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EXPERIMENTAL RESULTS OF DRY DRILLING OF WEAR RESISTANT STEEL

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Nowadays, adverse human induced impacts on the environment are constantly increasing, which urges engineers to make their production planning activities more environmentally conscious. In addition, during the realization and manufacturing processes of goods, the application of environmentally demanding and polluting materials is expected to be reduced or even eliminated. The application of the increasingly popular minimal lubrication method or even dry cutting could be considered to be efficient methods for reducing adverse environmental impacts. On the other hand, the mentioned methods have drawbacks since they considerably shorten tool life, result in a more significant cutting tool wear and lead to increase in friction. As a result, the tool and the work place temperature rise. This article aims to give an overview of how the feed direction force, the cutting torque, the tool wear, and the surface roughness change during the cutting procedure, if cutting is done under dry conditions while different cutting speed and feed motion parameters are applied.

Keywords: environmentally friendly metal cutting, dry drilling, drilling force, torque, wear, surface roughness

Introduction

Modern technologies have to meet several, in many respects, contradictory requirements. By means of cutting, increasingly sophisticated spare parts have to be manufactured from advanced materials that are more and more difficult to machine. The production of spare parts involves growing productivity and an increasingly accurate sizing. In order to make production operations cost-effective, expensive and multifunctional machine tools and tool equipment (etc) are required [1, 2, 3]. When aiming for a higher productivity, an increase in material flow (cm^3/min) is required, which goes out with an increase of main speed and auxiliary motion speeds. Increasing of feed motion and especially intensifying cutting speed result in a drastic rise of chip removal zone temperature [4, 5].

Cutting fluids (oils, emulsions, synthetic fluids) have not only influenced the reduction of machine time beneficially, but favourably contributed to the reduction of tool wear as well. Moreover, the size accuracy and surface roughness attained were appropriate. In the past some experts expressed their doubts regarding operation mediums and claimed that the application, handling (filtering), storage and disposal of cooling and lubricating materials involved huge costs [3, 5].

Since the 1990s, there have been mounting doubts regarding the rising costs related to cutting fluids as well as concerning environmental regulations that have been becoming increasingly rigorous. Not to mention the psychical effects machine operators have been subjected to: inhaling poisonous steams produced by cutting fluid at cutting temperature and fumes with unpleasant smell, which develop allergy. In the case of long-lasting work even various pulmonary diseases can be suffered. What is more, skin irritation as a bacteriological effect can also be detected. The other factor which enforced the change is of ecological nature: the strict environmental regulations set out in the workers' interest, as well as obeying these regulations consciously – all this must give a larger scope to a thoroughly new technological approach. In the present article, we give an overview of our experimental results in the field of environmentally conscious cutting.

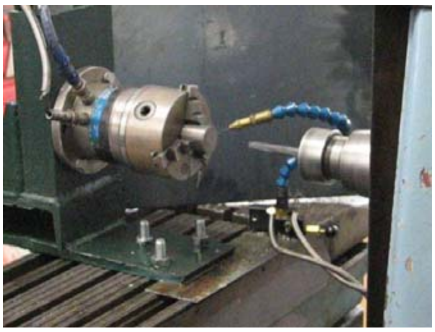

Figure 1: The experimental setup

In cutting, the most effective (and at the same time most radical) method of mitigating environmental damage is the switch-over to dry machining *(Fig. 1)*. At present, this technology change is very much on the agenda and draws a great deal of attention. Of course, in order to achieve some success in this area, it is necessary to analyse the factors influencing the success of machining procedures. Starting from the geometry, as well as the shape and size accuracy of machined parts, factors like machinability of the work piece, the applied operations and cutting conditions as a whole are to be examined.

The main advantages of dry cutting are as follows [6]:

- this machining method is environmentally friendly, i.e. it does not generate air pollution in the workshop;
- the machine operator is not subjected to insalubrious effects: no respiratory or skin diseases are experienced;
- the expenses of chip cleaning (oil, emulsion or chemical relief) can be decreased;
- there are no coolant and lubricant fluid- related (purchasing, storing, cleaning, disposal) costs;
- the structure of machining-related expenses changes (the tool-related increases, but the cooling- and lubrication-related expenses do not change), thus, the production expenses decrease.

