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Effects of a variety of cutting fluids administered using the minimum quantity lubrication method on the surface grinding process for nickel-based alloys

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Abstract: This paper presents the characteristics of nickel-based alloys, alongside their division into groups, and describes the features that make such materials difficult to grind. The possibilities of exerting a positive influence upon machining conditions, especially through the proper application of grinding fluids, are briefly presented. Both the precise methodologies for, and the results of, the experimental tests carried out on flat surfaces are also detailed. The aim of these tests was to determine the influence of the application of two types of grinding liquid (Ecocut Mikro Plus 82 and Biocut 3000) upon the grinding force values and surface roughness of the machined workpieces made from three nickel alloys (Nickel 201, INCONEL® alloy 600, and MONEL® alloy 400). An additional goal of the tests was to determine the influence of grinding wheel structure on the course and results of the machining process. The results indicate that the physical and chemical properties of Biocut 3000 enabled the most advantageous properties of the machined surface roughness, alongside a simultaneous increase in grinding power, when compared to the results when applying Ecocut Mikro Plus 82. The results showed an almost inversely proportional dependence upon the specific tangential grinding force F_t' and arithmetic mean deviation of the surface profile R_a values, especially in cases of machining Nickel 201 and INCONEL® alloy 600. The original traverse grinding methodology used in the tests made it possible to assess the changes of the grinding conditions within the conventionally selected zones.

Key words: Nickel-based alloys; Surface grinding; Minimum quantity lubrication; Hard-to-cut materials; Grinding force; Surface roughness

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1 Introduction

Industrial development, including the automotive, aviation, and medical sectors, has led to greater demands on both construction materials and manufacturers who use them. Developments in material engineering have led to an increase in the number of materials described as hard-to-cut due to their physical and chemical properties. Both nickel and its alloys are increasingly the most frequently used. Indeed, they constitute approximately 40%–50% of the total weight of plane turbines and are most often used in the production of engine elements such as combustion chambers and turbine parts that are exposed to high temperatures during operation (Nickel Development Institute, 2002; Pollock and Tin, 2006). Moreover, nickel alloys are characterized by a greater resistance to high temperatures, as well as corrosion and oxidation (Nickel Development Institute, 2002). The high pressure created during the machining of nickel-based alloys reinforces them, making further machining considerably more difficult, or even impossible (JM Precision, 2000).

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Nickel-based alloys can be divided into five groups, marked A to E, as well as two subgroups labeled D1 and D2 (JM Precision, 2000; Nickel Development Institute, 2002; Pollock and Tin, 2006), on the basis of the alloy's properties and the types of alloy additives. Group A includes those alloys that contain 95% nickel. Such alloys are characterized by moderate mechanical resistance and a high degree of hardness. They maintain their properties only during operation at low temperatures. In high temperatures they become malleable, which is why the producer recommends machining them in a cold state for the best results. Group B mainly consists of nickel-copper alloys. Such alloys are characterized by a higher resistance and a slightly lower degree of hardness than group A alloys. The machining technique recommended by the producers is cold broaching with stress relief annealing. Group C includes a wide range of alloys whose composition is similar to austenitic stainless steel. The main elements that compose this alloy group are nickel, chromium, and iron. The recommended machining conditions are the same as those in group B. Group D contains mostly those nickel alloys that undergo the aging process easily during hardening. It contains two subgroups: D1 and D2. Subgroup D1 includes alloys that did not undergo the aging process. Subgroup D2 contains those nickel alloys from the D1 subgroup that underwent the aging process and a few alloys that either underwent, or did not undergo the aging process. Group E involves only MONEL® alloy R-405 (UNS N04405). This alloy was developed solely to obtain a high production capacity, e.g., in turning operations. MONEL® alloy R-405 is similar to MONEL® alloy R-400 in terms of hardness, strength, and resistance to corrosion. Moreover, it is less demanding in the cutting machining process. The machined surface is not, however, of as good a quality as MONEL® alloy R-400.

Nickel-based alloys belong to hard-to-cut materials because of the specific properties listed below (Klocke, 2009):

(1) High mechanical resistance and hardness, which contributes to an increase in the mechanical wear of the cutting blades;

(2) Low heat conductivity, which is the cause of temperature increase in the machining zone, and which, in turn, contributes to cutting edge wear;

(3) High malleability, which leads to the creation of smearing and accretions on the edges of the cutting blades;

(4) Alloy compounds found in the material structure that comprise the abrasive materials which speed up the abrasive wear process of the cutting edges;

(5) Hardening during machining.

Table 1 and Fig. 1 present the basic features by which each of the nickel-based alloy groups is characterized during the machining process (Nickel Development Institute, 2002).

Table 1 Groups of the nickel-based alloys and their main representatives

Group	Alloys
A	200, **201**, 205, 212, 222
B	**400**, 401, 450, 36, K, MS250
C	**600**, 690, 601, 825, DS, 330, 20, 800, 800HT, 802, 270, K-500, 75, 86
D	301, K-500 (annealed), 925, 902, 301, 81, G-3, HX, 625, 716, 725, MA754, 80A, 718, PE11, 706, PE16, C276, 751, X750, 901, 617, 263, 105, 90, PK50, 115, B-2, 903, 907, 909
E	R-405

Note: the words in bold type mean that alloys 201, 400, and 600 were used in the experimental investigations in this study

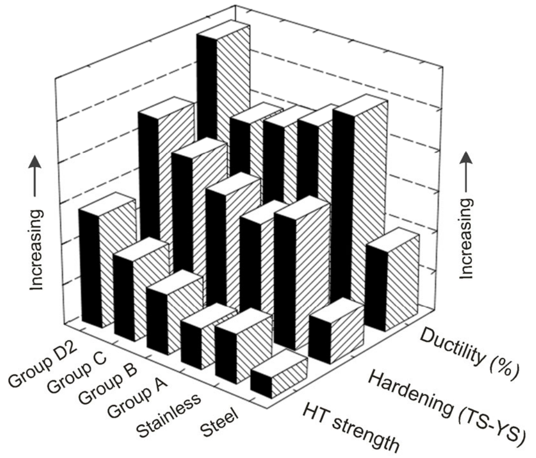

Fig. 1 Nickel-based alloys grouped according to increasing mechanical properties as a result of increased cutting difficulty (Nickel Development Institute, 2002)
HT: heat treatment; TS: tensile strength; YS: yield strength

