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Reducing cutting forces at advanced plastic deformation of metals

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Abstract. The article carries out the analysis of models for studying the effect of reducing cutting forces when cutting mechanically hardened materials from the standpoint of the theory of dislocation and energy balance. The article presents the perspective model of researching the process of cutting with the advanced deformation allowing calculating the cutting force reduction. The model takes into account the history of damage accumulation considering changes in the stress state at each stage of the combined treatment process.

1. Introduction. Energy model

Modern trends in developing cutting theory [1, 13, 16, 17] affect both the problems of creating new types of machine tools [9] and metal-cutting tools [2, 6, 10, 18, 20], evaluation of the metal cutting quality [8], and the problem of optimal application of cutting fluids [4, 12], study of residual surface stresses in metal cutting [3], as well as modeling the cutting process [11, 14, 15], including the use of modern numerical methods [5, 7, 19].

One of the perspective directions of developing the theory of cutting is studying the effect of cutting force reduction under treating “strengthened” (mechanically strengthened) metals from the standpoint of the plastic deformation balance, which was first explained by Ya.G. Usachev [21]. He wrote that: “before the metal collapses, it goes through all the stages of hardening. The fracture of metal will occur at the moment when strengthening reaches the greatest value. To fracture the metal, already strengthened to some extent, it needs to be less deformed than the unstrengthened metal by the amount corresponding to the preliminary strengthening.” And further: “the difference of works will be equal to the work that is required to bring the sample metal to this degree of strengthening.”

However, experiments of hardened and annealed samples with broaching to failure, did not confirm this last conclusion. The work spent on rupturing non-strengthened samples was four times as high as the work spent on strengthened samples, and when cutting this excess was from 1.1 to 1.4 times.

2. Dislocation model

According to A.M. Kuznetsov, the theory of dislocations explains the process of improving metal machinability by cutting after applying the cold plastic deformation. [22].

The authors differentiate 3 stages of hardening at applying the deformation stress on the metal. In the first stage of hardening, voltage is applied and the microscopic limit of elasticity is achieved. So, the source of dislocations begins to operate, generating loops of dislocations moving under the action of stress in the sweeping plane [23].

Step occurs in the last loop when the loops achieve the surface of the crystal. The part of the loops is delayed in the sweeping plane and generates a reverse voltage that impedes the action of the source. The sliding line can grow under the influence of constantly applied voltage. And if the voltage is sufficient, the source can send new loops that pass freely through the entire sweeping plane.

Since new obstacles do not arise due to the lack of dislocation forest (sliding occurs only along one system of planes). This process can be repeated at the same voltage level. That’s why hardening is
little at the first stage under the shear conditions. The height of the step is usually small 50-100 Å, while a sliding line length is 1 mm.

According to Hirsch the transition from stage I to stage II occurs at a time when the distance between the dipole accumulations becomes very small, and the internal stresses caused by heaps of dislocations, together with the applied voltage become sufficient for the occurrence of dislocations in the secondary system. In the second stage, the sliding lines are shorter and less regular than in the first stage. Studying the dislocation structure of copper shows that here there are plexuses of dipoles with the forest dislocation, resulting in an irregular grid of dislocations. The average density of dislocations reaches 1016 cm\(^{-2}\) by the end of the stage. The density of dislocations in the annealed material is on average 106-108 cm\(^{-2}\). The beginning of the second stage corresponds to the catastrophic avalanche-like process of dislocations generated by Frank Reed’s sources in the secondary system of sweeping planes. As a result, a large number of sedentary dislocations are formed, which are effective barriers for passing new dislocations, i.e. there appear their piles. The number of dislocations increases in proportion to the strain.

The third stage is characterized by the development of slip bands, the length of which depends on the magnitude of the previous deformation. At a certain stage, developing transverse sliding is observed, in this case, the slip strips expand slightly. As a result of the dislocations accumulation in front of the obstacle, the shift in the original sweeping plane can be slowed down. Screw dislocations can move to the adjacent parallel plane by means of cross-sliding under certain conditions, and this plane forms a new source, which under the action of the applied voltage generates additionally a number of dislocations and thereby provides a plastic shift. At this stage, the coefficient of strengthening decreases in comparison with the observed coefficient at the second stage, as a result, the intensity of the flow resistance growth decreases. At the third stage, the dislocation structure of the crystal depends not only on the magnitude of the stress or strain, but also on the stress state.

The nucleation or presence of dislocations in the crystal does not directly lead to violating the crystal lattice continuity, i.e. to forming a free surface (submicrocrack). However, the atomic layers at the dislocation place are elastically distorted in such a way that there is a local stress concentration.

Dislocation serves as the elastic deformation center. Distancing from this center stress concentration decreases according to the law L/r. Dislocations, in which Burgers vector is located in the sweeping plane, are quite mobile and under the action of the applied stress move in the sweeping plane, so that a plastic shift occurs. Dislocations are able to multiply in the plastic deformation process, the number of them in the metal increases by many orders of magnitude. In the undeformed metal dislocation density is 106-108 cm\(^{-2}\), in the metal strengthened by plastic deformation dislocation density reaches 1011-1012 cm\(^{-2}\).

The free energy of the crystal lattice increases in the dislocation area. Therefore, the dislocation itself is a thermodynamically unstable formation, but because of the balance of forces acting on the dislocation, it will be in some metastable state. To remove it from this state, it is necessary to energize additionally from the outside (for example, to give thermal energy). The energy of the crystal will decrease, and the dislocation will either move to a new metastable state, or leave the crystal.

The convergence of dislocations of different signs leads to their annihilation, and that of one sign leads to increasing the stress concentration, because the fields of one sign repel. The energy of the crystal in the general case increases due to the free energy increase of each dislocation and due to the interaction of dislocation fields and dislocations with crystal interfaces and foreign phases.

