Journal of Engineering Physics and Thermophysics, Vol. 78, No. 3, 2005

INFLUENCE OF VIBROSHOCK INTERACTION BETWEEN A CUTTING TOOL AND THE PROCESSED BILLET ON THE CONDITIONS OF FORMATION OF ITS ROUGHNESS IN MECHANICAL SAWING OF BRITTLE AND HARD MATERIALS

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UDC 621.9.048.4

A modernized unit of the ShP-2 sawing machine for vibroshock sawing of hard and brittle materials in three modes of vibrodrive operation has been described. The mechanism for forming the roughness of the sawn surface is presented. The data that allow judgment on the effect of the vibroshock mode of processing brittle materials on the parameters characterizing initial roughness of the sawn surface are obtained from results of the experiments. Based on these data, formation of the topography of the processed parts of billets made from a hard material is analyzed.

In manufacturing products from precious stones, including diamond monocrystals, which are among the a group of brittle materials, mechanical sawing of them is a typical operation. Along with high efficiency, this operation must guarantee a minimum surface roughness of the sawn billets. This requirement is dictated by the necessity of minimizing irrevocable losses of expensive raw materials due to a decrease of tolerance removed at the subsequent stage of polishing the sites of the sawn half-products.

As is known [1, 2], by introducing forced vibrations into the zone of cutting it is possible to substantially affect the output parameters of the process at the expense of variation of the direction of their action and intensity. Previous studies [3] showed that, as applied to mechanical sawing of gems, forced vibrations must be transferred to the processed billet in the direction perpendicular to the end (cutting) surface of the sawing disk. Here it is found that the enhancing effect of such vibrations on improvement of the efficiency and change of the roughness of the surface of sawn specimens manifests itself only when the vibroshock mode of processing is used. In this case, interaction between the end surface of the sawing disk and the processed billet is characterized by a periodic breaking of their contact with subsequent collision. Simultaneously, the conditions of interactions of the side surfaces of the sawing disk with the already-sawn surface of the billet change, which is caused by the presence of additional relative vibrational displacements of them acting in the contact plane and directed along the disk radius. The mentioned special features of the vibroshock regime of sawing results in changes in the mechanism of billet material failure, which, in turn, leads to variation of the conditions of roughness formation on the processed surfaces.

In order to reveal these special features, we conducted a complex of comparative experimental studies on sawing of specimens in both ordinary and vibroshock conditions of processing.

The experiments were conducted on the commercial unit of the ShP-2 machine used for mechanical sawing of diamond monocrystals. A vibrodrive was additionally introduced to its structural scheme, shown in Fig. 1. A DPM-25-N1-03 d.c. microelectric motor fastened on the upper plane of the boom between the adjusting screw and the processed billet was used as the vibrodrive. To excite vibrations, an angle with unbalanced mass was placed on the output shaft of the electric motor. Since, in the process of sawing, the boom, via the adjusting screw, bears against the elastic laying, in rotation of an unbalanced mass the boom, together with the billet, executes vibrational displacements in the direction perpendicular to the end (cutting) surface of the sawing disk. The amplitude and frequency of these displacements were adjusted by varying the value and position of the unbalanced mass relative to the axis of the shaft and frequency of its rotation. The data that characterize the main parameters of the vibrodrive used are given in Table 1.

It should be noted that mode 1 of vibrodrive operation corresponds to resonance of the setup, which explains the large value of the amplitude of vibrational displacements of the billet. Mode 2 is characterized by a doubled, com-

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Belorussian National Technical University, 65 F. Skorina Ave., Minsk, 220013, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 78, No. 3, pp. 171–176, May–June, 2005. Original article submitted May 19, 2004.

