

ASSESSMENT OF THE EFFECT OF DIAMOND-SPARK GRINDING WITH THE USE OF SOLID LUBRICANTS ON THE FORMATION OF SURFACE ROUGHNESS OF A PART

Aleksandr Rudnev ^[0000-0002-4091-6748], Magomediemin Gasanov ^[0000-0002-2161-2386],

Oleksii Kotliar ^[0000-0001-7664-0395], Mykhaylo Stepanov ^[0000-0002-2224-6509],

Dmytro Kulina ^[0009-0001-5973-1516] and Petro Litovchenko ^[0000-0002-4483-597X]

National Technical University «Kharkiv Polytechnic Institute», 2, Kyrpychova St., Kharkiv 61002, Ukraine

E-mail(s): Oleksandr.Rudniev@khpi.edu.ua (✉) (corresponding author's e-mail),

Magomediemin.Gasanov@khpi.edu.ua, Oleksii.Kotliar@khpi.edu.ua, Mykhaylo.Stepanov@khpi.edu.ua,

Dmytro.Kulina@mit.khpi.edu.ua, petro.litovchenko@khpi.edu.ua

Abstract - The object of this study is the process of diamond-spark grinding of hard-to-machine materials using solid lubricants. The problem of improving the surface quality of machine parts by means of modern environmentally friendly machining methods has been addressed. Tools for assessing the influence of diamond-spark grinding with the use of eco-friendly solid lubricants on the surface roughness of parts have been developed.

Experiments were conducted to verify the lubricating performance of four investigated solid lubricants based on stearic acid. For 10Kh11Kh23T3MR steel, the values of the surface roughness parameter Ra were determined depending on the type of solid lubricant used and the grinding parameters—cutting speed and transverse feed. For all investigated lubricants, the average Ra values were found within the range of Ra = 0.29–0.48 μm at cutting speeds Vs = {25, 40, 50, 63, 80} m/s and transverse feeds St = {0.005, 0.01, 0.015} mm/stroke.

For each lubricant, experimental dependences of the form Ra = F(Vs, St) were established, as well as feasible application domains for combinations of solid lubricant – cutting speed – feed – resulting roughness. For each type of solid lubricant, recommendations were developed for selecting cutting speed and feed values that ensure the specified surface roughness of parts with different functional purposes. It was established that at cutting speeds Vs ≥ 50 m/s, surface defects in the form of burn marks may occur for all investigated lubricants, which is associated with insufficient lubrication of the grinding wheel. When applying this process under production conditions, automatic feeding of the solid lubricant into the cutting zone is required to ensure the specified surface roughness.

The results of this study demonstrate significant potential for practical implementation, particularly in the defense industry.

Keywords: Hard-to-machine materials; Diamond-spark grinding; Solid lubricants; Surface roughness.

1. Introduction

The most critical sectors of a modern, economically developed state—including the defense, aerospace, and energy industries—require large volumes of high-performance machine parts. The reliable operation of these components is ensured by the high hardness and wear resistance of the materials from which they are manufactured, many of which belong to the category of hard-to-machine materials (HTMMs).

The widespread use of HTMMs, such as high-strength titanium alloys and nickel-alloyed stainless steels, necessitates the development of efficient machining technologies.

Among these, grinding remains the dominant finishing operation, particularly when energy-intensive methods are used. Therefore, this paper aims to address the challenge of improving the surface quality of machine parts—specifically those of the «shaft» type – by optimizing modern

environmentally friendly grinding processes, which holds significant potential for the defense sector.

2. Literature Review

The machining of HTMMs is a critical area of research due to their extensive application in manufacturing modern aircraft components, such as wing skins, fuselage frames, and engine turbine parts [1, 2]. These materials, including high-strength titanium alloys (e.g., Ti-5.5Al-3.5Sn-3Zr-1Nb-0.25Mo-0.3Si) and nickel-alloyed stainless steels (e.g., 10Kh11N23T3MR, AISI 310S, and Inconel 600), are characterized by high thermal stability and corrosion resistance [2, 3]. The efficiency of manufacturing such parts, particularly "shaft" types, often depends on the precision of the kinematic schemes used in gripping and positioning devices [1]. Given the necessity of processing these materials, numerous studies have focused on advancing machining technologies. Grinding remains the dominant operation for finishing HTMMs, with many studies investigating additional energy input to the cutting zone. According to data from the automotive industry, the proportion of grinding operations reaches 27–30% and shows an increasing trend [4]. In the aerospace industry, diamond-spark grinding accounts for approximately 40% of the machining processes for titanium alloys and up to 50% for stainless steels [5]. Research indicates that combined methods, such as high-speed diamond-spark grinding (HSDG), are effective for conductive materials by applying electrical discharge in the cutting zone alongside mechanical cutting [6]. As shown in [7], the application of electrical discharge technologies makes it possible to address the problem of universalizing the control of grinding processes for high-strength steels and alloys, as well as to ensure stable achievement of both high process productivity and maximum utilization of the cutting potential of diamond grinding wheels. Furthermore, ensuring the accuracy of such processes often requires specialized steady rests to compensate for cutting forces and elastic deformations, especially when processing complex parts like shafts [8]. However, the issues of cleaning the cutting surface of the grinding wheel from grinding debris and restoring its cutting ability remain unresolved. These challenges may be associated with insufficient cooling and lubrication of the cutting zone. Grinding, including diamond-spark grinding (DSG), is characterized by high thermal intensity of the process; therefore, the selection of an appropriate cooling method for the cutting zone is a key condition for ensuring process stability, high dimensional accuracy, and superior surface quality.

