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Article

Influence of machining parameters on surface texture of Inconel 718 after grinding with multi-granular wheels

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Abstract: Requirements currently imposed on machine elements are constantly growing. It requires to develop new, advanced machining processes. One of the commonly used finishing process is grinding. The article presents the results of the exploratory research in the process of surface grinding with abrasive multigrain wheels of samples made of Inconel 718. The influence of input parameters was investigated: cutting speed V_c, transverse feed speed F_p, longitudinal feed speed F_w, on roughness parameters (*Sa*) and the bearing capacity curve. Based on the conducted research, statistical models of the grinding process were elaborated, which allow to select the most favorable processing parameters depending on the required quality of the surface texture.

Keywords: grinding process; abrasive grains; Inconel 718; regression equations

Introduction

The development of material technologies leads to the production of new alloys, whose properties such as creep resistance, heat resistance allow their use, e.g. in advanced constructions of aircraft engines or gas turbines. Due to the mechanical properties of nickel-based superalloys, such as Inconel 718, they belong to the group of difficult-to-machine materials. Research conducted in scientific centers deals, among others, with the effective shaping of their geometry using unconventional machining technologies such as: electrical discharge machining [1÷4], electrochemical machining [5÷7], hybrid machining [8,9]. An important area of research is also the analysis of the use of finishing treatments in shaping the desired state of the surface layer [10÷12]. The only one of the main finishing machining technologies is grinding.

The development of the grinding process is directly related to the emergence of newer, difficult-to-machine construction materials. This results in higher requirements for cutting tools. Also thanks to this, the development of innovative machine tools is recognized based on new kinematic varieties of grinding processes. The Inconel 718 finishing process in the grinding process is difficult because the material exhibits low thermal conductivity. In the discussed case of material removal machining, this is unfavorable. The resulting accumulation of large amounts of heat in the contact area of the abradant with the workpiece shortens its service life. This phenomenon also affects the formation of dimensional and shape imperfections of the workpiece [13,14]. Attention should also be paid to the emergence of new materials from which abrasive wheels are made [1]. A rapid development in the field of new abrasives was not observed until the 1930s, when 3M (1981) and then Norton (1986) presented a new type of abrasive microcrystalline corundum grains, which was obtained by sol-gel method. The grinding process as a representative of the finishing of the responsible parts of machines and devices is subjected to many applications. With the development of technology, one can observe a systematic increase in the efficiency of the process, the reasons for which are set out above. When discussing the process, attention should be paid to the method of intensification of machining based largely on the constitution of a well-developed active profile of the abradant's surface (CPS) [2]. Conducting experimental tests of the grinding process is mainly about determining the effects of the process depending on the machining parameters used and the characteristics of the machine tool along with the tool. The most frequently treated surfaces are those where the machining allowance for grinding was left from the previous operation.

The material particles constituting of the machining allowance are usually mechanically and thermally damaged. The conditions of destruction of a part of the material to be grinded have a direct impact on the dimensional and shape accuracy of the workpiece, the technical condition of the surface layer, as well as on the change in tribological characteristics of CPS. In the area of contact between the abradant and the workpiece, there are variable distributions of unit pressure, temperature and speed of relative deformations of the material which is being removed.

The course of the experiment and research methodology

The experimental tests carried out were in accordance with the static determined five-level rotatable plan. The used plan includes experiments in stellar arms, which are equally spaced on each axis by +/- α (Table I). The plan was completed by three repetitions at the central point (0,0,0) [3,4]. A schematic plan of the experiment is shown in Figure 1.