Due to these properties, grinding defects are often created on nickel-based alloys' surfaces, such as burns, plastic deformations, and the creation of a white layer, even in the application of low material removal rates (Huang and Ren, 1991; Choudhury and El-Baradie, 1997; Osterle and Li, 1997; Neslušan and Czán, 2001; Neslušan, 2009). This is as a result of the low heat conductivity of such materials, which causes considerable temperature increase within the grinding zone. The high machining temperature also has a negative influence upon the operational resistance of the machined surface, mainly on the workpiece fatigue properties (Chen *et al.*, 2001; Liu *et al.*, 2006; Ulutan and Ozel, 2011).

The greatest problem of nickel-based alloy grinding processes is their high susceptibility to clogging, loading, and smearing (these three terms describing this phenomenon can be found in the literature) of the grinding wheel active surface (GWAS) with chips of the machined material (Xu *et al.*, 2003). This is as a result of the properties of the nickel-based alloys which are characterized by high endurance and resistance to corrosion and fatigue, as well as by low heat conductivity and high malleability (Nickel Development Institute, 2002). Clog, smear, and load creation on the GWAS have considerable influence upon the conditions in the machining zone, resulting in an increased grinding strength, power, and temperature, all of which lead to a shortening of the grinding wheel life, and a deterioration of the machined surface quality–both in terms of stereometry and internal stresses (Neslušan, 2009). What are obtained as a result are low G-ratio values, unfavorably strong negative stresses, and a decrease in the dimension-shape precision of the machined surface due to an unstable grinding process (Neslušan and Czán, 2001).

A considerable influence upon the conditions in nickel-based alloy grinding zones is exerted by the proper selection of grinding fluids and anti-adhesive substances. This is also applicable to the way they are applied (Schlindwein, 2008; Webster, 2008). There are numerous methods that limit the adhesion of the machined material to the abrasive tools surface, including:

(1) The application of intensive cooling using the flood method which, despite a high flow rate of the grinding fluid (3–5 L/min), is often insufficient due to the limited amount of the liquid stream actually reaching the machining zone; this method makes a considerable impact upon the environment because of the need to use the grinding fluids;

(2) The use of various cleaning nozzles, such as shoe, injector, by-pass or needle nozzles, as suggested by Webster (1995);

(3) The application of the minimum quantity lubrication (MQL) method, in which a mixture of the grinding fluid with air (aerosol) is applied with a considerably limited flow rate (of approximately 50 ml/h) (Tawakoli *et al.*, 2010; Wójcik *et al.*, 2010; Maruda *et al.*, 2015a);

(4) Oliveira *et al.* (2012) tackled the problem of optimization of the angle of the cleaning nozzle during grinding operation in relation to the grinding wheel, where the cleaning medium was compressed air with the simultaneous application of MQL;

(5) In the internal cylindrical grinding process, the best results are obtained when the grinding fluid is applied centrifugally, through special channels or pores in the grinding wheel, as well as with the use of the MQL method (Aurich, 2013);

(6) The application of the minimum quantity cooling lubrication (MQCL) method, in which a mixture of the special oil (rarely emulsion) with cooled air is applied into the machining zone (Zhang *et al.*, 2012; Maruda *et al.*, 2015b; 2016);

(7) Tool impregnation, i.e., introduction of additional chemical substances such as sulphur, graphite, silicon or composite mixtures, into the free intergranular spaces of the GWAS (Nadolny *et al.*, 2013; 2015).

Of the above mentioned methods of cooling the grinding zone, the MQL method has been developed quite intensively in the last few years. This method makes it possible to considerably limit grinding fluid expenditure as compared with the commonly used flood method. The MQL method's properties enable the cutting of costs connected with the purchase and disposal of machining fluids. This also helps to limit the health risks that operators might face.

This paper presents the results of experimental tests in the grinding of flat surfaces made from Nickel 201, INCONEL® alloy 600, and MONEL® alloy 400, using two grinding fluids (Ecocut Mikro Plus 82 and Biocut 3000) conducted by the use of the MQL method. These tests can be seen as supporting the modern trend of the development of manufacturing techniques known as green manufacturing, sustainable or clean production.

2 Methodology

The aim of the tests was to determine the influence of the application of two selected grinding fluids on the grinding force values and surface roughness of machined workpieces made from three different nickel alloys. An additional goal of the tests was to determine the influence of grinding wheel construction on the course and results of the machining process, as well as to determine the difference in values of the grinding force and machined surface roughness within three zones of the machined surface.

2.1 Characteristics of the tested hard-to-cut materials

Workpieces made from alloys that belong to Groups A (Nickel 201), C (INCONEL® alloy 600), and B (MONEL® alloy 400) were selected for the tests. The first was Nickel 201 (Special Metals Corporation, 2006), whose characteristics are similar as those of Nickel 200, but differ in carbon content. Nickel 201 has a lower carbon content so as to avoid the brittleness caused by the presence of intergranular carbon at temperatures over 315 °C. The low carbon content causes the alloy's hardness to decrease, which makes Nickel 201 suitable in cases of cold-shaped parts. The next material was INCONEL® alloy 600 (Special Metals Corporation, 2008). It is a nickel-chromium alloy characterized by a high resistance to oxidation at high temperatures, as well as to corrosion and corrosive cracking in a chloride ion environment. As a result of its properties, it is commonly used in heat treatment devices (e.g., elements of industrial furnaces), as well as in the chemical and food industries (e.g., in devices used for alkalization). The third examined alloy was MONEL® alloy 400 (Special Metals Corporation, 2005). It is a nickel-copper alloy that is highly resistant to corrosion, even in environments such as seawater, hydrofluoric acid or sulfuric acid. MONEL® alloy 400 is used in the construction of naval machines and devices, aviation structures, as well as within the chemical industry (e.g., valves, pumps, shafts, junctions, and heat exchangers), among others.