The stability of the thermal regime is directly linked to the efficiency of heat removal and the temperature dynamics of the coolant within the machine's circulation system [9]. Numerous studies and publications have been devoted to the development of new and the improvement of existing cooling methods for the cutting zone during machining, including grinding of hard-to-machine materials (HTMMs). Reference [10] presents an analysis of various cooling methods applied during machining, including the processing of HTMMs. At present, the leading position in industrial application is occupied by the minimum quantity lubrication (MQL) method, which is considered a sustainable and environmentally friendly alternative cooling/lubrication technology.

In addition to conventional MQL, hybrid approaches based on this method are also employed, such as cryogenic MQL, nanofluid-assisted MQL, and MQL combined with ultrasonic vibration. A comparative analysis of the most commonly used cooling methods reported in [11] indicates that MQL is the most recommended cooling/lubrication option for machining HTMMs. In the MQL approach, a small amount of lubricant—typically supplied in aerosol form—is used to reduce friction and wear during cutting or extrusion. The advantages of MQL include efficient heat dissipation, a friction coefficient in the range of 0.20–0.30, which ensures high grinding wheel durability, and a resulting surface roughness of $R_a = 0.2\text{--}0.4\ \mu\text{m}$. However, significant disadvantages of this method include its relatively high cost, which limits its applicability in low-budget projects and small enterprises. According to [12], conventional cutting fluids (CFs) used during machining provide a favorable friction coefficient in the range of 0.25–0.40, maximum grinding wheel stability, and a minimum achievable surface roughness of $R_a = 0.1\text{--}0.3\ \mu\text{m}$. However, it is well known that most industrial cutting fluids are toxic and non-biodegradable in nature. Their regeneration and disposal are costly, and their use increases the overall machining cost. This is primarily due to the toxicity of the main components of industrial cutting fluids. Recently, the possibility of mechanically protecting the cutting zone to prevent heated coolant from contacting machine components has been investigated. Such an approach was implemented in [13], resulting in improved grinding accuracy and allowing its recommendation for the machining of high-precision parts made of HTMMs. Nevertheless, this approach requires additional equipment and increases the processing cost. The analysis of cooling/lubrication methods presented in [11] suggests that these challenges may be addressed through the use of solid lubricants. The advantages of this approach include the elimination of environmentally hazardous liquid coolants and the

feasibility of machining HTMMs under specific conditions. Solid lubricants based on stearic acid are considered particularly suitable for machining HTMMs, for example, a composition consisting of stearic acid (80%) + boron nitride (BN) (20%). This lubricant provides a low friction coefficient in the range of 0.15–0.25, good grinding wheel durability, and a surface roughness of $R_a = 0.3\text{--}0.6\ \mu\text{m}$. It is environmentally friendly, cost-effective, and can be used at temperatures up to 700°C. At cutting zone temperatures up to 400°C, the most rational choice is a lubricant with the following composition: stearic acid (65%) + molybdenum disulfide (MoS_2) (35%). This formulation provides the lowest friction coefficient among all cooling agents—0.10–0.18—good grinding wheel stability, and a surface roughness comparable to that achieved with MQL ($R_a = 0.2\text{--}0.5\ \mu\text{m}$). It is environmentally friendly and has the lowest cost among the considered cooling agents. However, the reported results were obtained for conventional diamond grinding without additional energy input into the cutting zone, which limits their applicability for intensifying diamond grinding processes. Surface roughness is one of the primary indicators of surface quality and largely determines the functional performance and service life of parts. Reference [14] experimentally confirms that grinding parameters—including the peripheral speed of the grinding wheel, grinding depth, and feed rate—significantly affect roughness parameters. According to the reported experimental results, increasing the grinding depth up to 21 μm leads to a significant reduction in the surface roughness parameter R_a – to 0.1624 μm . In addition, increasing the grinding wheel peripheral speed and moderately adjusting the grinding depth can substantially improve machining quality. For example, at a peripheral speed of 45 m/s and a grinding depth of 0.015 mm, the R_a value decreases to 0.1876 μm . However, systematic information on the factors influencing surface roughness during diamond-spark grinding with the use of solid lubricants is currently lacking. The analysis of published studies indicates that a considerable body of research is focused on two main directions:

1. Improving machining accuracy in grinding operations;
2. Minimizing the use of environmentally hazardous liquid lubricants.

