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DEVELOPMENT OF TECHNOLOGICAL RESTRICTIONS WHEN OPERATING DISC POLYMER-ABRASIVE BRUSHES

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Polymer-abrasive brush rotating tools are increasingly used for finishing operations in automated manufacturing. Given this, studying the process of their fibers' wear has become important; and such a type of wear as the detachment of a whole fiber at the point of fixing has not been investigated in detail up to now. This phenomenon can lead to the disruption of stable equipment operation and the catastrophic wear of brushes. Therefore, it is a relevant task to search for and identify those limitations that could prevent fibers from detachment.

This study involved the disc and cylindrical polymer-abrasive brushes as the most common in production.

The current study has established that the detachment occurs at an unfavorable combination of the processing regimes and brushes' parameters at rotations close to the limits specified by the manufacturer.

When checking the temperature level at the fiber anchoring point, it was determined that the heating of the fibers in this region during operation was not enough to melt the polymeric base of the fibers and detach them.

It has been established that the reason for the detachment of fibers is the accumulation of fatigue changes, which significantly accelerate under the limit modes. Studying the cyclical durability of fibers has made it possible to determine the ratios of critical processing modes to the tool parameters, which lead to the fatigue destruction of fibers at their fixing point.

The following technological restrictions have been defined to warrant that fibers are not detached:

– it is not recommended to use circumferential cutting speeds exceeding 40 m/s;

– the tension during operation should not exceed 10 % of the fibers' overhang magnitude.

These limitations ensure the integrity of the tool, its high durability, as well as the stability of the process of parts' finishing machining under an automated mode

Keywords: polymer-abrasive disc brush, fiber detachment, fiber temperature, cyclical durability

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1. Introduction

The abrasive brush tool is used for a wide range of finishing machining of parts and structures: rounding sharp edges, removing burrs, and polishing surfaces [1, 2]. In some cases, polymer-abrasive brushes (PABs) replace outdated, less productive, non-environmental-friendly methods [3, 4].

One of the advantages of these tools, the ability to eliminate manual labor and mechanize finishing processing, is made use of when implementing PABs in semi-automatic or fully automated installations [5, 6]. The application of PAB at processing centers for the finishing surface machining after blade treatment makes it possible to reduce the time of manufacture and the cost of production [7]. However, when using PAB on machines with CNC, it is necessary to take into consideration the wear of polymer-abrasive (PA) fibers of the brush. This is required to adjust the position of the tool and to ensure the stability of their operation. And while the dimensional wear abides a certain pattern, the detachment of whole fibers at the place of joining the hub can disrupt the uniform operation of the tool and lead to some difficulties in the use of PAB on machines with CNC.

The application of PAB in automated production is not yet very common, although it has a large potential. Therefore, it is relevant to study this issue related to ensuring the stable operation of the tool in order to obtain the high quality and efficiency of machining.

2. Literature review and problem statement

Most literary sources study the possibilities of PAB in terms of achieving a minimum roughness and determining rational modes when machining surfaces and edges [1, 8]. The use of PABs for polishing certain materials [9, 10], as well as parts whose surface requires special treatment [11], is also being considered. The issues of wear were studied indirectly as the tools refer to the self-sharpened ones. And only when trying to use these tools in automated installations of different complexity, the question arose about predicting the wear of polymer-abrasive brushes.

PAB fibers consist of abrasive grains, evenly distributed throughout a polymeric base, which has low heat resistance. The heat resistance of PAB is stipulated in the technical documentation to the tool. Exceeding a temperature regime leads to intense wear and melting of the working end of the fibers [12]. The search for technological possibilities of temperature limitation in the area of contact with the machined surface when using PABs is addressed in [13, 14]. It was established that the intensive cooling of the machining area prevents the melting of the polymeric base of the cutting part of the fibers.

Studies [15, 16] investigated the causes and types of wear of polymer-abrasive brushes under different operating conditions, technological factors that affect the wear of the work surfaces of fibers. The cited studies make it possible to predict the dimensional wear of PAB and the inter-adjustment period for the automated machining of parts.