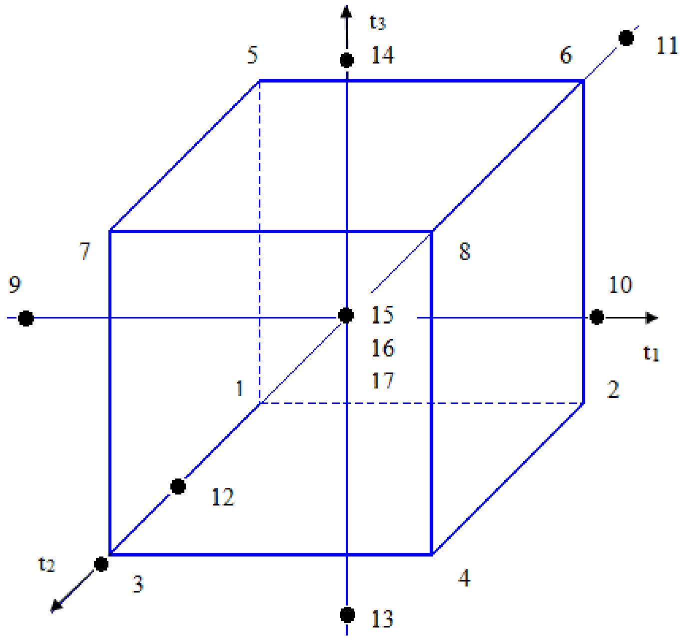


Fig. 1. Adopted experimental model

Prior to the start of the research, the ranges of individual variables participating in the experiment were determined. Assumptions for the experiment are presented below:

- stock: Inconel 718;
- tool:
    - dial 01_80x15x32_39C120-LVS,
    - dial 01_80x15x32_39C120/150-LVS;
- cutting speed Vc=15÷40 m/s;
- longitudinal feed Fw=50÷300 mm/s;
- transverse feed Fp =1÷10 mm/s;
- cutting depth ap =0,03 mm;
- number of grinding passes z=3.

Measured values:

- Sa – average arithmetic deviation of surface ordinates in a 3D system;
- load bearing area.

The tests began with the setting of individual parameter values on the machine, and then the grinding tests with the use of conventional wheel were carried out. After the first stage of the research, the station was re-armed by assembling a multi-granular wheel and the treatment was repeated with the same machining parameters.

Table I. The ranges of used parameters depending on the levels of α arm

Levels	Parameters		
	Vc **(m/s)**	***Fw*** **(mm/s)**	***Fp*** **(mm/s)**
$-\alpha$	15	50	1
-1	20	101	3
0	27	175	6
1	35	250	8
α	40	300	10

After conducting experimental tests and surface topography measurements on the Taylor Hobson FORM TALYSURF Series 2 scanning profilometer, statistical models were developed. Using the STATISTICA program, the regression equations were determined, which is described by the function of the second-degree polynomial (showing the relationship between the cutting speed, the longitudinal feeding speed, the transverse feeding speed and the *Sa* roughness parameter). The *Sa* parameter is one of the basic values describing the 3D space, which is equivalent to the *Ra* parameter in the 2D system. The work focused on this parameter, because these were exploratory tests that were aimed at checking the impact of using a multi-granular wheel on the machined surface.

Two abrasive wheels measuring 80 x 15 x 32 mm by NORTON SAINT-GOBAIN were used during experimental investigations: conventional with a granulation of 120 and hybrid with a granulation of 120/150 (Fig. 2). The obtained tools are dedicated to machining Inconel 718.

Fig. 2. Used grinding wheels

The grinding wheels used are made of green silicon carbide with a ceramic binder. The used material for the building of abradants is characterized by the content of abrasive grains (rhombohedral) with very sharp edges, which are harder than the grains of aloxite. The grains used are a chemical compound that SiC consists of. The Mohs scale defines it as a very hard material, according to which it is 9.5. Due to the high hardness, it is a brittle material. The silicon carbide in question is characterized by good thermal conductivity and low thermal capacity. SiC is a refractory material. The material crystals, which are free from impurities, turn out to be colorless and transparent, at the moment of contamination they appear blue-green, green and black. This material is resistant to adverse chemical environment. Acids and leaches do not cause dissolution. As a material used in grinding wheels, two species are distinguished:

- green silicon carbide SZ,
- black silicon carbide SC.