The predominant technology recommended for machining hard-to-machine materials (HTMMs) to address these issues is minimum quantity lubrication (MQL) applied in abrasive and diamond grinding processes. At the same time, MQL is a relatively expensive cooling/lubrication technology and is not always economically feasible for small enterprises with limited production volumes. Moreover, aerosolized lubricant delivery requires the use of personal protective equipment by

operators, which entails additional costs. In this context, the use of diamond-spark grinding (DSG) instead of conventional grinding makes it possible to enhance machining efficiency by increasing process productivity and reducing the consumption of diamond grinding wheels.

All of the above provides sufficient grounds to assert the expediency of conducting a study aimed at assessing the influence of diamond-spark grinding with the use of solid lubricants on the formation of surface roughness of a part. The aim of this study is to develop an assessment framework for evaluating the influence of DSG process parameters in combination with solid lubricants on the surface roughness of parts, as well as to formulate recommendations for selecting lubricant compositions and grinding parameter ranges to achieve a specified roughness. This will enable the development of practical recommendations for assigning solid lubricants to specific machining regimes when grinding HTMM parts of various functional purposes in industrial production.

To achieve the stated objective, the following tasks were defined:

- to conduct a series of experiments to evaluate the lubricating performance of four solid lubricants when machining 10Kh11N23T3MR steel;
- to experimentally determine, for all investigated lubricants, the average values of the surface roughness parameter R_a within the specified ranges of cutting speeds and transverse feed values;
- to establish, for each investigated solid lubricant, the experimental relationships $R_a = f(V_s, S_t)$ and to determine the corresponding cutting parameter ranges for the effective application of different types of solid lubricants;
- to perform a preliminary assessment of the presence of surface defects on the polished surface under the proposed solid lubricants and grinding regimes.

3. Material and Methods

The object of the study is the process of diamond-spark grinding (DSG) of hard-to-machine materials (HTMMs) using solid lubricants.

The main research hypothesis is that the required surface roughness of a surface ground by the AIS method can be achieved through the selection of an optimal combination of cutting parameters and the type of solid lubricant used for cooling/lubrication of the cutting zone.

The study is based on the well-established premise that the primary factors influencing the surface roughness parameter R_a are the grinding wheel speed, the transverse feed, and the diamond grain size. These factors can be described by the relationship presented in [15, 16]:

$$Ra = K \cdot V_s^{-\alpha} \cdot S_t^\beta \cdot d_{ab}^\gamma, \quad (1)$$

where V_s is the grinding wheel peripheral speed, m/s; S_t is the transverse feed, mm/stroke; d_{ab} is the diamond grain size, μm ; K , α , β , γ are empirical coefficients depending on the workpiece material and the abrasive.

Material. Austenitic stainless steel 10Kh11N23T3MR was selected as the material for the experimental study, as it is widely used in major industrial sectors for manufacturing components operating under extreme temperature conditions and high mechanical loads.

Experimental specimens. The experiments were performed on test specimens in the form of a steel bar with a circular cross-section (diameter $\varnothing 18$ mm). The area of the machined end face was 254.3 mm^2 .

Machining scheme. Grinding was carried out using a combined method: each operation consisted of 10–15 main passes with current pulses (AISH mode) followed by two finishing passes without current pulses (conventional diamond grinding, ASH mode).

After every two passes, the lubricating composition was supplied into the contact zone between the grinding wheel and the workpiece. Upon completion of the machining cycle, the surface roughness parameter R_a was measured.

Tools. Grinding was performed using metal-bonded diamond wheels of type AC4 50/40 100% M1-01. The selection of tool parameters was justified by the fact that medium-strength AC4-type diamond wheels with a metal bond are recommended for grinding hard alloys and do not require a special dressing regime.

Laboratory setup. The experimental setup was developed on the basis of a modernized universal grinding machine, model 3D642E (Fig. 1).

The machine modernization consisted of supplying the grinding wheel drive motor through an additionally installed frequency converter (Fig. 2). This modification made it possible to perform experiments at increased spindle rotation speeds. In this case, the supply voltage frequency was set to 50, 75, 100, 125, and 150 Hz.