On the other hand, there are some drawbacks of dry cutting. They are as follows [6]:

- the operation becomes less flexible and less complex (primarily in the case of drilling);
- cutting data need to be reduced, consequently, the machining time increases and the productivity decreases n;
- tool life shortens, consequently, tool costs mount;
- the reliability of the process generally worsens due to the significantly stronger scatter of tool life;
- in some cases, when turning or milling castings, rusty or scaled pieces at a high productivity level, dry cutting jeopardizes workers' health;
- there is a limited accuracy and surface roughness attainable.

As a general experience, it can be stated that the application of dry cutting is possible only if the accuracy requirements for the machined parts are not too high. Thus, pre-machining rough cutting and/or half-finishing operations can also be performed by dry cutting, however, further steps required for attaining the final shape or position accuracy, can only be achieved by further operations with the application of coolant & lubricant fluid.

HARDOX wear resistant steel sheets must meet strict requirements as steady quality, flatness and surface condition. The unique consistence of qualities like high hardness, high strength and outstanding shock-resistant toughness makes HARDOX wear resistant steel sheets extremely suitable for a wide range of use. HARDOX steels have been in the market since the 1970s and are continuously being developed to meet customer preferences *(Fig. 2)*. The sheets feature a thickness of 3 mm up to 130 mm. The high hardness and wear resistance significantly increase the useful life of final products. Due to their increased toughness, HARDOX steels are also very resistant to low temperatures.

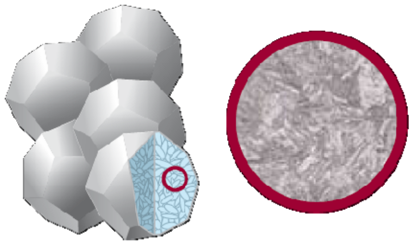

Figure 2: Heat treatment of HARDOX steel is unique [7]

They are relatively well machinable and make production and renovation easy [7]. The hardness of HARDOX 450 wear resistant steel comes to 450 Brinell; some other characteristics are plotted in *Table 1*.

Table 1: Typical properties of different steels [7]

Type of steel	Elastic limit, N/mm^2	Tensile strength, N/mm^2	Hardness, HBW
S235 (Structural steel)	235	400	120
S355 (Structural steel)	355	480	170
HARDOX 450	1200	1400	450

Objective

The experiment aimed to examine the effects the technological cutting parameters exerted on the cutting procedure during drilling by means of dry machining and minimal lubrication machining HARDOX 450 wear resistant steel. During the course of this activity, the effect depending on the tool feed and the set cutting speed is being measured: the feed force and the drilling torque demands as well as the average surface roughness of the machined hole vary correspondingly. The evaluation of the results of hole machining experiments is carried out by applying the factorial experiment design in order to determine connections between technological drilling parameters and the average surface roughness measured in the hole.

Research conditions

The type of drill used in the experiment: Ø10.2 mm L102/55 d12 marked Sirius210 (high productivity, dimension-keeper, safe for drilling) HELICA (AlCrN based) coated drill. The workpiece materials are HARDOX 450 (Rm=1400 MPa) wherein we made 30 mm long holes with the occasion of experiments.

The experiments were conducted under the following parameters:

Cutting speed: $v_{c1} = 28.82$ m/min
$v_{c2} = 44.83$ m/min
Feed: $f_1 = 0.08$ mm/rev
$f_2 = 0.14$ mm/rev
Length of hole: $l_w = 30$ mm

Equipment used for measuring feed force and torque

The thrust (F_f) as well as the torque (M_c) were measured by a two-component compact dynamometer of KISTLER 9271A type, which features a high dynamic strength. Therefore, it has a high eigen-frequency that allows measuring smaller dynamic force impulses even during high basic loads

Measurement of tool wear:

The drill wear in the characterization of the corner wear (VB_C) and flank wear ($VB_{3.5}$) were chosen. The flank wear was measured on 3.5 mm radius from the centre line of the twist drill; the flank wear is the width of the wear from the main edge to the flank face. We measured the tool wear after every 30 mm drilling both edge then the measured values are averaged. The drilling distance is the product of the numbers of holes and the thickness of the material ($s = z_f \cdot L_p$). We created high quality digital images of drill. Images processed with CorelDraw software. We issued the image with reference size *(Fig. 3)*. The wear value is the difference of the after-edge-image of various drilling distance and the reference line *(Fig. 4)*.