Both types of silicon carbide grain are used for machining hard and brittle materials. Silicon carbide was also used in the production of lightning arresters or heating elements of electric furnaces [2].

The research involved rectangular samples with dimensions of 38 x 8 x 5 mm made of Inconel 718. Nickel-based alloys are the most widely used and currently account for over 50% of the mass of advanced aircraft engines. The existing trend indicates that in the future this value for new engines will systematically increase. The most common type is the discussed Inconel 718 [5]. Due to the properties of the material used, i.e. high mechanical strength at high temperatures (870 °C), it exhibits a strength of 340 MPa [6]. High creep resistance as well as resistance to oxidation enabled wide use of this alloy in the aerospace and energy industries [7]. Increasing the strength in the alloy is ensured by titanium, which also increases its resistance to corrosion. The use of chromium along with aluminum results in improved surface stability due to the formation of oxides [8÷10].

Research results

The significance of individual coefficients in the regression equation was tested with the t-student test (at the significance level α = 0.15). In each equation, the multiple correlation coefficient *R* was determined, which shows the variability of a given feature. The closer the *R* coefficient is to the unity, the more faithful is the representation of variability of the examined feature. Next, the adequacy of the multiple correlation coefficient was verified by means of the Fisher-Snedecor test. The obtained test value *F* was compared to the critical value F_k. The *R* coefficient is significant if $F/F_{kr} > 1$.

The created equations are characterized by a high degree of *R* correlation. A high accuracy of matching the second-degree polynomial to the obtained measurement points was obtained.

Table II. Summary of the results of regression equations

Used abrasive wheel	Regression equations	R	F/F$_{kr}$
Conventional grinding wheel	$S_a = 1{,}22 + 0{,}04 \cdot F_p^2 + 0{,}009 \cdot V_c \cdot F_p$	0,71	1,78
Mulitgrains grinding wheel	$S_a = 4{,}17 - 0{,}3 \cdot V_c + 0{,}005 \cdot V_c^2 + 0{,}002 \cdot V_c \cdot F_p$	0,73	1,23

The graphic interpretation of the developed regression equations is shown below (Fig. 3 and 4). The presented results indicate that for grinding with a multi-granular wheel, the main independent variable affecting the value of the *Sa* parameter is the cutting speed *Vc*.

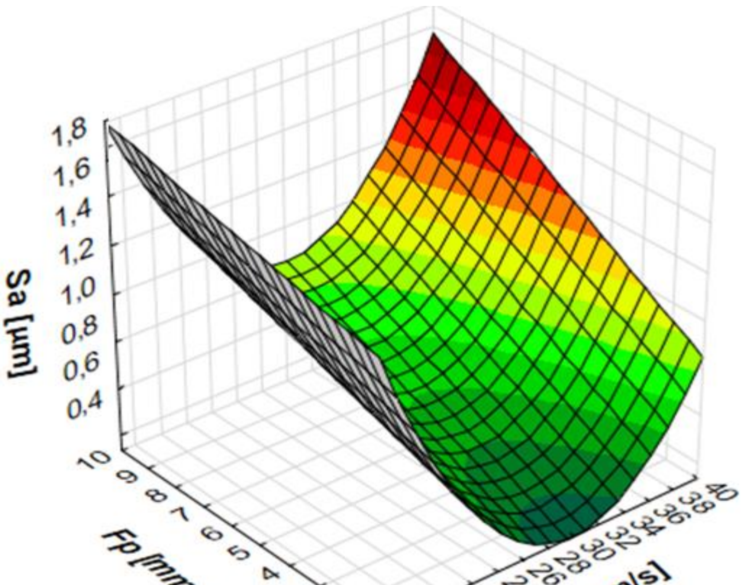


Fig. 3. Dependencies of surface roughness parameters *Sa* from transverse feed *Fp* and cutting speed *Vc* for mulitgrains grinding wheels