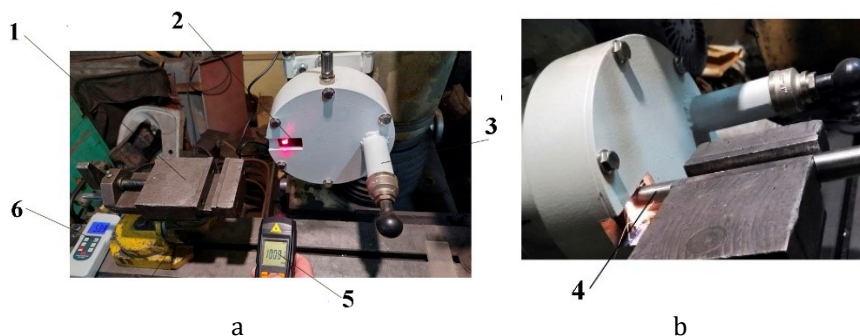


Figure 1: Experimental procedure: (a) experimental setup; (b) grinding process; 1 – vise for clamping the workpiece; 2 – grinding wheel; 3 – lubricant supply device; 4 – workpiece; 5 – grinding wheel rotational speed measurement unit; 6 – system vibration control unit.



Figure 2: Modernized universal grinding and sharpening machine, model 3D642E

The main cutting parameters were determined based on preliminary tests (trial passes). In this study, experiments were conducted at grinding wheel speeds of $V_s = \{25, 40, 50, 63, 80\}$ m/s, which correspond to wheel rotational speeds of 3200, 5120, 6400, 8060, and 10,200 rpm. For each speed value, three experiments were carried out for transverse feeds of $S_t = \{0.005; 0.01; 0.015\}$ mm/stroke. The longitudinal feed rate was 1 m/min.

Lubricant compositions

The selection of the SL compositions was based on an analysis of their characteristics reported in [17-19]. Since one of the study objectives was to evaluate technological means of lubrication and cooling as alternatives to water-based cooling, four solid lubricant compositions (SL) were selected for the experiments (Table 1).

Table 1. Composition of the experimental solid lubricants

Lubricant components	Chemical formula	Composition designation and content of components, %			
		SL1	SL2	SL3	SL4
Stearic acid	$\text{CH}_3(\text{CH}_2)_{16}\text{CO}_2\text{H}$	100	80	65	90
Molybdenum disulfide	MoS_2	-	-	35	-
Hexagonal boron nitride	BN	-	20	-	-
Bell bronze	Cu - 78...82%+Sn - 18...22%	-	-	-	10

One of the main criteria for using solid lubricants is their environmental friendliness, which is ensured by the use of eco-friendly lubricants, a typical example of which is stearic acid. Graphite, molybdenum disulfide (MoS_2), boron nitride (BN), and Bell bronze were used as anti-friction modifiers. Lubrication was applied by bringing a lubricant stick with a diameter of $\varnothing 12$ mm into contact with the working surface of the diamond grinding wheel for 1–2 seconds in the operating mode, after every two passes. The experimental procedure described above was carried out for all four types of TL.

Measurements. Surface roughness during the experiments was evaluated using the Ra parameter, measured with a SURTRONIC 3+ profilometer (Taylor Hobson).

4. Results

A series of experiments was conducted to evaluate the lubricating performance of the selected solid lubricants. Based on the experimental records, diagrams were constructed showing the dependence of the surface roughness parameter Ra on the main cutting parameters during grinding (Fig. 3).

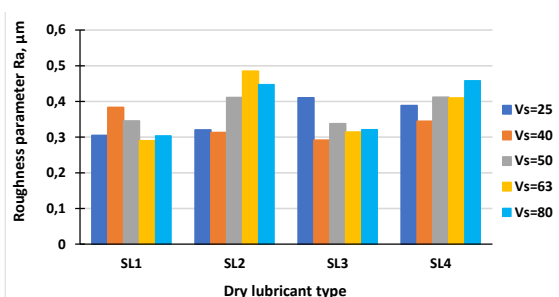


Figure 3: Average Ra values as a function of Vs and SL for different lubricant types

Figure 3 shows the overall diagram of the surface roughness parameter $Ra = f(Vs, SL)$ for all four lubricants, where Vs is the grinding wheel peripheral speed, m/s, and SL is the type of lubricant used.

For the lubricants under study, the average values of the surface roughness parameter Ra were experimentally determined within the specified ranges of cutting speeds and transverse feeds.