However, some sources [17] point to another type of brush wear – the detachment of the whole fiber at the site of fixation. This type of wear is common for metallic brush tools; it is extremely rare for the polymer-abrasive ones. At the same time, since of importance for the automated operation of PAB is the factor of tool operational stability, whose additional verification leads to additional time costs when the equipment stops, it is a relevant task to investigate the causes of this phenomenon.

An analysis of the scientific literature, as well as our practice of using PAB industrially, has shown that compliance with reasonable conditions and modes of operation is guaranteed to prevent the detachment of fibers in the place of fixation. However, when production is intensified, the maximum possible modes are typically assigned to reduce the time of machining and to improve productivity. However, their unfavorable combination can lead to the destruction of fibers at the anchoring site (Fig. 1). Partial destruction of the brush fibers can lead to a chain reaction and mass detachment. This is dangerous for staff in an open work area and can also lead to a sharp decline in productivity and unstable machining in automatic installations.

Various sources suggest different causes of this phenomenon: the temperature of fibers in the fixation, due to the intense cyclical deformation and friction, exceeds the melting point of polyamide, there is a possibility of fatigue destruction. However, there have been no targeted studies to tackle this issue (measuring temperature in the fiber fixation and fatigue tests).

Therefore, it is a relevant task to practically study the boundaries of the area of intense modes under which fibers are pulled out, the causes and nature of such destruction.

Fig. 1. Examples of the fiber loss by a disc PAB in the place of fixation due to a violation of operating conditions

3. The aim and objectives of the study

The aim of this study is to find the causes of the fiber detachment from disc PABs and to determine the boundary conditions and modes during their application. This would make it possible to maintain the working condition of PABs, could ensure stable uniform operation of the brush tool, would improve the quality and performance of the finishing treatment on machines with CNC.

To accomplish the aim, the following tasks have been set:

– to determine the effect of regimes on the fibers' temperature level at their anchoring point;

– to study the cyclical strength of fiber material when tested for fatigue;

– to determine the effect of bending intensity (speed, frequency, amplitude) and the examined fibers' parameters (diameter, detachment) on their durability.

4. The methodology and equipment used in the study

Before the study, we examined in detail the recommendations for the machining regimes involving PABs specified by LESSmann (Germany), Abtex (USA), Xebec (Japan), Osborn (Germany), Weiler (Slovenia) in their catalogs [18–22]. The maximum rotation frequencies of the tool claimed by the manufacturers in terms of the circumferential treatment speed were in the range of 30...75 m/s. The authors of most of the above studies consider that the moderate-rational circumferential machining speed for PABs should be to 20 m/s depending on the material being treated.

To investigate the boundary conditions, it was decided to conduct experiments at speeds in the range of 20...75 m/s.

4. 1. Analysis of the movement of PA fibers in contact with a flat surface

The reason for the detachment of fibers in the fixation may be the heating of the fiber above the allowable temperature of the fiber's polymeric base disintegration at the point where they are fixed. The source of heating may be a cyclical deformation (bending) of fibers or their warming due to the heat in the cutting zone.

It is difficult to measure the temperature of fibers in the fixation due to the high frequency of rotation of the disc brush (50...300 rev/s). In addition, the fibers in the middle are heated to a larger degree than the fibers at the edge. Therefore, it was decided to recreate the kinematics of the contact between a PAB and the machined surface using a cam and to measure the temperature applying a stationary thermocouple, installed in the middle of the bunch of polymer-abrasive fibers.

To determine the geometric parameters of the cam, which enables the deformation of fibers similar to the deformation of PAB fibers during machining, we considered the character of the bend and its dependence on tension provided the work part of the fiber is sliding on the treated surface without rebounding when hit. The fiber bend is simulated using an example where the disc PAB is applied on a flat surface (Fig. 2). The fiber curvature radius decreased, as it moved from point A, a point of contact, to point B, the maximum fiber bend point, from $R_{\max}\to\infty$ to $R_{\min}$. The curvature radius increased from $R_{\min}$ to $R_{\max}\to\infty$ from point B to point D, the fiber detachment point.

