particles of non-radical nature requires overcoming a high-energy barrier and a chemical reaction cannot be carried out at a noticeable rate [52].

It should be noted the specific adsorption behaviour of the considered system, which consists of many chemical elements (LCTF). Adsorption from such a multicomponent system is a complex process, depending both on the interaction of the components among themselves in the bulk and surface phases, and on their interaction with the adsorbent. Such polymolecular adsorption is so complex and specific that until now its theoretical development is limited to only the most general ideas [53]. At the same time, some hypotheses about the processes of such adsorption make it possible to draw a number of conclusions.

First, polymolecular adsorption should be considered as a result of the interaction of the separated phases [53]. This means that the solid

phase (polymer) and the liquid (low molecular substances) that make up the multicomponent system, which is LCTF, are adsorbed separately, not displacing each other from the surface. Secondly, the peculiarity of the adsorption of polymers from a multicomponent system is its increase with increasing surface temperature of the adsorbate [50], which will accelerate the decomposition of the polymer macrochain.

Thus, at the adsorbing LCTF, its two parts, high-molecular and low-molecular organic compounds, due to the condensation saturate the unbalanced bonding forces lying on the metal surface and interact with its real structure, and the third part, the water base, evaporates. If the temperature of the chips is more than 600 °C, the water vapour can interact with the heated surface and form molecular hydrogen according to the scheme  $3\text{Fe} + 4\text{H}_2\text{O} \rightarrow \text{Fe}_3\text{O}_4 + 4\text{H}_2$ .

Thus, polymer-containing and polymer-free LCTF give a different concentration of hydrogen in the cutting zone, which also causes a different influence of such technological means on the cutting process.

The foregoing facts and arguments give grounds to state that in the constant heat fields of the cutting zone chemical transformations of the substances that make up the LCTF occur. At the same time, the speed and kinetics of chemical reactions of substances of even the same atomic composition, but differing by different combinations of atoms or the structure of atomic groupings, depend on their molecular weight [21].

The products formed under the influence of sources of heat release when cutting metal are intermediate and participate in further chemical transformations.

### **6.3. Phenomenological Criteria for the Plasma Effect Formation**

The generalization of the studies devoted to various physicochemical phenomena observed in the destruction of solids allows us to conclude that the final formation of a hydrogen plasma from a gas mixture occurs under the action of a different hydrocarbon gas mixture of various physical processes and phenomena of a quantum nature and accompanying the process of destruction. Such transformations of the gaseous medium are possible in some microscopic space separating the crack tip and the wedge of the tool (Fig. 1). To describe the physicochemical reactions in the reaction zone, it is necessary not only to designate this area, but also, to reveal its properties.

Taking into account the importance of information on the microscopic and phenomenological features of the crack propagation kinetics that determine the theoretical and actual strength, it seems important to evaluate the role of the above factors on its movement under environmental conditions. In this respect, the main role is played by the decisive role

of the formation and development of cracks as a factor initiating chemical transformation, which was shown in direct experiments: mechanical action on a metal at a fixed temperature leads not only to its destruction, but also is accompanied by chemical transformation of the environment [14, 51]. In this connection, the study of the nucleation and propagation of a crack under such conditions is one of the most important areas of research in this field, which contributes to the development of ideas about the nature of the destruction of a solid in various media.

### **6.3.1. Crack as a Factor Forming Conditions for Chemical Activation of the Medium and Its Transport into the Destruction Zone**

The break of the interatomic bonds in the solid is localized in the places of concentration of stresses of different origin, but mainly in the microareas adjacent to the tops of the cracks. Therefore, the article deals with the situation that forms in such areas of the material in connection with the possible influence of the medium at the time of the formation of a new surface. In this case, we are not talking at all about defects (microcracks) emerging on the surface of a deformable metal, but only about those microcracks whose vertices are used to open new surfaces, i.e. located and developed in close proximity to the cutting edge of the tool. Such a microcrack, having a wedge shape with a mouth that converges to an interatomic distance, will be considered as a source of subsequent destruction (Fig. 1). As for the medium in which the fracture grows, it is an ionized, radically active gas mixture formed in the previous stages of chemical activation of the initial hydrogen-containing liquid.

The results of studies of the kinetics of the cutting process, confirmed by experiment [13, 55], show that the chips do not contact the tip of the tool cutter at the microscale, forming a gap that mates with the fracture cavities (Fig. 1). Due to the mechanical impact on the material, crack growth occurs, its juvenile surfaces are exposed and various physicochemical processes and phenomena that are permanent satellites of destruction occur.

The zone bounded by the cavities of the crack, the wedge of the tool and the crack tip can be represented as a kind of reactor in which, under the influence of various processes and phenomena accompanying the mechanical processing, the hydrogen-containing gas mixture is converted to radically active hydrogen plasma. Consequently, in the process of cutting between the crack tip and the wedge, an atmosphere-free space is formed in which the final stages of medium activation take place.

As known, in the process of crack growth, pure, juvenile surfaces are formed, along which uncompensated interatomic interaction forces (surface tension) are applied. Such surfaces of iron and its alloys have a

high catalytic activity. Moreover, catalytic reactions do not occur on the entire new surface, but on the so-called active centres, which are formed in those places of the surface where the force field of the atoms is least saturated. The resultant energetically unequal surface of iron has a large number of active centres, which can be different crystalline facets, edges and peaks, as well as areas with a broken crystal structure (vacancies, dislocations, grain boundaries and subgrains).

We also know [8] that in the deformation of polycrystals, there are innumerable variants of fracture at the tip of a crack. The resulting periodic relief of the surface, having a varying degree of distortion and looseness, therefore also has a different set of combinations of surface activity. The steps of the cleavage, the presence of microscopic and molecular-scale protrusions, and other active surface elements are in fact microelectrodes that are single-source electrons and ions that participate in surface reactions, and, on the other hand, can act as retarding or accelerating potentials on the crystal surface at various physical and chemical processes with the environment. In its turn, the contact interaction of the environment with mosaic, electrically active surfaces resulting from the destruction of the metal, can initiate and then self-accelerate the reactions of chemical transformations of the environment up to the formation of hydrogen plasma [21]. Moreover, all these chemical transformations take place when the material is destroyed in cramped (tunnel) conditions, where physical factors have an enormous influence on these processes: the electric field, heat fluxes and their heat removal, the supply of reagents, the deformation rate in combination with extremely high local pressure of the wedge of the tool on surface of the processed metal, as well as its chemical composition and structure, etc. Consequently, while cutting, the interacting system will change and form, depending on the conditions imposed by the course of the mechanical process.

Indeed, the ability of the metal surface to generate hydrogen ions into the volume due to its interaction with the hydrogen molecule has been known since the time of Langmuir's work, based on which one of the simple methods of obtaining H in active form was created. According to this procedure, the process proceeds according to a two-stage scheme [15]:  $Me + H_2 \rightarrow Me-H + H$ ,  $Me-N \rightarrow Me + H$ .

It is also known [16] that when chemisorption on the surface of metals subjected to ultra-vacuum cleaning ( $10^{-10}$  mm Hg), a very significant increase in the chemical activity of molecules is achieved. For instance, in the chemisorption of hydrogen, nitrogen, and oxygen on iron, their dissociation into atoms is observed even at a liquid air temperature  $-188^\circ\text{C}$  (in some cases, at a hydrogen liquefaction temperature,  $-253^\circ\text{C}$ ) and proceeds very rapidly, practically without activation energy [13, 56].



Thus, it can be assumed that the surfaces that limit the formed space between the top of the crack and the wedge of the tool have a high catalytic activity that promote further chemical transformation of the gas mixture. It follows that in the process of cutting before the wedge of the tool, the growing crack forms a reaction area, which is filled with a hydrogen gas mixture. A specific feature of this zone is the following. (a) It is permeated with a stream of high-energy electrons emitted from the top of the crack as a result of the restructuring and rupture of the forces of interatomic bonds. (b) It is penetrated by an electromagnetic field formed in connection with the occurrence of thermoelectromotive force in the system ‘machine tool–tool–workpiece–earth’. (c) On the metal surfaces bounding the reaction zone, point defects, representing macro-electrodes taking part in surface phenomena, are periodically located. (d) The surfaces that bound the reaction area have catalytic activity.

Two other physical phenomena acting in the gap space are of particular importance for the realization of the mechanoplasmic effect. This electromagnetic field, created by induction current due to the electromotive force in the ‘machine tool–tool–workpiece’ system, as well as the polarization of the material at the crack tip due to the displacement of negative electric charges into the most inhomogeneous, defective area. Both these phenomena determine the vector of the timely transfer of electrically active particles composing the plasma, directly to the source of destruction, and affect the rate of the chemical transformations of the medium in the gap space.

In conclusion, it is important to note that an important feature of the proposed model is the inverse positive connection between the growing crack and the medium: a developing crack creates conditions in the gap space for the activation of the medium to hydrogen plasma, and the formed plasma has a positive influence on its development.

### **6.3.2. Electric Field in the Fracture Zone and Electric Charges on the Cavities of the Crack**

The discussion of electrical phenomena in the gap space and on the interfaces is limited by definite, though somewhat arbitrary, frames. Particularly, here we will not delve deeper into special areas of research into these phenomena and processes, since it is sufficient to know the causes of the appearance of electric charges on the surfaces of the gap and the electromagnetic field in its space, and the new phenomena arising from these processes.

In connection with this, we conclude that as a result of contact between two dissimilar metals (tool and material being processed), under the condition of different temperatures of the contacting bodies, a thermoelectromotive force arises and in the closed chain ‘machine tool–

tool–workpiece–earth’ electric current starts and electric and magnetic fields appear. In addition, during the process of plastic deformation and friction, some electrons on the contact surfaces in the chip formation zone acquire kinetic energy sufficient to overcome the potential barrier of their separation from the metal boundary, which leads to the appearance of a thermocurrent and electron emission.

The total current arising in the chip formation zone consists of two components: a constant due to the presence of a closed chain of heterogeneous metals, and a variable created by thermionic processes. Since the main current carriers (electrons) diffuse from the heated area (tool blade) into the cold (processed metal), the processed metal will be enriched by charge carriers (electrons) and acquire a negative charge, and the tool, being depleted by electrons, is charged positively. This process in the system ‘machine tool–machined material–earth’ is continuous, as well as continuous ‘pumping’ of electrons in one direction from the tool to the workpiece, which results to high values of electric current: 0.2–80 mA [21].

Thus, in this system there is a clear separation of the direction of the motion flow of charged hydrogen particles: particles with negative electric charge ( $H^-$ ) will get an attraction to the tool and repulsion by from processed material. Similarly,  $H^+$  will move in the direction of the processed material.

In addition, the presence of electromotive force (in the closed circuit) creates conditions for the realization of a known physical phenomenon, viz. the effect of the electronic ‘wind’, i.e. ambipolar diffusion of hydrogen into the processed material.

In the considered system, the direction and velocity of the displacement of  $H^+$  from the gas phase to the fracture zone will depend not only on the atomic structure of the given material and the magnitude of the electric potential. Thus, when a proton approaches the surface, the structural heterogeneity emerging to the surface, various micro- and macro-voids, and uneven distribution of stresses, dislocations, vacancies and other defects of the crystal lattice begin to play an important role in its mass transfer. All these features, which are usually more or less characteristic of any real metal crystal, will change the intensity, strain and directivity of the electric fields created by the metal atoms [9]. In addition, cathodic inclusions (carbides, alumina, silica, graphite, and other nonmetallic inclusions) on the general anodic background of the surface cause the ejection from the gas phase of  $H^-$  in the direction of the tool. Because of this, a spatial separation of the surface of the metal into anode and cathode areas occurs, which will attract or repel electrically charged hydrogen particles.

It is equally important, however, that in the area of a plastically deformed metal near the top of the crack, i.e. in the zone of the limiting

energy concentration, where the interatomic bonds are restructured and broken, a large number of different defects are concentrated. All these defects complicate the motion of electrons in the crystal lattice and they are their traps. Consequently, in the area of plastic deformation of the metal, an elevated electron concentration (Hall effect) will be observed at the crack tip. This means that the material area near the crack tip acquires an extremely concentrated negative electric charge. Here it is necessary to note one more important phenomenon, which contributes to the ionization of hydrogen. It is known that free electrons do not leave the metal at ordinary temperatures, since they are kept by the electric field of the double layer. However, at the moment of crack growth, a double electric layer breaks at the tip of the crack and some of the free electrons emerge into the vacuum space of the reaction zone, as a result of which mechanoelectronic emission is observed [46]. In addition, the electrons of the conductivity of the metal, making random thermal motion, also fly out beyond the surface of the crack cavity, creating an electron cloud, constantly exchanging electrons with the metal in such a way that the electrons of the cloud and the metal are in dynamic equilibrium with each other [10]. It should be noted that an appreciable concentration of electrons in the cloud is observed only from the metal surface for several interatomic distances. Consequently, electrical charges are induced at the same distance from the internal surface of the crack, which can also affect the kinetics of the approach of hydrogen protons to the destruction site.

The presence of defects usually facilitates the transition through the surface of neutral hydrogen atoms and their diffusion into the volume of a solid, since there are many paths of increased mobility in the solid, and energy barriers on these paths, and, consequently, the activation energy is less than in the volume of the crystal. At the same time, these same defects for the hydrogen proton are its traps.

In general, thus, in the chain of physicochemical processes creating a plasma effect, the following phenomena are important links that accompany the destruction of material during cutting. First, it is the possibility of hydrogen plasma formation and, secondly, ambipolar diffusion of positively charged hydrogen particles from the surface into the volume of the processed material due to the electronic 'wind' effect known in physics.

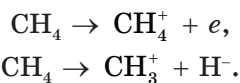
Let's note one more important feature of formation of hydrogen plasma at metal cutting in LCTF. As is known, when a sharp tool is mechanically applied to a machined surface in an interelectrode gap, when a contact breaks, repeated short-lived electrical discharges occur between the workpiece and the tool. When mechanical processing takes place in a dielectric LCTF (for example, oil, kerosene), a thin layer of liquid breaks down, as a result of which the liquid can ionize to form a plasma.

### 6.3.3. Diffusion of the Gas Mixture into the Reaction Zone

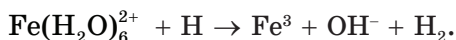
The penetration into the reaction zone of a gas mixture, formed on the hot surfaces, can occur in various ways. For example, in the process of crack growth the vacuum gap between the tip of the crack and the cutting wedge of the tool will instantly be filled with a gas mixture. Other ways of penetrating the medium to the source of destruction are possible. Basically, these are various defects that occur in the area of the plastically deformed material at the crack tip, as well as defects caused by spark electric discharges at the points of contact of the tool with the processed material. In the first case, the area of the material at the crack tip where new cells are opened is an inhomogeneous material with a distorted crystal lattice structure, grain boundaries, subgrains, dislocations, a large number of microcapillaries of molecular dimensions, ultramicroscopic, and microscopic cracks [24]. Through all these defects, the diffusion of the gas mixture to the source of destruction is possible. In the second case, the movement of the gas mixture occurs through microcracks, which are formed in places repeated during the cutting of short-term contacts of the unevenness of the cutting edge of the tool with irregularities of the processed material, causing short-term electrical discharges. If the tip does not have contact with the surface of the crystal, then after the corona and spark discharges on the surface of the crystal, small groups of dislocations are present, representing the paths of accelerated diffusion. In this case, fresh dislocations, after the action of a spark over the crystal, are formed in areas on which there were no previous dislocations [14].

### 6.3.4. Heterogeneous Catalytic Reactions

The fact that the juvenile, clean surfaces of the reaction zone, formed at the time of the destruction of the metal, contribute to the acceleration of chemical reactions of the hydrocarbon gas mixture can be judged from the results of known studies carried out on pure iron surfaces [10]. For example, on such surfaces, the CH<sub>4</sub> methane molecule firstly transform into the CH<sub>4</sub><sup>+</sup> molecular ion, then into the CH<sub>3</sub><sup>+</sup> methyl ion and radical — an atomic hydrogen:

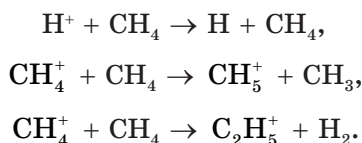


Further, H atom can act as an electron donor ( $\text{H} \rightarrow \text{H}^+ + e$ ), and can participate in further chemical reactions, e.g., by tearing off the second hydrogen atom from the hydration shell of the ion:



The ionization of the hydrogen that forms part of the gas mixture on a newly emerging clean surface can proceed in several ways and, in

limiting cases, ends with the formation of a negatively charged ion H<sup>-</sup> and a positive proton H<sup>+</sup>. The direction and degree of ionization of hydrogen atoms will be determined by the nature of the force field of metallic atoms, which in turn depends on the atomic structure of the metal and on the external conditions of the system. If the intensity of the force field is insufficient for complete ionization of hydrogen to the proton, then the hydrogen atom will be in a state of excitation and partial ionization. It should be noted that positive ions have a higher reactivity than negative ions. For instance, the simplest high-rate reaction, the charge (electron) transfer, can occur according to the scheme [10]:



The most important reactions of ions on the metal surface include also possible internal rearrangement and decomposition, which leads to the formation of new ions, molecular products, and free radicals. In parallel with this process, some ions undergo neutralization, usually accompanied by the release of a significant amount of energy. As a result, the neutralization products are in a state of high excitation and are able to participate in further reactions, activating even the molecules of the initial substance, thus releasing energy [47, 48].

