Theoretical and Experimental Analyses of the Sawing Process for Hard and Ultra-Hard Materials

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***Abstract*—The justification of the correctness of the selected regimes for silicate glass, leucosapphire, and diamondite sawing based on the finite element modeling of friction node deformation is given. The natural oscillation frequencies for the shaft with the saw disk and the forms of stability loss are observed. The analysis of the temperature fields recorded during the sawing process is performed for the hardest sample (diamond). The nature of destruction for the side surfaces of the sawn pieces is analyzed.**

***Index Terms*—sawing process, diamond, silicate glass, sapphire, eigenfrequencies, stability, surface destruction, temperature**

I. Introduction

The classical concept of the crystal sawing process involves the abrasive wear of the workpiece by solid particles of the abrasive fixed on a saw disk surface [1]. There are a number of studies dedicated to both improvements in the mechanical splitting of workpieces into parts, for example, by creating forced disk vibrations [2], as well as the development of new methods, such as hydroabrasive processing by high-speed liquid flow with abrasive particles [3] and laser thermocleaving of workpieces from hard and ultra-hard materials [4]. Newly developed methods have a number of drawbacks (heavy gage of cut, significant losses of raw materials, difficulties in controlling the shape of the surface splitting the workpiece into parts, etc.). Therefore, until now, the most widespread technique is mechanically charged disk sawing.

One of the main problems in the mechanical splitting of workpieces is the curvature of the disk shape under increased load and the speed of rotation. In this case, there is the possibility of the side surfaces of the sawn workpiece interacting with the curvilinear surface of the disk, causing pulse-changing cyclic temperature and mechanical stresses that lead to workpiece fatigue cracks propagating perpendicular to the cutting surface and deteriorating its quality [5]. The presence of cracks and areas of chipping in the workpiece material require the removal of a sufficiently thick layer during follow-up operations. At the same time, there is an increase of raw material losses as well as time and money spent on additional processing.

Further, there are studies dedicated to the analysis of workpiece sawing. However, they consider situations when the saw disk has greater hardness than the cutting material [6, 7]. For example, the thermal processes occurring during frictional contact are studied in [8, 9]. At the present time, only some phenomena observed during the sawing of workpieces from hard and ultra-hard materials have been studied [10, 11, 12].

The purpose of the present paper is to justify the loading conditions of the saw disk in the case of the splitting of leucosapphire, diamondite, and silicate glass, as well as to analyze the influence of thermal processes on the destruction of the side surfaces of the saw cut.

II. Experimental Techniques

The sawing of leucosapphire is carried out on a saw disk–workpiece butt-end high-speed machine (Fig. 1) [13]. Samples of sapphire (2)—cylindrical plates with a diameter of 18 mm and height of 1 mm—are installed on a work-holder (3) and fixed by a clamping device (1). The saw disk (4) with a diameter of 76 mm and thickness of 0.07 mm is made of bronze BrOF 6.5-0.15. With the help of technological equipment, the cylindrical surface of the disk is charged with diamond powder ASN20/14 (dispersity: 14–20 microns).

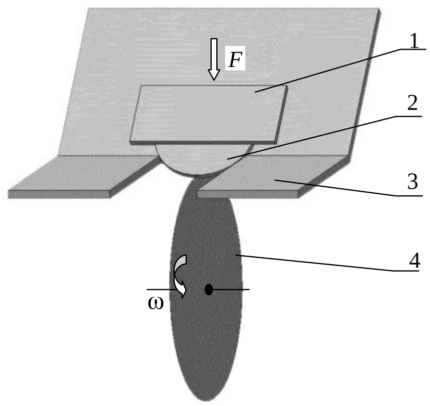

Figure 1. Schematic of the disk–sample contact when sawing sapphire: 1: clamping mechanism; 2: sample; 3: work-holder; and 4: saw disk

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Before and during the test, the cutting edge of the disk is charged with a mixture of diamond powder and castor oil every 2–3 min. The linear velocity of the points of the saw-disk working surface during the tests with sapphire and silicate glass samples are varied in the range of 10–30 m/s. The nominal load on the disk is selected as 0.22, 0.65, 0.43, or 0.87 N. The test duration is either for about 60 s or until the sample integrity is lost.