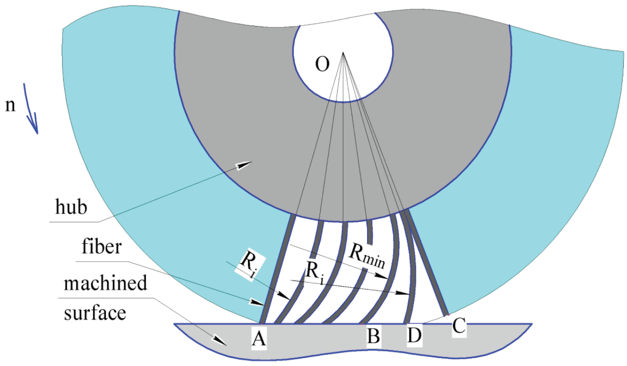


Fig. 2. A disc PAB fiber's bend trajectory without a rebound

It was assumed that the point of contact between the fiber and the machined surface is at the intersection of the circle with a diameter equal to the double overhang of the fiber ($2L_B$) and the center located at the fiber fixation. In this case, the fiber was conditionally depicted without a bend radius and with a hinge fastening instead of a console one (Fig. 3). Rotating the center of the conditional circumference with a diameter of $2L_B$ relative to the center of the brush in the direction of rotation at angle $\beta=0...\alpha$ produced the key points. Point A is the beginning of fiber contact with the surface being machined. In the diagram, conditional letters B, C, D, E mark the tops of the fibers that do not experience bending. Points B_1, C_1, D_1, E_1 are the tops of the deformed fibers due to tension i. The AE_1 segment is the area of contact between the fiber and the machined surface. Point E_1 is the point of fiber detachment; point D_1 is the point of maximum fiber bend.

We determined the α angle between the brush contact spot (the AOD segment) and the surface being machined from the following formula:

$$\alpha = 2\cdot\arccos\left(1-\frac{2i}{D}\right),\text{degree,} \qquad (1)$$

where i is the brush tension, mm; D is the brush diameter, mm.

When the fiber moved from point A to point D_1 (Fig. 3, a), the fiber was curved at an angle from 0 to μ. The maximum angle between the curved fiber and its natural position, based on the similarity between the D_1DK and AOD triangles, corresponded to the angle $\mu=\alpha$. The maximum fiber bend amplitude was determined as follows:

$$L_{bend\max} = 2\cdot L_B\cdot\sin\left(\frac{\alpha}{2}\right),\text{ mm,} \qquad (2)$$

where L_B is the fiber overhang, mm.

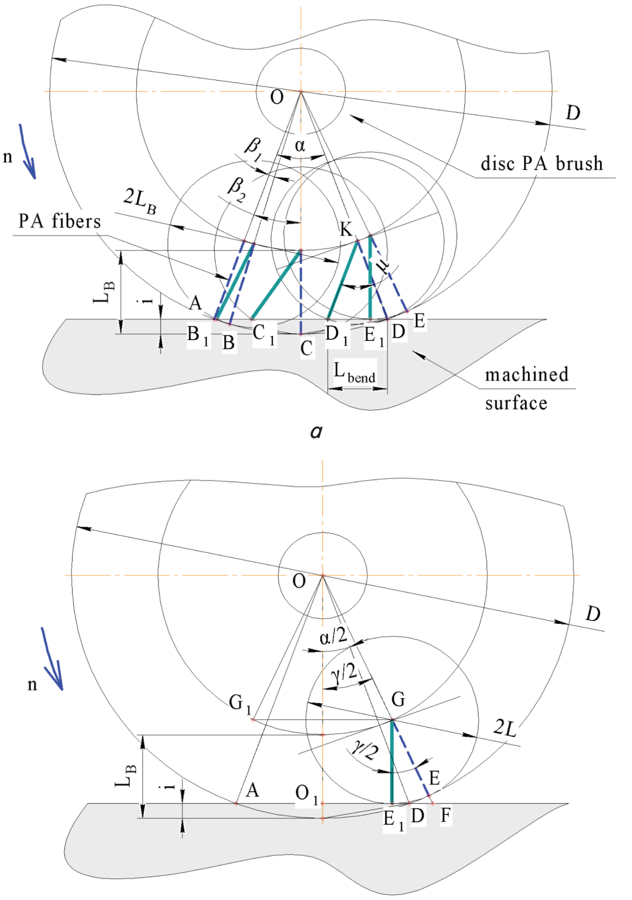
The fiber rebound angle (Fig. 3, b) was calculated on the basis of the similarity between the O_1OF and GE_1F triangles, by solving the OG_1G triangle:

$$\frac{\gamma}{2}=\arccos\left(1-\frac{2\cdot i}{D-2L_B}\right),\text{degree.} \qquad (3)$$