Figure 3: The sharp drill (M=300)

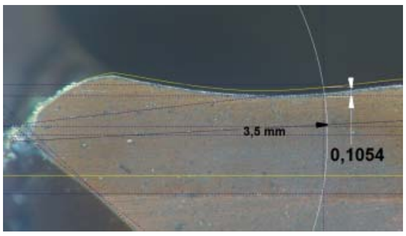

Figure 4: The worn drill L=1350 mm (M=300)

During the measurements, using the same parameter settings, we repeated every measurement three times, and subsequently we processed the measurement results by means of mathematical statistical methods. We plotted the average values measured against drilling distance, then, by regression analysis, we determined the correlation index as well as the equation of the particular graph that follows the measurement points best.

Measurement of surface roughness

In order to determine the average surface roughness of the holes made, SJ-201 (Mitutoyo) was used. The surface roughness values were measured on 30 mm length specimens, along 5 contour lines per hole. During the measurements, the same parameter settings were used. Every measurement was repeated three times. The measurement results were processed by means of mathematical statistical methods. The average values measured against drilling distance was plotted, then, by regression analysis, we determined the equation of the particular graph that follows the measurement points best.

Experimental results

Results of drilling with sharp tool

The experimental results are summarised in *Table 2*.

Table 2: Experimental results

Thrust, kN	**f_1 = 0.08 mm/rev**	**f_2 = 0.14 mm/rev**
v_{c1} = 28.82 m/min	0.784	1.072
v_{c2} = 44.83 m/min	0.830	1.213
Torque, Nm		
v_{c1} = 28.82 m/min	4.59	4.96
v_{c2} = 44.83 m/min	6.59	6.97
Surface roughness, µm		
v_{c1} = 28.82 m/min	2.29	2.95
v_{c2} = 44.83 m/min	2.45	3.24

By using the entire factorial experiment design, out of the measurement results, we obtained the equations of the surfaces for the case of dry cutting (1) – (3)

$$F(v_c, f) = 0.3128 - 0.00239 v_c + 7.48 f - 0.03851 v_c f \quad (1)$$

$$M(v_c, f) = 0.52389 + 0.12396 v_c + 5.8471 f + 0.010331 v_c f \quad (2)$$

$$Ra(v_c, f) = 1.4292 + 0.00066625 v_c - 7.1597 f - 0.13325 v_c f \quad (3)$$

Based on the measurement results it can be ascertained *(Fig. 5)* that dry machining and the low feed increase feed direction force by nearly 6% when the cutting speed is accelerated from 28.82m/min to 44.83 m/min. In the case of a higher feed, the increase in feed direction force amounts to 13%. The results show that when dry cutting is applied and the feed is increased, the feed force increases by about 37% in the case of a higher cutting speed; in the case of a lower cutting speed it goes up by over 46%.

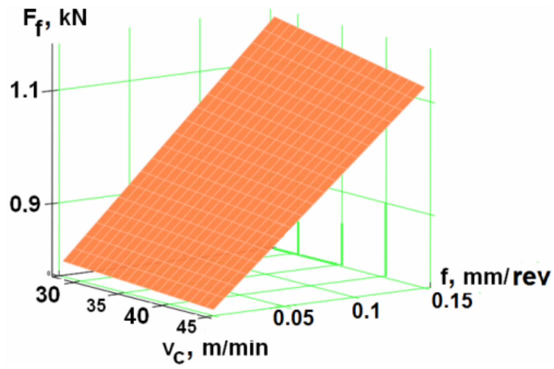

Figure 5: The changes of the thrust in cutting speed and feed rate depending on dry machining with sharp tool

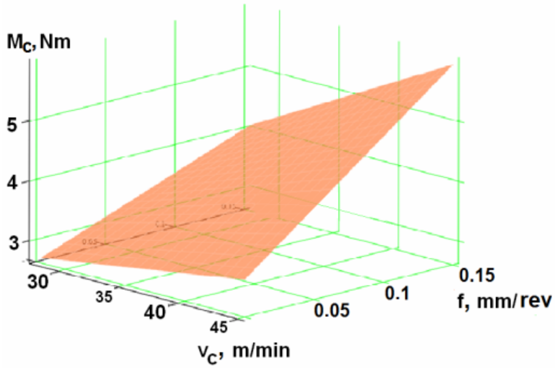

Figure 6: The changes of the torque in cutting speed and feed rate depending on dry machining with sharp tool

