The use of intermittent wheels, impregnated by the contact method to reduce the thermal stress of the grinding process

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Abstract. The proposed composition of solid technological lubricant applied to the working surface of the abrasive wheel directly in the grinding process. Experimental studies have been carried out to identify the effect of implanting on the normal and tangential components of the cutting effort and temperature that occur when grinding with abrasive wheels with continuous and intermittent work surfaces. It is established that when grinding with impregnated intermittent circles, the magnitude of the ratio \( F_z/F_y \) normal to the tangential component of the cutting force is less than when grinding with impregnated wheels with a solid working surface. It was established experimentally that the impregnation of the working surface of intermittent wheels reduces the thermal stress of the grinding process and increases the number of actively working grinding grains. The decrease in the \( F_z/F_y \) ratio during intermittent grinding with an impregnated wheel compared to dry intermittent grinding can be explained by a decrease in \( F_z \) with a simultaneous increase in \( F_y \). A decrease in temperature when using solid lubricant indicates a decrease in the coefficient of friction of grinding grains with the processed material and, therefore, a decrease in the tangential component of the cutting force \( F_y \). An increase in the number of actively working grains during grinding with intermittent impregnated circles compared to dry intermittent grinding indicates an increase in the normal component of the cutting force \( F_z \). It is established that the maximum temperature during grinding with impregnated intermittent circles shifts towards the rear point of the contact arc compared to dry grinding, where the temperature reaches its highest value near the front point of the contact arc of a circle with the material being processed.

1. Introduction
The proposed composition of solid technological lubricant applied to the working surface of the abrasive wheel directly in the grinding process. Experimental studies have been carried out to identify the effect of implanting on the normal and tangential components of the cutting effort and temperature that occur when grinding with abrasive wheels with continuous and intermittent work surfaces. It is established that when grinding with impregnated intermittent circles, the magnitude of the ratio \( F_z/F_y \) normal to the tangential component of the cutting force is less than when grinding with impregnated wheels with a solid working surface. It was established experimentally that the impregnation of the
working surface of intermittent wheels reduces the thermal stress of the grinding process and increases the number of actively working abrasive grains. An experiment showed that the magnitude of the ratio \( F_y/F_z \) normal and tangential components of the cutting force during processing with intermittent and intermittent impregnated abrasive wheels during a 25-minute grinding period does not change its value, which indicates the high durability of these circles. It is established that the maximum temperature during grinding with impregnated intermittent circles shifts towards the rear point of the contact arc compared to dry grinding, where the temperature reaches its highest value near the front point of the contact arc of a circle with the material being processed.

2. Literature review and problem statement

One of the factors hindering the increase in grinding productivity is high thermal stress, which causes the formation of technological residual stresses and burns in the surface layer, significantly reducing the durability and performance of products [1-16]. An effective way to reduce the heat-intensity of the grinding process is the impregnation of abrasive wheels - impregnating them with lubricating active substances or applying solid lubricants to their working surface [17-27]. At the same time, there is a sharp decrease in cutting forces, processing power costs and, as a result, temperatures in the cutting zone. However, in the literature there are no recommendations on the creation of lubricant technological means for impregnating grinding wheels with intermittent working surfaces. Studies on the immersion of circles with a discontinuous working surface are few and contradictory [28-30]. A large number of works are devoted to the impregnation of grinding with a continuous working surface. The impregnation of intermittent wheels with lubricating active substances opens up additional possibilities for ensuring the quality of the surface layer of the parts to be ground. This predetermined the need for research in this direction.

3. Materials and methods

The aim of the work is to develop the composition of solid technological lubricant, which provides an increase in processing performance without reducing the quality of the surface layer of parts made of steel R6M5 in the grinding operation with intermittent abrasive wheels.

Materials and methods. The experiments were carried out on a Model 3701 surface grinding machine. The machine has a 2.2 kW motor, hydroficated drives for moving the table, which ensure the variation of the speed of the longitudinal feed in the range of \( 0.016 \leq V_{det} \leq 0.416 \) m/s, cross feed from \( 0.3 \cdot 10^{-3} \) m/run to \( 15 \cdot 10^{-3} \) m/run. Price division vertical limb feed 0.001 \( \cdot 10^{-3} \) m.