Tables 2 and 3 present the chemical composition, as well as the physical and mechanical properties of Nickel 201, INCONEL® alloy 600, and MONEL® alloy 400 (Special Metals Corporation, 2005; 2006; 2008).

The workpieces were shaped as rhomboids sized 20 mm×10 mm×100 mm. The machined surfaces of the samples were conventionally divided into three areas numbered I to III (Fig. 2).

These areas correspond to (in the direction congruent with the table feed direction) the entrance of the grinding wheel into the machined material (Area

Table 2 Limiting chemical composition of Nickel 201, INCONEL® alloy 600, and MONEL® alloy 400 (Special Metals Corporation, 2005; 2006; 2008)

Alloy	Limiting chemical composition (%)							
	Ni (+Co)	C	Fe	Cr	Mg	Si	S	Cu
Nickel 201	99.0 (min.)	0.02 (max.)	0.40 (max.)	–	0.35 (max.)	0.35 (max.)	0.010 (max.)	0.25 (max.)
INCONEL® alloy 600	72.0 (min.)	0.15 (max.)	6.00–10.00	14.00–17.00	1.00 (max.)	0.50 (max.)	0.015 (max.)	0.50 (max.)
MONEL® alloy 400	63.0 (min.)	0.30 (max.)	2.50 (max.)	–	2.00 (max.)	0.50 (max.)	0.024 (max.)	28.00–34.00

Table 3 Physical and mechanical properties of Nickel 201, INCONEL® alloy 600, and MONEL® alloy 400 (Special Metals Corporation, 2005; 2006; 2008)

Alloy	Physical property					Mechanical property (plate, hot-rolled)			
	Density (g/cm^3)	Melting range (°C)	Specific heat (J/(kg·°C))	Curie temperature (°C)	Thermal expansion at 100 °C (μm/(m·°C))	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Hardness, Rockwell B
Nickel 201	8.89	1435–1446	456	360	13.2	345–485	83–240	60–35	55–80
INCONEL® alloy 600	8.47	1354–1413	444	−124	13.3	580–760	240–450	50–30	80–95
MONEL® alloy 400	8.80	1300–1350	430	21–49	14.2	517–655	276–517	45–30	70–96

I), stable operation (Area II), and exit from the material (Area III).

2.2 Experimental arrangement

The test described was carried out on a stand equipped with a flat-surface grinder SPD-30 by JoteS Co. Ltd. (Poland), as shown in Fig. 3.

A grip equipped with a type 9321B force gauge by the Kistler Company (Switzerland) was mounted on the grinding wheel table, which made it possible to measure the tangential component of grinding force F_t with a sampling frequency of about 10 kHz. The signal from the force gauge was directed through a type 5011A amplifier, made by the same producer, to a type KUSB-3108 measurement data acquisition module, by the Keithley Company (USA), and processed in quick data acquisition (DAQ) software. The tangential grinding force F_t was then calculated per 1 mm of grinding width as a specific tangential grinding force: $F_t'=F_t/b_s$ (where b_s is the width of the grinding wheel measured parallel to the wheel axis). In this case, b_s=15 mm. The experimental stand was additionally equipped with a system for applying oil spray using the MQL method, a technique which is described in more detail in Section 2.3.

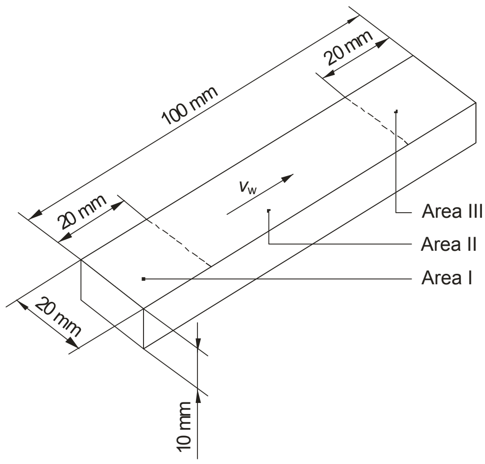

Fig. 2 Workpiece dimensions with marked conventional areas (Areas I–III) on the machined surface
v_w is the workpiece speed

2.3 Cooling method and liquids

The grinding fluids were administered to the grinding wheel contact area using the MQL method and the MicroJet® MKS-G100 system, by the Link Company (Germany) (Link GmbH, 2003). The machining liquid was inserted through a single atomizing nozzle with a flow rate of Q_{gf}=40 ml/h. Table 4 lists the specifications of the minimum quantity lubrication system used in the studies.

Two types of dedicated machining fluids were used which, according to the producers' data, were