Figures 4–7 below present diagrams illustrating the dependence of the measured surface roughness on cutting speed and transverse feed for each lubricant, i.e., the experimental functional relationship $Ra = f(Vs, St)$.

When constructing the graphs in Figs. 3–7, data from measurement protocols with an accuracy of $0.0001 \mu\text{m}$ were used.

For all studied solid lubricants, the experimental relationships $Ra = f(Vs, St)$ and the corresponding ranges of cutting parameters for the effective application of each type of solid lubricant were established (Table 2).

The required surface roughness for parts made of difficult-to-machine materials, according to the recommendations in [20], is as follows:

- 1 – parts of aircraft engines that are assembled: $Ra = 0.2\text{--}0.4 \mu\text{m}$;
- 2 – turbine blades and parts for polishing: $Ra = 0.4\text{--}0.8 \mu\text{m}$;
- 3 – pipelines of hydraulic and fuel systems: $Ra = 0.4\text{--}1.6 \mu\text{m}$;
- 4 – threads and flange connections of pipelines: $Ra = 0.8\text{--}1.6 \mu\text{m}$;
- 5 – housing components of gas turbine engines and turbofan engines: $Ra = 1.6\text{--}3.2 \mu\text{m}$.

A preliminary assessment of defects on the polished surfaces of the parts was carried out.

The study established that at elevated cutting speeds ($Vs \geq 50$ m/s) with insufficient lubrication of the grinding wheel, all types of the solid lubricants tested can lead to defects in the form of burns on the machined surface (Fig. 8).

To identify the nature of the discoloration on the machined surfaces, chemical etching of the parts was performed (Figs. 9 and 10).

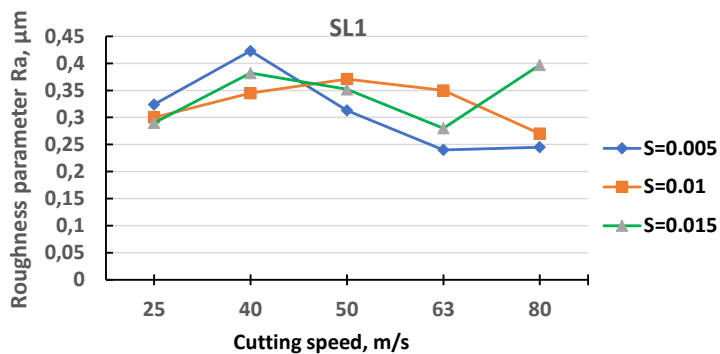


Figure 4: Dependence of the surface roughness parameter $Ra = f(Vs, St)$ for SL1 lubricant.

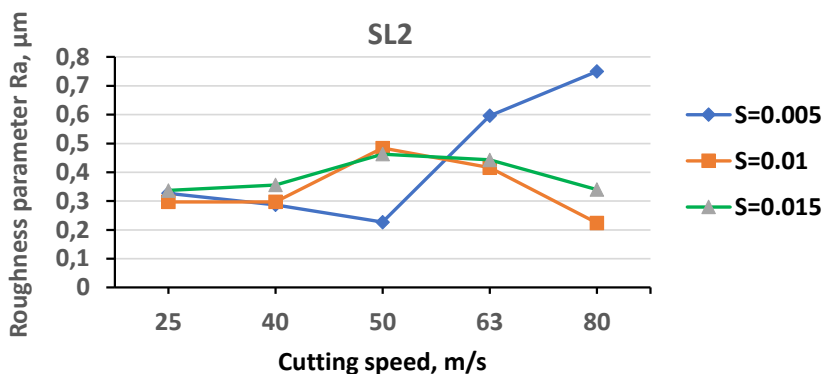


Figure 5: Dependence of the surface roughness parameter $Ra = f(Vs, St)$ for SL2 lubricant.

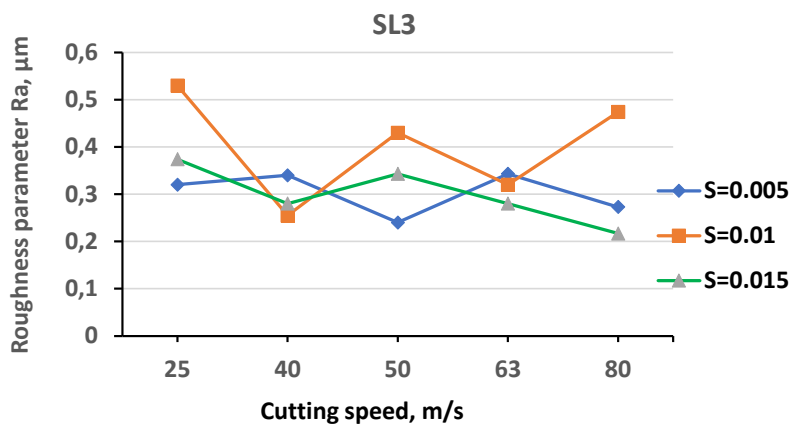


Figure 6: Dependence of the surface roughness parameter $Ra = f(Vs, St)$ for SL3 lubricant.