During the experiments used abrasive wheels straight profile ПП 200×20×76 24А 40 C2 5 K6 with continuous and intermittent work surfaces. Tool steel was used as a material to be processed. P6M5, hard tempered HRC 62….64. European analogues of this steel: S6-5-2 (Germany), HS6-5-2 (Spain), Z85WDCV (France). To determine the temperature in the cutting zone, an artificial thermocouple was placed in the grinded sample. Thermoelectrodes were chromel and alumel wires with a diameter of \( 0.2 \cdot 10^{-3} \) m. Insulation of thermoelectrodes from the sample was carried out by capacitor paper with a thickness of \( 0.01 \cdot 10^{-3} \) m. Thermoelectric signals arising during the passage of the junction along the length of the arc of the contact of the grinding wheel were recorded by the storage oscillograph model C8-17.

4. Research results

To reduce the thermal stress of the grinding process, a solid lubricant composition was developed and tested, including the following components:

1. Stearic (octadecanoic) acid \( C_{17}H_{35}COOH \) – 65%.
2. Oleic (Octadecene-9-oic) acid \( C_{17}H_{33}COOH \) – 19%.
3. Acetamide \( CH_3CONH_2 \) – 13%.
4. Potassium hydroxide \( KOH \) – 3%.

Stearic and oleic acids were binding components. They have good lubricating properties, are surface-active substances, have high thermal stability, which allows them to remain unchanged for a
long period of grinding. At elevated temperatures, stearic and oleic acids react with the metal to be treated. As a result of the interaction, salts of higher fatty acids — soaps, stearates, and oleates — are formed. An example is the product of the interaction of stearic acid with iron Fe(C_{17}H_{35}COO)_2 iron (II) stearate. The thermal and lubricating properties of metallic soaps are higher than those of the original higher fatty acids. As a result of the formation of metal soaps on the submicro-profiles of the cutting grains, the coefficient of friction decreases. At the stage of manufacturing a solid lubricant to increase the heat capacity and lubricity of the binder component, partial saponification of the used fatty acids was carried out with alkali - caustic potassium. KOH. The presence of potassium soap in the solid lubricant, along with free higher fatty carboxylic acids, makes it possible to increase the heat capacity of the lubricant and its antifriction properties. In addition, the possibility of chemical interaction with the material being processed is provided.

Oleic acid under severe conditions is oxidized with a rupture of double carbon-carbon bonds, and a mixture of pelargonic is formed. (C_{8}H_{17}COOH) and dicarboxylic azelaic acid according to the scheme:

\[
\text{CH}_3-(\text{CH}_2)_7-\text{CH}=\text{CH-(CH}_2)_7-\text{COOH} \rightarrow \text{CH}_3(\text{CH}_2)_7\text{COOH} + \text{HOOC-(CH}_2)_7\text{COOH}
\]

With an increase in the number of carboxyl groups, their reactivity to interact with the material being processed increases. In an alkaline medium, acetamide is hydrolyzed to form the potassium salt of acetic acid and ammonia:

\[
\text{CH}_3\text{CONH}_2 + \text{KOH (water)} \leftrightarrow \text{CH}_3\text{COOK} + \text{NH}_3.
\]

Further, when heated, ammonia decomposes into hydrogen and nitrogen, using iron as the catalyst of the process, using the following scheme:

\[
2\text{NH}_3 \leftrightarrow 3\text{H}_2 + \text{N}_2 \text{ (1200-1300) } ^\circ\text{C, Fe – catalyst.}
\]

The hydrogen released during the decomposition of ammonia and the resulting water vapor intensifies the oxidation of iron shavings. The formation of a coarse oxide film on the chips facilitates its removal from the surface of the circle. The formation of water vapor contributes to the chemical interaction of the lubricant with the treated surface.

In figure 1 shows the scheme of grinding the processed material grains \(\sqrt{\text{cut depth } t_0}\) circle speed \(V_{cr}\) and the speed of moving the table \(V_{det}\). From figure 1 shows that the same parts of the workpiece under the moving center of the grinding wheel \([A_0A_1\rightarrow A_1A_2\rightarrow A_2A_3\rightarrow A_3A_4]\) correspond to different sizes of thermocouple sections \([A_0A_1] > [A_1A_2] > [A_2A_3] > [A_3A_4]\), ground by abrasive tool grains. Within the first half of the contact arc (with a relative displacement of the center of the grinding wheel at a distance \([A_0\rightarrow A_2]\)) deletes \(\frac{3}{4}\) all that passed i.e. \(\frac{3}{4}t_0 = t_1 + t_2\).