It has been shown experimentally that various chemical reactions occur on the clean surfaces formed due to the steel turning in polymer-containing LCTF.

Using the AES-spectroscopy method, the surface of the processed by turning iron and steel was investigated. Samples of armco iron and steel 45 (HRC 42–45) after turning (cutting edge BK8, cutting modes  $n = 8.3 \text{ s}^{-1}$ ,  $t = 0.8 \text{ mm}$ ,  $S = 0.1 \text{ mm/rev}$ ) were ultrasonic cleaned (7 min), followed by keeping in an inert atmosphere (30 min) at 125 °C, and then analysing the surface.

It was found that on the surface of iron and steel after turning in water with a polymer additive (PVC), signals of chlorine and carbon appear, indicating chemical reactions on the newly formed metal surfaces (Fig. 12).

The surfaces of various metals after turning in LCTF with a 1.5% PE additive (steel 45, Fe, Ti, Co, Ni, Mo) are approximately 70–80% coated with carbon, whose concentration continuously decreases as it moves away from the surface. At a depth of approximately 1000 Å, the chemical composition of the material becomes equal to the original material (Fig. 13).

We note that on the surface of the samples after turning in LCTF without a polymer, carbon was also detected, but its concentration is insignificant and amounted to only 8–10 atomic percent.

Fig. 12. The Auger spectra for steel 45 (HRC 42–45) after longitudinal cutting in the polymer-containing cooling lubricants on the surface (1) and at the depth of 18–22 nm (2) [21]

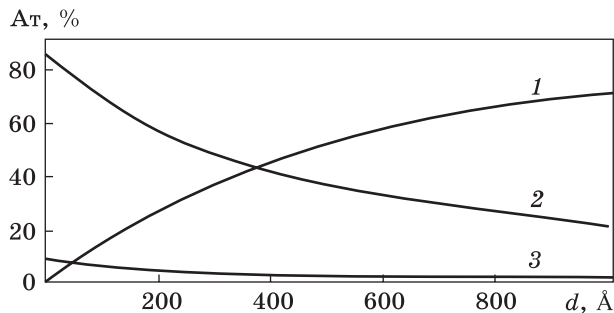
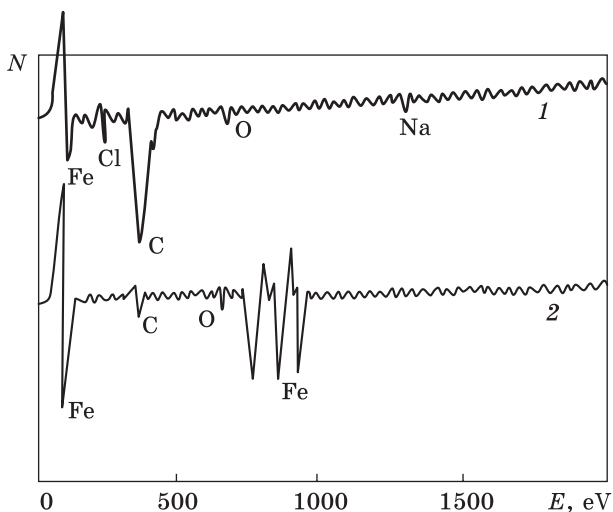


Fig. 13. The distribution of chemical elements in the steel 45 (HRC 42–45) surface layer after longitudinal cutting in the polymer-containing cooling lubricants, where 1 corresponds to Fe, 2 — C, and 3 — O [21]

Thus, an interaction is established between the adsorbent and the adsorbate on the surfaces of the reactor zone. In connection with this, it is important not only the chemical composition of the material surface and its ‘primary’ structure, i.e. type of symmetry and spatial arrangement of surface atoms, but also ‘secondary’, under the surface: steps, edges, and other microtopological features.

Even very pure metals are not completely homogeneous, since they consist of crystals of different sizes that come to the surface with different faces, with a lattice containing various defects. In this case, the smallest defects have increased free energy. Because of this, there is also a spatial separation of the metal surface from the intensity of the interaction with hydrogen and carbon that make up the gas mixture. The most heterogeneous surface will be observed in steel, which is due to its chemical and physical inhomogeneity, which arises as a result of mechanical and thermal processing, and in connection with the presence of various chemical inclusions. In the course of chemisorption on such surfaces, especially under high-temperature conditions, adsorbed atoms,

hydrogen molecules and molecules of hydrocarbon compounds become more active. Their structure is broken, and the bonds between atoms are weakened and torn [46]. According to the calculation results [46], the activation energy of this process is minimal (7 kcal/mol), if the length of C–C bonds is 3.5 Å. The speed and depth of the course of such chemical reactions depends to a great extent on the processes of heat generation during the chemical reaction, heat removal through the surface of the banks of the microcrack, and the supply of reagents from the outside. In the reactor zone there is a competition of heat release and heat removal and, apparently, in the case under consideration, there is an excess of heat release over the heat sink. Such reactions very quickly self-accelerate, acquiring an explosive nature. However, the thermal explosion does not occur due to the excess of the rate of death of the active centres (as a result of the collision of three particles) over the rate of their multiplication [48].

Based on the above-mentioned, it one can assume that because of catalytic reactions, a weakly ionized gas is formed in the reaction zone. Usually, this gas is a mixture of electrons of positively and negatively charged ions, neutral atoms and molecules. The resulting dissociated hydrogen is a carrier of a significant amount of energy, and when interacting with one another or with a metal, a large amount of thermal energy is released:  $H + H \rightarrow H_2 + 100 \text{ kcal/mol}$ ,  $Me-HH_5^+ \rightarrow Me + H + 100 \text{ kcal/mol}$ ,  $Me-HH_5^+ \rightarrow Me + H + 100 \text{ kcal/mol}$ .

The forms of interaction of ionized hydrogen with a metal have found wide application in industry. For instance, on this principle, ‘atomic-hydrogen’ welding and metal cutting are developed, when atoms or ions of hydrogen, in contact with the cold surface of a metal, reconnect to molecules, releasing previously absorbed energy. At the same time, the temperature on the surface of the metal reaches 3500 °C or more.

The process of formation of a weakly ionized gas in the gap space does not end there, and as the gas moves to the tip of the crack, the reaction deepens due to the interaction of the chemical elements with the flow of high-energy electrons emanating from the crack tip at the time of its growth.

### 6.3.5. Collisional Ionization and Homogeneous Catalysis

Exogenous emission plays a significant role in the formation of hydrogen plasma in the reactor area. In this case, electrons are emitted with a high intensity ( $6 \cdot 10^3$  pulses per minute) and with energy ( $10^2$  eV) [10] from the mouth of the crack are additionally accelerated by the electric field and acquire kinetic energy exceeding the ionization energy of the hydrogen atom (13.595 eV). This means that in the reactor zone conditions are created for impact ionization of hydrogen molecules and residual gas hydrocarbons, the model of which is presented in Fig. 14.

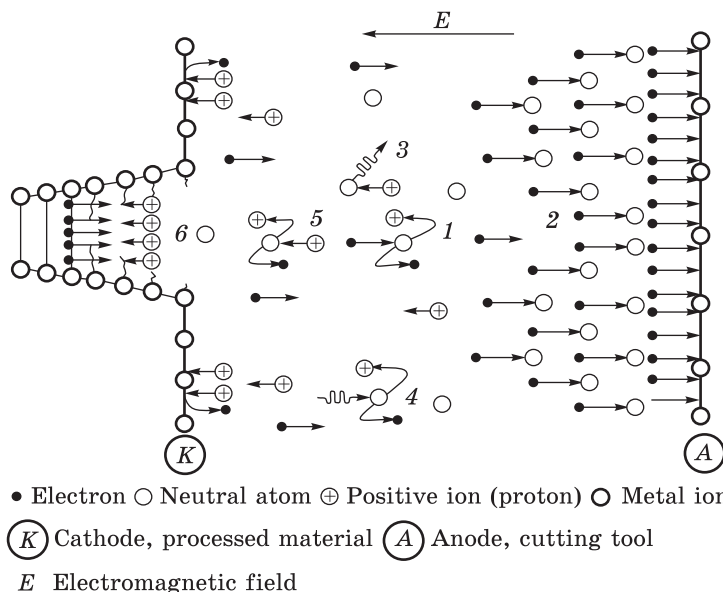


Fig. 14. Model of the impact ionization of hydrogen [16]

Departing from the top of a growing crack with high energy and further accelerated by an electric field ( $E$ ), electrons, colliding with neutral molecules and neutral atoms, ionize them, resulting in the formation of secondary electrons and positive ions (process 1). Positive ions will move to a concentrated negative charge, i.e. towards the cathode (crack tip). After the collision, the electrons gain energy, and the next collision will have four electrons and four ions. After the third ionization, there will be eight of them, after the fourth — sixteen, etc. (process 2). Therefore, the total number of electrons and ions will increase in an avalanche manner as the electrons move toward the anode (tool). Simultaneously, positive ions collide with neutral atoms and transfer them to an excited state, and their transition to the normal state is accompanied by the emission of a photon (process 3), which in turn can be absorbed by the neutral atom and ionized (process 4). If the formed positive ions under the action of the electric field acquire sufficient energy to ionize the hydrogen atom, the process 5 is possible [58, 59]. Simultaneously with the process of ionization of the gas, there is always an inverse exothermic process — the recombination process: positive and negative ions, positive ions and electrons recombine with the formation of neutral atoms and molecules. The processes of ionization and recombination go on as long as metal cutting takes place. However, for the formation of large masses of ionized matter in the gap space with the necessary velocity (process 6), which would provide an optimal manifestation of the mechanoplasma effect, a number of other physical



factors must be fulfilled. These include the processes of excess heat release over the heat sink through the surface of the slit, heat flows from one part of the reactor to the top of the crack, the supply of reagents from the outside and the outflow of products to the destruction zone, the presence of an electric field, etc. All this makes it possible to believe that since the manifestation of these factors depends on type of machining, cutting modes, properties of the processed metal, and finally, the most important, on the composition of LCTF, then it is possible to determine an optimal mechanoplasma effect by the experimental way only.

In practice, all the foregoing means that in a narrow zone in front of the crack tip, where the forces of the interatomic bonds of the deformed solid are rearranged and broken, a simultaneous action of mechanical load and additional thermal energy is observed on these processes. In this regard, due to the parallel course of mechanical and thermal effects on the stability of a solid, there will be an increase in the probability of rupture of the binding forces between solid-state ions in comparison with the probability of their recovery and, as a consequence, a decrease in its strength.

Thus, according to the proposed model, a gas mixture, formed as a result of multi-stage chemical reactions of the polymer component of the initial LCTF, enters the reactor zone and accumulates. In connection with catalytic reactions of chemical elements of the gas mixture on new surfaces of the reactor zone, as well as 'collisional' ionization, the concentration of electrically charged hydrogen particles in the reactor zone will increase with the formation of hydrogen plasma.

More specifically, we have understand a plasma only as strongly ionized gas, which can appear due to the electron-ion interaction. Apparently, two processes run parallel in the reactor zone: first, with the formation of a highly ionized gas (plasma), and the second, with the formation of a weakly ionized gas, when electrons collide with neutral hydrogen atoms. Concerning this, the resulting mixture of electrically charged hydrogen particles can be only conditionally called a plasma.

Thus, we believe that the change in the physicomechanical properties of a deformed solid in various media have to be considered as a result of the contact interactions of a hydrogen proton, which possesses an electric charge, with a new electrically-active real solid structure, which arises after the mechanical impact on the material.

## **7. Transport of Electrically Active H Particles to the Destruction Zone**

In the process of penetration of protons to the focus of destruction, there are three basic stages to be distinguished: the transfer of hydrogen along the gap to the surface of the crack tip, penetration through the

surface, and displacement into the depth of the metal, that is actually a diffusion.

The proposed model in the form of a relative idealization of the phenomena, taking place in the reaction zone, suggests that a high concentration of negative electric charge in the ultramicroscopic areas directly in the zone of overcoming the adhesion between atoms causes their stronger interactions with protons, selectively 'sucking' them from the hydrogen plasma into the reaction zone.

Approaching the surface, a part of the protons can recombine when colliding with electrons as well as because of the interaction with metal ions and structural defects emerging on the surface. In all these cases, thermal energy is released [22, 56].

The conditions that are created in the reaction gap focus the flow in a narrow cone; its vertex is mated to the surfaces near the crack tip (Fig. 1). Therefore, in the region where the material becomes not homogeneous, the growth of the streamer can occur along the channels of the microcrack grid, as well as along the grain boundaries, subgrains and dislocations. One part of the proton flux recombines when approaching the crack tip when it collides with the electron beam. Surface traps capture another part of the protons. The remaining part of the proton flux moves over the crystal, passed through the surface at the tip of the crack to the surface of the cut layer, and is captured by the volume traps. When contact interactions of protons with the real structure of the deformed solid, significant thermal energy is released. A pulsed thermal flare on the surface where the largest number of capture centres is concentrated and the maximum proton flux intensity can cause heating of the surface layer and its melting to a depth of several tens of the crystal lattice parameters of the given solid. Due to heat transfer, the temperature of the surface at the tip of the crack propagates to the surface of the cut layer. Volume thermal flashes of temperature are local in nature as a thermal shock in a microvolume, a metal where pores, surfaces, boundaries, impurity atoms, dislocations and other traps are concentrated.

The topography and the speed of the proton transfer through the surface are unequal in all its sections. As already noted, this is because the state of the surface of a solid depends on its chemical composition and surface defects.

It is important to note that the surfaces of linear lattice defects and the boundaries of grains, phases and twins can be regarded as surrounded by a thin layer of electrons, giving them a negative charge. Therefore, real crystals whose surfaces emerge on the crack cavity and its apex are actually permeated by ways of increased mobility that can be modelled as negatively charged independently operating gaps interacting with positively charged hydrogen particles.

Therefore, the structural and physical state of the newly formed surfaces determines not only the 'points' and the strength of the proton contact interactions, but also local parts of the surface that determine the predominant 'entry' of protons into the metal and its further displacement in the volume.

When protons 'come in' the solid, they must pass an imperfect transition region between the surface and the volume of the metal. In this region, a part of the protons will be captured by traps and recombined according to a known scheme with the formation of atomic hydrogen. A thermal flash also accompanies this reaction.

Another part of the protons will pass through the transition region without any obstacles and continue moving along the cut off layer of the workpiece, where some of the protons will also be captured by the traps and recombined with the formation of atomic hydrogen. Thus, in the near-surface transition layer, at the crack tip, a new gas mixture is formed, consisting of conduction electrons and atomic hydrogen, in which the electrons are surrounded by a 'cloud' of atomic hydrogen. The resulting value of this formation will exceed the electron charge and therefore the electron, together with the surrounding 'cloud' of hydrogen, will be attracted to another free electron [24]. The conduction electrons and hydrogen actually become 'tied' to each other and (under the action of an external electric field) continue move together along the cut-off layer. Thus, at the tip of the crack conditions are created for the manifestation of the known effect of the electronic 'wind', due to which the rate of movement of hydrogen will greatly exceed the speed of the process of destruction. This assumption is confirmed by the following experimental data.

Steel-45 was drilled in water and water with an additive (1.5%) of polyethylene latex. The obtained holes were drilled in the air with a drill, its diameter was 1 mm larger than the diameter of the hole and their surfaces were analysed. After obtaining the initial hole and reaming it, a method of temperature programmable heating of the samples placed in a vacuum volume with simultaneous mass spectroscopic recording of the evolving hydrogen was used to detect hydrogen in the material. It was found that the mass-spectrometric signal characteristic of hydrogen gave samples, both after drilling in water, and in water with the addition of a polymer. However, the peak of the hydrogen signal while drilling in water with the polymer was many times higher than the peak of the hydrogen signal, which gave the samples after drilling in water without a polymer additive, which indicated chemical transformations of the polymer with the formation of a large concentration of hydrogen. It is important to note that in the spectrum after drilling the sample in water with polymer addition and then after its reaming in air, in contrast to the material that was treated in pure water, a hydrogen peak with an

intensity equal to 10% of the initial value was detected. This means that during the machining of the metal, hydrogen managed to diffuse from the surface into the material at a distance of at least 0.5 mm. The rate of such collective movement of electrons and hydrogen atoms will decrease in comparison with the velocity of electron movement by a factor of  $(m_{H^+}/m_e)/2$ . However, it will still exceed the rate of crack growth, which means that in the case under consideration hydrogen arrives in time overcoming the adhesion between the atoms of the solid, that is, in the centre of destruction.