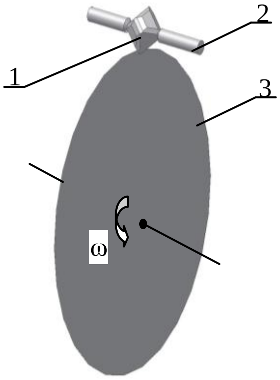


Figure 2. Scheme of diamond–disk contact when sawing; 1: diamond crystal; 2: work-holder; and 3: saw disk

The contact scheme of the saw disk with a diamond monocrystal is shown in Fig. 2. The saw disk (3), abrasive powder, technology, and charging frequency used are the same as that when sawing sapphire. The diamond workpiece (1) has been marked, fixed in a work-holder (2), and oriented; then, the workpiece is undercut and sawing is undertaken. The rotation speed of the work spindle, n, is 12,000 rpm, which corresponds to a linear velocity of the disk working surface point, v = 42.6 m/s. The load F is varied within 0.43–2.4 N. The duration of the tests has been determined by the technological time of the full sawing of the diamond crystal.

III. Finite Element Model

In order to determine the frequencies of the natural oscillations of the sawing tool as well as the critical force by the criterion of disk stability, a finite element model of the shaft with a saw disk has been created using ANSYS software, similar to that in [14]. One of the ways to do this is to create a three-dimensional model according to which the key points and lines defining the shape of half of the cross-section of the shaft including its axis of symmetry constructed along the coordinates have been chosen. Areas are created from the given figures. To obtain a three-dimensional model, the constructed section is rotated around the axis of rotation (here, the X axis).

To resolve the problem involving linear elastic strains, the materials' properties are assigned by using the (Structural-Linear-Elastic-Isotropic) option. The developed model considers two materials: bronze and steel (saw disk: bronze; all other volumes: steel). For the first material (bronze), the Young's modulus, E_1 = 9.5 GPa; Poisson's ratio, ν_1 = 0.35; and density, ρ_1 = 8900 kg/m^3. For steel, the parameters are as follows: Young's modulus, E_2 = 200 GPa; Poisson's ratio, ν_2 = 0.35; and density, ρ_2 = 7800 kg/m^3.

When creating a finite element model, an 8-node volumetric element SOLID185 is used. The finite element mesh has been created in the automatic mode. A visual inspection shows that the most interesting aspect for analyzing the protruding area of the saw disk is that it has been divided into six parts in the radial direction, which is enough to calculate disk bending. The total number of finite elements is 73,000, and the total number of equations is 230,000. The given finite element model is shown in Fig. 3.

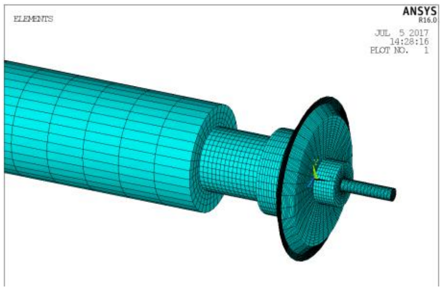


Figure 3. Finite element model of the shaft with the disk

When setting the boundary conditions, the movement of four points of the shaft located in the sections corresponding to the locations of the bearings in the radial direction is forbidden and so is the displacement along the X axis for two points of the section of the bearing close to the location of the saw disk. Thus, the fastening conditions corresponding to the real deformation of the shaft in the bearings have been created.

IV. Analysis for Eigenfrequencies

When calculating the frequencies of the natural oscillations of the shaft with the disk, an option to find 10 lowest frequency oscillations from the range of 0–10,000 Hz has been chosen.

Modeling the process of rotation for the geometrical model of the sawing unit shows that the first natural frequency appears at a rotation speed equal to 1,250 Hz. As evident from Fig. 4 where the form of shaft vibrations equal to the indicated frequency is shown, the structural deformation in this case is determined by the stiffness of the shaft. The amplitudes of oscillations of the disk are insignificant. Subsequent vibration frequencies of 1959 and 2321 Hz are also associated with the deformation of the shaft with the disk assembly. Further, only when the frequencies are 2686 and 2862 Hz, the forms of oscillations caused mainly by the bending of the disk appear (Fig. 5).