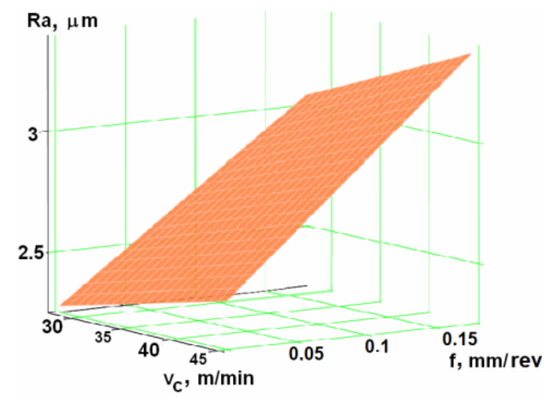

Figure 7: The changes of the average surface roughness in cutting speed and feed rate depending on dry machining with sharp tool

Examining the cutting torque values obtained during the drilling experiments *(Fig. 6)* we experienced that when dry drilling is applied, the cutting torque increases more significantly, if the cutting speed is increased from a lower value to a higher one (then, at f=0.14 mm/rev drilling torque increases by 40%; at f=0.08 mm/rev by 43%). By increasing feed and maintaining a steady cutting speed, the increase in drilling torque is significantly lower.

When evaluating the measurement results pertaining to the quality of the dry-machined surface *(Fig. 7)* we noticed that, according to our expectations, the surface roughness of the machined hole increased by about 6%, if we increased the cutting speed from 28.82 to 44.83 m/min, using lower feed. In the case of a higher feed, this increase amounted to about 9%. When we adjusted a higher feed value during a steady speed, the increase in surface roughness will be nearly 28% at a speed of 28.82 m/min and it will be 32% at 44.83 m/min.

Results of drilling with worm tool

During the course of the experiments, after each drilling distance of 90 mm, feed direction cutting force, drilling torque, flank wear, corner wear and average surface roughness were measured. The experimental results are summarised in *Tables 3-6.*

Table 3: Experimental results when the cutting speed is 44.83 m/min and the feed rate is 0.14 mm/rev.

L, mm	M_C, Nm	F_f, kN	$VB_{3.5}$, mm	VB_C, mm	Ra, µm
0	6.97	1.213	0.000	0.0000	3.2400
90	6.92	1.121	0.0189	0.0365	3.1351
180	7.17	0.992	0.0382	0.0655	3.4628
270	7.42	1.111	0.0542	0.1123	3.2256
360	7.82	1.171	0.0797	0.1452	3.4681
450	7.96	1.148	0.0945	0.1719	3.6814

Table 4: Experimental results when the cutting speed is 44.83 m/min and the feed rate is 0.08 mm/rev.

L, mm	M_C, Nm	F_f, kN	$VB_{3.5}$, mm	VB_C, mm	Ra, µm
0	6.590	0.830	0.0000	0.0000	2.4500
90	6.720	1.004	0.0164	0.0323	2.5450
180	7.114	1.155	0.0277	0.0553	2.6936
270	7.471	1.046	0.0479	0.0933	2.7989
360	7.739	1.185	0.0557	0.1282	2.8808
450	7.830	1.225	0.0695	0.1453	3.0710

Table 5: Experimental results when the cutting speed is 28.82 m/min and the feed rate is 0.14 mm/rev.

L, mm	M_C, Nm	F_f, kN	$VB_{3.5}$, mm	VB_C, mm	Ra, µm
0	4.960	1.072	0.0000	0.0000	2.9500
90	5.144	0.982	0.0089	0.0186	2.7360
180	5.425	1.035	0.0193	0.0366	2.7553
270	5.541	0.994	0.0295	0.0595	3.2106
360	5.831	0.986	0.0382	0.0690	3.1034
450	6.312	1.016	0.0457	0.0958	3.0109
540	6.546	0.951	0.0564	0.1104	3.1530
630	6.930	1.015	0.0704	0.1430	2.9695
720	6.981	1.132	0.0803	0.1530	3.2942
810	7.478	1.178	0.0825	0.1741	3.0846
900	7.489	1.006	0.0969	0.1928	2.9266
990	7.520	1.032	0.0949	0.2082	3.2411
1080	7.990	1.140	0.1077	0.2298	3.2513

Table 6: Experimental result if the cutting speed is 28.82 m/min and the feed rate is 0.08 mm/rev.