Thus, hydrogen will not only interfere with the acts of restructuring and bursting of the forces of interatomic bonds, but also advancing the growing crack to influence the properties of the material that has not yet been deformed. Therefore, with the next turn of the workpiece, the properties of the cut sheet will differ from the original ones.

As already noted, by analogy with electrons, protons under the influence of an electric field also pass through an ideally regular crystal lattice freely, without scattering at the nodes. However, scattering of proton waves and the associated resistance of the material to the motion of protons nevertheless arise if scattering centres exist in the crystal lattice: distortions in the correctness of the crystal lattice, pores, boundaries, impurity atoms, and other defects [19]. Since all real solids contain point, linear or surface defects, which are traps for hydrogen [25], in the process of ambipolar diffusion, from the stream of co-moving electrons and hydrogen, the latter will be captured by defects, i.e. traps. The capture process becomes possible when the state of the metal atoms allows keeping the protons by its electric field, which exceeds the strength of the external electric field. Most researchers believe that the capture energy is large enough and amounts to several tenths of electron volts, which greatly exceeds the strength of the electronic 'wind' [25, 60].

It is known that from the whole variety of hydrogen traps the most effective are the pores [12], which are formed in the results of proton interaction with each other, due to either the clustering of vacancies, or mechanical, thermal, radiation and other metal processing. Structural materials even in the initial state contain pores that are of technological origin and appear due to of different effects on the material. The total volume of pores can reach tens of percent of the volume of the material [25]. It is reasonable to assume that the presence of pores can significantly affect not only the ability of the material to accumulate but also to pass hydrogen. This assumption is justified by the fact that reaching the pore surface, hydrogen protons recombine with other protons or with (conduction) electrons and can diffuse into the cavity, where they will accumulate in the form of a molecular gas, and then dissociate on its surface and dissolve in the material. Therefore, the amount of hydrogen

in the cavity is determined by two flows through its surface: the diffusion flux from the material into the cavity and the desorption flow from the cavity to the material. It is likely that during the cutting process, due to the continuity of the diffusion process, the accumulation of hydrogen can occur in the pores.

Consequently, there is a reason to believe that when cutting in the 'metal-hydrogen' system, there are two types of traps: traps in which hydrogen accumulation is possible (clusters, pores, i.e. volume defects) and traps by which hydrogen is captured but not accumulated in them (grain boundaries and subgrains, vacancies, impurity atoms, dislocations, i.e. point and linear defects).

Generally, all other conditions being equal, the parameters of hydrogen transfer are related not only to the presence of the electric field and the properties of the metal, but also to the features of the electroactive microstructure [21] in the area of the opening of a new surface arising during the machining of the material. In many respects, the same circumstances determine the intensity of the physical-chemical processes in the zone of destruction, which in turn reflects on the resulting effect — the workability of the material.

## **8. Some Aspects of the Destruction of Metal with a Combined Effect of Mechanical and Thermal Energy**

It becomes clear that under the influence of high temperature in the cutting zone and the participation of various catalysts, hydrocarbon heterogeneous mixtures (LCTF) decompose first to the level of nanoscale compounds, and then, after their separation, to the formation of the elementary substance constituting the hydrogen plasma. The reliable results of the research show that it is hydrogen in its active forms, due to its unique properties, plays a major role in the processes of metal deformation and deformation in surface-active media.

The study of the interaction of hydrogen with metal is one of the most interesting directions in the field of physics, physical chemistry, solid-state physics and materials science, both from the point of view of fundamental research and applied research. Already established patterns formed the basis for the various innovative technologies being developed. The use of hydrogen in the machining of metals is another example of the new use of hydrogen in engineering.

Despite the annual growth of research in various aspects of this direction, there is an abundance of contradictory assumptions, hypotheses and theories. In our opinion, this is because most of them mainly based on phenomenological representations, limited by a lack of reliable experimental data [22, 56].

The fact that hydrogen, the simplest of all chemical elements, plays a decisive role in changing the mechanical properties of a metal when it

breaks down in any technological hydrocarbon surface active liquid, poses the task of further studying the patterns of its influence on deformation and fracture processes. Such studies are of exceptional importance, both in the development of methods for accelerating the destruction of solids, as well as methods for protecting metal structures from the negative effect of hydrogen on their operational durability.

The interaction of hydrogen protons with a metal in the area of its destruction is a complex process involving various reactions occurring on external and internal surfaces, at the boundaries of grains and subgrains, as well as the interaction of hydrogen with dislocations, solid-state atoms, nonmetallic inclusions, etc. For instance, when protons interact with metal ions, several reactions can occur. There are reactions that cause or do not cause structural changes, which are not leading to formation of chemical compounds on the internal surfaces, and reaction with formation of compounds, as well as reactions, in which molecules of a chemical compound are immediately formed on the internal surfaces and then immediately turn into a gas phase [24, 25].

For multiphase alloys, the situation becomes even more complicated, since a preferential interaction of the protons with individual phases of the metal is possible [24].

These problems are repeatedly complicated in the process of cutting, when the contact interactions of electrically active hydrogen particles with the electrically active real structure of the material continuously change and proceed under extreme conditions.

In this work, we try to elucidate some potentially possible mechanisms of contact interactions of hydrogen with external and internal surfaces at a time of their formation, i.e. with defects of the crystal lattice, with an expressed influence on these processes of the various quantum effects accompanying the destruction of metal in the process of cutting.

During machining by cutting, various contact interactions of electrically active hydrogen particles with the electrically active real metal structure formed during deformation and fracture occur throughout the volume of the elastically plastic deformable metal layer before the crack tip. The nature of the manifestation of such processes has its own peculiarities, and it is associated with differences in the interaction of hydrogen with the real structure of the material, which varies at all stages of its deformation and destruction. At the same time, the diversity of these interactions and the form of their manifestations ultimately lead to the same result: the simplification of the processes of deformation and destruction. The reason for this is the parallelism of the thermal and mechanical stability of solids [60].

Therefore, the released thermal energy in the interaction of hydrogen with a metal affects the processes of deformation and fracture similarly

to mechanical loads, i.e. will facilitate their flow. For example, because of the interaction of hydrogen with atoms of the elements dissolved in it, particles of precipitates, solid phases and sessile dislocation loops, the obstacles to the movement of dislocations are eliminated, thereby reducing the level of structural hardening [16]. Such processes contribute to an increase in the velocity of displacement of dislocations and facilitate or, in general, eliminate the energy costs for their escape to the internal surfaces, i.e. increase the rate of plastic deformation [10].

We sure that any argument about the influence of hydrogen on the process of metal destruction during cutting can be formed only based on modern ideas about the mechanism of the reaction of a material on the presence the stress concentrators. Sharp cracks are one of the examples of the concentrators, since the microcrack is a source of subsequent destruction as in fragile, elastoplastic, and plastic destruction of metal. The kinetics of the process of crack propagation is connected with the foundations of the theory of strength and destruction of solids, since it represents extremely important information about microscopic and phenomenological features of the mechanism of destruction.

Therefore, the development of ideas about the mechanism of the influence of hydrogen on the cutting process (or, generally, on fracture) can be carried out by revealing the role of hydrogen at various stages of the manifestation of individual mechanisms of the fracture process in the local area before the tip of the crack. This concerns all the process: from the initial stage of loading (the development of elastic deformation) to the final one (propagation of the fracture).

The difficulty in solving this problem is because there are countless varieties of material destruction at the tip of the crack. As Cottrell notes, atoms can be simply pulled off from each other, as with a purely fragile fracture upon stretching. They can slip one by one, as in various cases of plastic destruction. In fragile crystals, a crack can go along certain atomic planes, but it can jump from one grain to another, spreading in each along certain planes, or to circle the grain and go along their boundaries, or spread in some more complicated way, causing parts of the path plastic deformation, and other parts of the material are fragile. In the two-phase materials, the crack can spread fragile in one phase and cause fluidity in another, or bypass one of them, or, finally, both can go along weak interfaces [8].

These are just some of the possible types of destruction. Each of them has its own stress value at a certain area along the direction of crack motion, which is necessary for crack growth during fragile fracture and for the onset of simple shear during plastic cracking.

We have to keep in mind, however, that in many cases it is impossible to draw a clear line between the different variants of destruction and exclude the existence of a series of other mechanisms of destruction.

Therefore, in the metal–hydrogen system, there is also a variety of processes of interaction of hydrogen with the real metal structure at a given destruction, which ultimately affects the degree of degradation of the mechanical properties of the metal.

Despite the existence of a connection between the different levels of the description of the mechanical behaviour of the metal for various types and rates of deformation, the processes of fracture during cutting have their own distinctive features. Moreover, the specificity of the mechanical behaviour of the metal during cutting must be shown at the level of the piercing connections of the macroscopic description of phenomenon is especially important when considering the various contact interactions of protons with the material structure at various distances from the top of the growing crack, when the interacting ‘metal–medium’ system changes.

Shaping of the detail during cutting occurs by removing chips from the workpiece when the force applied to the front surface of the tool creates a stress in the shear layer that exceeds the resistance of the material in the shear plane. At the same time, the chip-forming process is accompanied by the destruction of only a small part of the material of the cut-off layer. Although the remaining volume of the localized area of the solid lying below the cut line also suffers significant plastic deformation, but the stress intensity factor that controls this plastic zone is not sufficient to destroy the material. Nevertheless, the residual stresses distort the crystal lattice near the glide planes and thereby create obstacles to the movement of dislocations, which make the movement of dislocations increasingly difficult. The accumulation of dislocations in strong obstacles results to the appearance of high stresses as well as high strain hardening. If these stresses cannot be removed by local plastic deformation, then a network of microcracks may appear. Even in cases where microcracks do not appear, these areas of the material are characterized by extreme heterogeneity caused by point, linear, surface and volume defects. The resulting defects in the local volume of the plastically deformable metal are good traps of hydrogen. Because of various interactions with them, recombination of protons will occur, as a result of which thermal energy is released and atomic and molecular hydrogen is formed. Thus, in contact with the front surface of the cutting part of the tool, the material which properties are significantly different from the properties of the workpiece. Thus, the properties of the material entering the chip formation zone will differ substantially from the properties of the preform. In this regard, it is necessary to emphasize the specific nature of hydrogen influence on the process of destruction. In this case, it is caused by various interacting ‘metal–medium’ systems in connection with changes in both the structural state of the processed metal in the cutting zone and the



interaction of protons with the material that is changing in connection with this. Taking into account the above, let us consider the situation that is creeping in the focus of destruction.

In the considered model, around the vertex of the reaction gap, there are a number of areas, each of which is an interacting 'metal-medium' system, and gives the boundary conditions for the next. At large distances from the top of the reaction gap to the initial boundary of the chip formation, the material is in the elastic area and the concentration of proton traps in it approximately corresponds to the material of the preform. Closer to the vertex of the gap, a concentration of stresses causes plastic deformation to be limited to this chip formation. In this area, a large number of defects-proton traps arise in the material. Finally, the area where the material becomes even more defective and heterogeneous: the pores expand and merge near inclusions and other irregularities, the appearance of pores from the intersection of dislocations, the emergence and growth of submicroscopic cracks, the formation of slip bands, and a whole series of point, linear and surface defects of crystal lattices. All this means that as the material approaches the top of the crack, the number of interacting elementary particles in interacting systems will increase; i.e., the number of sources of heat release will increase, and hence the amount of heat released in the chip formation zone until the near-surface layer melts.

It is also important to note that the effects of atomic and molecular hydrogen, which are formed due to the recombination of protons, are also possible on the processes of deformation and fracture.

Consequently, depending on the specific nature of the particular interacting system and the external conditions imposed on these processes in which they occur, the acceleration of the processes of deformation and destruction of the metal under the influence of hydrogen can have either an insignificant or, on the contrary, a preferential or even exclusive development.

As already noted, the effect of hydrogen on various mechanisms of the fracture process is due to its interaction with the real structure of the metal. This will first reflect on the reaction of the material in connection with the presence (or newly arising) of sharp cracks in it in the presence of hydrogen, and then on the final form of these effects — a significant decrease in the total forces acting on the cut material layer. In the phenomenological aspect, this qualifies as an improvement in the parameters of the technological characteristics of the material, i.e. improve its machinability.

The destruction of metal at the cutting in LCTF is, generally, a quasi-fragile process. Therefore, when the opening of a fast crack occurs due to the direct breaking of bonds in its mouth, which is typical for fragile fracture, the surface effect of the interaction of ionized hydrogen will have a major effect on the change in the strength of the material.

Conversely, when the plastic character of the fracture predominates, the influence of protons in the bulk of the metal increases in the zone of maximum stress concentration at the crack tip. Therefore, if the rate of energy supply of the crack can be so great that it compensates for the costs of plastic deformation, then the fracture will have all the visible features of fragile. In this case, the surface processes of interaction of ionized hydrogen with the metal at the tip of the crack will have a decisive influence on crack growth, and hence on the energy consumption of the cutting process. Therefore, at the cutting machining of the high-strength, hardened steels in hydrogen-containing media, the influence of surface processes of interaction of the medium becomes more pronounced.

After the 'penetration' of the proton into the metal, some of the protons, due to the considerable electric forces of mutual attraction with ions, can be retained by the electron shells of the metal atoms. For example, even one  $\gamma$ -iron atom can bind up to 5 hydrogen protons [20, 21]. This means that the ability of the iron atom to retain the valence electron is weaker than the proton's ability to attach an electron. As a result, the proton of hydrogen attaches an electron and forms an atom, and the reaction proceeds with the release of thermal energy.

Thus, in the first stage of the interaction of the proton in the cut-off layer, a single electron is rapidly transferred from the electron shell of the iron atom to the hydrogen atom, that is, the known unique ability of the proton to polarize the electron shells of the iron atoms interacting with it. Because of deformation of the electron cloud of the iron atom, the binding forces between its atoms decrease and such group interactions are displayed at the level of the energy costs of the process of metal destruction.

The formed hydrogen atom, being electrically neutral, most likely can penetrate into the interatomic spaces of the lattice, and replace vacant places in it. Consequently, it can be assumed that each embedded hydrogen atom will cause the metal atoms to shift from their equilibrium positions, and the resulting distortions of the crystal lattice will lead to a number of changes in physical properties and a decrease in the strength of the metal [25, 32]. For example, according to the x-ray data, the complex effect of the hydrogen atom, as a result of its interaction with the iron atom and the formation of a solid solution, causes an increase in stresses of 8–10 kg/mm<sup>2</sup>, which in order of magnitude approximates the strength characteristics of iron–carbon alloys (32–60 kgf/mm<sup>2</sup>) [25].

Another type of hydrogen capture can be carried out by metal impurities, especially embedded atoms of N, C, and Ni, i.e. elements specially introduced into the iron to improve its strength and electrochemical properties. Such interactions are fairly expressed and their energy is usually of the order of 0.2 to 1.5 eV [25]. The high capture

energy indicates the possibility of chemical reactions between the proton and the impurity, which neutralizes the effect of impurities on the properties of the metal, i.e. will reduce its strength and corrosion resistance in the path of a growing crack.

In addition to contact interactions with metal atoms, impurity atoms, nonmetallic inclusions, and other point and volume defects, atomic hydrogen can interact with one another to form molecular hydrogen, and thermal energy  $H + H \rightarrow H_2 + hv$  is also released.

It is generally accepted that the plastic deformation and phase transformations become possible or are accelerated by the motion of dislocations [10]. Consequently, to what extent and how hydrogen will affect the dislocation displacements in a particular crystal, the limits of its elastic and plastic deformation under the action of the applied force largely depend, as well as the stress that leads to the destruction of the crystal.

A whole series of special studies has been and currently are carried on the mechanism of the hydrogen effect on the motion of dislocations. In most of the suggested hypotheses and theories, the role of hydrogen in the same processes and phenomena is interpreted in different ways, depending on the concepts developed by the authors [6, 13, 16, 24, 30, 36, 55–57]. For example, supporters of the mechanism of interaction of hydrogen with dislocations, built on the theory of brittle fracture developed by Cottrell, argue that the presence of hydrogen leads to an increase in the brittleness of all metals without exception [12, 19, 25, 36]. At the same time, it was shown in [14] that hydrogen unlocks dislocations and facilitates the plastic flow of the metal. It is possible to carry out other examples, when the mechanisms of the processes proceeding at the final stage of destruction to the same results are interpreted ambiguously.

It is important to note that the above examples of chemical reactions in the cutting zone proceed with the release of a large amount of thermal energy. As the number of substances participating in the reactions increases, the intensity of the dissipating heat increases and, as might be expected, the temperature in the local volume of the processed material increases in parallel. Consequently, during the cutting process, different interactions of hydrogen (with its active particles and deformed metal) are accompanied by peculiar thermal microexplosions, which lead to a ‘group’ heat release. Such microexplosions, accompanied by the release of heat, will lead to an increase in the internal energy of the system, which will help to reduce the total energy needed to destroy the solid.