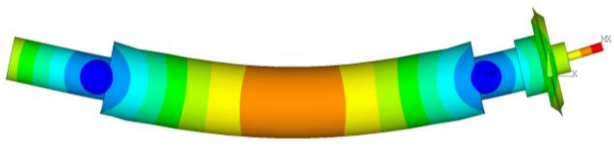
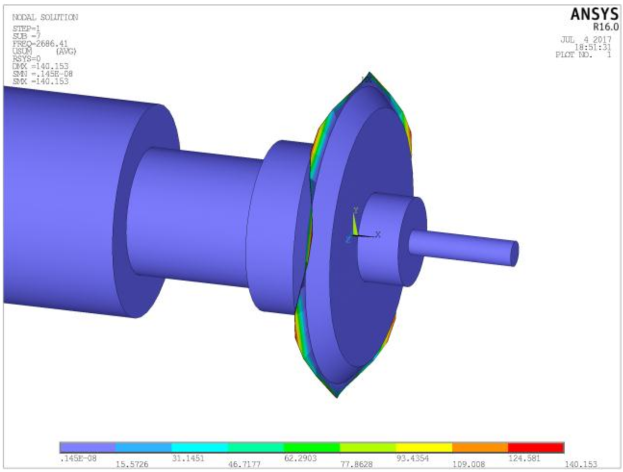
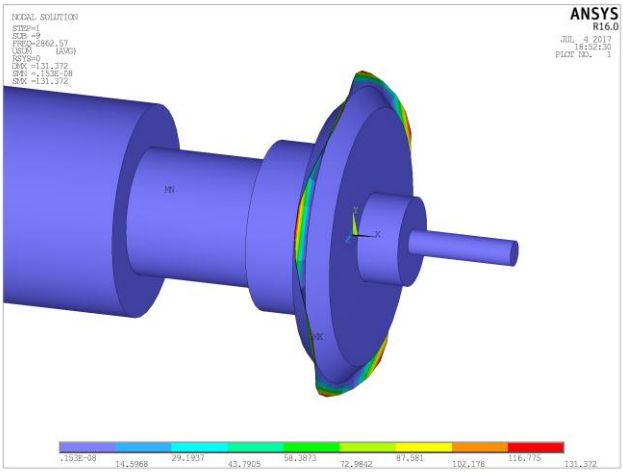


Figure 4. Natural form of oscillations for the shaft with a disk, equal to a frequency of 1250 Hz



(a)



(b)

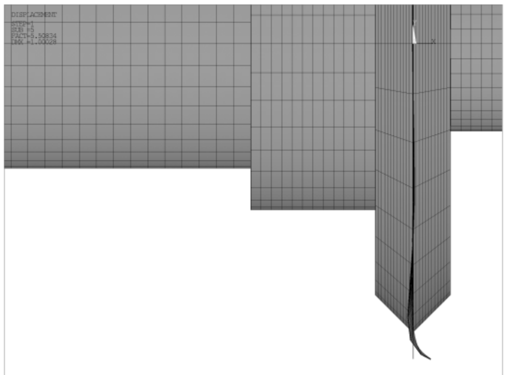
Figure 5. Forms of oscillations equal to eigenfrequencies: (a) 2686 Hz; (b) 2862 Hz

The determined eigenfrequencies correspond to the resonances under forced oscillations. When the load is applied at these frequencies during processing, the probability of breaking the saw disk due to scoring or uncontrolled destruction of the workpiece increases dramatically. The calculation results show that the appearance of resonances when materials are being sawn is primarily determined by the deformations of the shaft. Disk hardness is sufficient to ensure the necessary sawing accuracy. Since the maximum rotational speeds of the shaft at which the sawing is performed correspond to 100 Hz, random oscillations arising in the process of sawing due to imperfections in the bearing assemblies will not lead to resonances.

V. Defining of Critical Force

To define the critical force at which a non-planar form of stable disk equilibrium arises, a concentrated force equal to 1 N lying in the plane of the disk and passing through its center has been applied to its rim. The calculation results show that the minimum safety factor of stability in this case is 5.5. It corresponds to a critical force value of 5.5 N at which an unstable equilibrium form appears, as shown in Fig. 6, *a*. With a further increase in the pressing force of the disk to the object being processed, new forms of unstable equilibrium may appear, as shown in Fig. 6, *b-c*, and the number of waves on the surface of the disk may differ.

The obtained result shows that for pressing forces not exceeding 5 N, because of insignificant oscillations of the applied load (both in magnitude and direction) leading to the exit of disk points from its plane, the original disk form is restored. In particular, such a situation will be observed when there is an interaction of sapphire and diamond because of the much greater hardness of the sawing counterbody as compared to the bronze saw disk. However, these deformations have an elastic characteristic and are realized only at the load action time. In the contact exit zone, the saw disk will resiliently restore its original shape.