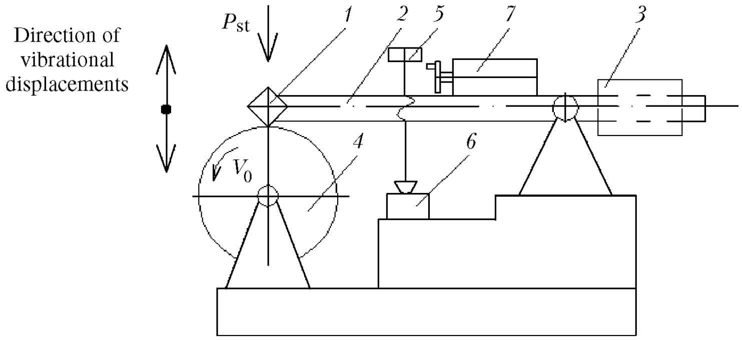

Fig. 1. Schematic diagram of the experimental unit for sawing brittle materials in a vibroshock mode: 1) processed billet; 2) boom; 3) counterweight; 4) sawing disk; 5) adjusting screw; 6) elastic laying; 7) vibrodrive.

TABLE 1. Main Parameters of the Vibrodrive in the Three Modes of Operation

Mode of vibrodrive operation	n, rpm	f, Hz	A, μm	V_{0vib}, m/min	a_{0vib}, m/sec^2
1	2480	41.3	87.4	1.38	5.88
2	5110	85.2	32.4	1.07	9.29
3	6049	100.8	25.3	0.96	10.14

pared to mode 1, frequency of forced vibrations, i.e., it is a multiple of resonance. The vibroshock mode 3 is obtained at a maximum frequency of rotation of the vibrodrive electric motor, and the highest frequency of excited vibrations is typical of it. We also note that, according to the data presented in Table 1, the amplitude of vibrational speed decreases and that of vibrational acceleration increases with increase in the mode number.

The experiments on sawing were conducted with specimens made of synthetic corundum and glass K8. The choice of glass specimens is justified by the convenience of investigation of failure products the particle size of which is larger than that of corundum, thus making simpler the procedure of their collection during sawing and improving the accuracy of subsequent evaluation of their geometric parameters. Specimens in the form of cubes with a side of 5 mm were made from the mentioned materials by mechanical processing. They were fastened on the mandrels of the sawing unit so that sawing of specimens started from the cube edge, similar to the procedure of separation of diamond crystals.

Glass specimens were sawn by a steel cutting disk (diameter 76 mm and thickness 0.7 mm) on the side surfaces of which a diamond-bearing layer with graininess 20/14 was formed by the galvanoplastics method. For sawing the synthetic corundum specimens use was made of bronze sawing disks (diameter 76 mm and thickness 0.05 mm), which are applied for separation of diamond monocrystals. During sawing, the end surface of the specimens was charged by ASN 20/14 diamond powder.

In the experiments, the specimens were sawn both under traditional conditions of processing and under forced vibrations in three modes of vibrodrive operation. The frequency of tool rotation n was constant and equal to 12,000 rpm. Static loading on the specimen P_{st} varied and amounted to 2.10, 3.06, and 4.00 N.

We note some special features in formation of the roughness of the sawn surface of the specimen, which are caused by the technological scheme of the processing itself. In contrast to metal-cutting tools of the type of disk mills, saw blades, and saws, the end surface of the sawing disk does not have regularly positioned cutting teeth that are set properly. Therefore, in sawing, as the disk goes deeper into the billet material the sawn parts of the billet tend to close up at the expense of internal stresses. As a result, the value of forces acting along the normal to the side surfaces of the disk increases, thus causing a constant sliding contact with the processed parts of the billet.

Proceeding from the abovesaid, the mechanism of roughness formation on the sawn surface can be presented as follows. Due to mechanical interaction of the end (cutting) surface of the sawing disk with the billet, spalling (brittle failure) of particles of the billet material occurs in the contact zones adjacent to the disk edges; as a result, microasperities that form the so-called initial roughness appear on the sawn surface.