Upon contact of the solid and gas phases, the reaction of hydrogen particles on both internal and external surfaces proceeds through their recombination. Formed H atoms are chemisorbed on the surface:  $2H + Fe \rightarrow H_2 + Fe^* + hv$ ,  $Fe + H_2 \rightarrow Fe - H + H + hv$ , where  $Fe^*$  is an excited atom.

Thus, the change in the processes of deformation and fracture during the cutting of metal in LCTF occurs because of the contact interactions of the active forms of hydrogen formed as a result of the multistage transformations of the initial surface active medium with the formed structure of the material resulting from the formation of a new surface.

Let us consider schematically some variants of the causes that can cause a decrease in the mechanical properties of the metal in connection with its interaction with hydrogen in the zone between the initial and final boundary of the chip formation.

As the metal is separated during cutting, we assume that this process involves fracture with the formation and development of cracks. Note that this concept of the cutting process is not generally accepted; in some works there are doubts about the presence of a crack in front of the cutting tool [52]. Currently, the results of the studies do not allow clear defining the set of characteristics that uniquely determine the mechanism of destruction. At the same time, the author is a supporter of the following ideas about the process of destruction.

Now, there is no doubt that plastic deformation is a constant companion for the destruction of a solid during the cutting process. Only its role at all stages of destruction changes: if plasticity is necessary for the initiation of cracks, then its role is much more modest in the propagation of cracks [13]. From the physical point of view, when cutting, the external force is applied very quickly and a moving impulse or strain wave that can move inside the solid must appear in the substance [65]. Such a process of destruction takes place and has been thoroughly investigated in the explosion of an explosive charge when there is a huge pressure pulse that arises inside the solid and creates tearing stresses, fragile and plastic deformation of the solid parts. It can be assumed that something similar is observed when the wedge of the tool is pressed into the metal and the metal is destroyed due to compression and tension waves. The basis for this assumption is the enormous rate of deformation of the metal ( $10^3$ – $10^6$  1/s or more) when the tool wedge is pressed into it, under the pressure developed on the surface at the contact point of the treated metal with a tool of 200 kgf/mm<sup>2</sup> or more. In this regard, we can assume that the resulting stresses on the contact area of the tip of the wedge with the metal exceed the value of the dynamic yield strength and two waves propagate in the material-elastic and plastic. The propagation of the shock wave and the compression of the material in this case will be accompanied by the appearance of tangential stresses in it and the formation of radial submicroscopic cracks (Fig. 15). Their formation, apparently, is the result of the interaction of dislocations at the initial stage of plastic deformation, and the formation of a microcrack of an atomic scale due to the slip of material

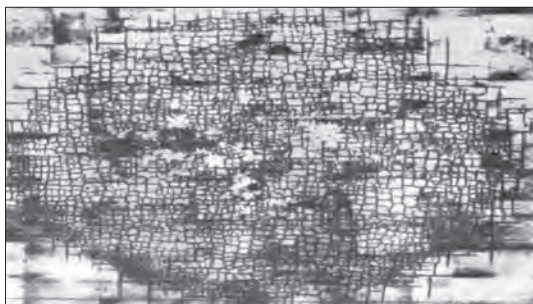


Fig. 15. Affected area of LiF(100) crystal after the plasma shock [13, 65]

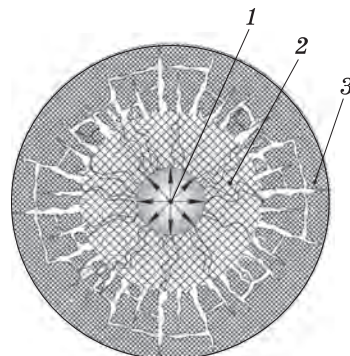


Fig. 16. The distribution of cracks after the thermal impact, where 1 is the chemical transformation flash zone, 2 — the material crushing zone, and 3 — the distribution of cracks in the cracking fissuring zone [13, 65]

layers relative to each other. A compression wave that approaches the outer surface of the chip formation zone will move and cause the separation of the cut-off metal layer. After reaching the surface, the compression wave reflected from it will follow in the opposite direction as a stretching wave and cause the formation of annular cracks (Fig. 16).

As regards the effect of hydrogen plasma on deformation and fracture processes, here we consider two limiting variants: when the plasma flux interacting with the metal has the maximum and minimum effect. In the first case, a high density characterizes the plasma flow and (because of the contact interactions of the protons with the metal surface) a large thermal energy is released. Significant heat pulses transmitted to the narrow near-surface layer increase the thermal motion of ions and increase the temperature of this zone before melting.

At low flux densities, the resulting temperature on the metal surface may not be sufficient to melt it. Mono believes that the effect in this case is achieved in connection with the decrease in the shear modulus, which, as is known, decreases with increasing temperature.

Another part of the proton stream moves through the volume of the material freely through the crystals, but is trapped. There are also processes associated with the recombination of the proton as a result of which thermal energy is formed. In this case, the heat pulse causes processes similar to pressing the tool wedge into the metal: a wave of compression and tension, a powerful sliding and interaction of dislocation bands, the generation of a large number of radial and annular cracks (Figs. 15 and 16).

At microscale, in the mechanoplasma processing of the metal, both the viscous and fragile nature of the destruction will be observed, and

there cannot be a rigid boundary between these processes [13]. The leading role of this or that kind of destruction is determined by the processing parameters, physical and chemical properties of the metal, as well as by the intensity of the manifestation of the plasma effect, which depends on a few factors. (i) The rate of formation and timely supply of the hydrocarbon gas mixture to the reaction gap, its concentration and composition. (ii) The rate of chemical transformation of the gas mixture into hydrogen plasma. (iii) Displacement vector and diffusion rate of ionized hydrogen, both to the top of the fracture crack, and directly to the zone of overcoming the adhesion between atoms. An extremely important role in increasing the thermal effect of the reaction is played also by the composition of the initial surface-active medium (LCTF).

The combination of the factors mentioned above determines not only various variants of destruction and energy consumption for processing, which are reduced due to synergistic action on the material of external mechanical energy and internal thermal energy.

Such processes are most pronounced directly in the area of overcoming the clutch between atoms in front of the crack tip, where the increase in the internal potential energy of the crystal lattice, due to thermal flares, promotes the solidification (recrystallization) of the material. An increase of temperature in this area commonly leads to the increase of the velocity of dislocations, decrease of the yield strength and length of the yield plateau, decrease of the concentration of stresses around the accumulation of dislocations, elimination or reduction of the number of obstacles to the displacement of dislocations [10]. In addition, due to temperature activation, there is a possibility of changing the mechanism of destruction. For example, when intercrystalline bonds are weaker than the grains itself, then the destruction of the material can occur along the boundaries of the grains, not inside them [63].

Here, it is important to note the systematic studies of the influence of high-speed methods of heating the metal on its properties, which allowed us to obtain the results of theoretical and practical significance for phase and structural transformations in the alloys with impulse heating [65]. These studies give reason to believe that similar processes can occur in the metal and in the heat flare during the cutting process in LCTF.

In connection with the above, the processing of metal by cutting in different LCTF should be considered not as a purely mechanical process, but as mechanoplasmic. Its implementation involves the use of energy stored on the juvenile surfaces of the reaction zone, which, together with exoelectronic emission, carries out self-acceleration of the chemical transformations of the medium. Such processes proceeding in a narrow zone with an expressed polar effect greatly facilitate the deformation and destruction of the metal. The effectiveness of such treatment is repeatedly increased because of the introduction of additives of high-molecular

compounds into the composition of LCTF, which give a large concentration of hydrogen in the chain of pyrolytic transformations [28, 44].

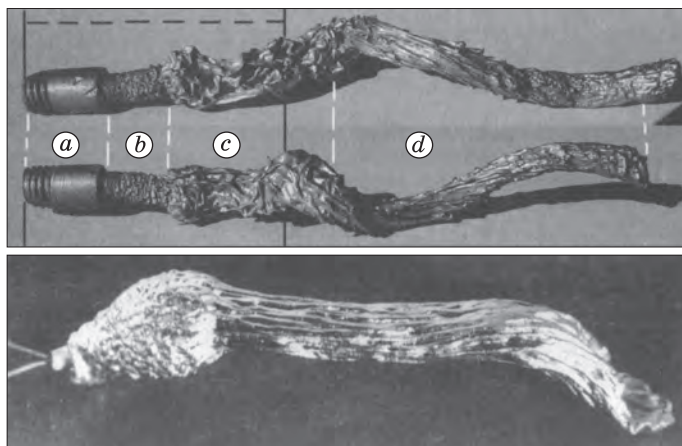
Thus, it should be noted that the facilitation of deformation and material destruction processes in surface-active LCTF is due to the fundamental phenomenon of nature — the thermal movement, the additional impulse which gives rise to the release of heat due to recombination of the proton. In the most pure form, such a mechanism is implemented with brittle fracture, and with other types of destruction, it begins to accompany the relaxation processes, which, as the temperature rises, play an increasingly important role.

It is perfectly clear that at the cutting, when the destruction of metal occurs at huge speeds, relaxation processes cannot play a major role. Therefore, according to the proposed hypothesis, H protons ‘prepare’ the basic changes in the physical and mechanical properties of a metal deformable in a surface-active medium. The main thing is that these processes are accompanied by the release of a large thermal energy, which is localized mainly in the region of structural defects in metal (in traps) and can increase the temperature of this zone to melt. In the same ultramicroscopic regions, the limiting concentration of mechanical energy is localized. Therefore, the combined effect of mechanical and thermal energy increases the processing efficiency. This means that the loss of the solid of stability with the joint action of mechanical energy and the environment occurs because of the implementation of the mechano-plasma effect.

It is important to note that the proposed model is in accordance with the previously stated positions that melting is the destruction of the crystal due to the thermal motion of the ions, and the mechanical destruction is the melting caused by the action of mechanical stress [60].

The fact that when the proton is discharged, there are thermal micro explosions, resulting in a temperature in the atomic groupings of the metal that can significantly exceed the temperature of its melting, is confirmed by the results of studies on the effect of hydrogen on the behaviour of the iron during thermal cycling in hydrogen [61].

Study of the metal behaviour during the thermal cycling in a molecular hydrogen environment revealed that hydrogen under these conditions reduces the melting point of metals and reduces the yield strength by more than three orders of magnitude. The analysis of some studies by the authors of this discovery shows that the iron melting really does occur when the temperature of the hydrogen filled-in test chamber is about 600 °C below its melting point. The authors explain this as the formation between the growing and disappearing crystals of the transition layer supersaturated by hydrogen, because of the restructuring of the crystal lattice and leading to the spontaneous deformation of metals in the solid state.



*Fig. 17.* The Armco-iron samples after thermocycling (950 °C) [61, 62]

From our point of view, the observed ‘effect’ of lowering of the melting temperature of metals is actually caused by the following processes.

Microcracks, the cavities of which have catalytic activity occur during thermocycling (heating-cooling) process on the surface of the sample. The initial temperature in the chamber accelerates the process of dissociation of molecular hydrogen on these surfaces. The formed protons diffuse into the volume of metal, caught in traps in which their recombination takes place, with the release of thermal energy.

Consequently, it can be assumed that thermocycling in the material results in thermal microscopic explosions and a large amount of heat is released due to the reaction. At the same time, the ultramicroscopic regions of the material warm up and dissipate heat in the adjacent region. As the number of reactions increases, the temperature rises and the process of melting the material begins. Over time, the amount of heat absorbed during the reaction increases, the fusion region expands, involving an increasing amount of material in this process.

Thus, the melting of iron, both without hydrogen and with hydrogen, always occurred and occurs at 1539 °C. In the experiment, this temperature in the material was achieved due to the sum of the external heat source causing heating of the material up to 950 °C and the internal, adding the temperature first locally, and then in the entire volume of the sample. That is why, in the photographs of the samples after the tests at a temperature of 900 °C, there are places of iron melting in the local parts of the material (Fig. 17).

We can assumed that exothermic processes, which accompany chemical reactions during the interaction of hydrogen with deformable metal, as well as the plastic deformation, increase the temperature of the material in front of the crack in the narrow zone along the slip plane,



facilitating the breakdown of the interatomic bonds and the most energy-saving costs on the destruction process.

In the cut-off metal layer, hydrogen interacts not only with electrons and with various linear defects in a crystal lattice. Protons can be captured and interact with bulk defects: permanent impurities, doping elements, non-metallic inclusions, etc. For example, as established in Ref. [15], hydrogen with impurities form  $\text{SiH}_4$ ,  $\text{Si}_2\text{H}_6$ ,  $\text{NH}_3$ ,  $\text{PH}_3$ ,  $\text{P}_2\text{H}_4$ , etc. In addition, hydrogen can interact with carbon contained in the solution ( $4\text{H} + \text{C} = \text{CH}_4$ ) and with carbon in the composition of carbides, destroying them ( $4\text{H} + \text{Fe}_3\text{C} = 3\text{Fe} + \text{CH}_4$ ). At the same time, a thermal effect, corresponding to 20 and 34 kcal, is formed [24].

Nonmetallic inclusions (silicates, alumina, silica, and titanium nitrides) present in the steel can also be trapped in hydrogen and its interaction with inclusions will result in the formation of collectors, fragile chemical compounds and various voltage concentrators. All these reactions also occur with the formation of thermal energy.

Thus, there is a reason to believe that the main role in facilitating the processes of deformation and destruction of metals in the LCTF belongs to hydrogen. Hydrogen acts as a part of the technological environment, H is ionized in the cutting zone, and its interaction with the actual structure of the strained metal, leads to the release of thermal energy, which reduces the stability material to its destruction.

By the way, the hydrogen introduced into the metal, affects not only its strength properties. At the same time, a whole set of physical properties of the material also changes. For example, this is manifested in the appearance of superconductivity in metals and alloys, where it is absent from hydrogen, or in a significant change in superconducting parameters [25]. Here, apparently, we are confronted with the problem of the general reorganization of the electron spectrum, the change in the electron impact and the phonon spectrum, and the change in a number of physical properties of metals of interest both for fundamental investigations and for their applications [25].

In the general case, the heat release associated with various interactions of the proton with the actual structure of the deformable metal generates the following processes and phenomena that affect its strength:

(i) increases the frequency of thermal vibrations of metal atoms, which leads to the activation of the process of plastic deformation and increasing the probability of breaking the forces of interatomic bonds;

(ii) facilitates the processes of sliding crystals;

(iii) reduces the friction voltage of the crystal and the voltage required to start the dislocation movement due to their release from impurity atmospheres;

(iv) increases the speed of displacement of dislocations and facilitates the overcoming of obstacles;

(v) reduces the level of deformation stress required for the movement of dislocations across intersecting sliding systems;

(vi) increases the probability of 'dragging' the proton into the electron shells of iron ions up to the deepest levels, which also leads to an increase in the occlusion of hydrogen;

(vii) causes a decrease in yield strength, reduces the yielding area and strain hardening strain, which promotes acceleration of the process of nucleation of cracks, their subcritical, and then subcritical growth.

In turn, some of the above processes and phenomena are capable of causing new changes in deformable material:

(a) increase the concentration of hydrogen in traps, as well as increase the probability of possible occurrence of hydrides and hydride-like formations, can contribute not only to the formation of clusters, but also their transition to the atomistically sharp crack;

(b) a variety of processes and phenomena caused by additional heat generation in the zone of restructuring and breaking of bonds can lead to a change in the nature of the destruction of the metal;

(c) significant heat pulses transmitted to the material as a result of recombination of the proton are capable of generating a powerful wave of stresses, and as a consequence, the formation of the microcracker grid and its development.

In this way thermal activation (in addition to possible metal fusing), as well as mechanical stresses, contributes to the formation of abundance of defects and small submicrocracks and creates a general favourable background for destruction. It is equally important that, although the high temperature weakens the solid, it, under certain conditions, can contribute to the relaxation and diffusion processes that 'heal' disorders in the solid.

This report confined itself to examining only the basic interactions in the metal-hydrogen system leading to a change, mainly, of the mechanical properties of the metal. Further identification of the role of separate mechanisms of such interactions on the background of physico-chemical processes arising because of metal destruction is a necessary step towards consciously changing the properties of the metal in order to obtain the necessary critical parameters and to create highly effective methods for the mechanical treatment of solids.