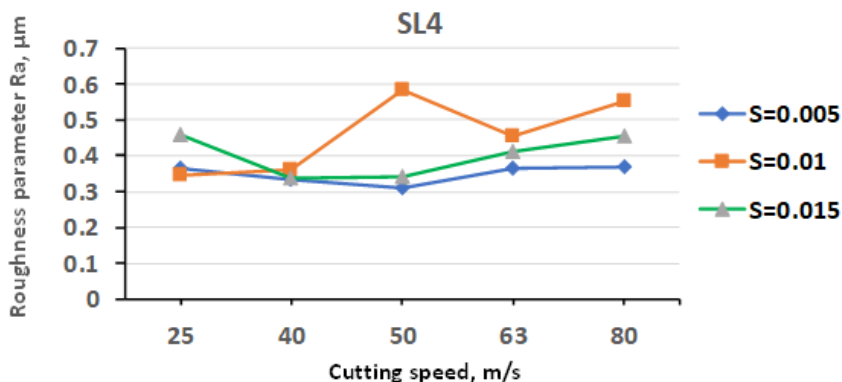


Figure 7: Dependence of the surface roughness parameter $Ra = f(Vs, St)$ for SL4 lubricant.

Table 2. Recommended solid lubricants and cutting parameters for grinding stainless steel 10Kh11N23T3MR

Solid lubricant	Processing modes		Predicted value of Ra, μm	Possible areas of application
	Cutting speed Vs, m/s	Feed St, mm/stroke		
SL1	25-80	0,01	0,28-0,38	1, 2
	25-63	0,015		
	50-80	0,005		
SL2	25-50	0,005	0,22-0,34	2, 3, 4
	63-80		0,60-0,75	
	25-40	0,01-0,015	0,3-0,36	1, 2, 3
	50		0,48-0,49	4
	63-80		0,22-0,42	1, 3
SL3	25-80	0,005 та 0,015	0,21-0,38	4
	25	0,01	0,58	
	40		0,25	
	50		0,43	
	63		0,32	
	80		0,56	
SL4	25-80		0,005 i 0,015	0,38-0,46
	25 i 40	0,01	0,33-0,36	2, 3, 4
	50-80		0,47-0,59	4, 5

The etching was carried out using an alcoholic solution of nitric and hydrochloric acids in the following ratio: 3 ml nitric acid, 10 ml hydrochloric acid, and 100 ml ethanol.

In conclusion, the results demonstrate that the use of advanced lubrication strategies significantly reduces thermal stress in the cutting zone, thereby improving the surface integrity of difficult-to-machine materials.

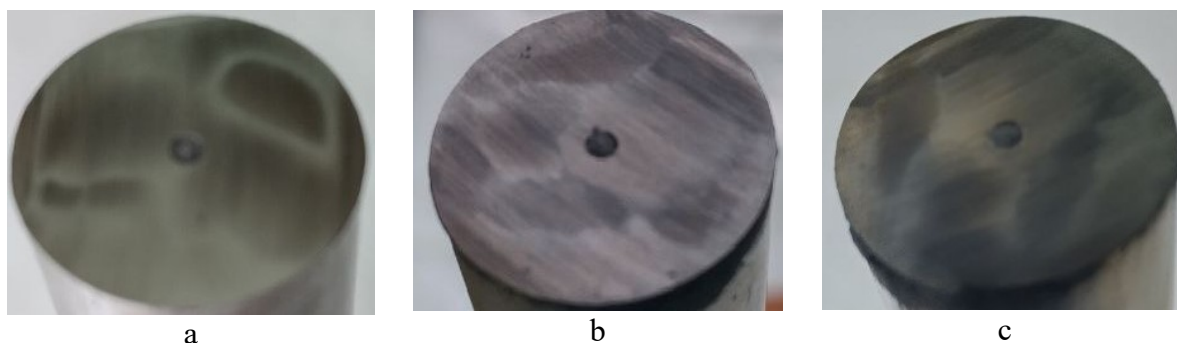


Figure 8: Burned surfaces of parts at elevated cutting speeds ($V_s > 50$ m/s) for the following lubricants: (a) – SL2; (b)– SL3; (c) – SL4.



Figure 9: Investigation of surface burns using SL3 lubricant: (a) – initial sample with burns; (b) – surface after treatment with etching solution.