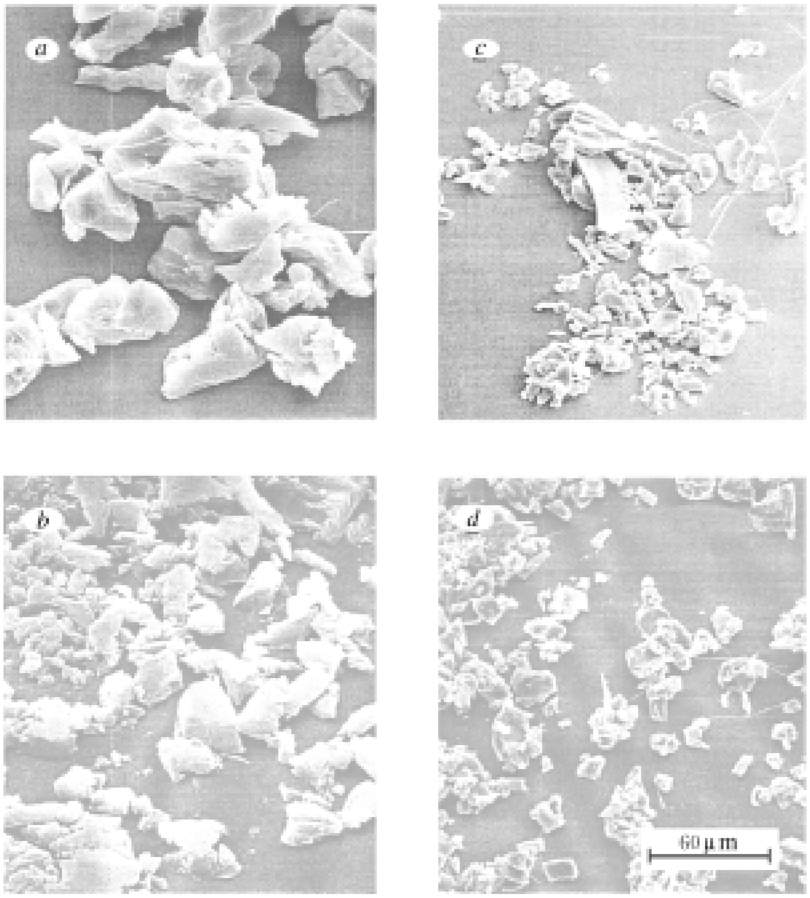

Fig. 2. Photos of the failure products in sawing of glass specimens: a) ordinary operation conditions; b) vibroshock mode 1; c) vibroshock mode 2; d) vibroshock mode 3. ×500.

As the disk goes deeper into the billet, the sawn portions come in contact with the disk side surfaces and are subject to wear due to sliding friction of the interacting surfaces. During the whole operation this is accompanied by variation of the initial roughness of the surfaces of the billet sawn portions. The character of variation of the initial roughness will be determined by the conditions of processing, in particular, by the predominant shape of the wear of frictional surfaces, pressure on the contact sites, sliding velocity, and duration of their interaction, which is equal to the length of relative sliding of the contact surfaces.

The formation of initial roughness on the processed surface of the billet can be indirectly evaluated by the particle size of the billet material in the failure products. It is clear that the larger the particles, the higher the degree of billet material failure in the contact zones adjacent to the edges of the sawing disk and, correspondingly, the higher the value of the initial roughness formed in these zones.

Figure 2 shows photos of the products of glass-specimen failure in sawing of them both under ordinary conditions and in the three vibroshock modes of processing. It is seen that the largest mean size of glass particles is observed in traditional sawing (Fig. 2a) when constant mechanical contact takes place between the end surface of the disk and the processed billet. If sawing occurs in the vibroshock mode, then in all cases the mean size of particles in the failure products turns out to be smaller compared with traditional processing. This is explained by the fact that in this mode of sawing, interaction between the end surface of the disk and the billet processed occurs under the conditions of their periodic collision. As a result, the process of billet-material failure takes place under the effect of pulse loads, which leads to variation of particle parameters in the products of processing.