## **9. Influence of Plasma Effect on the Processability of Metal**

It is generally considered that the solid has a good processibility, if the cutting forces are insignificant at the machining this material and the wear-resistance of the tool and the quality of the treated surface are high. Consequently, the machinability is the technological characteristic of this material and the method of its processing. In this regard, the proposed method of mechanoplasma processing (MPP) can be found to

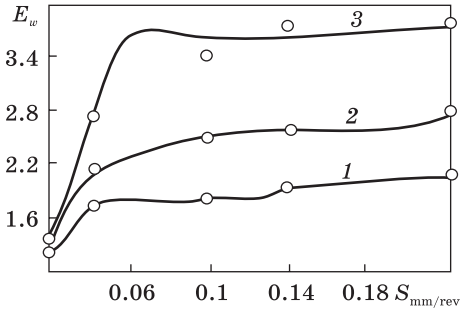


Fig. 18. The dependence of cooling lubricants efficiency coefficient when sharpening for tool life on the tool advance: 1, 2, 3 — steel of I, II, III groups, respectively [16]

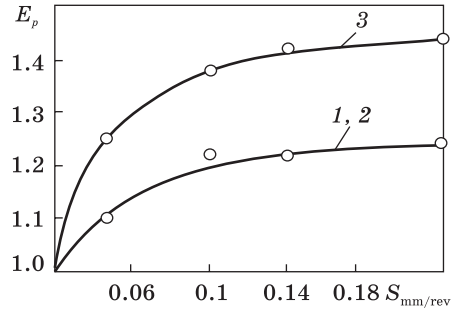


Fig. 19. The dependence of cooling lubricants efficiency coefficient when sharpening for power loss on the tool advance: 1, 2, 3 — steel of I, II, III group, respectively [16]

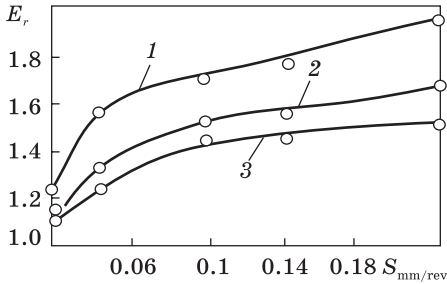


Fig. 20. The dependence of cooling lubricants efficiency coefficient when sharpening for surface roughness on the tool advance: 1, 2, 3 — steel of I, II, III group, respectively [16]

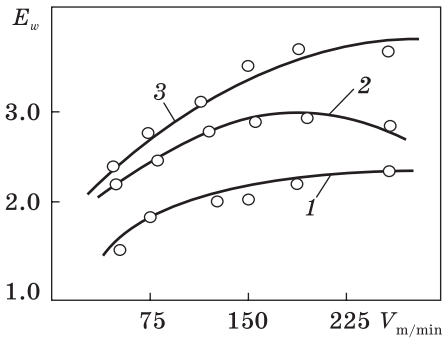


Fig. 21. The dependence of cooling lubricants efficiency coefficient when sharpening for tool life on the tool advance: 1, 2, 3 — steel of I, II, III group, respectively [16]

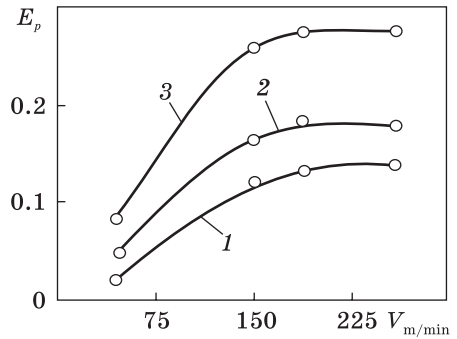


Fig. 22. The dependence of cooling lubricants efficiency coefficient when sharpening for power loss on the cutting velocity: 1, 2, 3 — steel of I, II, III group, respectively [16]

be practical in case when all parameters in MPP exceed similar parameters in conventional mechanical processing. Therefore, in order to evaluate the method of MPP, extensive experimental studies were carried out on constructional materials with different physical and mechanical properties, with different parameters of MPP. The main criteria of processability

were estimated: instrument wear, surface finish quality, and power-strength parameters of processing, which were determined at different cutting speed, supply, material of the cutting part of the tool and the workpiece, instrument geometry.

Due to the large amount of experimental work required for evaluation of processibility under MPP, tests were conducted only on individual representatives of carbonaceous and alloy steels. For this test, subjects were conditionally divided into three groups: 1 — carbon high-quality structural steel; 2 — structural doped, and 3 — instrumental alloyed steels. Steels 10, 20, and 45 represented first group, steels 40X and 40XH — the second one, and steels XBT and X12M — the third one. The first group steel had hardness of 160–180 HB, the second one — 180–200 HB, and the third one — 220–240 HB. The technological efficiency of the MPP was assessed on the operations of turning, drilling and end milling. For the convenience of evaluating the test results, the coefficients of effectiveness of the comparable values were used, as the ratio of the result of the experiment obtained in the MPP to the comparable. Therefore, the result graphs are constructed for several efficiency coefficients  $E_w$  (wear resistance),  $E_r$  (roughness), and  $E_p$  (energy-power parameter) versus the investigated characteristic of the cutting process.

Figures 18–21 shows a typical picture of the kinetics of wear on the posterior surface of the cutter with two methods of treatment — conventional, using lubricating cooling technology (LCTF) and mechanoplasma, realized with the help of a polymeric additive to LCTF. In this case, the blinding criterion is the permissible value of the bevel chamber, equal to 0.5 mm, since during further work there comes a catastrophic wear with all undesirable consequences. As can be seen from the figure, the permissible wear of the cutter in the MPP is 3–4 times larger than with the conventional processing method.

Figure 22 shows the microgeometry of the surface of the steel, which has been treated in two ways: using the plasma effect in the process of MPP and destruction and the usual machining. In this case, the MPP also has a significant advantage.

Thus, the results obtained indicate the high efficiency of the proposed method of MPP. In addition, the accumulated experimental data, established regularities discussed in the previous sections, as well as the results of studies in related fields of science, enable us to assume as follows. During the MPP, there is a possibility at the last stage of forming the surface of the product to make changes in its properties in order to increase many performance characteristics of the elements. The ability to combine the process of manufacturing the elements with the directed increase of its physical and mechanical properties is confirmed by good correspondence with the experience, which is discussed in the subsequent sections.

## **10. Technological Heredity of the Mechanoplasma Processing**

Practical studies show that the service life of products in the conditions of operation is largely determined by the state of their surface, the nature of which is due to prehistory, in particular, mechanical processing. There is a connection between the working capacity of the metal structure and the parts of the machines with their surface properties, composition and structure, the formation of which is significantly influenced by the parameters of mechanical machining of metal cutting. For example, it is known that cutting is accompanied by the formation of an area of advanced hardening in front of the cutter and a hardened metal region under the treated surface. The dimensions of these plastic-deformable metal zones are sensitive to the processing parameters of the cutting tool and the sharpening angle of the cutting tool. Contributing deformation, due to the contact of the workpiece with the surface of the cutter, makes an additional contribution to the general hardening of the surface layer of the metal. Therefore, depending on the technological parameters of the surface treatment of the machined parts, they differ in heterogeneity, which is reflected in the durability of the operation. Mechanical treatment also has an effect on the formation of an internal surface that is localized under the molecular layer and is a heterogeneous plastically deformed material formed because of the concentration of grain boundaries, sub-grains, dislocations. An inhomogeneous surface not only reflects directly on the mechanical properties of the solid, but also represents an electrically active real structure of the metal interacting with the environment, which influences the physical and mechanical properties of the metal. It has been experimentally established that the electrical structure of real solids plays an important role in the physicochemical degradation of solids, including their interaction with electrically active and passive elements of the environment.

The range of examples of the effect of mechanical processing on the formation of the surface metal layer and its influence on the physical and mechanical properties of the solid, especially if the processing is implemented in the environment, can be significantly expanded, but the data presented above show how great they are applied. In this connection, the mechanoplasma processing was evaluated for the ability to control the physical and mechanical parameters obtained during the cutting process, in order to achieve high performance. The resistance of the processed MPP samples of fatigue and corrosion fatigue, their fine crystalline structure and phase composition, roughness of the treated surface, microhardness, cyclic cracking resistance, and others were studied.

The obtained results show that the whole complex of investigated physicochemical, chemical properties and structure of the near-surface

Fig. 23. The surface profilogram of the 9XC (HRC 32–64) samples processed by sharpening: 1 — MPP, 2 — in the water with addition of cooling lubricants [21]

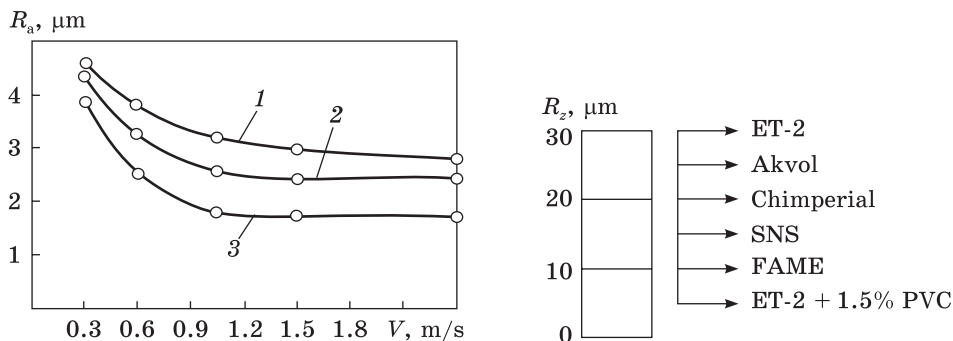


Fig. 24. The dependence mean absolute error of the profile on the sharpening velocity of steel 45 in different cooling lubricants: 1 — ET-2 emulsions, 2 — Chimperial, 3 — ET-2 + 1.5% PVC [16]

Fig. 25. The peak-to-valley heights at the processing steel 45 in different cooling lubricants ( $V = 1.5$  m/s) [16]

and surface layer formed by MPP differ considerably from the same properties of the surface formed after treatment using conventional LCTF. This difference is most clearly demonstrated by profilograms of treated surfaces (Fig. 23).

As it can be seen from the Fig. 23, the geometric relief of the surface of the samples after the MPP is significantly less expressed than the metal processed in the usual manner. In the processing of MPP, the arithmetic mean deviation of the profile ( $R_a$ ) and the height of the irregularities is considerably less than that of other known LCTF (Figs. 24 and 25).

As seen in Fig. 26, the MPO leads to a decrease in microhardness on the surface of steel, however, at a depth of 10  $\mu\text{m}$ , the microhardness becomes greater than that of conventional processing.

Moreover, the increase in microhardness is maintained at a relatively large distance from the surface (50  $\mu\text{m}$ ). A similar character of the distribution of  $H_\mu$  also holds for other structures, although a large difference is observed in terms of the microhardness.

For example, during MPP for 9XC steels of different hardness, hardened layers of different depth are formed in the surface layer of the samples (Table 4). On the sorbitol steel (HRC 37–38) and the cane structure steel (HRC 37–38), the depth of the hardened layer is 35–40  $\mu\text{m}$  and plastically deformed layers of higher microhardness are found in the

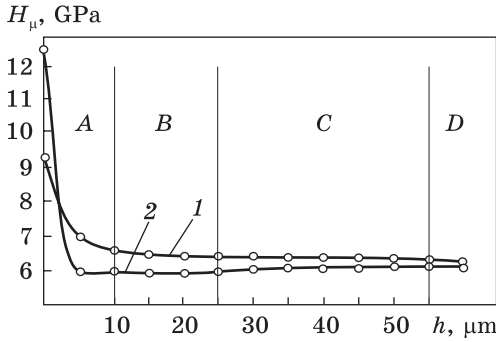


Fig. 26. The microhardness after sharpening: 1 — ET-2 + 1.5% PVC, 2 — ET-2 [16]. A — Deep deformation; B — Lange-sale deformation; C — Week deformation; D — Metal is not affected by surface processes

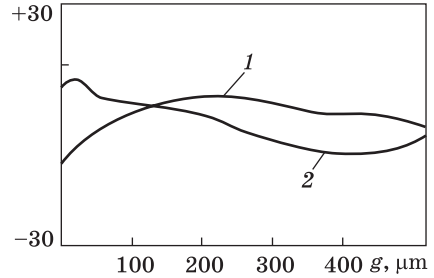


Fig. 27. The first type residual stress diagram after polishing 9XC (HRC 36–38) steel samples in water + 1.5% PVC (1) and water (2) [21]

microstructure as compared to the core of the sample. In samples made of martensitic steel (HRC 57–64), non-building white layers with a depth of up to 10 μm are formed. The depth of the hardened layers increases from 3 to 10 μm when turning with increasing supply. These layers are carbides, residual austenite, the particle size of which is an order of magnitude smaller than that of conventional quenching, and highly disperse martensite [21]. The mechanism of the impact of MPP on the formation of white layers is still unclear and requires separate studies.

One of the basic physicomechanical characteristics of the state of the surface formed by machining is also the sign and magnitude of the residual stresses.

Thus, grinding the steel of a sorbitol structure in a polymer-containing LCTF, when the plasma effect affects the cutting process, causes residual compressive stresses in the surface layers of the specimen (Fig. 27), while grinding in LCTF without a polymer additive causes residual tensile stresses, particularly, fatigue resistance [21].

Table 4. Microhardness of  $H_{\mu}$  (GPa) on the surface of steel 9 XS after turning in different media [21]

Hardness	Medium			
	Water	Oil $\mu$ -12	Water + 1.5% latex PVC	$\mu$ -12 + 1.5% PE
63–64	14.1	10.8	12.4	8.3
57–58	12.1	7.5	9.7	5.3
36–37	7.5	5.9	5.1	4.8
10–32	4.8	4.6	4.5	4.2

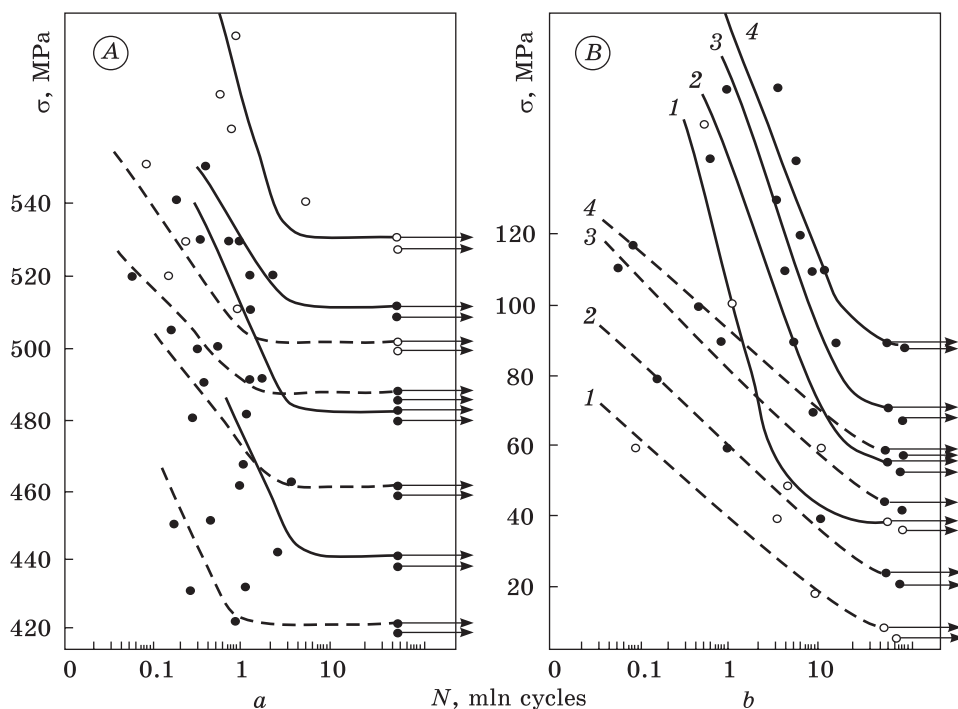


Fig. 28. The fatigue (a) and corrosion fatigue (b) curves of 9XC steel samples after polishing in cooling lubricants, water (dashed lines) and polymer-containing cooling lubricants (solid lines), heat-treated for various hardness (HRC): 1 — 62–64, 2 — 57–59, 3 — 44–48, 4 — 32–36 [21]

The occurrence of tensile stresses is probably associated with a decrease in the surface layers of the specific volume of the metal, which may occur, for example, during tempering. At MPP, the residual compressive stresses arise due to an increase in the work hardening (degree of deformation), saturation with carbon and other elements, which, on the contrary, leads to an increase in the specific volume of the processed metal.

Grinding LCTF as compared with grinding in a polymer-containing LCTF is accompanied by a more significant temperature and pressure in the contact zone of the abrasive wheel–part [21]. This increases the structural heterogeneity, increases the amount of residual austenite

Table 5. Thin crystal structure of steel after grinding in various media [21]

Steel	Medium	Size of blocks, nm	Distortion of the second kind, %	Amount of residual austenite, %
9XC HRC 46–48	Water	26.67	3.70	5
	Water + 1.5% latex PVC	16.40	1.05	Not found



formed because of secondary hardening. The increase in mosaic blocks in the surface layers of samples after grinding in water, apparently, is caused by the tempering of steel (Table 5).

The increase in mosaic blocks can mainly be explained by the effect of a higher temperature occurring in the treatment zone when grinding in water compared to grinding in a polymer-containing LCTF. The growth of distortions of the second kind is likely to be affected not so much by the temperature factor as by the higher level of mechanical stresses in near-surface layers of the material [55].