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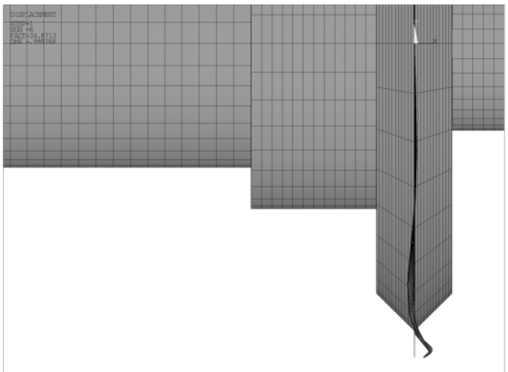

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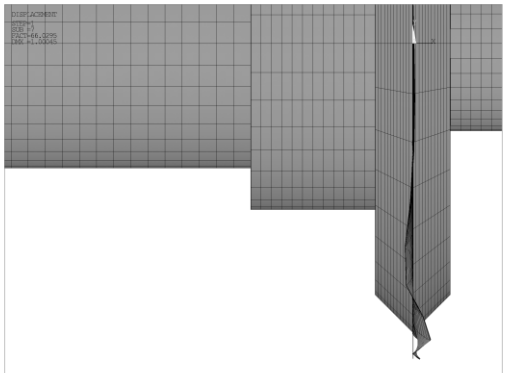


(c)

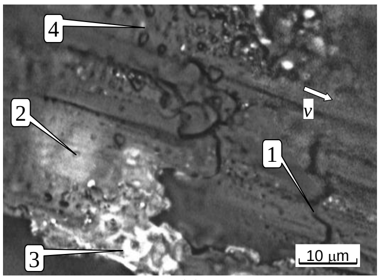
Figure 6. Forms of saw disk stability loss for various loads in the contact area: (a) 5.5 N, (b) 34.6 N, and (c) 66.0 N

VI. Experimental Results

The model experiment allows to confirm the correctness of the selected ranges of load and speed of rotation in the contact area and to verify that the safety factor in the angular velocity of the saw disk for the condition of avoiding resonance is 12; on load application (based on the stability condition of equilibrium), it is 2.7.

Elastic deformations of the disk and the formation of a wave-like surface, which during the splitting of the workpiece come into momentary contact with the vertices of the protrusions of the side sawn surface, are also observed at F < 5.5 N and *n* < 1250 Hz. This can be confirmed by the appearance of bronze transfer spots from the disk to the sawn surface on the workpiece. Cyclically repeated stresses during the realization of such contact can lead to the destruction of the layer of the workpiece adjacent to the sawn surface. In particular, the appearance of fatigue microcracks and spots of material crumbling on the side sawn surfaces have been detected during the splitting of workpieces from silicate glass, leucosapphire, and diamondite (Fig. 6).

The reason is that the temperature and tangential stresses in the contact points increase pulse-wise. The repeated cyclic action of these factors leads to the formation of microcracks in the workpiece surface layer, and of course, to the chipping of the material in the area with higher concentrations (Fig. 7).



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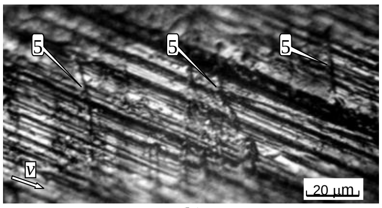

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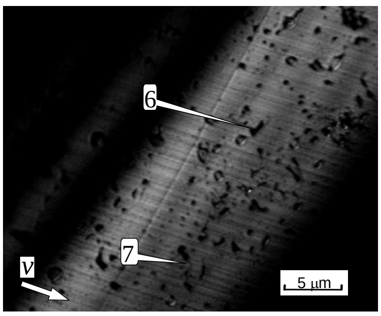
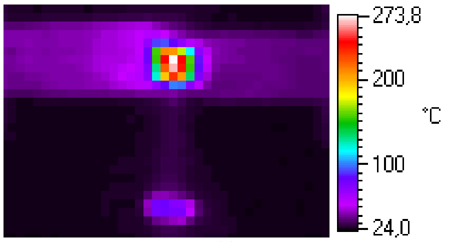


(c)

Figure 7. Destruction of side sawn surfaces of samples: (a) silicate glass, (b) leucosapphire, and (c) diamondite

Thus, fatigue cracks perpendicular to the velocity vector of the displacement of the points on the disk's working surface are noted on the sawn surface of silicate glass (Fig. 7, *a*, arrow 1). There is also an interference light decomposition on a wedge of raised material (Fig. 6, *a*, arrow 2), traces of locally molten glass (Fig. 7, *a*, arrow 3), and adhesive transfer of copper (Fig. 7, *a*, arrow 4). The sawn surface of leucosapphire contains microcracks at an angle to the velocity vector *v* (Fig. 7, *b*, arrow 5). The surface of diamondite is covered with fine abrasive strips appearing as a result of the interaction of abrasive grains with the surface of the sample. There are focuses of chipping (Fig. 7, *c*, arrow 6) and microcracks connecting these focuses (Fig. 7, *c*, arrow 7).