It should be noted that for a given cutting speed *Vc*, the increase in transverse feed results in an increase in the *Sa* parameter. The indicated graph shows the local optimum (*Vc* = 28 m/s), for which the lowest value of the Sa parameter is obtained. The obtained value of the cutting speed in the Inconel 718 grinding process is in the range of literature values. Too much cutting speed reduction results in a situation in which the tool is more heavily worn in relation to the workpiece. Removed particles of abrasive grains under the influence of high cutting forces, at low rotational speed of the tool, causes excessive wear of the abrasive wheel. In the conventional wheel, the relationship shown in figure 4 takes place. The transverse feed rate *Fp* has the greatest influence on the *Sa* parameter.

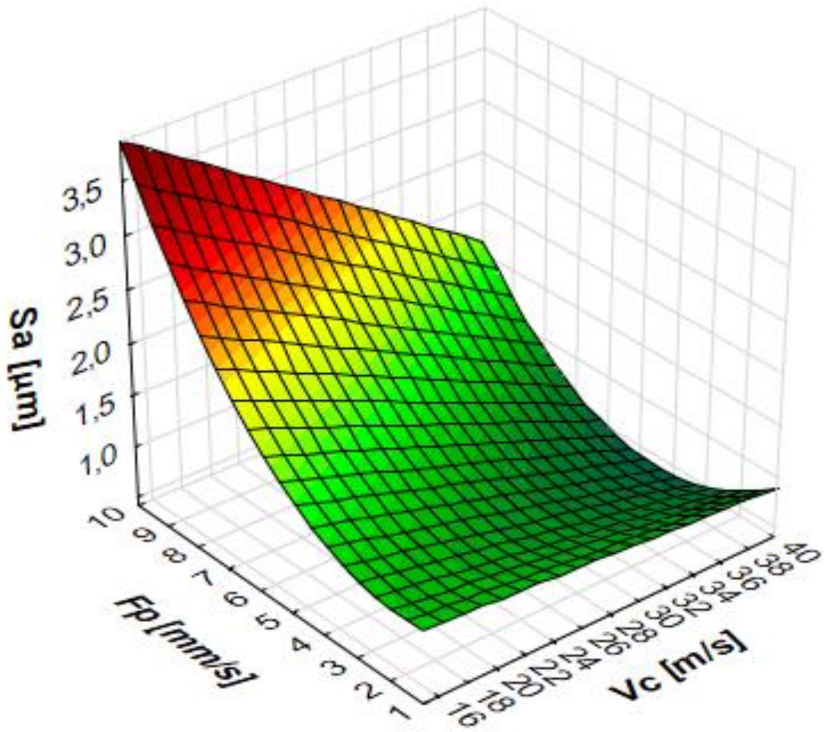


Fig. 4. Dependencies of surface roughness parameters *Sa* from transverse feed *Fp* and cutting speed *Vc* for conventional grinding wheels

Figures 5 and 6 present stereometric images of surfaces treated with conventional and mulitgrains grinding wheels with parameters:

- cutting speed *Vc* = 27,5 m/s;
- longitudinal feed speed *Fw* = 175 mm/s;
- transverse feed speed *Fp* = 5,5 mm/s.

In the analyzed sample, the geometric structure of the surface is of a directional nature. The traces created are the result of the contact of abrasive grains with the workpiece. Analyzing the height scale of the surface profile (gradient of colors on the graph) an increase in profile height for the conventional wheel is observed, which shows the deterioration of the effects of the grinding process [15,16].