Grinding of steel in a polymer-containing medium also increases its resistance to fatigue failure in both air and corrosive environments. Moreover, with the increase in the metastability of steel, the effect of increasing the cyclic strength of the samples increases (Fig. 28, *a*), which is explained by the improvement in the physicomechanical properties and the action of residual compressive stresses arising in the surface layers of the parts during grinding.

Thus, polymer-containing LCTFs have a determining effect on the formation of the state of the near-surface layer of steel during its MPO: they contribute to the creation of a favourable structural stress state, the formation of residual compressive stresses, and improve the micro-geometry of the surface.

Thus, MPP creates such a structurally stressed state on the surface of steel parts, which contributes to the increase of their operability during operation [21].

The conducted researches give grounds to believe that the proposed MPP technology combines not only the intensification of the process of forming products, at its optimum cost, but also the possibility of obtaining products with pre-set high mechanical properties.

The model for the realization of this method of obtaining articles is substantiated by the data of many years of research by the authors on various physicochemical phenomena and processes observed in solids during their deformation in the environment.

## **11. Influence of the Plasma Effect on the Diffusion Saturation of the Contacting Surfaces**

As already mentioned, at MPP due to pyrolysis of the polymer component of LCTF, two phases are formed: gaseous, consisting of hydrogen in various forms and carbon compounds (if polyethylene is an additive to the LCTF), also a solid phase representing carbon.

In this section, we present the results of a study of the role of the second phase, the pyro-polymer residue, or more accurately of its chemical elements, on the wear rate of the tool, the main index of machinability. These studies also take into account the possible influence of

the formed products of polymer decomposition on the surfaces of the workpiece that are saturated with them, which, as was supposed, can give an opportunity to regulate the surface properties of products, and hence their operational durability.

An analysis of research in related fields of science shows that high-speed (pulsed) heating of steel is an effective method of influencing the structural state of a metal. For example, in the case of high-speed heating of steel, austenite forms in extremely short intervals, despite its diffusional nature of formation. We believed that in the zone of formation of chips (formed due to the interaction of protons with the real structure of the contacting surfaces of the workpiece with the tool) the pulsed thermal energy could also cause structural changes in metals and the diffusion mobility of the chemical elements of the pyro-polymer residue, particularly, carbon [22]. The true specificity of heating in a thermal flare is evidently that the thermal energy necessary for various phase and structural changes in steels is created directly in the reacting volume, and does not come to it from the peripheral regions due to thermal conductivity, as is the case with external heating.

In connection with the foregoing, studies were carried out of the influence of specific conditions that are created in the contact zone of the wedge of the tool with the workpiece, created in connection with the chemical activation of LCTF.

### **11.1. Some Electrophysical Properties of the Pyropolymer Residue**

Investigation of the formation of a solid residue during the pyrolysis of the polymer component of LCTF was carried out on an EPR spectrometer, as well as by electrophysical measurements. A solid residue sample that was accumulated on the tool during the cutting process was collected in a quartz ampoule and placed in the resonator of the ESA-2A spectrometer. As a standard for EPR signal intensity, diphenylpicrylhydrazyl (DPPH) was used; as a standard for magnetic field, MgO was used.

In order to study the dielectric and electrophysical properties of the solid residue, a spectral cell was used in which the pyropolymer was placed. The measurements were carried out in the temperature-time range of 25–250 °C, every 5 °C with holding at each temperature. Determination of the percentage of radicals in the total number of paramagnetic centres of the material was carried out according to the following procedure: 0.2 wt.% solution of DPPH in benzene and the intensity of the signal of the solution was determined, with a volume of 0.1 ml. A sample of the pyrolyzed polymer was placed in a container with a solution of DPPH, and then the intensity of the EPR signal of a given volume of the solution with a polymer residue was measured. The percentage of

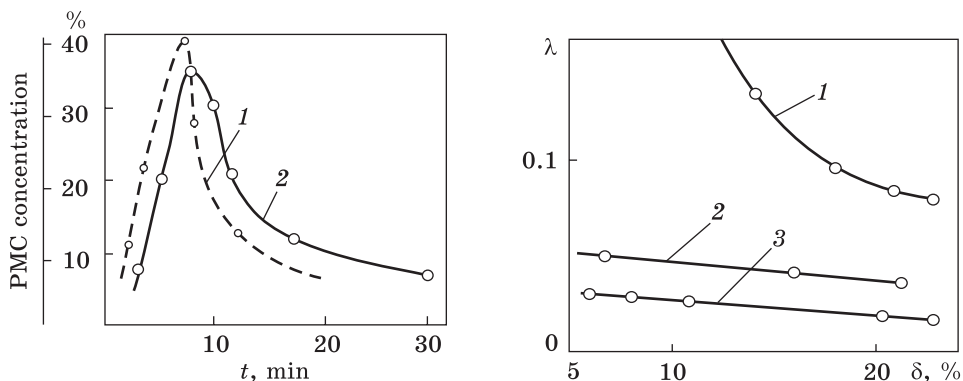


Fig. 29. Time-dependent concentration of active products formed during the MPP based on PE: 1 — the percentage of free radicals in the total number of paramagnetic centres (PMC), 2 — relative PMC concentration [21]

Fig. 30. The dependence of the contact friction coefficient on the reduction ratio of steel-10 in lubricants: 1 — industrial oil, 2 — palm oil, 3 — 1% -solution of polymer in oil ИС-12 [21]

free radicals in the total number of paramagnetic centres was determined from the intensity difference of the signals. The received signal, for a polymer additive made of PE, was a singlet that corresponded to the PE signal after its thermal synthesis. It refers to a conjugated system of the form  $-\text{CH}=\text{CH}-\text{CH}=\text{CH}-\text{CH}=\text{CH}-\text{CH}=\text{CH}-$ , i.e. to stable radicals that can be stored in the pyrolyzate matrix at positions in which there are steric hindrances to their recombination [16]. It should be noted that a signal of this kind is often fixed in pyrolyzed polymers forming a polyconjugated, polycyclic system consisting of graphitized aromatic rings. Indeed, the study of this process showed that the polymer additive formed by pyrolysis to LCTF is amorphized graphite and, according to data, such an organic pyrolyzate has specific electrophysical and magnetic properties.

It is known that in a lamellar lattice of graphite, carbon atoms form a flat, two-dimensional hexagonal grid, with distances of C-C 1.42 Å, whereas planes are spaced by 3.42 Å and are connected only by very weak van der Waals forces. That is why individual layers of graphite easily split into thin flakes, representing, thanks to this property, an effective lubricant. Apparently, the resulting graphitized system in the cutting zone is able to not only saturate the tool edge, the processed surface of the workpiece and the chips, but also effectively separate rubbing surfaces, reducing the coefficient of friction.

Figure 29 presents kinetics data on the emerging paramagnetic centres and free radicals upon pyrolysis of the polyethylene additive in LCTF from the time of mechanoplasmic processing. From the presented data, it is evident that during the cutting, as a result of the pyrolysis

of the polymer additive (in this case PE), an organic substance with radically active properties is formed, which not only accelerates the diffusion processes in the contacting metal surfaces but also catalyses the chemical reactions of the transformation of the activated environment. The dependence of the increase in the concentration of paramagnetic centres (PMC) and free radicals in the pyro- polymer, which has an extreme character on the time of machining, is also established. Moreover, with increasing processing time, the maximum concentration of paramagnetic centres narrows and shifts to the region of shorter processing times, that is, a certain temperature-time analogy of this process is observed. With a further increase in the processing time, the PMC decline begins to predominate in the pyropolymer [10].

Thus, the polymer chain consisting of carbon atoms, as a result of pyrolysis, forms not only a gas phase consisting of hydrogen in active forms, simple organic compounds and macrochain fragments, but also a poly-conjugated polycyclic system consisting of graphitized aromatic rings. Moreover, the formed active system simultaneously performs several functions: deepens the chemical transformations of the gas mixture, divides the rubbing surfaces, and is a carburettor to saturate the cutting edges of the tool and the processed surface of the workpiece.

### **11.2. Diffusion Saturation of the Processing Surface with Products Polyconjugate Polycyclic System**

By the method of scanning Auger spectroscopy, the chemical composition of the surface layer of steel after turning in a polymer-containing LCTF was studied. It is known (Figs. 29, 30) that a large concentration of carbon is observed on the surface of the treated material and at the same time, signals O and Fe are practically absent. Thus, the fact of thermal diffusion saturation is established in the process of cutting a steel surface by carbon.

Generally, the obtained data on the carbon saturation of the steel surface at a sufficiently large depth under extreme cutting conditions is surprising, since the transition of carbon atoms with the replaced velocity into the volume requires overcoming a high activation barrier. In the cutting conditions, the temperature at the time of separation of the chips from the workpiece and the concentration of carbon on the surface is too low, and the metal passing velocity of the zone of probable saturation is too high for the carbon to penetrate into the surface layer of the metal to a sufficient depth. It remains to be assumed that the high rate of carbon transfer to the near-surface layers of the metal at the time of plastic deformation can be associated with a very strong instantaneous 'warming up' of those degrees of freedom in the crystal lattice that are most responsible for carbon transport. Consequently, the

transport of carbon into the metal during its plastic deformation during the cutting process cannot be described within the framework of the equilibrium thermodynamics of the diffusion process and requires other theoretical approaches.

Most likely the mechanism of accelerated saturation of the treated steel with carbon is similar to the previously described group of scientists in the well-known monograph [57]. In the experiment, the developed special equipment was used, which allowed simultaneously recording the change of several parameters that obtain wide information of the proceeding process with high reliability of the experiment. Studying phase structural changes in steels at high-speed heating, unexpected results were obtained. It turned out that with direct heating by electric current, austenization occurs much faster than at the same temperatures in furnaces or baths. It was shown that the specificity of accelerated austenization is that the thermal energy necessary for the reaction is created directly in the reacting volume, rather than coming to it from the peripheral regions due to thermal conductivity.

During the cutting steel in LCTF, the positively charged hydrogen particles are forming in the fracture zone. Due to their recombination on the surface and adjacent layers of material, a large thermal energy is released. The thermal energy created directly in the reacting layer can cause phase and structural transformations, as well as accelerated diffusion of carbon. This leads to an important practical conclusion: the final stage of machining can be combined with various technologies that allow for the thermodiffusion saturation of the surface layer of articles by means of a special operation (i.e., MPP) in order to increase their various physical and mechanical properties.

The activating influence of hydrogen was studied using the example of cementation of steel Cв-0.8Г2С, which, it seems to us, to a certain extent, allows modelling the saturation process occurring under MPP conditions.

Powders of low-density polyethylene (containing carbon and hydrogen) as well as dispersed carbon were chosen as saturating media. Saturation of samples was carried out according to the same temperature–time regime: temperature 950 °C, saturation time 30 and 60 seconds, followed by quenching in water. It was found that the depth of the cemented layer after saturation in the PE was 150 and 225 microns with a maximum surface microhardness of 3.7–4.2 GPa, while for dispersed carbon with the same surface microhardness, the depth of saturation was only 50 μm.

Apparently the reason for this can be the occurrence of thermal energy directly in the region of material destruction increases the thermal vibrations of atoms, as a result of which individual atoms acquire sufficient energy to leave their equilibrium position in the lattice

and form a vacancy, and then complexes and even pores of a nanoscale size. The resulting defects can be considered as centres of capture of diffusive carbon atoms, which will lead to its accumulation. Due to these processes, heterogeneous diffusion of carbon is significantly accelerated. The activating effect of hydrogen on the diffusion of carbon can also be associated with the unlocking of dislocations, which increases their mobility, as well as by reducing oxides on the steel surface.

Thus, the obtained results indicate that the use of polymers of given physicochemical properties, as an effective additive to LCTF, allows, in parallel with the mechanical treatment, to carry out the process of increasing the operational durability of products. Consequently, the activating effect of hydrogen formed due to pyrolysis of the polymer on the diffusion processes, can be considered as one of the directions for the creation of hydrogen nanotechnology for the chemical-thermal treatment of metals. The goal of such a treatment is obtaining optimal physicomachanical properties with significant acceleration of the technological process of forming the parts and simultaneously increasing its economic indicators.

### **11.3. Diffusive Saturation of the Tool with Pyropolymer Residue Products at MPP**

The obtained data show that the pyro-polymer formed in the MPP process can be an excellent carburettor for the diffusion saturation of steel with chemical elements whose atoms either are in the macrochain of the polymer or are previously specially introduced into its composition. In this case, we are talking about a poly-conjugated polycyclic system consisting only of graphitized aromatic rings, since PE is recommended as an additive to LCTF. The saturation ability of the pyroprotest which differs on the cutting part of the tool during the MPP process by comparison with the concentration in the system of radical active paramagnetic centres, the maximum activity of which arises already at the initial stage of the tool. At the same time, the rate and concentration of formation of active saturating products and active forms of hydrogen increases with increasing parameters of mechanical processing.

To determine the mechanism of saturation of the instrument with MPP, special studies are needed. However, in general, the saturation process can be represented in the following form.

Rapid heating and heat removal from the high-heated region promotes the flow of structural transformations of the quenching and tempering type, which creates favourable conditions for accelerated diffusion of carbon. Postponed in the cutting process on the cutting edges of carbon, gradually dissolves in the metal, giving to the general fund of the crystal two electrons. This means that carbon being in austenite in

the form of a doubly ionized ion will react to a singly ionized iron atom, thereby causing its diffusion mobility. In the process of accelerating the diffusion of carbon into the instrument, an important role is played by the thermoelectromotive force, which is present in the 'machine-tool-workpiece' system.

Let us consider the possibility of activation of machining by drilling with 08X17T steel in a polymer-containing medium, which provided clarification of the plasma effect. Drilling was carried out with a constant axial force (drill diameter is 7.3 mm, cutting speed is 4 m/s, tool material is steel P6M5).

The parameters of the efficiency of the drilling process were the tool resistance, which was determined by the maximum number of drilled holes to a certain wear ( $h = 0.5$  mm), and the tangential force. As the coolant used a technological environment based on PE, as well as clean water. It has been established that with the cathode polarization the tool life increases, while at the anode one it decreases by approximately 1.5 times in comparison with the initial one. Tangential force in the range of application of the potential from  $-15$  to  $15$  V monotonically decreases. When drilling in pure water on the contrary, the tangential force in this range increases monotonically. The presence of an external electric field significantly catalyses the rate of movement of activated carbon in the metal.

Thus, favourable conditions for accelerated diffusion of carbon are created in the contact zone of the cutting edges of the tool with the workpiece and chips. It is important to note that the gradient of temperature and the high pressure in the contact zone also contribute to saturation of pure juvenile surfaces. Finally, the properties of tool steel are formed, and, first-of-all, the high wear resistance of the tool is the subsequent quenching, at which high-carbon martensite is obtained. Apparently, after a pulsed rise in temperature, local structural changes in the microvolumes of the material can be associated with a sharp temperature drop due to a high cooling rate. It should be noted that the high wear resistance of the cutting tool is confirmed not only by experimental data, but also by the results of the introduction of MPP [22].

In connection with the establishment of the fact of saturation of steel with carbon, an analysis of the surface layer of the cutting blades of the tool was carried out after its long operation in various technological environments and after MPO. Cutters, drills and cutters were tested. The distribution of carbon along the depth of the diffusion layer was studied on 'Comeca' microanalyzer by scanning over the surface of the uncoated section. The results obtained indicate an increase in the total carbon content in the surface layer of the cutting tool after MPP. In this case, the depth of the diffusion layer depends on the machining modes and the tool life. For example, when drilling steel-45 for 30 se-

conds in a state of delivery with a drill (10 mm diameter) made from high-speed steel P6M5 in a LCTF with 1.5% PE, carbon saturation with a depth of 20  $\mu\text{m}$  is ensured and an increase in the microhardness of the surface layer from 95 GPa to 115 GPa. The presence of a hardened layer is also confirmed by the formation on the microstructure of light diffusion layers characteristic for carburization.

Let us give one more example. After a long work, the P6M5 steel drill was discarded due to wear. The microhardness of its surface layer was about 9.3–9.5 GPa. Then, the same bit was used to work under the same conditions, but with LCTF with the addition of 1.5% PE. After approximately 90 seconds of continuous operation, the surface hardness increased to 11.5 GPa, and further processing was already in the normal mode. Based on these results, the recovery of 10 rejected drills by their ‘trainings’ in polymer-containing LCTF was carried out. As a result, the cutting properties of all the drills were restored to their original values.

Thus, the partial decarburization of the surface layers of the tool during cutting in the polymer-containing LCTF is replenished with carbon from the active carburettor formed in the cutting zone, which has catalytic properties.

The obtained results allow drawing a conclusion that the multiple increase in wear resistance of the tool with MPP is a consequence of several factors: reduction of cutting forces, reduction of the coefficient of friction of the surfaces of the tool with the material being processed and replenishment of the loss of carbon by cutting edges of the tool. This means that the use of polymers as an additive to LCTF, which provides a manifestation of the plasma effect in the destruction zone, can be considered as one of the directions for creating a hydrogen technology for the chemical-thermal processing of structural steels in order to obtain optimal physicomachanical properties.