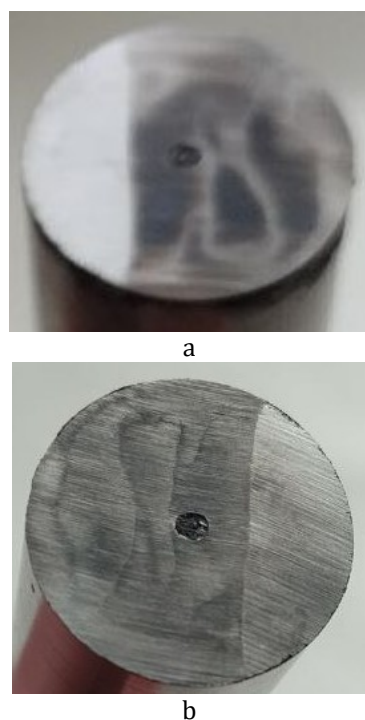


Figure 10: Investigation of surface burns using SL2 lubricant: a – initial sample with burns; b – surface after treatment with etching solution.

5. Discussion

Analysis of the diagram (Fig. 3) shows that when using SL1 lubricant, stable surface roughness values in the range $Ra = 0.29\text{--}0.38\ \mu\text{m}$ are maintained across all cutting speeds from 25 to 80 m/s. An additional advantage of this lubricant is its relatively low cost.

The diagram for SL2 indicates that stable Ra values ($0.31\text{--}0.32\ \mu\text{m}$) are only achieved at cutting speeds of 25–40 m/s. When the cutting speed increases to 50–80 m/s, the Ra parameter rises to $0.42\text{--}0.49\ \mu\text{m}$, despite the high thermal stability of SL2 lubricant (up to 1000°C). A positive feature of SL2 is that it does not leave visible marks on the machined surfaces. Analysis of the diagram for SL3 shows that at a low cutting speed ($V_s = 25\ \text{m/s}$), the lubricant does not provide stable surface roughness ($Ra = 0.41\ \mu\text{m}$). This can be explained by the insufficient cutting speed, which, according to Equation (1), is a critical factor for reducing roughness. However, at cutting speeds of 40–80 m/s, SL3 achieves stable results in the range $Ra = 0.29\text{--}0.34\ \mu\text{m}$. This lubricant performs well under high specific loads due to the high strength of molybdenum disulfide. A drawback of SL3 is the possibility of leaving dark marks on the polished surface [19], which, while not affecting roughness (the spots have the same Ra as the surrounding surface) or causing burns or structural defects, is undesirable for visible polished parts, such as aircraft cabin components or plumbing products.

SL4 lubricant proved to be relatively ineffective at all cutting speeds, providing acceptable roughness values ($Ra = 0.34\text{--}0.39\ \mu\text{m}$) only at low speeds (25–40 m/s). At higher speeds (50–80 m/s), roughness increases to $Ra = 0.42\text{--}0.46\ \mu\text{m}$. Moreover, SL4 can leave metal traces on the part surfaces, and at elevated temperatures, fusible tin may adhere to the wheel surface [19]. Thus, the analysis above allows evaluation of the suitability of each dry lubricant based on the average Ra value of approximately $0.385\ \mu\text{m}$, measured over cutting speeds of 25–80 m/s. According to Equation (1), with constant wheel parameters, Ra decreases with increasing cutting speed V_s and increases with increasing transverse feed St . For SL1 lubricant (Fig. 4), the graphs of $Ra = f(V_s, St)$ at $St = 0.005$ and $0.01\ \text{mm/stroke}$ show stable roughness values in the range $0.25\text{--}0.41\ \mu\text{m}$, decreasing as cutting speed increases. When the transverse feed is increased to $St = 0.015\ \text{mm/stroke}$, Ra rises to $0.40\ \mu\text{m}$, indicating that the effect of increased feed outweighs the roughness-reducing effect of higher cutting speed.

For SL2 lubricant (Fig. 5), at a transverse feed of $St = 0.005\ \text{mm/stroke}$ and cutting speeds $V_s = 25\text{--}50\ \text{m/s}$, satisfactory surface roughness is achieved with Ra values in the range $0.22\text{--}0.34\ \mu\text{m}$. When the cutting speed exceeds 50 m/s, a sharp increase in roughness is observed ($Ra \approx 0.75\ \mu\text{m}$), which is also influenced by the increased effect of the transverse feed. For feeds $St = 0.01\text{--}0.015\ \text{mm/stroke}$, SL2 provides relatively stable Ra values within $0.28\text{--}0.48\ \mu\text{m}$ across all cutting speeds. Based on these observations, it can be concluded that AISH processing at $V_s = 50\text{--}80\ \text{m/s}$ with $St \leq 0.005\ \text{mm/stroke}$ is ineffective for SL2 lubricant.