Dislocations moving in the crystal, give rise to defects, which arise by the mutual intersection of dislocations and the diffraction of their small inclusions. These defects, dislocated atoms and vacancies, cause the formation of submicrocracks and, ultimately, lead to the material destruction.

There are three types of mechanisms for forming microcracks:
1. Dislocation reaches a critical value in the same sweeping plane
2. Piles of dislocations occur due to their interaction in the intersecting sweeping planes.
3. Cracks are formed as a result of interacting defects in the crystal lattice of vacancies and dislocations.
For example, Stroh and Griffiths suggested that a crack should occur if its formation leads to a decrease in the energy of the lattice distortion, and the fracture should occur when the elastic energy in magnitude exceeds the surface energy required for forming the crack.

Pitch suggested that brittle fracture should occur at a time when theoretical strength exceeds as a result of piling dislocations.

Gilman in the zinc single crystal made an artificial obstacle in the form of a brass bracket, which served as a reliable barrier to advancing dislocations on the shear planes, because the yield point of brass is higher than that of zinc. As a result of the sweeping plane at an obstacle of a heap, there was a weakened layer which opened in a crack under the action of the broaching component which was approximately perpendicular to the sweeping plane.

Not yet proven, but noteworthy, is Price model, in which the origin of the crack occurs due to the local combination of dislocations moving in parallel sweeping planes, which can create areas that combine large internal stresses near the source.

Despite the fact that most of the models leading to various mechanisms of brittle crack nucleation have not yet been confirmed experimentally, it is doubtless that they are the main factor of merging cracks leading to brittle fracture. The possibility of closing and self-healing microcracks, determines rather a low efficiency of the destruction process.

When cutting metals, the energy goes mainly to deforming the adjacent zone, and only a negligible part goes to increasing the system surface energy, i.e. to forming the main crack, leading to separating the material layer. The total energy of destruction exceeds the surface energy by more than 3 orders of magnitude. As the deformation degree increases, the cracks lose their “stability” and the subsequent cutting of such a layer leads to individual microfractures merging into a macrofracture under the action of the cutting tooth.

With the preliminary surface plastic deformation, transverse cracks are gradually moving in the macrocracks, while under the repeated stress they are moving in the longitudinal ones, thereby forming a scaly exfoliation.

The maximum values of the submicrocrack density should, obviously, be in the zone having the maximum value of microhardness, as this is where the maximum density of dislocations is. It should be noted that neither the direction of the microcracks, nor the nature of changes in their depth density relating to the surface plastic deformation has been studied in detail, although this is important to determine the reduction of energy consumption for cutting at advanced deformation.

3. The model considering the depletion of the plasticity resource at different damage accumulation

The accumulation of microcracks in any type of plastic deformation, including cutting, depends on the damage accumulation [24]. Damage accumulation is associated with both the degree of deformation and loading conditions, which are determined by many factors, including the stress state and loading history. The dynamics of the microcrack accumulation is influenced by the sign and the value of the hydrostatic pressure, with the growth of which the intensity of healing the microcracks increases and the efficiency of the destruction process decreases.

In recent years, much attention has been paid to the combined machining with advanced deformation (MAD), such as dimensional combined machining by rolling and deforming-cutting broaching [25, 26]. However, there is still no reliable and valid mathematical apparatus for calculating the reduction of cutting force in MAD. The reason for this is that while the complex deforming action and cutting there are different mechanisms of damage accumulation with different indicators of the stress state, which must be taken into account. In addition, when developing a model of the cutting process with MAD (Fig. 1), it is necessary to lead the damage accumulated during the advanced deformation (curve 1) to the damage accumulated during the cutting (curve 2) [24], through the plasticity diagram of the processed material (curve 3), which determines the degree of shear deformation corresponding to the moment of the material destruction depending on the stress state.
At first, the process of damage accumulation of the preliminary deformation takes place along curve 1 with the stress state $\sigma / T$ less than the stress state of the cutting process, and then along curve 2 with a large value of $\sigma / T$.

Thus, in the work balance model it is necessary to take into account not all the work of pre-plastic deformation and the corresponding shear deformation, but only a part with a smaller value of shear deformation.

For example, while having deforming-cutting broaching with MAD and elastic-plastic loading (EPL) [26], first there is damage accumulation to the corresponding MAD process with a negative stress state indicator-$\sigma / T$, since there is a deforming element before the cutting-deforming tooth in the course of broaching. Further, a deforming-cutting element enters the treatment zone, at the same time, the deformed layer starts broaching in the cutting zone. There is significantly reduced the magnitude of the shear deformation degree of the corresponding damage accumulated earlier in the MAD, rendering into a positive indicator of the stress state characteristic of uniaxial tension. Elastic-plastically broached layer of metal, located between the cutting teeth acquires additional damage under the stress state characteristic of the uniaxial tension process. The cutting tooth, located between the deforming, cuts the broached surface layer, with a new value of $\sigma / T$, characteristic of cutting the broached layer. The known index of the stress state of the cutting process is corrected using the principle of superposition, i.e. imposing additional tension on one of the axes. The total adjusted degree of shear strain corresponding to the cutting with MAD and EPL are used in the model of the work balance proposed by Ya.G. Usachev.

**Conclusion**

From the position of the dislocation theory and plastic deformation balance, theoretical studies do not fully identify and explain the reasons for improving the machinability of materials by cutting while these materials were pre-treated with surface plastic deformation.

Promising models for calculating the machinability of cutting with MAD and EPL should take into account the change in the stress state and the history of damage accumulation considering the change
in the stress state and the corresponding change in the shear deformation degree at each stage of the combined action.

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