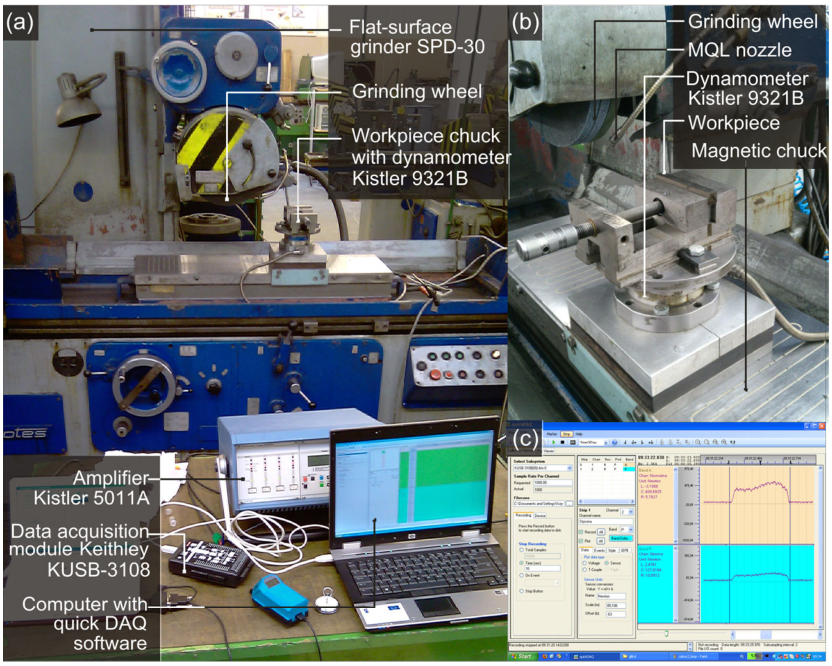

Fig. 3 Experimental arrangement equipped with flat-surface grinder SPD-30 by JoteS Co. Ltd. (Poland)
(a) Overall view; (b) Machining zone; (c) Quick DAQ software window

designed for use with the MQL method. The first of these was Ecocut Mikro Plus 82, by the Fuchs Company (Germany) (Fuchs Europe Schmierstoffe GmbH, 2013) and the second was Biocut 3000, by Molyduval (Germany) (Molyduval, 2009). These are fluids based on fatty alcohols with good cooling-smearing properties, widely recommended in material removal machining processes. The physical properties of these fluids are presented in Table 5.

Table 4 Specifications of the MicroJet® MKS-G100 minimum quantity lubrication system (Link GmbH, 2003)

Parameter	Value
Maximum supply pressure (MPa)	1
Maximum pressure (MPa)	0.7
Working pressure (MPa)	0.05–0.6
Air consumption up to approx. (L/min)	50–70
Lubricant consumption up to approx. (ml/h)	5–200
Maximum capacity of lubricant container (L)	1.6

Table 5 Physical properties of the grinding fluids used (Molyduval, 2009; Fuchs Europe Schmierstoffe GmbH, 2013)

Parameter	Value	
	Ecocut Mikro Plus 82	Biocut 3000
Density (15 °C) (g/m)	0.84	0.91
Kinematic viscosity (20 °C) (mm^2/s)	51.4	39–49
Kinematic viscosity (40 °C) (mm^2/s)	17	13
Flash-point (°C)	>150	>150
Freezing point (°C)	−20	−20
Solubility in water	Immiscible	Immiscible
Colour	Colourless	Yellow

2.4 Grinding wheels

Two kinds of grinding wheels of type 1 were used in the tests, with ceramic bond and abrasive grains on the basis of Al_2O_3: 3TGP 54K VX and 3XGP 54K VY, produced by the Norton Company (USA). The grinding wheels, sized 340 mm×20 mm×137 mm, were made from a mixture of fused alumina abrasive grains, with an elongated shape of the "pencils" type TGP™–3TGP 54K VX (Fig. 4a) or a "scaly" shape TGX™–3XGP 54K VY (Fig. 4b), and of pink fused alumina CrA in the proportion of 30%/70% (Jackson and Davim, 2010). The grain number (54) and hardness (K) were the same in both grinding wheels.

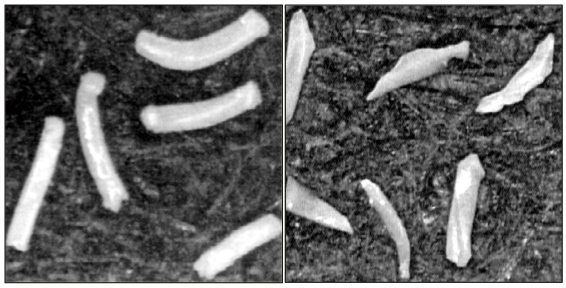

Fig. 4 Differences in the shape of microcrystalline sintered corundum abrasive grains with elongated shape: (a) "pencil" shape grains; (b) "scaly" shape grains (Jackson and Davim, 2010)

2.5 Grinding conditions

The component tangential grinding force F_t was measured after the grinding process was finished, and the machined surface roughness profiles were registered, on the basis of which, values of the arithmetic mean deviation of the workpiece roughness profile R_a in Areas I–III were determined.

Fig. 5 presents an exemplary graph of the course of F_t obtained during the grinding of INCONEL® alloy 600 using a 3TGP 54K VX grinding wheel and Biocut 3000 machining fluid.

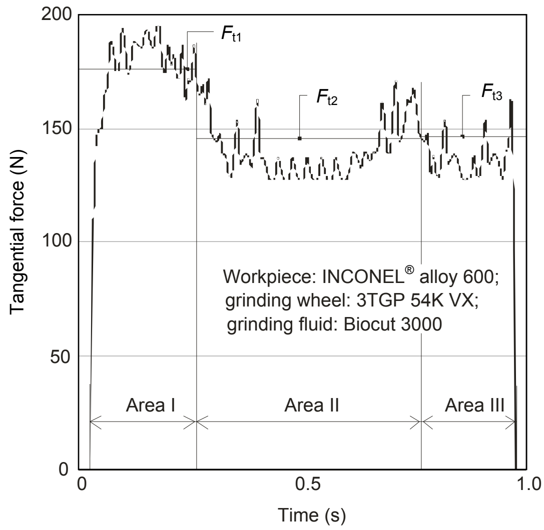

Fig. 5 An exemplary course of the tangential grinding force F_t during the grinding of INCONEL® alloy 600, using a 3TGP 54K VX grinding wheel and Biocut 3000 grinding fluid delivered via the MQL method

Three time frames were marked on the graph, which involve areas (I–III) of the machined surface.

For every frame, an average tangential component grinding force value was determined and stated as the value corresponding to given areas (Areas I–III). The results of initial tests reveal that F_t is dominant among all three components of grinding force, while the following measurements were conducted only with the F_t component.