The duration of the fiber's deformed state before the onset of leaving the contact was determined from the following formula:

$$T_S=\frac{\frac{\alpha}{2}+\frac{\gamma}{2}}{360\cdot n},\text{ s,} \qquad (4)$$

where n is the frequency of brush rotation, s^{-1}.



a

b

Fig. 3. Estimation diagram to determine the parameters of fiber bending when machining a flat sample using a disc PAB: *a* — schematic calculation of the fiber bend amplitude when turning the brush; *b* — schematic calculation of the rebound angle when the fiber loses the contact with the machined plane

The duration of the fiber unbending process was determined from the following formula:

$$T_p=\frac{\frac{\gamma}{2}-\frac{\alpha}{2}}{360\cdot n},\text{ s.} \qquad (5)$$

The length of the contact of the AB fiber (Fig. 3, b) was determined from the following formula:

$$L_{AB}=\frac{D\cdot\sin\left(\frac{\alpha}{2}\right)}{2}+\left(D-2\cdot L_B\right)\cdot\sin\left(\frac{\gamma}{2}\right),\text{ mm.} \qquad (6)$$

These calculations are necessary for the design and adjustment of the cam (section 4. 2) when examining PA fibers in a special installation.

4. 2. Procedure for determining the temperature of the fiber at its anchoring point during a cyclical bend

A special installation (Fig. 4) was designed and manufactured to determine the temperature of the fibers in their point of fixation at cyclical bending. It enables determining the temperature of fibers 1 using thermocouple 2 at the point of fixation during the cyclical loading provided by cam 3.

The cam simulates the kinematics of fiber contact with the surface being machined.

Fixation 3, made from a low-heat-transmission material, ensured that the fibers were fixed at the required overhang, as well as the tight contact with the thermocouple. We adjusted the necessary tension by moving the fixation along base 4.

The original temperature of each test was 20±2 °C. The purpose of the experiment was to answer the question if the cyclic deformation was the reason why the temperature of the fibers at the point of fixation reached the level of the boundary temperature for the loss of strength by the polyamide base of the fibers. Therefore, the experiment was stopped in two cases:

1) the fibers were not destroyed but the temperature at the site of fixation reached a maximum and did not grow further;

2) in the case of fiber detachment.

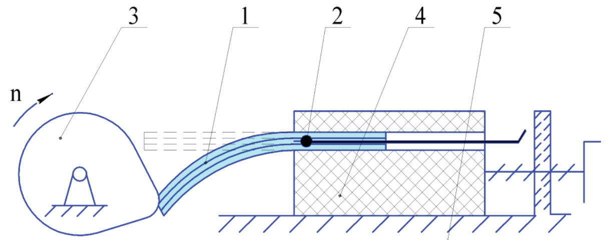


Fig. 4. An installation for determining the cause of the fiber strength loss in the fixation

When designing the cam (Fig. 5, *a*), we minimized the amount of deviation of the trajectory of the fiber bend *h* when the cam rotates at frequency *n*, from the true trajectory of the fibers' movement (Fig. 5, *b*).

In Fig. 5, *b*, point A marks the beginning of the contact, point *B* – losing the contact.