![Figure 1](image.png)

**Figure 1.** Different-sized thermocouple fragments \(t_1 > t_2 > t_3 > t_4\), ground by grains of the abrasive disc for the same periods of time, equal \(t'' = \sqrt{(2-Rt_0)/(V_{det}\cdot4)}\)

In figure Figures 2 and 3 show oscillograms of temperatures obtained by grinding without lubrication (upper curve) and with lubrication (lower curve) on the mode: \(V_{cr} = 30\) m/s; \(t_0 = 0.05\) water
$10^{-4}$ m; $V_{det}=0.1333$ m/s. The experiments were carried out according to the method described in [40]. The fixation of thermoelectric signals arising during the passage of the junction along the arc of the contact of a circle with the material being processed was carried out using a storage oscilloscope mod. C8-17. The first five cells on the oscillograms, counted from right to left, correspond to the length of the arc of contact of the circle with the workpiece equal to $\sqrt{(2 \cdot R \cdot t_0)}$. From the oscillograms obtained by grinding dry (upper curves) it can be seen that the maximum temperature is formed at the central point of the contact arc (at a distance of $\frac{1}{2}\sqrt{(2 \cdot R \cdot t_0)}$ it's start). In this area of the contact arc, the cutting grains are crushed $\frac{3}{4}$ stock $t_0$. Within the remaining part of the contact arc (within 2.5 cells), the temperature stabilizes and begins to decrease after the grinding wheel has left the thermocouple. Oscillograms obtained by grinding with the use of solid lubricant (curves in Figure 2 and 3) have a slightly different character. The maximum temperature when grinding with an impregnated wheel is set at the end point of the contact arc. At the same time, the temperature level throughout the contact arc (within five cells) remains lower than during dry grinding. The thermal intensity of the process occurring in the cutting zone can be judged by the composition of the sludge collected after grinding. Analyzing the appearance of chips formed when grinding dry (Figure 2 above) and using solid lubricant (Figure 2 below), we can conclude that in both cases the sludge contains deformed comma-like chips and chips in the form of melted balls, with than in the case of dry grinding the sizes of balls are larger, and their number is smaller. The large size of the balls with dry grinding indicate higher local temperatures. The increase in the number of spherical shavings during grinding with an impregnated wheel indicates that the hydrogen released during the decomposition of ammonia and the formation of water vapor intensifies the process of oxidation of iron chips.

![Figure 2. Temperature oscillograms (beam sweep speed $V_L=2$mks/sm) in grinding chips from steel processing P6M5 (S6-5-2 (Germany), HS6-5-2 (Spain), Z85WDCV (France)), hardened to a hardness HRC63 with circle ПП 200x20x76 24A 40 C2 5 K6 without the use of solid lubricant (top) and with lubricant (bottom)](image_url)
Figure 3. The nature of the temperature change within the arc of contact of a circle with a talanum (within 9 mks) during grinding without lubrication (curve 1) and with lubrication (curve 2).

Temperature oscillograms obtained by grinding with a discontinuous wheel without lubrication and with lubrication on modes \( V_{kr} = 30 \text{ m/s}; V_{det} = 0.1333 \text{ m/s}; t_0 = 0.01 \times 10^{-3} \text{ m}; t_0 = 0.02 \times 10^{-3} \text{ m} \) shown in figure 4 and 6, respectively. These figures show photographs of chips formed during dry grinding (top) and lubrication (bottom). In figure Figures 5 and 7 show the zones including temperature bursts on the oscillograms arising from the grinding of the material being processed in the junction area of the thermocouple by separate cutting projections of the discontinuous circle. With intermittent grinding without the use of grease, the chips look like large melted balls (Figure 4, 6 above). After the surface impregnation of intermittent circles, the sizes of the balls are significantly reduced, and an insignificant amount of deformed cartilage chips appears in the sludge (Figure 4, 6 below), which indicates a decrease in temperature in the zone of contact of the circle with the workpiece.

Figure 4. Temperature oscillograms (beam sweep speed \( V_L = 1 \text{ mks/sm} \)) and grinding chips from steel processing P6M5 intermittent circle ПП 200х20х76 24А 40 C2 5 K6 with 12 depressions on its working surface without lubrication (above) and with lubricant (below) in the mode: \( V_{kr} = 30 \text{ m/s}; t_0 = 0.01 \times 10^{-3} \text{ m}; V_{det} = 0.1333 \text{ m/s} \)
**Figure 5.** The nature of the change in temperature differences resulting from the interruptibility of the process of grinding a thermocouple, when grinding with a depth of cut $t_0 = 0.01 \times 10^{-3}$ m intermittent wheel without lubrication (zone limited by lines 1 and 2) and lubricated (zone limited by lines 3 and 4).