A Hommel-Tester T8000, manufactured by the Hommelwerke Company (Germany), with a Waveline 60 Basic moving measurement head unit, was used to measure surface roughness. The R_a parameter value was calculated each time as the average of the three measurements in each of the examined machined surface areas (Areas I–III). All surface roughness measurements were carried out according to the ISO 4288 standard: the sampling length was 0.8 mm and measurements were conducted on a tracing length of 4.0 mm (which is five times the sampling length) plus pre-travel (0.4 mm) and post-travel (0.4 mm) what gives 4.8 mm in total. The R_a parameter is commonly used by researchers and in industry. The authors are aware of the limitations resulting from the use of only one parameter from the group of vertical parameters, while omitting horizontal parameters, functional parameters, etc. However, as a widely acceptable set of surface roughness parameters has not so far been developed and standards define several dozen of them, it was decided to use just R_a, in order to enable a comparison of results with other work.

Having been mounted on the grip, the top surface of each sample was initially ground in 10 passes, along with sparking-out, at a working engagement of a_e=0.005 mm. As a result, 0.05 mm of material was removed in order to eliminate location error and initially shape an even workpiece surface microgeometry. In this preparatory procedure, the grinding fluid was applied using the flood method.

Tests were carried out on the kinematics of rectilinear tangential peripheral grinding, while the grinding wheel performed just a single pass, starting from the side of Area I (Fig. 2), and after which the machining was performed. Such a single-pass flat surface grinding procedure was carried out with a working engagement of a_e=0.02 mm, a grinding wheel peripheral speed of v_s=25 m/s, and a workpiece speed of v_w=0.1 m/s. A comprehensive list of single-pass circumferential tangential surface grinding conditions is presented in Table 6.

3 Results and discussion

Fig. 6 shows the values of the specific tangential force F_t' recorded during the tests, the values of the arithmetic mean deviation of the workpiece

Table 6 Grinding conditions

Item	Property
Grinding process	Single-pass circumferential tangential surface grinding
Grinding machine	Flat-surface grinder SPD-30 by JoteS Co. Ltd. (Poland)

Grinding parameter	Grinding wheel peripheral speed, v_s=25 m/s;
	workpiece speed, v_w=0.1 m/s;
	working engagement (machining allowance), a_e=0.02 mm;
	grinding fluid flow rate, Q_{gf}=40 ml/h

Grinding wheel dressing parameter	Dresser: single grain diamond dresser type M1020, Q_d=2.0 kt; grinding wheel peripheral speed while dressing, v_{sd}=10 m/s; dressing allowance, a_d=0.01 mm; axial table feed speed while dressing, v_{fd}=5.0 mm/min; the number of dressing passes, i_d=4
Grinding wheel	3TGP 54K VX and 3XGP 54K VY; grinding wheel external diameter, d_s=350 mm; grinding wheel width, b_s=15 mm; grinding wheel internal diameter, h_s=76 mm
Grinding fluid	Ecocut Mikro Plus 82 and Biocut 3000 given by MQL method
Workpiece	Bars with dimensions of 20 mm×10 mm×100 mm made from Nickel 201, INCONEL® alloy 600, and MONEL® alloy 400
The number of test repetitions	n=3

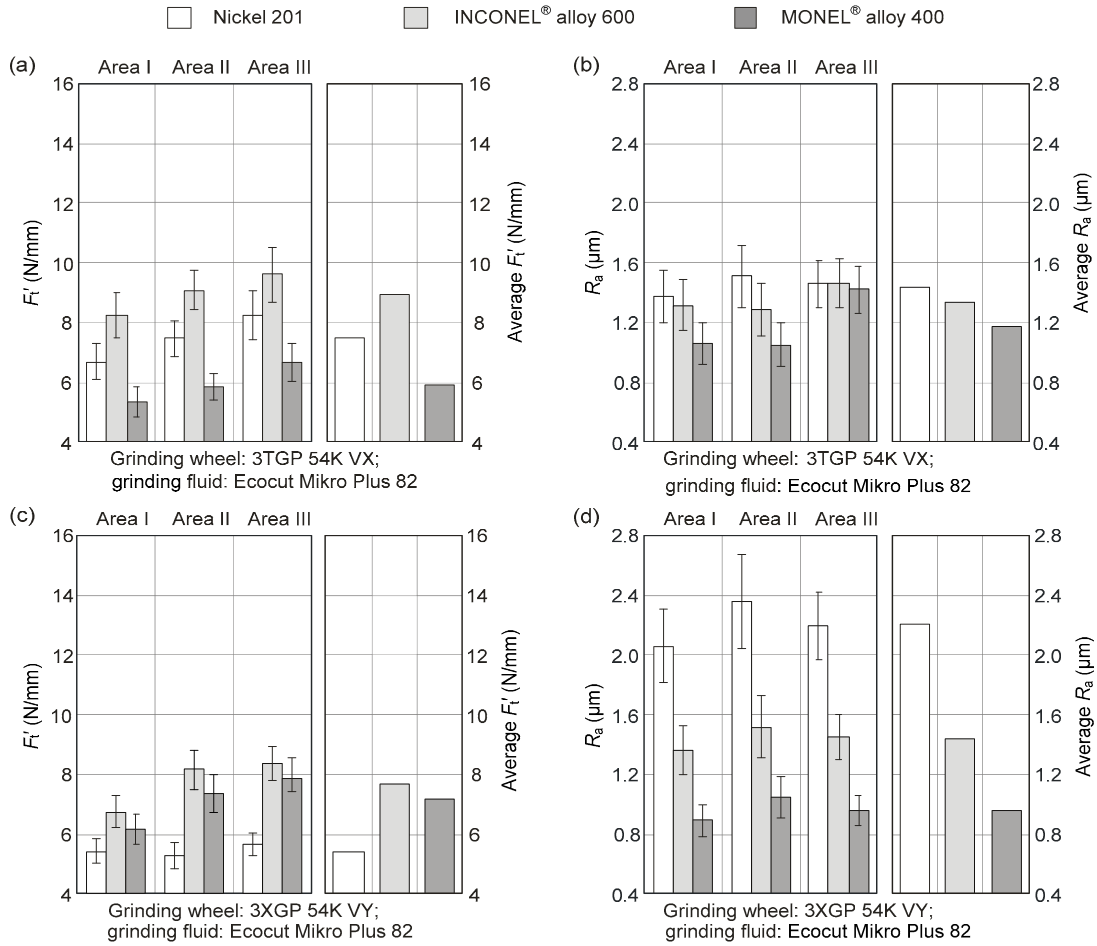

Fig. 6 Specific tangential force F_t' (a) and (c) and arithmetic mean deviation of the workpiece roughness profile R_a (b) and (d) in Areas I–III, as well as their average values obtained in studies carried out using Ecocut Mikro Plus 82 grinding fluid and two types of grinding wheel, namely, 3TGP 54K VX (a) and (b) and 3XGP 54K VY (c) and (d)