The cam's dimensions were calculated from the following formula:

$$R=\frac{\left(\frac{L_{bend\ \max}}{2}\right)^2+h^2}{2h},\ \text{mm}. \qquad (7)$$

The geometric parameters that provide for the necessary location of the cam relative to the examined fibers such as the angle of contact β, the displacement of the cam l_{dis}, and the distance to the cam's axis *H* cam were calculated as follows:

$$\frac{\beta}{2}=2\operatorname{arctg}\left(\frac{2h}{L_{bend\ \max}}\right), \qquad (8)$$

$$l_{dis}=\left(R\cdot\cos\left(\frac{\beta}{2}\right)+L_{bend\ \max}\cdot\cos\left(\frac{\alpha}{2}\right)\right)\cdot\sin\left(\frac{\alpha}{2}\right),\ \text{mm}, \qquad (9)$$

$$H=\left(R\cdot\cos\left(\frac{\beta}{2}\right)+L_{bend\ \max}\cdot\cos\left(\frac{\alpha}{2}\right)\right)\cdot\cos\left(\frac{\alpha}{2}\right),\ \text{mm}. \qquad (10)$$

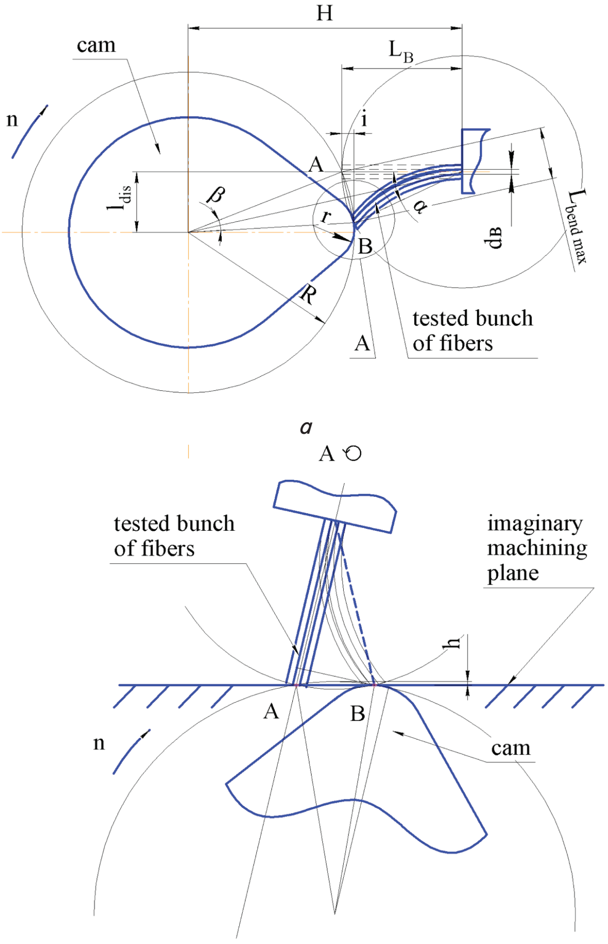
In the series of experiments to study PA fibers, we varied the following machining modes and fiber parameters:

– tension i=0.5; 1; 2; 3 mm;

– circumferential cutting speed V=20...90 m/s);

– fiber overhang L_B=10; 16; 20; 25 mm;

– fiber diameter d_B (grain size)=0.6 mm (P180); 1.2 mm (P120); 1.7 mm (P80).



a

b

Fig. 5. Geometric parameters of the cam: *a* – estimation diagram; *b* – comparing the bend of fibers under the influence of a cam at their bending when machining a flat surface

4. 3. Procedure for determining the PA fibers durability

A special installation (Fig. 6) was designed to determine the durability of a single PA fiber or a bunch of fibers. It consists of drive mechanism 3 that enables control over the frequency of rotations, machined sample 2, tension adjustment device 5, and fixation 4. The fixation hosts tested fiber 1 at one side (a bunch of fibers) and counterweight 13 at the other side. Fixation 4 makes it possible to fix fiber (a bunch of fibers) 1 at the required length (overhang). Drive mechanism 3 was the direct sander *Makita GD 0800 C*, which adjusted the frequency of rotations from 7,000 to 28,000 rpm. That corresponded to the circumferential speed of the fibers in the machined zone of *V*=20...90 m/s. The frequency of rotations was controlled by a mechanical tachometer. The machined sample of steel 20 with a roughness of Ra3,2 was fixed at control device 6 [23]. It includes damper 11 to prevent excessive rocking of the top of the device, and inductive sensor 8, which measures the amount of displacement of the support arm with the sample. Sensor 8 is connected via converter 9 to personal computer 10. Using an electrogram on a personal computer monitor, one can observe a change in the fiber bend under the influence of impacts. The sharp decrease in the bend indicated a detachment of fibers; the experiment was stopped. From the side of the fiber losing the contact, there was catcher 7 for shavings, spent particles, and fiber elements. Nozzle 12 was used to air-cool the sample machining area under modes that cause the fiber's work end to melt so that the polymer basic was smeared on the surface of the sample.