The process of side surface destruction of the sawn workpiece is caused by both its friction against the disk side surface and the temperature stresses arising in the sawing zone. Fig. 8 shows the changes in temperature during the sawing process. A large temperature gradient exceeding 1,000 ℃/mm leads to significant temperature stresses, which, in combination with contact stresses, are accompanied by the appearance of fatigue cracks, followed by chipping of the material.



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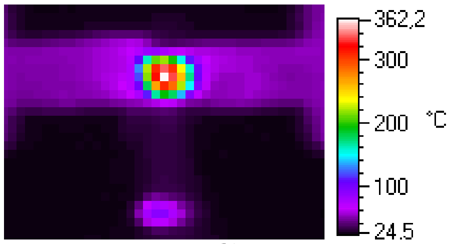

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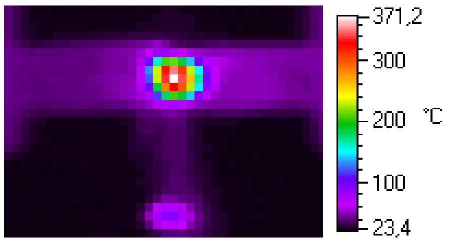

(c)

Figure 8. Thermograms of diamond crystal sawing: (a) after 3 min, (b) after 7 min, and (c) after 15 min

The results from this study reveal that the thickness of the silicate glass layer to destroy may exceed 10 microns (Fig. 9). From the dependences obtained, it is seen that at low loads and v = 7.6 m/s, the fracture propagates to a considerable depth, which may be due to the impact of abrasive particles on the sawn material caused by the discrepancy between the geometrical axis of the disk and the axis of rotation of the shaft. With load increase, the beating of the saw disk decreases. In this case, the impact loads and depth of propagation of the glass contact deformations reduce. As a result, a thinner layer of glass adjacent to the side surface of the cut is subjected to fatigue failure. When the load increases (beyond 0.5–0.6 N), the disk bends, and the disk's flat surfaces become wavy and frictional interaction between the disk and the glass sawn surface appears. Because of this, the glass is heated and the hardness of its surface layer decreases, the amplitude values increase, and contact deformation propagates to a greater depth. The repeated loading of this kind in aggregate leads to an intensification of fatigue failure and an increase in *h*.

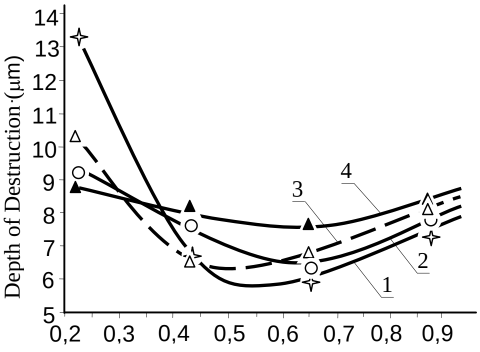

Figure 9. Influence of load on the depth of glass sawn surface destruction: 1–v = 7.6 m/s; 2–v = 9.8 m/s; 3–v = 12.5 m/s; and 4–v = 15.1 m/s

An increase in the disk rotation speed does not significantly change the dependences of $h(F)$; however, they become less pronounced. The influence of this factor on *h* is ambiguous and is due to the competition between two factors. On one hand, as *v* increases, the time of glass–disk surface contact decreases, and consequently, the depth of contact deformation propagation decreases, which decreases *h*. On the other hand, the increase in speed causes a higher temperature to reach the local contact areas. Because of this, the hardness of the glass decreases and contact deformations increase. Besides, there is an increase in the circulation of air supplied by the disk to the friction zone and having a cooling effect on the vicinity of the contact spots. As a result, the material undergoes a periodic sequence of alternating stresses of a higher level that may promote the propagation of fatigue cracks to a greater depth and increase the thickness of the defective layer.

The occurrence of the described type of defects in the process of sawing necessitates removing a layer of expensive material, the thickness of which is determined by the depth of defect penetration.

VII. Conclusion

The performed analysis shows that the decrease in the probability of appearance and depth of defect propagation in the surface layer of a sawn workpiece from hard or ultra-hard materials can be achieved by reducing the friction coefficient of the saw disk along the side sawn surface.

Acknowledgment

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