L, mm	M_C, Nm	F_f, kN	$VB_{3.5}$, mm	VB_C, mm	Ra, µm
0	4.590	0.784	0.0000	0.0000	2.2900
90	4.761	1.024	0.0080	0.0125	3.1655
180	4.734	0.955	0.0184	0.0276	2.2103
270	4.808	1.071	0.0250	0.0378	2.3864
360	5.027	0.959	0.0331	0.0514	2.3235
450	5.265	1.203	0.0430	0.0681	2.2749
540	5.227	1.206	0.0455	0.0728	2.2122
630	5.226	1.013	0.0635	0.0862	2.2139
720	5.685	0.986	0.0718	0.1139	2.3723
810	5.759	0.951	0.0693	0.1254	2.3089
900	5.862	0.980	0.0749	0.1336	2.2073
990	6.060	1.098	0.0894	0.1350	2.0300
1080	5.953	1.003	0.0886	0.1705	2.2230
1170	5.990	1.219	0.1005	0.1791	2.1967
1260	6.305	1.098	0.1105	0.1821	2.2808
1350	6.326	1.185	0.1064	0.2012	2.4134
1440	6.391	1.237	0.1312	0.2231	2.5811
1530	6.817	1.173	0.1326	0.2309	2.2407
1620	6.586	1.120	0.1295	0.2336	2.5526
1710	6.628	1.166	0.1508	0.2745	2.3392
1800	6.840	1.033	0.1611	0.2884	2.5649
1890	7.382	1.180	0.1519	0.2888	2.2708
1980	7.110	0.979	0.1672	0.3002	2.6339
2070	7.604	0.966	0.1824	0.2962	2.5618
2160	7.414	0.979	0.2012	0.3036	2.4164
2250	7.316	1.019	0.1837	0.3495	2.3495
2340	7.656	1.059	0.2112	0.3585	2.6585
2430	7.840	1.221	0.2099	0.3439	2.6018
2520	7.690	1.141	0.2279	0.3538	2.4726

When drilling, a slight increase in the cutting force can be noticed *(Fig. 8)*.

The values vary mostly between 0.8 and 1.2 kN, i.e. they can be regarded as approximately stable during drilling.

From the torque values measured it became apparent *(Fig. 9)* that the torque raised depending on the drilling distance.

The highest value (6.97 Nm) was measured at a cutting speed of 44.83 m/min and a feed value of 0.14 mm/rev. According to our expectations, the lowest value (4.59 Nm) was measured at the lowest cutting speed and feed. The used tool fractured at an average cutting torque of almost 8 Nm.

After examining the flank wear, we can state *(Fig. 10)* that this value was the highest at parameters of 44.83 m/min and 0.14 mm/rev.

The slowest wear was noticed at parameters of 28.82 m/min and 0.08 mm/rev. The highest flank wear also emerged in this case: 0.23 mm at the measurement before tool fracture, however, this did not reach the wear criteria set by us.

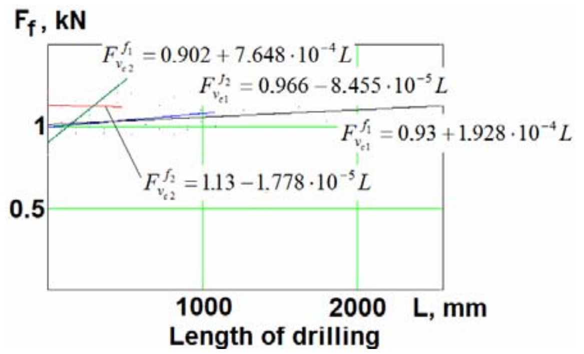

Figure 8: The changes of the thrust in cutting speed and feed rate depending on dry machining