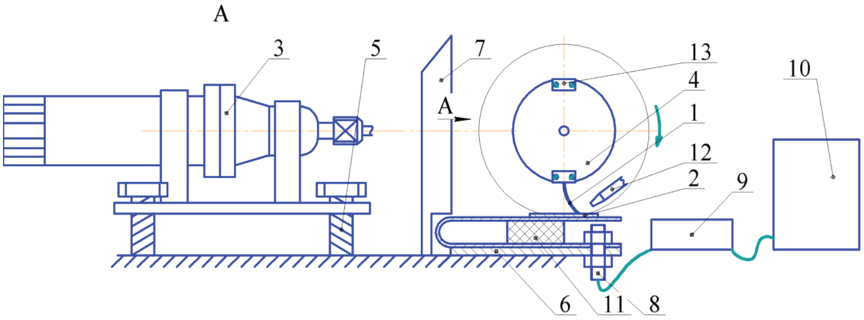


Fig. 6. Diagram of the installation to study the durability of fibers

After each hour of operation, the installation was stopped to examine the fibers and adjust the tension.

The machining modes and fiber parameters were similar to those specified in section 4. 2.

5. Results of studying the causes of PAB fiber detachment

5. 1. Determining the temperature level in the region of fiber fixation

The results from the series of experiments in this part of our study (Fig. 7) have demonstrated the predictable dependences of temperature on cutting modes (speed and tension) and the tool parameters (the fibers' overhang and diameter). However, in general, at the ranges of cutting modes studied, the temperature of the fibers in the fixation did not exceed 40...45 °C, even at extreme speeds and at the time of the fibers breaking off. This suggests that the heat release from the fiber deformation and fiber heating is not enough to reach the melting point of the polymeric base of the fibers.

Since the thermal component is not enough to destroy the fibers in the place of fixation, the main reason is the accumulation of fatigue.

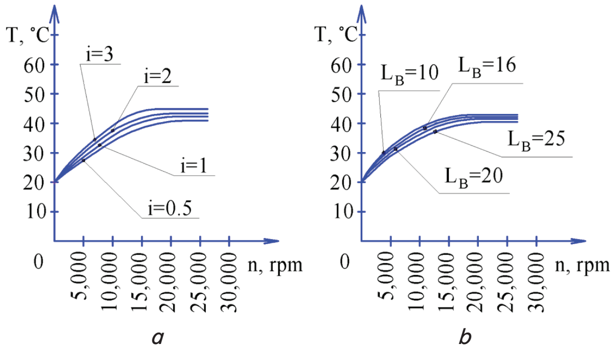


Fig. 7. Temperature dependence in the fixation region for the fibers with a diameter of 1.2 mm at different values of the tension *i* and the fiber overhang L_B: *a* — for a fiber length of 16 mm; *b* — at a tension of 2 mm

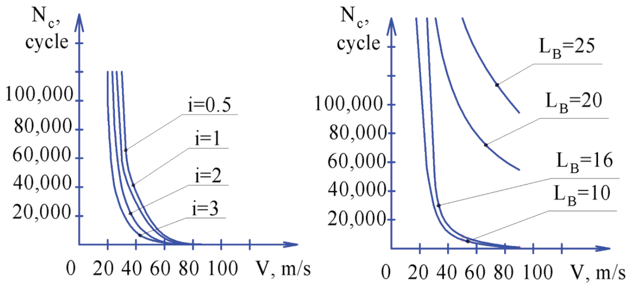
5. 2. Results of testing for fatigue

The main criterion, determined in testing for fatigue, is the endurance limit. However, the value of the fiber endurance limit as it is does not yield any practical benefit for PAB operation, so we determined the cyclical durability of fibers using the procedure specified in section 4. 3. That makes it possible to assess the durability of the tool when operating under the modes close to the boundary ones.