**Figure 6.** Temperature oscillograms (beam sweep speed $V_{l}=1$ mks/sm) and grinding chips from steel processing P6M5 intermittent wheel with 12 depressions on its working surface without lubrication (above) and with lubrication (below) in the mode: $V_{cr}=30$ m/s; $t_0=0.02 \times 10^{-3}$ m; $V_{det}=0.1333$ m/s.
Figure 7. The character of the change in temperature differences resulting from the interruptibility of the process of grinding a thermocouple, when grinding with a depth of cut $t_0=0.02 \cdot 10^{-3}$ m a discontinuous circle without lubrication (zone delineated by lines 1 and 2) and with lubrication (zone delineated by lines 3 and 4).

Figure 8. Temperature oscillograms (beam sweep speed $V_L=0.7$ mks/sm), obtained by machining steel P6M5 in a discontinuous circle with 12 cavities without lubrication (top) and lubrication (bottom) in mode: $V_{cr}=30$ m/s; $t_0=0.02 \cdot 10^{-3}$ m; $V_{det}=0.1333$ m/s

Comparison of lines delineating the lower and upper points of temperature bursts on the oscillograms (Figure 5 and 7) implies that when grinding dry, the temperature reaches the maximum value at the point of the contact arc remote from its beginning $1/3 \cdot \sqrt{2 \cdot R \cdot t_0}$, and when grinding with a solid lubricant, at the rear point of the contact arc. From a comparison of figure 5 and 7, it follows that when dry-grinding the most thermally stressed part of the contact arc is its front fragment, the size of which is approximately 1/3 of the total length. When using solid lubricant with intermittent grinding, the level of heat-tension decreases by about 30%, and the lines outlining the minimum (lines 4) and maximum (lines 3) points of temperature bursts have a smooth increasing character throughout the arc. When Figures 6 and 8 show oscillograms obtained for the same grinding conditions, but differing only in the rate of sweep of the beam. A decrease in the beam sweep speed (Figure 8) led to an oscillogram stretching in the horizontal direction, which reduced the number of bursts on the oscillogram, but made it possible to estimate the number and size of temperature bursts arising from the operation of single cutting grains when grinding dry (top) and using a solid lubricant (bottom). From the oscillograms (Figure 8) it can be seen that the presence of a lubricant on the working surface of an intermittent abrasive wheel leads to an increase in the number of cutting grains. In the case of dry grinding, there is a tendency to decrease the number of actively cutting grains as the processed material is crushed in a vertical section. $[A_0A_4]$ and, as a result, to a decrease in temperature increments generated when the work is performed by single cutting protrusions of an intermittent wheel. When grinding with the use of a solid lubricant, there is no decrease in temperature bursts.
associated with the work done by single grains and individual cutting protrusions, as the total stock is removed $t_0$. Obviously, when grinding dry, most of the allowance $t_0$ is cut off by a smaller number of abrasive grains most protruding above the bunch level. This is one of the reasons for the higher temperature levels during dry grinding.

Figure 9. The dependence of the ratio of the components of the cutting force $F_z/F_y$ on the duration of grinding steel P6M5 solid (line 1 - without lubricant, line 3 - with lubricant) and intermittent (line 2 - without lubricant, line 4 - with lubricant) circles ΠΠ 200x20x76 24A 40 C2 5 K6 in mode: $V_{cr}=30$ m/s; $t_0=0.01\cdot10^{-3}$ m; $V_{det}=0.1333$ m/s

In figure 9 shows the nature of the change in the ratio $F_z/F_y$ tangential and normal cutting force components in time when grinding with conventional (line 1) and conventional impregnated (line 3), intermittent (line 2) and intermittent impregnated (line 4) abrasive circles. In the interval of a 15 minute grinding period with an ordinary wheel, there is a sharp decrease in the coefficient $K_\nu=F_z/F_y$, and in the time interval $15 \text{ min} \leq t' \leq 25 \text{ min}$ rate reduction ratio $K_\nu$ slows down. When grinding with a conventional impregnated wheel, a sharp decrease in the coefficient $K_\nu$ occurs during the first 10 minutes of grinding, and then (in the interval $10 \text{ min} \leq t' \leq 25 \text{ min}$) there is a slight increase. At the same time in the time interval $0 \leq t' \leq 15 \text{ min}$ coefficient $K_\nu$ when grinding with a solid lubricant less, and in the range $15 \leq t' \leq 25$ more than with normal dry grinding. Intermittent grinding (with or without the use of a solid lubricant in the entire test $0 \leq t' \leq 25$ characterized by the stability of the coefficient $K_\nu$. The coefficient $K_\nu$ when grinding impregnated intermittent wheel less than with intermittent grinding dry. Decrease in the ratio $F_z/F_y$ with intermittent grinding with an impregnated wheel compared to dry intermittent grinding, there are three reasons:

1. Reducing the numerator ($F_z$),
2. Increasing the denominator ($F_y$),
3. Decreasing the numerator ($F_z$) with a simultaneous increase in the denominator ($F_y$).

Experimental data indicate the validity of the third case. The decrease in temperature when using a solid lubricant indicates a decrease in the friction coefficient of the grains with the material being processed and, consequently, a decrease in the tangential component of the cutting force $F_z$. The increase in the number of actively working grains during grinding with intermittent impregnated circles as compared to dry intermittent grinding indicates an increase in the normal component of the cutting force $F_y$.

In figure 10 shows the oscillograms of temperatures obtained by intermittent grinding with different depths of cut $t_0$. From the oscillogram shows that with increasing depth $t_0$ the maximum temperature is shifted to the leading edge of the heat source, i.e. relative coordinate $L_{max}/L$ decreases ($L_{max}$ – the distance from the front point of the contact arc to the coordinate of the maximum temperature burst, $L$ is the arc length of the contact of the circle with the workpiece). In figure 10 the length of the contact arc corresponds to 7 cells (Figure 10, a), 8 cells (Figure 10, b) and 9 cells (Figure 10, c).
Figure 10. Temperature oscillograms obtained by grinding steel P6M5 with circle with 12 hollows on mode: \( V_{cr}=30 \text{ m/s}; V_{det}=0.1333 \text{ m/s}; \) (a) \( t_0=0.005 \cdot 10^{-3} \text{ m}; \) (b) \( 0.01 \cdot 10^{-3} \text{ m}; \) (c) \( 0.015 \cdot 10^{-3} \text{ m} \)

Experiments have shown that when grinding with an intermittent circle with the use of solid lubricant, the maximum temperatures shift towards the trailing edge of the heat source, and the overall temperature level decreases as compared to intermittent dry grinding. (figure 11 a, b, c). In figure 12 shows the effect of grinding conditions on the roughness of the machined surface. When grinding with interrupted circles (curves 2 and 4), the surface roughness increases by two digits compared to conventional grinding (curves 1 and 3), i.e. roughness parameter \( R_a \) rises from \( 0.20 \leq R_a \leq 0.30 \) to \( 0.35 \leq R_a \leq 0.43 \). From these graphs it can be seen that the solid lubricant applied to the working surface of the abrasive disc provides a reduction in the roughness of the treated surface by one discharge. From charts \( R_a = f(t_0) \) it is not possible to reveal any strict regularity of the effect of the cutting depth on the roughness of the treated surface.

Figure 11. The offset of the maximum temperature in the direction of the trailing edge of the heat source \( (L_{max}/L=1) \) when grinding with impregnated wheels (curve 1 - grinding with lubricant, curve 2 - grinding dry).

Figure 12. Roughness of the machined surface, formed when grinding steel P6M5 with circles ПП 200x20x76 24A 40 C2 5 K6 with continuous (curve 1 - without lubricant, curve 3 - with lubricant) and intermittent (curve 2 - without lubricant, curve 4 - with lubricant) working surfaces on modes: \( V_{cr}=30 \text{ m/s}; V_{det}=0.1333 \text{ m/s}; 0.005 \cdot 10^{-3} \text{ m} \leq t_0 \leq 0.025 \cdot 10^{-3} \text{ m}. \)
5. Conclusions
A new composition of solid lubricant was proposed and experiments were carried out to compare the thermal stress of grinding processes with intermittent abrasive wheels of hardened P6M5 steel using solid lubricant and without it. It has been established that the impregnation of the working surface of discontinuous circles reduces the temperature and shifts its maximum value towards the trailing edge of the heat source. It has been established that the presence of a solid lubricant on the working surface of an intermittent wheel contributes to an increase in the number of actively working abrasive grains. Reducing the thermal stress of the grinding process in cases of application of technological solid lubricant is a reserve for improving the performance of abrasive machining while providing a guaranteed level of quality of the surface layer of the workpiece.

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