## **12. Mechanoplasma Processing: an Example of Practical Using Nanomaterial**

The need for continuous updating of technologies in connection with the new and more complex tasks that science poses to science requires not only systematic work on obtaining new materials with the necessary properties, but also the development of new approaches to the creation of technologies for their processing. Among such approaches to the development of innovative ways to improve the efficiency of the shaping of machine parts, it is possible to single out the method of mechanoplasma processing (MPP).

Shaping of parts by this method is performed by separating the material from the billet as a result of the joint action of mechanical energy



and plasma on the metal, the radical active hydrogen particles possessing a positive electric charge. According to the proposed mechanism, a polymer, for example 1.5% of polyethylene, is added to the lubricating-cooling technological means (LCTF) in order to form a plasma effect in the zone of destruction. Under the influence of thermal, electric and magnetic fields, which are a constant destruction satellite in the 'machine-preform-tool-part' system, an ionized gas is formed, the interaction of such a radically active with the real structure of a solid body facilitates the deformation and destruction. This leads to a conclusion of great practical importance: for a radical increase in the efficiency of LCTF, additives to them should be sought among high-molecular compounds that give a large concentration of active forms of hydrogen and carbon in the chain of chemical transformations in the cutting zone.

Based on these recommendations, new generation of LCTF compositions have been developed, which have been successfully applied in various processes for the processing of solids in various industries [22]. Several production of LCTF, providing mechanoplasma processing of metal, for several years was carried out by enterprises of Ukraine and Belarus: Kalush Production Association 'Chlorvinil', Drohobych Oil Refinery, Scientific Production Association 'Masma', Lviv Oil Refinery, and Novopolotsk Chemical Complex.

Within the framework of this article, there is no a possibility to provide a more complete information about the use of MPP by industrial enterprises and discuss their results. We note only that in the course of several years of successful application by enterprises of specially designed LCTF compositions, which ensured the appearance of a mechanoplasma effect, a tangible ecological effect was obtained. Successful implementation was facilitated by the large preparatory work carried out by the employees of the branch laboratory of 'Mintiazhmash', who prepared unprepared documentation and implementation methodology, which determined the order of preparation of the material to be processed by this enterprise, the selection of the cutting tool, the necessary quality control of LCTF, etc. Ministry kept track of information about the use of the proposed method in the enterprises during one year and confirmed high technological effectiveness of such a processing way [22]. However, as the matter of the fact that a large number of different physicochemical processes and phenomena that form a complex processing mechanism occur in the MPP process, it is not yet possible to obtain accurate quantitative data.

Below, there are some average results of the mechanoplasma treatment.

### 12.1. Moulding of Parts via Removing a Layer of Metal from the Preform

The following results were obtained in the manufacture of articles by cutting from carbon steels, all types of alloyed steels and alloys and some non-ferrous metals and alloys.

When the cutting speed is increased above the usual one, the wear resistance of the cutting tool increases by 2–7 times with the MPP, the roughness parameter  $R_a$  is reduced by 50–70%, the power consumed for processing is reduced by 15–20% compared to conventional processing using modern LCTF. Moreover, the averaged industrial data were obtained during the operation of various enterprises within one year.

It should be noted that the effectiveness of MPP is manifested not only in the processing of iron and its alloys; it manifests itself when cutting other metals. So, for example, drilling various metals under laboratory conditions with a constant axial load on a tool 1200 N, the drill is R6M5 (diameter 10 mm). Comparative results of MPP and conventional processing are presented in Table 6. As can be seen from the presented data, the efficiency of MPP takes place at the forming products from other materials.

Technological efficiency at grinding of steel 30XГCA by MPP in comparison with synthetic, semisynthetic and emulsion LCTF: (a) the stability of the circle increased, respectively, from 70%, 90%, 570%; (b) the roughness of the processed surface  $R_a$   $\mu\text{m}$ , respectively, decreased by 0.9, 1.1, and 1  $\mu\text{m}$ ; (c) the coefficient of grinding by volume, respectively, is 130, 60, 200.

Comparative results of honing steel 40X, HRS 48-5 by MPO in comparison with the treatment with kerosene oil mixture depending on the characteristics of the hone-bar: (a) the average value of the layer to be removed along the diameter was 0.07 mm, it became 0.17 mm; (b) the roughness of the treated  $R_a$  surface has decreased; (c) average specific consumption of diamonds decreased by 2–3 times.

Table 6. Comparative data of the MPP results for different metals

Material	Depth of cut, mm	Rotation moment, nm	Drilling speed, mm/s	Material	Depth of cut, mm	Rotation moment, nm	Drilling speed, mm/s
Al	1.3	1.4	2.0	Mo	0.35	2.5	1.1
	1.2	1.7	1.6		0.25	2.5	1.1
Ni	0.5	2.5	0.9	Co	0.25	3.2	2.5
	0.5	3.2	0.6		0.2	4.7	2.1
Ti	0.6	1.9	1.5	Fe	0.9	2.7	0.9
	0.3	3.8	0.6		0.8	2.7	0.7

Comparative results of honing cast iron SCH-18-36, HB 170-180: (a) the average value of the layer along the diameter was 0.16  $\mu\text{m}$ , while became 0.3  $\mu\text{m}$ ; (b) the roughness of the machined  $R_a$  surface remained practically unchanged; (c) the average specific consumption of diamonds remained practically unchanged.

As follows from all above-presented, results of investigation of the plasma effect formation, as well as the data of its use in industry, are quite encouraging. Thus, we can consider the mechanoplasma processing of the shaping of parts, not only as a special high-performance and economically advantageous method of metal processing, but also as an effective method of control operational properties of parts.

**12.2. Moulding of Parts via Metal Processing with Pressure**

A pressure is one of those parameters can be used to affect some physical properties of metals and alloys (see, e.g., [66, 67] and references therein). The conclusion that contact interactions of plasma products with a real metal structure facilitate the process of deformation, gave grounds for using this effect in the technology of metal pressure processing (MPP). The LCTF compounds with polymer additives have been developed that ensure the manifestation of a weakly ionized gas in the contact zone of the deformed material with the surrounding medium. There is no doubt that the mechanism of activation of the initial medium in this case differs from the mechanism during cutting. However, the experimentally proved fact of the presence of hydrogen in the metal after the MPP testifies that hydrogen diffuses into the material being in the proton state. The dissociation of hydrogen probably occurred on the catalytically active surfaces formed during the mechanical process.

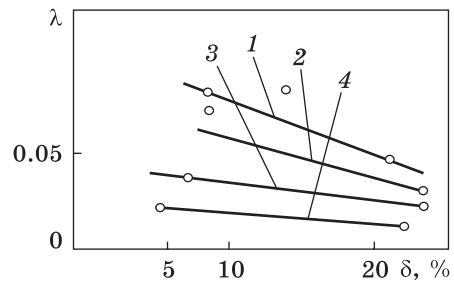
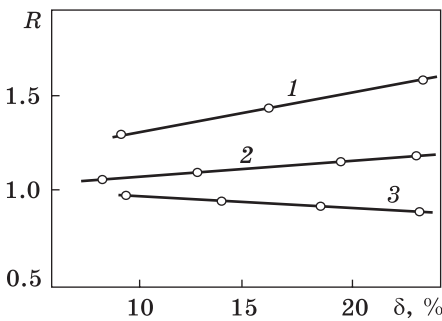


Fig. 31. The dependence of specific friction force on the reduction ratio of steel-10 in lubricants: 1 — RS-160 (Germany), 2 — ‘Tubanor-A6’ (France), 3 — 1% polymer solution in oil IC-12 [21]

Fig. 32. The dependence of the contact friction coefficient on the reduction ratio of steel-10 in lubricants: 1 — RS-160 (Germany), 2 — ‘Tubanor-A6’ (France), 3 — palm oil, 4 — 1% polymer solution in oil IC-12 [21]

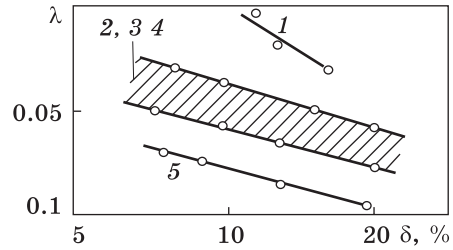
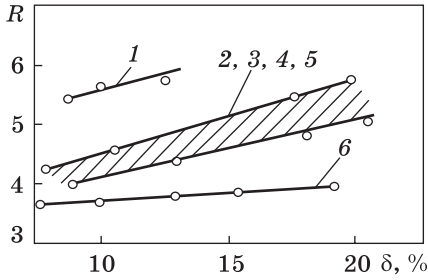


Fig. 33. The dependence of specific friction force on the reduction ratio of steel-X18H10T in lubricants: 1 — ‘Vitolid 47’ (Germany), 2 — ‘Lubronax’ (France), 3 — ‘Kastrol’ (Germany), 4 — palm oil, 5 — chlorinated paraffin wax, 6 — 1% polymer solution in oil ИС-12 [21]

Fig. 34. The dependence of coefficient of contact friction on the reduction ratio of steel-X18H10T in lubricants: 1 — ‘Vitolid-47’ (Germany), 2 — ‘Lubronax’ (France), 3 — ‘Kastrol’ (Germany), 4 — palm oil, 5 — chlorinated paraffin wax, 6 — 1% polymer solution in oil ИС-12 [21]

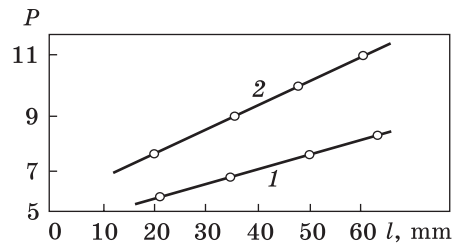
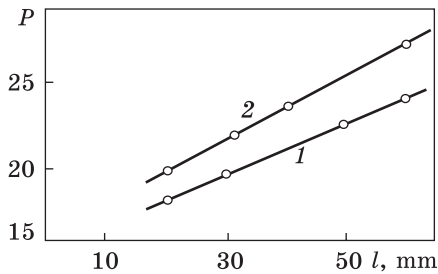


Fig. 35. The dependence of radial stress at the cold rolling steel-10 on the workpiece linear displacement in lubricants: 1 — 1% of polymer in ИС-12 oil (without preparatory bonderite), 2 — ИС-12 oil, soap + preparatory bonderite [21]

Fig. 36. The dependence of axial force at the cold rolling of steel-10 on the workpiece linear displacement in lubricants: 1 — 1% of polymer in ИС-12 oil (without preparatory bonderite), 2 — ИС-12 oil, soap + preparatory bonderite [21]

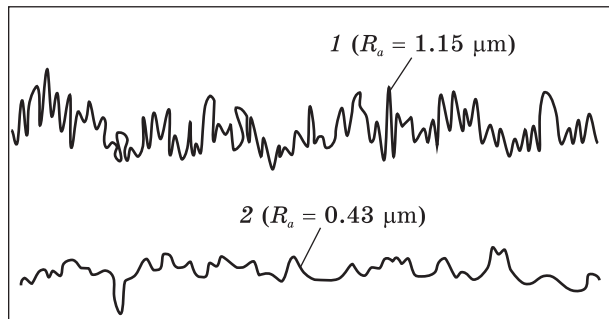


Fig. 37. Profilogram of the steel-10 sheet made with the use of palm oil (1) and 1% of polymer in ИС-12 oil (2) [21]

Formulations for pipe-rolling and pipe-rolling technological processes for the production of cold-deformed pipes, sheet rolling, especially for rolling a thin sheet of hard-deformed steels, cold stamping, drawing, volumetric stamping, drawing, etc. have been developed. The effectiveness of the proposed compositions was evaluated in various laboratory and industrial mills. Some results are contained in Fig. 30–37.

Presented data indicate a high efficiency of MPP in terms of reducing energy costs for the processing process, a significant reduction in the number of operations in the technological cycle for the production of cold-deformed pipes, increasing the productivity of rolling equipment, and improving the reliability and durability of its work, improving the quality of the pipes and sheet produced. High efficiency of MPP is demonstrated also in other technological operations of metal treatment with pressure.

At the MPP, the degree of plasticity of the metal mainly determines its efficiency, and thermal activation, reducing the level of mechanical stress at which the apparent plastic deformation occurs, increases the efficiency of the entire process. In practice, this property of the material formed the basis for the widely known method of hot metal working with pressure, when the temperature to the material to be treated is supplied from an external source. When a plasma effect is used in the technological process, the heat release source is located inside the material, as a result of the interaction of the hydrogen proton with it. Apparently, therefore, the developed technological methods based on high molecular compounds, when a high concentration of ionized hydrogen forms in the treatment zone, differ from conventional methods of processing with a striking efficiency.

### **12.3. Thermodiffusion Saturation of Steel**

Analysis of the kinetic and thermodynamic parameters of polymer destruction processes shows that at the temperatures of thermal destruction (TD), high rates of formation of a hydrocarbon gas mixture consisting of carbon and hydrogen in atomic and other active forms are observed. Since the effectiveness of metal processing depends on the concentration of the saturating element in the active form, then in the polymer-containing media, greater saturation should be expected than in low-molecular carburettors.

Really, at the TD of the polymer component of media in the temperature-time domain (1–3 min, 500–1000 °C), an increased concentration of reactive radical products appears directly on the surface of the metal, interacting actively with the surface, with the release of atoms of saturating elements. This causes a high saturation speed in the initial processing period and the entire process as a whole. Thus, it was believed that polymeric materials can be widely used to intensify the thermo-

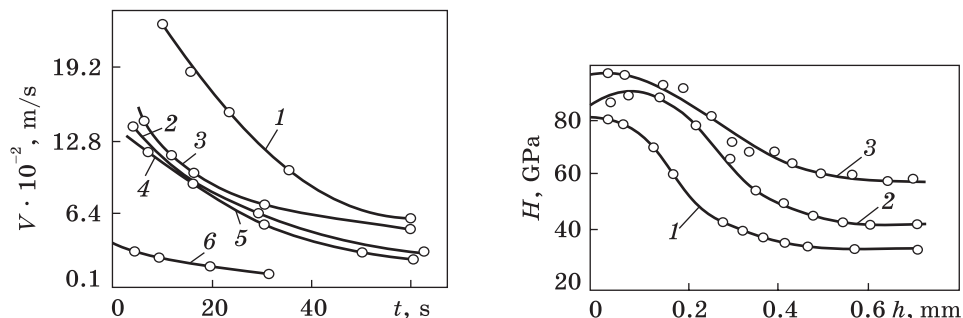


Fig. 38. The dependence of the velocity of isoconcentrational area of thermodiffusional saturation of steel-10 on the machining time in 1% polysterene in toluene solutions (1), polysterene in chlorbenzene solutions (2), PVC-based pastelike compositions (3), polymethyl methacrylate in chlorbenzene solution (4), PVC in chlorbenzene solution (5), toluene (6) [21]

Fig. 39. The dependence of microhardness along the sample section of steel СВ-08 after carburization in 1% polystyrene in toluene for 1 min at 800 °C (1), 870 °C (2), and 900 °C (3) [21]

diffusion saturation of steels with various elements (carbon, nitrogen, silicon, etc.) from active polymer-containing compositions destructive to the processing, which can ensure the production of coatings with high performance characteristics.

One can see in Fig. 38 that saturation of steel with carbon, both from solutions of polymers and from polymer-containing pasty carburizers, makes it possible to achieve high cementation rates ( $V = 0.256$  m/s), whereas known, most efficient carburizers cannot provide a saturation speed above 0.064 m/s.

Carburization for 1 min from polystyrene solutions in toluene at 900 °C resulted to the saturation depth of 0.6 mm. At the same conditions,

Table 7. Comparative data of cyanidation rate for different media [21] (here, before the processing, microhardness corresponded to 85–95 MPa)

Cyanidation medium	Temperature, °C	Time, min	Thickness of diffusion layer, mm	Microhardness, MPa
Polyacrylamide	560	1	0.030	103
	560	5	0.045	103
	800	0.25	0.040	103
	800	0.50	0.060	110
Urea-formaldehyde resin	560	1	0.020	103
	560	5	0.040	110
	800	0.25	0.040	118
	800	0.50	0.060	110.5

but from the solvent (toluene, chlorobenzene), the saturation reached a depth of 0.1 mm. However, commonly used in the industry liquid and solid carburizers, lead to the depth of saturation of 1 mm for 5–6 hours, and 10–15 min when high frequency currents are applied.

The characteristic feature of polymer-containing carburizers is that as a result of saturation and subsequent hardening, a high microhardness of the surface layer of the sample is achieved (Fig. 39). Apparently, this can be explained by the specificity of the structure of the hardened layer, formed during the carburization and further heat treatment

According to x-ray analysis, the martensite, austenite and iron carbides ( $\text{Fe}_3\text{C}$ ,  $\text{FeC}$ ) are the phase components of the surface diffusion layer after cementation and heat treatment.