Based on the results of our study, durability decreases with the increased tension, fiber diameter, and when the fiber overhang decreases.

This is due to an increase in the rigidity of fibers and, as a result, an increase in the local stresses in the fixation zone. Fibers with an overhang of 20 mm and 25 mm demonstrated maximum durability (Fig. 8, *a*), which was almost independent of the machining modes. When the length of the fiber was reduced to 10 mm during intensive machining modes, the duration of the fiber operation was drastically reduced before the destruction.

The chart in Fig. 8, *b* illustrates that for a «rigid» fiber with an overhang of 10 mm the speeds above 30...40 m/s, combined with a large tension, were the reason for the detachment at the site of the fixation. The installation's operation at 30...40 m/s with a work tension of 1...1.5 mm ensured a long-term working condition even for «rigid» fibers. With a further increase in speed to 70 m/s, the durability plummeted.



a *b*

Fig. 8. Dependence of the number of cycles N_c before the destruction of the fiber with a diameter of 1.2 mm on the circumferential speed *V*: *a* — for a fiber length of 10 mm; *b* — at the tension *i*=2 mm

This is due to that the high speeds increased the impact influence on the surface of the sample, the force of reaction, and, accordingly, the stresses in the console fixation of the fiber. One cycle of fiber operation includes one turn of the fixation. In this case, the fiber was at least once hit against the surface of the sample (depending on modes, there may occur 2–3 blows with rebounds) and continued a free part of the turning until the next contact with the sample. The number of cycles N_c before the destruction, according to the experiments, was defined as follows:

$$N_c = \frac{n_o}{60} \cdot t, \text{cycle}, \qquad (11)$$

where n_o is the frequency of fixation rotations, rpm; *t* is the duration of fiber operation before the destruction, s.

Compared to a single fiber, the durability of the fibers collected in a bunch was 2...3 times higher under similar experimental conditions. This is due to that, first, after coming out of contact with the sample, a single fiber continues to fluctuate, bending several times in the place of fixation in opposite directions until the next contact with the sample.

A given phenomenon is impossible for a bunch of fibers due to the existence of the tightly arranged neighboring fibers, damping instantaneously the large amplitude of bending, and executing in this part of the turning only light vibrational movements. Second, at the moment of contact of the working fiber, the neighboring fibers keep it from a strong bend (Fig. 9), thereby perceiving part of the load, so that the tension in the anchoring zone decreases.

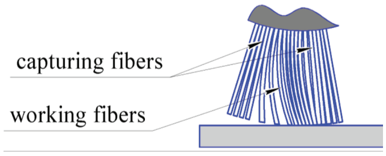


Fig. 9. Functional separation of PA fibers in a bunch

According to Fig. 8, it can be assumed that the function of the dependence of the number of fiber operation cycles before destruction has a geometric progression. Then the durability of the brush can be presented by the following formula:

$$N = 300\left(\frac{L}{L_{B\ boundary}}\right)^{3.5} \cdot 2^{\left(i_{boundary}-i\right)} \cdot 4^{\left(\frac{V_{boundary}-V}{10}\right)}, \text{cycle}, \qquad (12)$$

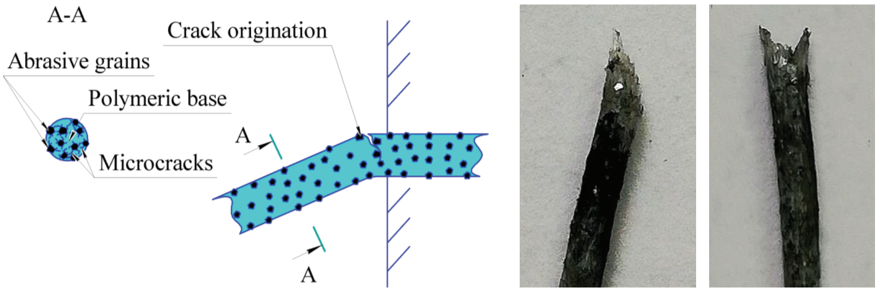
where $L_{B\ boundary}$, $i_{boundary}$, $V_{boundary}$ are the boundary PAB parameters.