roughness profile R_a in Areas I–III, as well as their average values in cases where Ecocut Mikro Plus 82 grinding fluid was used. Fig. 7 contains analogous data in cases where Biocut 3000 grinding fluid was used during grinding.

Analysis of the values presented in Figs. 6 and 7 indicated that lower values of the tangential component grinding force accompanied a surface with a greater roughness being shaped, than in cases of machining with lower force values. Such dependence is especially visible when comparing the grinding results obtained for Nickel 201 and INCONEL® alloy 600. This dependence is caused by the varying amount of elementary phenomena that accompany material removal. As the abrasive grains' active apexes face less cutting resistance, the chip formation frequency increases while the intensity of groove and side material pick-ups decreases. The abrasive grains' apexes remain sharp for a longer period of time while the friction share in the process is lower. As a result, the shaped workpiece surface is characterized by a higher level of development and the R_a parameter obtains higher values. The increased grinding forces are indicative of a greater friction share, probably connected with hampered chip formation, and greater groove and material pick-up creation. The surface shaped in this way is thus characterized by relatively low unevenness heights while the R_a parameter value is also lower.

When comparing the results obtained in the process of grinding Nickel 201 and INCONEL® alloy 600, distinct differences emerge. In the case of machining the Nickel 201 alloy, the grinding forces were lower than those for INCONEL® alloy 600 in all cases. This may be as a result of the considerable volume of alloy additives in the latter material (Fe: 6%–10% and Cr: 14%–17%), which are only trace constituents in Nickel 201 (Fe: 0.4% max. and Cr: –). As a result, the Nickel 201 alloy is characterized by an austenitic structure, with relatively low resistance and hardness. INCONEL® alloy 600, on the other hand, belongs to the Ni-Cr-Fe alloy group, which includes those classified as solution-strengthened alloys. As a result, it is characterized by a greater resistance. However, it seems that what contributed most to the considerable increase of the grinding force was this alloy's tendency for rapid work hardening (Fig. 8) (Special Metals Corporation, 2008).

Amongst the materials ground, the most advantageous conditions were registered in the case of MONEL® alloy 400 for which the lowest values of the R_a parameter–which describes machined surface roughness–were registered with relatively low F_t' values. Nickel and copper, of which this alloy is mostly composed, are elements characterized by perfect solubility in a solid state. This makes it possible to create single-phase solution-strengthened alloys. The more favorable course and results of machining MONEL® alloy 400, as compared to the two remaining nickel alloys examined in the tests, seem from the fact that this alloy belongs to group B. Nickel alloys from this group give both the best machinability and the smoothest finish (JM Precision, 2000).