The widest distribution and economic feasibility of the processing of polymer-containing compositions is found for hardening of tool steels. For example, carburizing of P6M5 steel drills for 20 s at 900 °C provides saturation to a depth of 0.06 mm and an increase in the microhardness of the surface layer from 95 MPa to 115 MPa.

The results of investigation of low and high temperature cyanidation of drills and taps made of P6M5 steel in compositions based on aqueous solutions of polyacrylamide and urea-formaldehyde resins confirm the possibility of processing the tool at a rate of 10–20 times the cyanidation rate in industrial media commonly used in industry (Table 7).

In case of using polymeric compositions for 5 minutes at 500 °C and 0.5 min at 800 °C, the saturation is reached to depth of 0.04 and 0.06 mm, respectively. For liquid cyanidation in salt baths, the saturation at 560 °C for 2 hours reaches a depth of only 0.045 mm, and nitrocarburizing in triethanolamine at 850 °C for 1 hour — at a depth of 0.080 mm. The wear resistance of drills after cyanidation increases by 1.5–2.5 times.

Currently, we established optimal MPP regimes and developed technological compositions for carburization, cyanidation and carbosilicide of steels.

Thus, the possibility and prospects of chemical-thermal treatment of steels in polymer-containing compositions are demonstrated. In this case, high efficiency, quality and manufacturability of the processes of saturation of steels with carbon, nitrogen, silicon and other elements included in the composition of polymer compositions, provide the processes of interaction of ionized hydrogen with a saturable metal.

#### **12.4. Processing of Silicate Glasses**

Abrasive treatment of most nonmetallic materials is practically impossible without LCTF. Currently widely used technological media for processing silicate materials (mineral oils and other oil distillates, aqueous emulsions of oils, various water-soluble compositions) do not have a high efficiency of glass removal during grinding. In addition, after

processing, the unsatisfactory quality of the surface is characteristic, which requires additional technological operations.

Based on the obtained results, a polymer-containing LCTF composition was developed that provided contact interactions of the hydrogen protons formed during activation of the medium with the material being processed. An industrial test have shown that, under equal technological conditions, grinding of glass MPP, in comparison with the earlier applied treatment, increase 1.7 times the intensity of glass removal and contributes to the reduction of defects in surface quality from 35% to 9.7% [21].

### **12.5. Processing of Semiconductor Materials**

To produce semiconductor plates from a pre-grown ingot of a single crystal, it is cut and then polished and dressing. Cutting is done in liquid formulations, and grinding and polishing with special diamond powders and pastes. It was found that the addition of polymer to the technological compositions used reduces the wear of disks that are reinforced with artificial diamonds, reduces its vibration, reduces the temperature in the cutting zone and the residual stresses in the surface layer of the material, and reduces microroughness and structural changes in the ingots of germanium and silicon [21].

### **12.6. Drilling of the Very Hard Rocks**

At the drilling of rocks of high-hardness category, especially in exploratory geological drilling, clay solutions are used that are poured into the well. The main purpose of such technological compositions is to increase the wear resistance of the tool and reduce the energy costs for the technological process. The wear resistance index of the cutting drilling tool significantly increases in price with the increase in the depth of the well, since the worn out tool must be replaced, for which it is necessary to perform an extremely laborious process: lifting the drill string from the well. If the depth of the well is several kilometres, then with this depth the tool must be raised to the surface, replace it, and then lower it to the depth [21].

Industrial tests of drilling muds with a polymer additive were carried out in the Olevsky geological party during geological prospecting drilling in the Zhytomyr region of the Ukraine.

After the saponification of the tar process, 43% aqueous dispersion of polyvinyl chloride (PVC) of E-62 grade was added to the concentrate of the mud, which was an aqueous emulsion of tar. After the dilution of the resulting concentrate with water, the desired result was a drilling mud containing 4-weight percent tar mixture, 0.45% weight PVC, and water in the rest.



The dispersion of PVC was diluted with water to a concentration of 0.3–0.4% by weight of the dispersed phase, which made it possible to obtain at such concentrations a technological product with sufficient sedimentation and aggregative stability.

The efficiency of the drilling mud using the addition of an aqueous dispersion of PVC was evaluated in comparison with the efficiency of the drilling fluid from the tar mixture (TM) based on drilling results of X–XII granites of hardness categories. Drilling was carried out on drilling rigs such as ZIF-650M (drilling pump-HFP 250/50, mast-МПУТУ-2, using diamond bit type 15 АИЗТ 200, diameter 59 mm).

When using a steel drill string with a diameter of 50 mm, the rotation speed of the rotor was 780 rpm, and when using a smoothbore column of light-alloy drill pipes it was 50 mm in diameter 1060 rpm. The axial load during drilling was 800–1000 kg.

Tables 8, 9 and 10 show the average results of work at 5 drilling rigs [21]. As can be seen from the data obtained, the presence of the

**Table 8. The results of industrial tests of drilling rocks (X–XII hardness categories): the number of turns of the drilling tool is 780 rpm, diameter of the diamond bit is 59 mm [21]**

No.	Drilling indicators	TM	PVC
1	Average specific power consumption kWh/m	5.42	2.77
2	Mechanical drilling speed m/hour	2.49	2.98
3	Bit penetration, m	25	32
4	Specific consumption of diamonds, carat/m	0.78	0.61

**Table 9. The results of industrial tests of drilling rocks (X–XII hardness categories): the speed of the drilling tool is 1060 rpm, diameter of diamond bits is 46 mm [21]**

No.	Drilling indicators	TM	PVC
1	Average specific power consumption kWh/m	9.06	8.13
2	Bit penetration, m	9.7	17.2

**Table 10. The results of industrial tests of drilling rocks (X–XII hardness categories): bench tests [21]**

No.	Drilling indicators	TM	PVC, %		
			0.45	0.75	1
1	Average mechanical speed cm/min	1.980	1.640	2.360	2.180
2	Average power consumption, kW	0.860	0.680	0.760	0.75
3	Average specific power consumption, kWh/m	0.725	0.693	0.538	0.574
4	Bit wear, mm	0.590	0.018	0.046	0.021

polymer component in the solution makes it possible to increase significantly the wear resistance of diamond bits, to reduce energy consumption for the drilling process with a significant increase in drilling speed.

The data obtained indicate that in the future, the MPP will enable high-performance drilling of hard rocks.

### **13. Conclusions**

The paper formulates the problem of the need for development of metalworking and the important research tasks put forward in connection with this, which are based on the fundamental laws of the physics of the cutting process and the constantly emerging and developing new border areas of science. The main task is related to the knowledge of the laws of such extremely complex in terms of their multidimensional and extreme conditions of the processes, which is the process of metal cutting with continuous watering of liquid with several tens of dissolved and emulsified in it the components. The solution of this problem will lead to a painful understanding of the physical essence of the phenomena accompanying this process, and on the basis of this, to develop new approaches to the creation of an optimal technology for the shaping of parts. One of such approaches can be the technology of mechanoplasma processing proposed here, which simultaneously combines not only the possibility of intensifying the process of manufacturing parts at an optimum cost, but also the production of products with adjustable in a certain range, operational properties.

The proposed model of mechanoplasma processing of solids is justified by the results of many years of research in the field of physical and chemical mechanics of materials, as well as by the analysis of literary sources from a number of disciplines, such as physics, chemistry, physical chemistry, and the emerging new fields of science.

An important result of the studies is the established facts of the presence of hydrogen in the chips and in the surface layer of the processed metal surface, which allowed to suggest and then experimentally confirm the chemical activation during the cutting of the initial surface active medium (LCTF) to the formation of hydrogen plasma. It is shown that the process of activation of the initial medium proceeds at many stages of its chemical transformations. Some of the reactions take place on the hot surfaces of the cutting zone with the formation of a hydrogen-containing gas phase. The remaining transformations, right up to the hydrogen plasma, flow in the reaction space between the tool wedge and the fracture top. These processes are initiated by various physicochemical phenomena of quantum nature, which are a constant companion of a growing crack. The decisive role of fracture is established, the growth

of which initiates and promotes self-acceleration of chemical reactions in its cavity. The problem of radical improvement of machinability of metal and methods of its solution are formulated. It has been shown experimentally that this problem is solved if a plasma effect is formed in the reaction zone between the wedge of the instrument and the crack tip. The diffusers from the plasma and the positively charged hydrogen particles accelerated by the electric field interact with the real, electrically active material structure and as a result, a large thermal energy is released. In this connection, in order to carry out the restructuring and rupture of the bonding forces of the deformed metal, it will be necessary to expend less mechanical energy on the amount of thermal energy that has been generated. The possibility of the manifestation of the plasma effect depends on the presence of hydrogen compounds in the medium, the atoms of which are part of virtually any technological means. Most important, however, that the greatest effect is achieved with the maximum degree of ionization and the concentration of hydrogen in the crack cavity. Such conditions in the reaction zone can be created only if a high-molecular compound is present in the technological composition. This conclusion is of great practical importance, since direct recommendations should be sought for effective additives to LCTF, among polymer compounds that give active forms of hydrogen and carbon in the chain of chemical transformations of their macrochains.

The obtained experimental data make it possible to conclude that the main role in facilitating the processes of deformation and destruction of metal in the process of cutting in surface-active technological means (LCTF) is played by the thermal effect resulting from the contact interactions of the proton with the real body structure arising in the course of the mechanical process. The released thermal energy is localized in a narrow region at the tip of the crack, raises the temperature of the atomic groupings to the loss of stability of the crystal lattice until its melting, and then the local volume of the body.

The connection between MPP and the active influence of the main component of the plasma, the proton, was established, which allowed one to study the mechanism of the destruction process in media, which is sufficiently reproduced and proved by various experiments. The necessity of solving new problems connected with the problem of solid body destruction in various active media that can be solved in a microscale to the level of a range of elementary particles is formulated.

The development of ideas about the mechanism of the phenomena observed during the shaping of parts by cutting in LCTF shows that these processes must be considered not as purely mechanical and even not mechanochemical, but as plasmomechanical ones.

The experimental results and data of industrial enterprises clearly demonstrate convincingly the unconditional advantage of MPP. Cutting

of the material at MPP is characterized by high machinability, which is characterized by a decrease in tool wear and cutting forces, increased tool life and the quality of the processed surface, and no less importantly, the process proceeds at high dimensional accuracy with a certain economic effect.

The possibility of using pulsed high-speed heating of a metal to create an effective method of influencing its structural state and on this basis to accelerate substantially the saturation of the material with alloying elements is demonstrated.

It is established that in order to implement technological process of MPP, it is necessary to use the unique properties of objects and materials of the nanoscale range and scale of elementary particles that differ from the properties of free atoms or molecules, and also from the bulk properties of compounds and substances consisting of the same atoms or molecules.

An essential feature of the proposed model is the spontaneous emergence in the destruction zone of metal cutting in the LCTF of a critical level sufficient to initiate an explosive and then spontaneous process of development of chemical transformations of the initial surface active medium (LCTF) into a radically active one. The possibility of controlling the chemical transformation of LCTF, the collapse of the macrochain, the collision of molecules, the rearrangement of their electronic shells, the exchange of atoms and the formation of new molecules are carried out via the predicted polymer additive to LCTF, as well as the parameters of mechanical processing. In this case, with a certain planned combination of the chemical composition of the macrochain of a polymer capable of containing atoms and atomic groupings of other chemical elements besides atoms of carbon and hydrogen, that optimal propagation of stress and compression stresses will be provided. In addition, this will contribute to the high speed and depth of the chemical transformation of the medium, which will greatly improve machinability in combination with hardening of manufactured products.

The most is the conclusion that the proposed mechanism for implementing the MPP is the opportunity to substantiate innovative ways in the technology of highly efficient methods of processing new construction materials, and new methods to improve the operational reliability of parts from these materials.

It should be noted that the plasma effect is not less brightly expressed in the technological processes of processing other solid bodies. For example, a significant effect is observed when grinding solid bodies of an inorganic nature: when drilling geological rocks of high strength, processing silicate glasses and semiconductor crystals, etc.

In the article, the author sought to show great promise of using mechanoplasma treatment of solids, and bearing in mind the importance and complexity of the problem under consideration, considered it possible to make some hypothetical considerations.

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#### ТЕОРІЯ ТА ЗАСТОСУВАННЯ МЕХАНОПЛАЗМОВОГО ЕФЕКТУ В ПРОЦЕСАХ ІНТЕНСИФІКАЦІЇ МЕХАНІЧНОГО ОБРОБЛЕННЯ

Оглядаються результати вивчення деформації та руйнування твердих тіл у процесі механічного оброблення різанням за умов впливу різних середовищ. Встановлено залежності особливостей процесів, що перебігають за деформації та руйнування металу, від сукупності механічних чинників, властивостей досліджуваного тіла та його фізико-хімічної взаємодії з навколишнім середовищем. Експериментальні дані та найважливіші досягнення в суміжних областях науки дали змогу запропонувати гіпотезу про ініціювання та самопришвидшення хімічних перетворень навколишнього середовища в результаті дії позитивного зворотного зв'язку між хімічним і механічним руйнуванням. Показано, що в цьому випадку тріщина, що зростає, відіграє роль спускового пристрою, який включає процеси хімічних перетворень середовища. Механізм цих процесів і явищ пов'язаний з контактними взаємодіями фізико-хімічних явищ, що мають квантову природу й виникають у момент зростання тріщини, з електрично активною новою структурою, що утворюється внаслідок механічного впливу на метал. Показано, що наявні на сьогодні погляди не зазнали змін з того часу, як було висунуто відоме положення про пониження міцності матеріалу як безпосередній прояв пониження вільної поверхневої енергії у разі його контакту з середовищем. Втім у дійсності полегшення процесів деформації та руйнування тіла внаслідок адсорбційного середовища не є основною причиною пониження механічних властивостей твердих тіл. Полегшення процесів руйнування металу в середовищах відбувається в результаті контактних взаємодій електрично активних частинок водню з електрично активною реальною структурою металу. Показано, що йонізаторами водневмісних середовищ слугують висока температура зони різання, ювенільні каталітичні активні поверхні щільного простору між вершиною різця та гирлом тріщини й екзоелектронна емісія. Запропоновано розглядати процес формоутворення виробів у середовищі не як механічний, а як механоплазманий. Обґрунтовано нові шляхи формоутворення металевих деталей з одночасним дифузійним насиченням поверхневого шару легувальними елементами, що підвищує експлуатаційну довговічність виробів. Запропоновано спосіб механоплазманий оброблення металів та організовано серійне виробництво масивно-охолодних технологічних засобів нового покоління.

**Ключові слова:** механоплазманий ефект, механічні властивості, механічне оброблення, дифузійний процес, міцність, тріщина, дислокація.



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## ТЕОРИЯ И ПРИМЕНЕНИЯ МЕХАНОПЛАЗМЕННОГО ЭФФЕКТА В ПРОЦЕССАХ ИНТЕНСИФИКАЦИИ МЕХАНИЧЕСКОЙ ОБРАБОТКИ

Обозреваются результаты изучения деформации и разрушения твёрдых тел в процессе механической обработки резанием в условиях влияния различных сред. Установлены зависимости особенностей протекающих процессов деформации и разрушения металла от совокупности механических факторов, свойств исследуемого тела и его физико-химического взаимодействия с окружающей средой. Экспериментальные данные и важнейшие достижения в смежных областях науки позволили предложить гипотезу об иницировании и самоускорении химических превращений окружающей среды в результате действия положительной обратной связи между химическим и механическим разрушениями. Показано, что в этом случае растущая трещина играет роль спускового устройства, включающего процессы химических превращений среды. Механизм этих процессов и явлений связан с контактными взаимодействиями физико-химических явлений, имеющими квантовую природу и возникающими в момент роста трещины, с электрически активной новой структурой, образующийся вследствие механического воздействия на металл. Показано, что существующие сегодня взгляды не претерпели изменений с того времени, как было выдвинуто известное положение о понижении прочности материала как непосредственное проявление снижения свободной поверхностной энергии при его контакте со средой. Однако в действительности облегчение процессов деформации и разрушения тела из-за адсорбционной среды не является основной причиной снижения механических свойств твёрдых тел. Облегчение процессов разрушения металла в средах происходит в результате контактных взаимодействий электрически активных частиц водорода с электрически активной реальной структурой металла. Показано, что ионизаторами водородосодержащих сред служат высокая температура зоны резания, ювенильные каталитически активные поверхности щелевого пространства между вершиной реза и устьем трещины и экзoeлектронная эмиссия. Предложено рассматривать процесс формообразования изделий в средах не как механический, а как механоплазменный. Обоснованы новые пути формообразования металлических деталей с одновременным диффузионным насыщением поверхностного слоя легирующими элементами, что повышает эксплуатационную долговечность изделий. Предложен способ механоплазменной обработки металлов и организовано серийное производство смазочно-охлаждающих технологических средств нового поколения.

**Ключевые слова:** механоплазменный эффект, механические свойства, механическая обработка, диффузионный процесс, прочность, трещина, дислокация.