Proceeding from the propositions of the theory of brittle failure [4, 5], we can state that, in sawing under vibroshock conditions, the shape and size of the particles split off of the billet surface are, first of all, determined by the degree of development of microcracks in the pre-failed layer. In this case, the depth of the layer and the degree of development of microcracks in it are determined by the intensity of the vibroshock mode of sawing, which is characterized by the amplitude and frequency of vibrations imparted to the billet. Thus, sawing of glass specimens in vibroshock mode 1 is characterized by formation of particles with a wide range of linear dimensions (Fig. 2b), with the size of large particles being close to the dimensions of particles obtained in traditional sawing. This situation is explained by the parameters of excited vibrations typical of the considered vibroshock mode of sawing. In particular, a large amplitude of vibrations causes formation of the pre-failed layer of large depth on the billet surface, but due to the low frequency of these vibrations the degree of development of microcracks in the layer appears to be low. Therefore, in sawing of the processed material in this mode there takes place spalling of particles of much larger size.

On sawing in modes 2 and 3 (Fig. 2c and d), a large number of small glass particles appear in the failure products. This is due to the fact that, as the frequency of vibrations increases and their amplitude decreases, the depth of the pre-failed layer on the billet decreases. However, simultaneously the degree of development of the network of microcracks in it, which are responsible for the dimensions of the material particles split off during sawing, increases.

Thus, based on the results obtained, one can state that, compared to traditional sawing, sawing of brittle material under vibroshock conditions leads to a decrease in the initial roughness of the billet surface.

As has already been mentioned, as the disk goes deeper into the billet, the sawn parts of it come in sliding contact with the side surfaces of the tool and, as a result of their wear due to friction, the initial roughness changes. It is evident that the degree of this variation will be determined by the form and the period of wear of the contact surfaces and also by kinematic and dynamic conditions of their relative sliding. Thus, in vibroshock sawing, the process of sliding friction of the sawn surface of the billet relative to the side surfaces of the disk is accompanied by additional vibrational microdisplacements acting in parallel to the contact surface and perpendicular to the vector of the cutting speed. This leads to enhancement of the process of wear due to an increase in the path of relative sliding of the surfaces passed per time unit compared with traditional sawing [2].

As the parameter characterizing the degree of this increment, we can use the value of the so-called velocity coefficient $k_v = V_{0\text{vib}}/V_0 = 2\pi fA/(\omega R)$. In this case, the smaller the value of k_v, the higher the degree of the increment of the friction path and, correspondingly, the higher the degree of the intensifying effect of vibrations on the process of wear of the contact surface. Here we should note that, at a constant value of $V_{0\text{vib}}$, the value k_v over the depth of the saw cut changes from the smallest on the periphery of the sawing disk, where V_0 is maximum, to the highest on the sections corresponding to the beginning of sawing where the speed of cutting is the smallest. If we assume that the increment of the path of relative sliding of the surfaces is accompanied by proportional intensification of the polishing effect, i.e., smoothing of microasperities, then we can expect that in vibrational processing the roughness of the sawn billet turns out to be smaller than its values under traditional conditions of operation.

To estimate the degree of the effect of the vibroshock mode of processing on formation of the topography of the sawn surface, experiments on specimens made of synthetic corundum were conducted. In this case, they were sawn with periodic application of the grains of diamond micropowders on the end surface of the disk, i.e., with slight charging. The presence of free diamond particles in the zone of processing allowed one to follow in more detail the effect of vibrations on the formation of traces of wear on the sawn surfaces of the specimen.

Figure 3 presents photos of the parts of the sawn surfaces of the specimens made of synthetic corundum obtained under both ordinary conditions of processing and using three vibroshock modes of vibrodrive operation. In all photos, feeding was executed in the direction from the lower right corner to the upper left one.