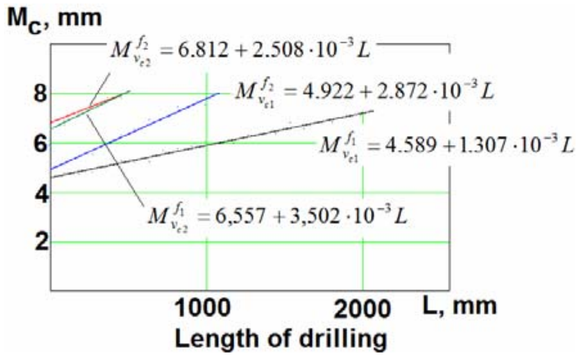

Figure 9: The changes of the torque in cutting speed and feed rate depending on dry machining

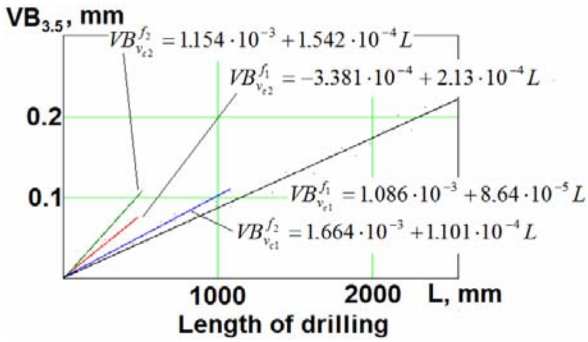

Figure 10: The changes of the flank wear in cutting speed and feed rate depending on dry machining

Having examined the corner wear *(Fig. 11)*, the same observations could be made as in the case of flank wear results: the highest speed of corner wear was observed at the maximum speed and feed and the corner wear reached its highest speed at the lowest parameters used. However, the highest wear value (0.35mm) was experienced in this case.

The change in average surface roughness *(Fig. 12)* shows a slim increase. Using a feed parameter of 0.14 mm/rev at a speed of 44.83 m/min, the best average surface roughness is 3.24 µm which spells a deterioration of 13% compared to the original value. We can obtain the best value by using the slowest feed at the slowest speed, thus, the initial value of 2.29 µm shows an increase of 7%.

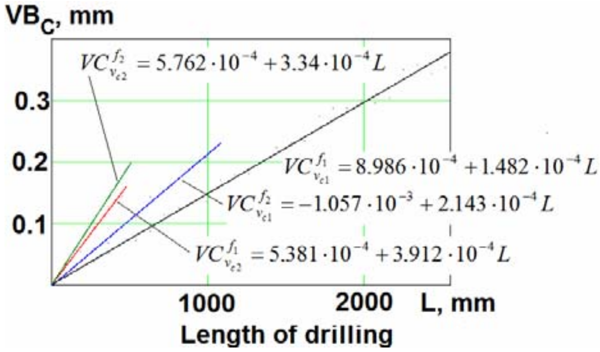

Figure 11: The changes of the corner wear in cutting speed and feed rate depending on dry machining

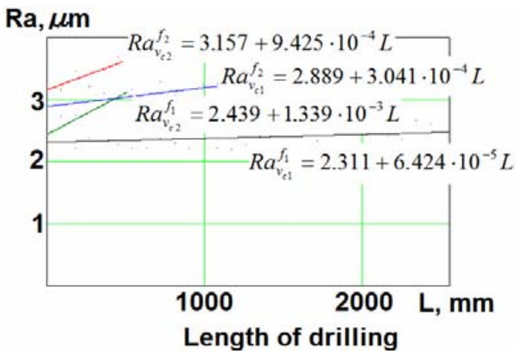

Figure 12: The changes of the average surface roughness in cutting speed and feed rate depending on dry machining

The tool fracture is illustrated in *Table 7*. During the experiment, the maximum tool usability was 2550 mm at parameters more suitably set.

Table 7: The breaking of the tools under dry cutting

Max drilled length, mm	**f_1 = 0.08 mm/rev**	**f_2 = 0.14 mm/rev**
v_{c1} = 28.82 m/min	2550	1080
v_{c2} = 44.83 m/min	510	480

Summary

Our paper demonstrated how feed direction force, cutting torque, corner wear, flank wear and surface roughness changes during dry-drilling wear resistant steel (HARDOX 450).

The most important conclusions drawn out of our investigations can be summarised as follows:

- The functions determined by the full factorial experiment design is suitable to determining how the important cutting parameters have effect on average surface roughness, thrust, or torque if a sharp cutting tool is applied.
- During drilling procedures, there is an increase in thrust, torque, tool wear and hole surface roughness, depending on the drilling distance.

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