When using SL3 lubricant (Fig. 6), grinding at feeds $St = 0.005$ and $0.015\ \text{mm/stroke}$ for all cutting speeds yields stable, relatively low surface roughness, $Ra = 0.21\text{--}0.38\ \mu\text{m}$. However, at $St = 0.01\ \text{mm/stroke}$, Ra exhibits unstable behavior across all cutting speeds, ranging from 0.27 to $0.53\ \mu\text{m}$.

SL4 lubricant (Fig. 7) is characterized by higher Ra values over the entire cutting speed range. For feeds $St = 0.005$ and $0.015\ \text{mm/stroke}$, Ra varies from 0.38 to $0.46\ \mu\text{m}$, consistent with the average values shown in Fig. 3. At $St = 0.01\ \text{mm/stroke}$, $Ra = 0.33\text{--}0.36\ \mu\text{m}$ for $V_s = 25\text{--}40\ \text{m/s}$, and increases to $0.47\text{--}0.59\ \mu\text{m}$ for $V_s = 50\text{--}80\ \text{m/s}$. The increase in roughness with higher feed and speed is explained by the limited thermal stability of SL4 components: stearic acid melts at 200°C , tin at 232°C , and the overall temperature resistance of the lubricant is $300\text{--}400^\circ\text{C}$. As speed and feed increase, heat generation reduces the lubricant's effectiveness. Based on these findings, practical recommendations for the use of solid lubricants were formulated (Table 2).

Surface burn-in (Figs. 8–10) occurred due to insufficient lubrication of the grinding wheel, caused

by untimely manual application of the lubricating pencil. Such defects were not observed when the wheel was properly or pre-lubricated. Etching allowed detection of not only surface oxide films but also temperature-induced structural transformations in the metal surface layer. Oxide films dissolved first, revealing the relief of structural changes (Figs. 9a,b). Comparative analysis of micrographs before and after etching (Figs. 9–10, a,b) showed that dark areas interpreted as burn-in did not disappear and their relief became more pronounced, indicating local overheating and phase transformations in the steel. These areas, referred to as «tempering spots», are characterized by altered structure and hardness, and in severe cases, may include hardening structures formed by rapid cooling of the heated region by surrounding cold metal.

The study established that during high-speed electric spark grinding ($V_s = 50\text{--}80$ m/s) using solid lubricants, temperature-induced structural changes can occur. Insufficient or untimely lubrication can cause scorching of the workpiece surface, potentially reducing microhardness and impairing operational properties. When manual lubrication is used, the supply frequency must be experimentally determined to prevent scorching. For industrial application, automatic lubricant supply (Fig. 1, pos.3) is necessary to maintain productivity and prevent surface defects.

The results and recommendations of this study are applicable to diamond spark grinding of a limited group of materials with similar properties, such as stainless steel 10Kh11N23T3MR, Inconel 600, and similar alloys. To generalize these findings for a wider range of materials, additional research is required. Future research aims to intensify the AIS process for difficult-to-machine, special-purpose materials using variable electrode polarity.

6. Conclusions

A series of experiments was carried out to evaluate the lubricating performance of four solid, stearic acid-based greases with different additives. For the processed material, stainless steel 10Kh11N23T3MR, the surface roughness parameter R_a of polished surfaces was determined as a function of the primary cutting parameters: cutting speed (V_s) and transverse feed (St).

For all four tested greases (SL1, SL2, SL3, SL4), the average R_a values were experimentally determined in the range of $0.29\text{--}0.48$ μm when machining at cutting speeds $V_s = \{25, 40, 50, 63, 80\}$ m/s and transverse feeds $St = \{0.005, 0.01, 0.015\}$ mm/stroke. The results of this study are consistent with findings reported by other authors in the field [15].

Experimental dependences $R_a = F(V_s, St)$ were established for all studied lubricants. Based on these dependencies, effective ranges of cutting speeds and feeds were identified, and corresponding values of R_a were determined. For each roughness range, potential areas of application were proposed, linking specific combinations of solid lubricant, cutting speed, and feed to the intended functional purpose of parts made from the studied steel. Practical recommendations for selecting lubricants and processing modes were provided depending on part type and function, highlighting significant prospects for industrial application, particularly in defense-related manufacturing.

It was established that at cutting speeds $V_s \geq 50$ m/s, insufficient lubrication of the grinding wheel can cause defects in the form of scorching on the machined surface. For production implementation, to ensure high-quality surface finish and prevent thermal damage, an automatic lubricant supply system to the cutting zone is required.

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