In traditional sawing (Fig. 3a), monodirectional marks are formed on the processed surface of the specimen; these marks are the traces of abrasive wear of the surface by the grains of diamond micropowders fastened (charged) on the side surface of the tool. This is explained by the fact that with such kinematics and dynamics of interaction of side surfaces of the disk with the sawn parts of the billet, the diamond grains that get into the gap between the contact surfaces are of limited mobility and thus are incorporated in the surface of the bronze disk, whose hardness is much lower than that of corundum.

Under the conditions of vibroshock sawing in resonance mode 1, a set of intersecting traces of processing is formed on the surface (Fig. 3b); some of these traces coincide in direction with the vector of the cutting speed, others are perpendicular to it. The formation of such a surface topography is related to the presence of additional vibrational displacements of the billet with a large value of the amplitude, which is typical of just the resonance mode of vibro-

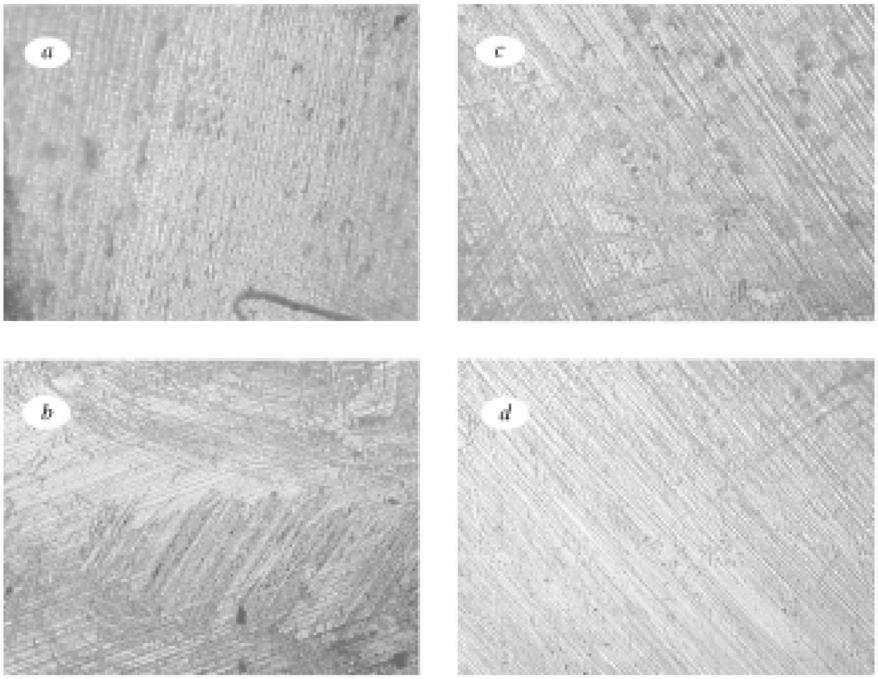

Fig. 3. Photos of the sawn surface of the corundum specimens: a) traditional sawing; b) vibroshock mode 1; c) vibroshock mode 2; d) vibroshock mode 3. ×200.

drive operation. As a result, grains of diamond micropowders charged into the side surface of the disk execute abrasive failure of the billet surface, marking it by an intersecting net of traces. Moreover, mobility of diamond particles in the zone of processing increases due to the action of alternating dynamic loads. This is manifested in constant reorientation of them and change of the position in the contact zone, which, in turn, leads to non-recurrence of the processing traces on the sawn surface. Simultaneously, under the action of vibration, the degree of mechanical effect of free diamond particles, which are in the zone of sliding contact, on the processed surface is substantially intensified. These particles cause salding of minute corundum particles, as if protecting the sawn surface and leading to decrease of its roughness.