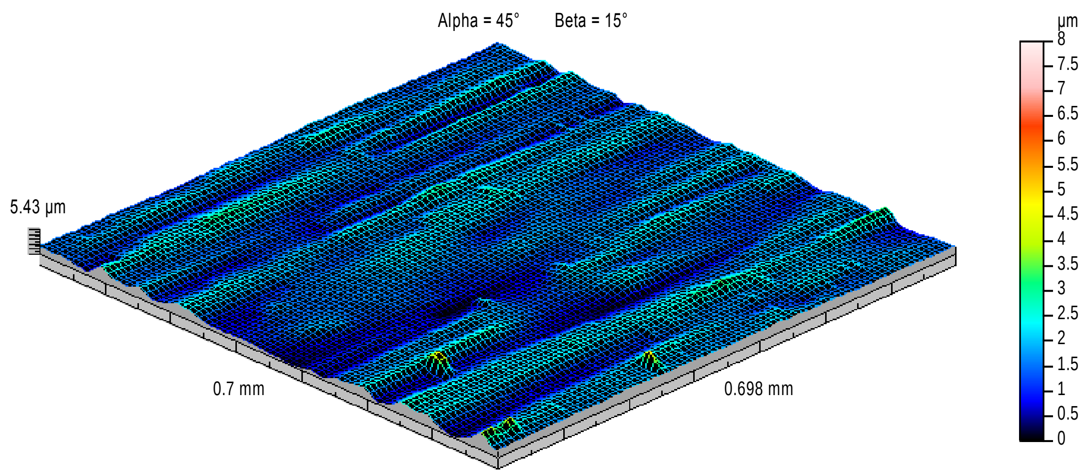


Fig. 5. Surface texture after treatment with the multigrain grinding wheels

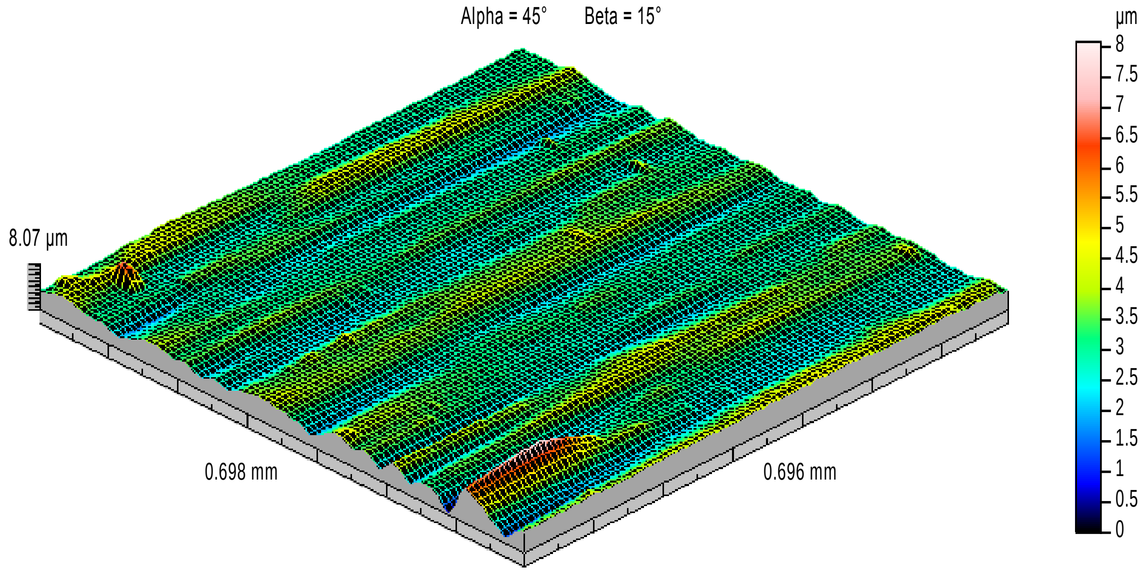
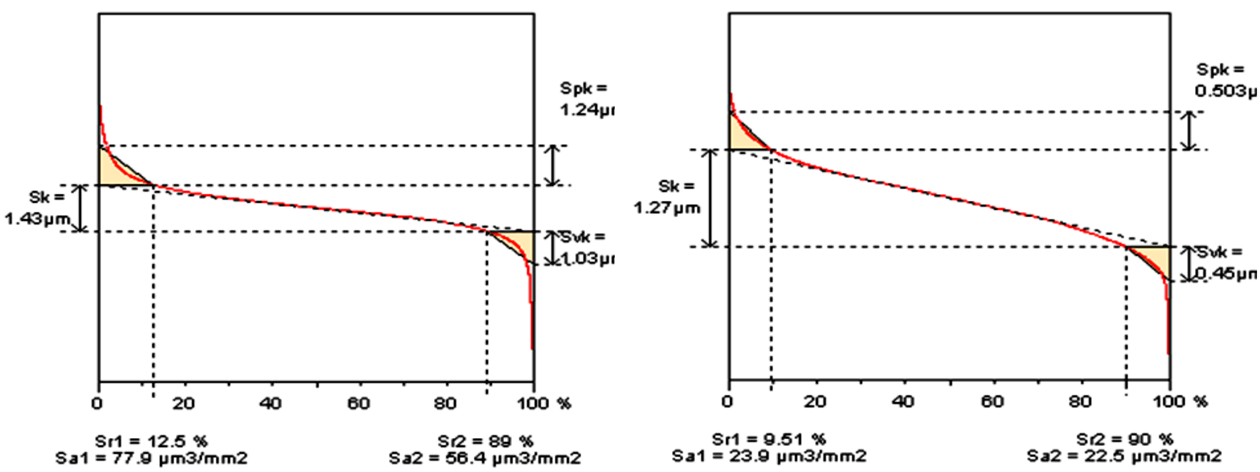