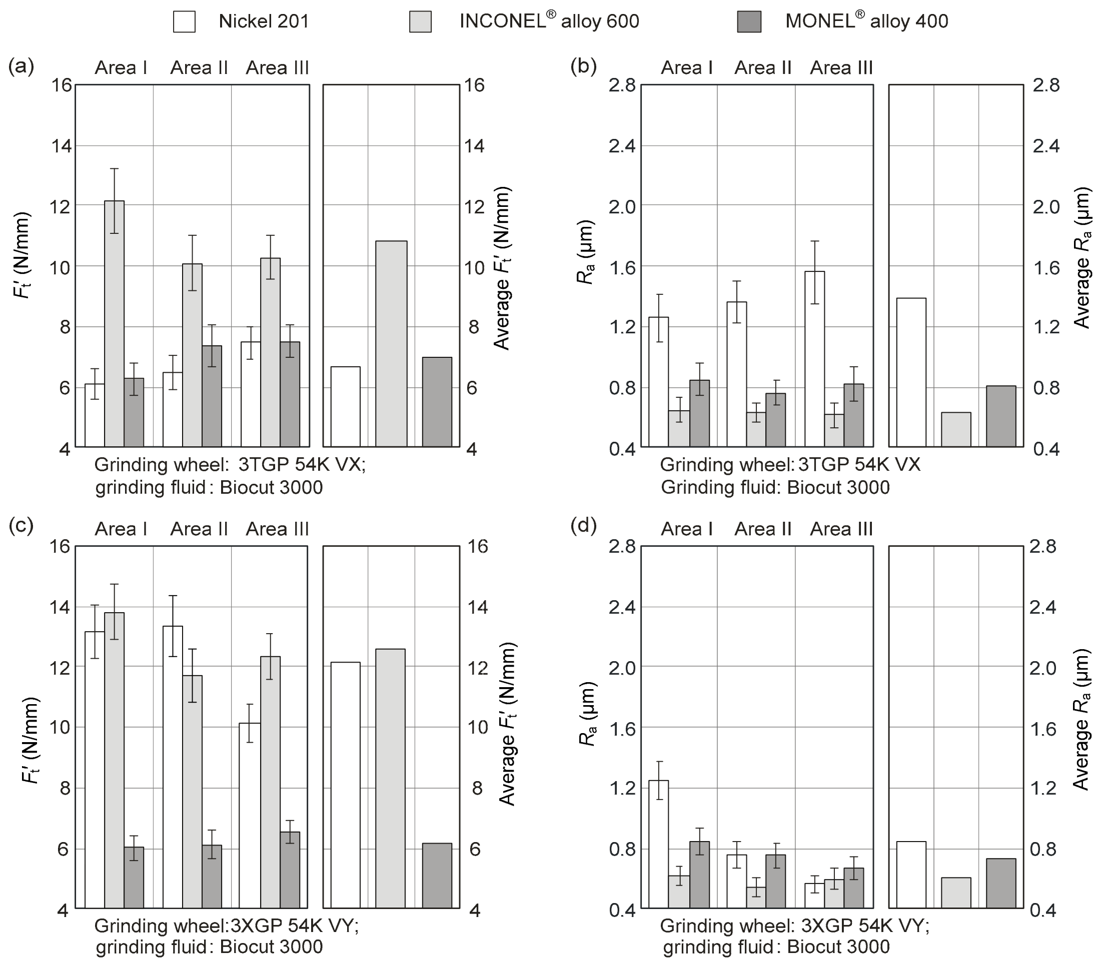

Fig. 7 Specific tangential force F_t' (a) and (c) and arithmetic mean deviation of the workpiece roughness profile R_a (b) and (d) in Areas I–III, as well as their average values obtained in studies carried out using grinding fluid Biocut 3000 and two types of grinding wheels, namely, 3TGP 54K VX (a) and (b) as well as 3XGP 54K VY (c) and (d)

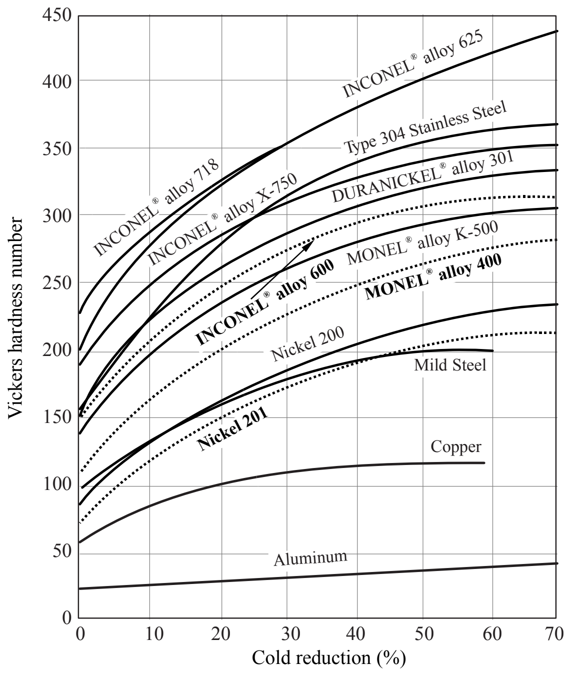

Fig. 8 Work-hardening rates of workpiece materials used in investigations and for other materials (Special Metals Corporation, 2008)

When analyzing the results obtained, and taking into consideration the influence of particular machining areas (Areas I–III) on the registered final values of the process, it may be concluded that in most cases the grinding force increased in subsequent areas in the grinding wheel feed direction (Figs. 6a, 6c, 7a, and 7c). This might be indicative of the rapid wear of the abrasive grains whose progressive dulling contributed to the increase in friction in the grinding zone and, consequently, in the force necessary to separate the material. In the case of the measured machined surface roughness values, no clear tendency toward change in particular areas of the ground surface was observed (Figs. 6b, 6d, 7b, and 7d).

Fig. 9 presents charts of the average F_t' and R_a values for all the machined nickel alloys in their various configurations. Figs. 9b and 9e present the differences that result from the application of two types of grinding liquids. Figs. 9c and 9f illustrate the influence of wear on different types of grinding wheels and the registered results of the examined grinding process.

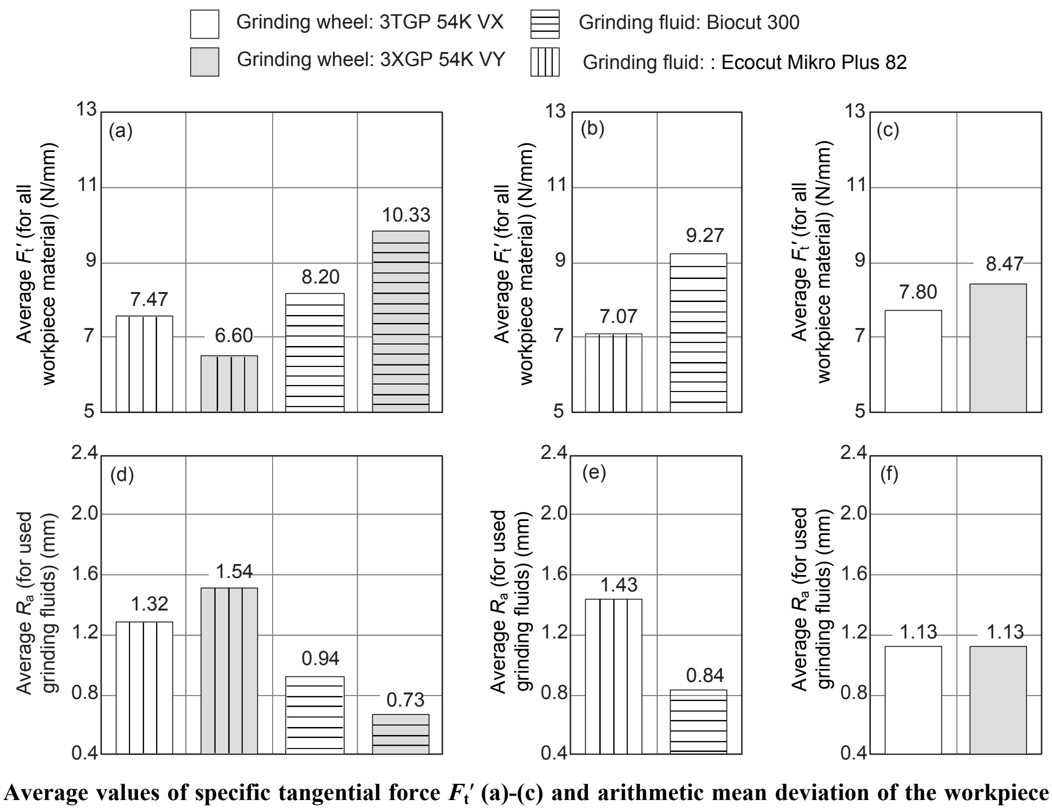

Fig. 9 Average values of specific tangential force F_t' (a)-(c) and arithmetic mean deviation of the workpiece roughness profile R_a (d)-(f) for all workpieces materials (a) and (d), for grinding fluids employed (b) and (e), and for grinding wheels employed (c) and (f)