On sawing in vibroshock mode 2, clearly pronounced intersecting traces of processing are absent on the billet surface (Fig. 3c). In this case, predominantly monodirectional traces, which coincide in direction with the vector of the sliding speed and are intersected by perpendicularly directed scanty and chaotically oriented marks, are formed on this surface. In contrast to the previous mode, the vibroshock mode of sawing under consideration is characterized by a higher frequency of billet vibrations at a smaller value of the amplitude of its vibrational displacements. In this case, the amplitude of the vibrational speed turns out to be smaller than its value corresponding to vibroshock sawing in mode 1. Therefore, the value of the velocity coefficient k_v, which characterizes the degree of the effect of vibrations on the increase in the friction path and, correspondingly, on the decrease of the initial roughness of the sawn surface, also appears to be smaller than in the previous case. At the same time, a higher level of dynamic loads acting in the zone of sliding contact is typical of vibroshock mode 2; this is caused by the high value of the amplitude of vibrational acceleration. This, in turn, leads to more intense failure of grains of diamond micropowders, which is accompanied by a decrease in the size of the particles of the split-off material of the billet (Fig. 2c) and corresponding decrease in the roughness of the sawn surface. The presence of chaotically oriented short marks on the surface is probably related to the effect of free diamond particles, which, under the effect of centrifugal forces, are carried away from the sliding contact zone.

Figure 3d gives a photo of the surface of the corundum billet sawn in vibroshock mode 3. It is seen that its topography is very similar to that of the sawn surface obtained in vibroshock mode 2, with the only difference being that monodirectional traces of processing turn out to be more pronounced and the number of transverse marks is much smaller. As compared with the above-considered mode, this mode of vibroshock sawing has the highest frequency of vibrations at the smallest amplitude of vibrational displacements. Such a ratio of these parameters determines the minimum value of the vibrational speed and the maximum value of the amplitude of vibrational acceleration. Under these conditions, the process of failure of grains of diamond micropowders in the sliding contact zone is more intense. This, as has been noted above, leads to a decrease in the size of the particles carried away from the billet surface by crushed diamond grains, thus causing a decrease in its roughness. In this case, small values of the amplitude of vibrational displacements do not allow diamond particles to make relative displacements in the direction perpendicular to the vector of the sliding speed which is the reason for the formation of monodirectional traces of processing on the sawn surface.

CONCLUSIONS

1. It is shown that formation of the roughness of sawn surfaces of a billet made from brittle materials involves two successive stages. In the first stage, the initial roughness, the parameters of which are determined by the size of particles split off from the billet in the zones of its contact with the end surfaces of the sawing disk, is formed. In the second stage, the sawn portions of the billet surface are worn due to friction as a result of their interaction with the side surfaces of the sawing disk, which is accompanied by changes in the initial roughness.

2. It is found that, compared with traditional sawing of brittle materials, use of the vibroshock mode of processing leads to a decrease in the initial roughness of the surface on the billet. The mechanism of this decrease lies in the fact that, due to periodic shock interaction between the end surface of the tool and the billet material, the process of development of microcracks in its pre-failed layer is enhanced. As a result, the size of split particles of the material turns out to be smaller than in traditional sawing and, correspondingly, the initial roughness of the processed surface of the billet decreases.

3. It is shown that formation of the final roughness of the sawn surface of the billet is determined by the conditions of its interaction with the side surfaces of the tool. It is found that in the vibroshock mode of processing the character of the topography on the sawn surface of the billet depends on the ratio of amplitudes of the vibrational speed and vibrational acceleration imparted to the billet. In this case, the first parameter exerts a p rincipal effect on the degree of mobility of grains of diamond micropowders in the sliding contact zone, thus causing a decrease in roughness due to a decrease in the size of material particles split off from the billet.

NOTATION

A, amplitude of vibrational displacements, μm; $a_{0\text{vib}}$, amplitude of vibrational acceleration, m^2/sec; f, frequency of billet vibrations, Hz; k_v, velocity coefficient; n, frequency of rotation of the shaft of the electric motor, min^{-1}; P_st, static load on the crystal, N; R, radius of the sawing disk, mm; V_0, cutting speed, m/sec; $V_{0\text{vib}}$, amplitude value of the vibrational speed, m/min; ω, angular velocity of rotation of the sawing disk, rad/sec. Indices: v, velocity; vib, vibrational; s, static.

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