Fig. 6. Stereometric surface texture after treatment with conventional wheels

An analysis of the load bearing capacity of the obtained surfaces in the conducted reconnaissance studies was also carried out. The graphical results are shown below in Figure 7.

Analyzing the obtained abbot-firestone curve (Fig. 7), it can be noticed that the occurring maximum value of the parameter *Spk* = 1.24 µm at the conventional wheel, results in a high bearing proportion of *Sr1* vertices equal to 12.5%. The use of a mulitgrains grinding wheel contributed to the reduction of the *Spk* parameter value to 0.503 µm. This minimizes the allowance needed during lapping and increases the abrasion resistance of the surface. Surfaces grinded with conventional wheels are characterized by better lubrication properties, because the *Svk* parameter has a higher value than in hybrid wheels [17].



(**a**) (**b**)

Fig. 7. Abbot-firestone curve: a) conventional grinding wheel, b) multigrain grinding wheels

Summary and Conclusions

The aim of the work was to check the theoretical assumption that the use of mulitgrains grinding wheels in the grinding process results in improved parameters of the geometric structure of the surface. 34 samples made of Inconel 718 were grinded. The experimental study was carried out in accordance with the Hartley three-level three-element plan. The use of multiple regression made it possible to determine the forces and relationships occurring between a given input factor and several output values at the same time.

The analysis of experimental results shows that for a multi-granular wheel, selected SGP parameters depend largely on the cutting speed *Vc*. The graphical interpretation of the determined regression equations indicates the range of the most advantageous machining parameters, for which it is possible to obtain the lowest values of the roughness parameters (cutting speed in the range of 25 and 32 m/s). The obtained dependence is not identical to the treatment with conventional wheel. The presented results of the single-granular wheel show the possibility of obtaining the minimum values of the roughness parameters at the lowest feed speed, which extends the processing time.

The analysis of stereometric images of treated surfaces shows that the surface has a directional character, with the depth and distance between the individual traces of treatment being uneven. The use of a multi-granular wheel contributed to the lowering of the value of the *Spk* parameter, which results in minimization of the allowance needed during lapping and increases the surface resistance to abrasive wear. Surfaces grinded with conventional wheels are characterized by better lubrication properties, because the *Svk* parameter has a higher value than in hybrid wheels.

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