A given experiment shows that when moderate cutting regimes are followed, the fiber operates normally without breaking.

6. Discussion of results of studying the causes of PAB fibers destruction

Owing to the devised procedures and equipment, the reasons for the detachment of fibers in disc brush polymer-abrasive tools were found and investigated.

Based on our results, it is safe to say that the maximum temperature of the fibers in the fixation did not exceed 45 °C, which is half the maximum temperature (80...120 °C) of the disintegration of the polymeric base of the PA-6 polyamide [12, 17]. Therefore, the cause of the destruction and detachment of fibers is not heat destruction but cyclical fatigue. The site of destruction was the abrasive grains (Fig. 10) that disrupt the solidity of the polymeric base, thereby causing a local concentration of stresses.



a *b*

Fig. 10. An example of the fiber destruction in the fixation zone: *a* – schematic origination of the fatigue crack in a fiber; *b* – the place where the fiber is detached

Less rigid PABs with the overhang of fibers exceeding 20 mm make it possible to operate at the maximum speeds specified by the manufacturer, without taking off the fibers at the anchoring point; the cyclical durability is above the study base of 10^5 cycles. The combination of large tension and short fibers (for example, i=3 mm, L_B=10 mm) leads at high speeds to an intense loss of fibers (Fig. 1) almost immediately.

The following restrictions have been established experimentally in order to avoid the detachment of PAB fibers during operation:

– the ratio of the fiber tension i to the fiber overhang L_B should equal $i \leq 0.1L_B$;

– speeds above 40 m/s are not recommended despite the maximum rotations specified by manufacturers.

It is also necessary to control the temperature of the spindle node, which heats the metallic hub of the PAB to the temperature limit for the polymer. Such a case was described in work [17] when using a corner grind machine. For the case of uncontrolled overheating of the spindle node, one can apply a PAB with a non-metallic hub.

The technological constraints specified above have been introduced industrially, both in manual machining and at the Starragheckart SX-051 B machining center. During the entire service life of the polymer-abrasive disc brushes used to polish the parts, there has been no case of fiber detachment.

In the future, it is possible to employ the procedures and devices proposed in this article in the development and testing of new polymeric materials for the base of fibers for the polymer-abrasive brush tools.

7. Conclusions

1. Our study of the fibers' temperature level at their fixation point as one of the possible reasons for their detachment, has demonstrated the following:

– under the maximally possible intensive modes and «tough» machining conditions, the temperature of the fibers at the place of their attachment did not exceed 40...45 °C even at the time of detachment. That is, the cyclical deformation (bending) of fibers that causes the release of heat, as well as the transfer of heat through the fiber from the cutting area, are not sufficient to warm the fibers in the fixation to critical temperatures;

– given that the lower temperature limit for the destruction of the fibers' polymeric base is 85...90 °C, heating in the fixation cannot be the cause of their detachment;

– the exceptions are those cases when the uncontrolled heating of the faulty spindle node intensely warms the metallic hub of the brush above the specified temperatures. Such operational conditions are unacceptable for PABs.

2. It has been established that the main cause of the detachment of PAB fibers is the accumulation of fatigue micro-effects in a dangerous cross-section with an unfavorable combination of brush machining regimes close to the limit. The study of the cyclical strength of fibers has shown that under these conditions the detachment occurred due to the rapid depletion of the strength reserve of the fiber material.

3. It has been established that the durability of fibers decreases with an increase in their bend: with the increase in speed V and tension i, as well as with the increase in the rigidity of the fibers (reducing the overhang and increasing their diameter). It is shown that the intensification of one of these factors does not lead to a sharp drop in durability. Therefore, when choosing the tension, one should take into consideration the overhang of the brush fibers and follow the ratio $i/L_B \leq 1/10$. When decreasing the fibers' overhang, one should reduce machining speed to the rational one (15...20 m/s). When choosing the fibers' diameter, it is necessary to take into consideration that the larger it is, the tougher the tool, so when applying a brush with a large diameter of fibers (1.2 mm or more), one should increase their overhang or reduce the machining speed. The assigned PAB work speed should not exceed 40 m/s even when cooled in bulk.

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