When comparing the results obtained for machining using Ecocut Mikro Plus 82 and Biocut 3000 fluids, averaged values across three areas (Areas I–III), and for all the machined materials (Figs. 9a and 9d), it may be concluded that regardless of the tool applied (grinding wheels 3TGP 54K VX and 3XGP 54K VY), higher grinding force values were registered during machining using Biocut 3000. At the same time, the surfaces machined in such conditions were characterized by less roughness. The difference in the composition of the grinding fluids employed displays a significant influence. Ecocut Mikro Plus 82 is based on fatty alcohols, the use of which allows for a significant cooling effect by rapid evaporation from the workpiece surface. However, Biocut 3000 contains ester oils, which produces a thin oil film on the machined surface. As a result, they provide primarily lubrication of the contact zone between the grinding wheel and the workpiece surface with a moderate cooling effect. In cases employing Biocut 3000, greater force is required to initiate the microcutting process and chip formation due to its lubricating effect (Fig. 9b). At the same time, a lower surface roughness was obtained, which most likely results from the relatively rapid thermo-fatigue wear of the abrasive grains' active vertices (Fig. 9e). Dulled grains generate unevenness of a less height on the machined surface than the process carried out using Ecocut Mikro Plus 82 fluid, which provides a better cooling effect in the grinding zone and less intensive wear of the abrasive grains. It may be also assumed that Ecocut Mikro Plus 82 fluid protects more efficiently against grinding defects caused by temperature on the workpiece surface.

The differences in the structure of the grinding wheels employed were minor and consisted of only a slightly different geometry of the 30% additive to the abrasive grains on the basis of microcrystalline sintered corundum. In the case of the 3TGP 54K VX grinding wheel, TGP™ grains were shaped as elongated "pencils" (Fig. 4a) while the second tool (3XGP 54K VY) contained TGX™ grains of a "scaly" shape (Fig. 4b). The different structures of the applied grinding wheels did not have any significant influence on the results (Figs. 9a, 9c, 9d, and 9f).

4 Conclusions

The tests on the tangential grinding of flat surfaces made of nickel alloys confirmed the hard-to-cut nature of these materials. Although the results indicated the possibility of employing grinding fluid with the MQL method, it is essential for such fluids to be properly selected for the machining operation being carried out. It needs to be remembered that not all of them provide proper quality parameters for the machined surface.

The most important conclusions drawn from the completed tests are:

1. The inversely proportional dependency of the specific tangential grinding force value F_t' and the mean-square deviation of machined surface roughness R_a, especially in the cases of machining Nickel 201 and INCONEL® alloy 600, were observed;

2. Each of the materials selected for the tests belonged to a different nickel alloy group (A, B, and C), which made the differences in the registered F_t' and R_a values considerable;

3. The most advantageous results were obtained when machining MONEL® alloy 400;

4. The original single-pass grinding test methodology used made it possible to assess the changes of the grinding conditions in the area of the grinding wheel entering the material (Area I), its stable operation (Area II), and its exit (Area III);

5. The registered process parameters showed that there are considerable differences in the values for the particular areas isolated on the workpiece surface (Areas I–III);

6. The results indicate that the physical and chemical properties of Biocut 3000 liquid make it possible to obtain more advantageous machined surface roughness parameters in the examined process, with a simultaneous increase in the grinding force, as compared with the machining results obtained with the application of Ecocut Mikro Plus 82 fluid;

7. The differences in construction of the two types of grinding wheels used in the above-presented tests did not have any significant influence on the results.

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中文概要

题　目：不同类型磨削液微量润滑对镍基合金平面磨削的影响

目　的：镍基合金是一种难加工材料，在磨削时工件表面经常会出现烧伤、弹性形变和白层。本文拟通过3种不同镍基合金工件（Nickel 201，INCONEL® 600和MONEL® 400）的平面磨削实验，研究在采用微量润滑方法进行冷却时，两种不同类型磨削液对磨削力和工件表面粗糙度的影响规律。同时，研究砂轮结构对磨削过程和磨削结果的影响。

创新点：通过实验比较2种磨削液对3种镍基合金工件磨削结果的不同影响，为在采用微量润滑方法时的磨削液合理选择提供有益借鉴，也为绿色制造、可持续生产或清洁生产等制造技术的发展提供技术支撑。

方　法：1. 对每个试件表面进行多行程无火花磨削预处理，并采用浇注式冷却；2. 进行单程磨削实验（图2），并采用微量润滑方法进行冷却；3. 在磨削表面标记3个区域，比较在不同磨削液、工件材料及砂轮结构条件下，每个区域平均切向力和表面粗糙度值的变化情况。

结　论：1. 磨削表面粗糙度与磨削切向力成反比，Nickel 201和INCONEL® 600的表现尤为明显。2.不同的镍基合金材料工件磨削时的切向力和表面粗糙度有很大不同，MONEL® 400获得的磨削效果最好。3. 初始单程磨削实验方法可以用来评价砂轮切入3个磨削区磨削状态的异同；不同磨削区域的磨削结果差异较大。4. Biocut 3000磨削液可以获得比Ecocut Mikro Plus 82磨削液更好的磨削表面，但磨削力也相应增大。5. 砂轮结构的不同对磨削结果没有太大影响。

关键词：镍基合金；平面磨削；微量润滑；难加工材料；磨削力；表面粗糙度