RESEARCHES REGARDING THE ROUGHNESS OF MACHINE-GENERATED SURFACES USING CURVED CUTTING EDGE DRILLS

Nicuşor BAROIU[1], Virgil ILIUȚĂ[2], Minodora RÎPĂ[2]

[1]"Dunărea de Jos" University of Galați, Department of Manufacturing Engineering,
[2]"Dunărea de Jos" University of Galați, Department of Machine Elements & Graphics,
nicusor.baroiu@ugal.ro

ABSTRACT

The multi flute drills with curved cutting edges are new constructions, particularly from their performance point of view regarding the common helical drill with two cutting edges. This paper presents a simplified geometrical model of the roughness of surfaces machined using drills with two straight lined cutting edges, versus a similar model for machining using drill with three curved cutting edges. At the same time, the experiments emphasis parameter values which define the roughness (Ra and Rq) at machining of A570 steel (OL 37) and the profiles resulted for various cutting conditions. The paper shows the influence of the working conditions regarding the machined surface.

KEYWORDS: geometric roughness, median line, helical drills, curved cutting edges.

1. INTRODUCTION

The surface is generally analysed according to its roughness, being defined as an assembly of irregularities forming the real relief of surfaces whose pitch is relatively small with respect to their depth. [5], [4]. The geometric roughness (the generation roughness) represents a first approximation of form and size for the transversal roughness being generated by the assembly of cutting edges during the kinematic process of machine-generated bore. The geometric roughness is in all cases much different from the measurable surface roughness but this can offer information on the influence of numerous factors: work feed, geometric parameters (attack angle), effective shape of the cutting edge on the transversal roughness of the generated surface. The most used system of reference for the numeric roughness evaluation is the median line system.– fig. 1.

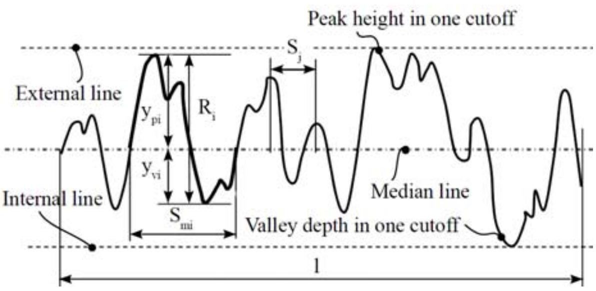


Fig. 1: Elements of profile irregularities

The profile median line (M) or an equidistant line [16], [9] is chosen as a reference line in order to evaluate the roughness within this system. Thus, the following parameters are defined:
- depth of profile gap *i*, (y_{vi}) – distance between the lowest cutoff of a gap and the median line;
- peak height of profile *i*, (y_{pi}) – distance between the highest cutoff and the median line.
- profile peak, (*i*) –part of profile oriented outwards between two consecutive intersections of the profile with the median line;
- height of profile irregularities *i*, (R_i) – the sum between the peak height and the depth of adjacent gap;
- profile irregularities step *i*, (S_{mi}) – distance between two intersection points of the median line with a profile irregularity;
- local profile peak step *j*, (S_j) – distance between the projections on the median line of the two highest points belonging to two adjacent local peaks;
- measuring or evaluation length, (l_n) – length measured along the general profile direction to characterize the profile;

Predictive roughness models were elaborated by numerous authors, based on the mechanics and the drilling process dynamics in order to prevision the

quality of drills made during the planning drilling stage. [12], [2], [6], [14], [7].
At the same time, an experimental study was carried out to observe the effects of cutting parameters on the surface roughness for different materials. [10], [8], [13], [11].

2. GEOMETRICAL MODELS OF SURFACE ROUGHNESS

2.1 Simplified geometrical model for surface roughness obtained with the straight main cutting edge drill

The following approximation is accepted, the geometrical roughness is generated by the main cutting edge and the secondary cutting edge (the helical line of the secondary cutting) for two successive positions of the drill while moving along its own axis with a distance equal to the feed per tooth. The generatrix of the cylindrical surface is seen as the successive winding positions of the assembly formed by the main cutting edge and the secondary cutting edge. The main cutting edge is defined as the straight generatrix (in the tool bore axial plan, as a first constructive approximation of the helical drill), while the secondary cutting edge is a helical generatrix – fig. 2.

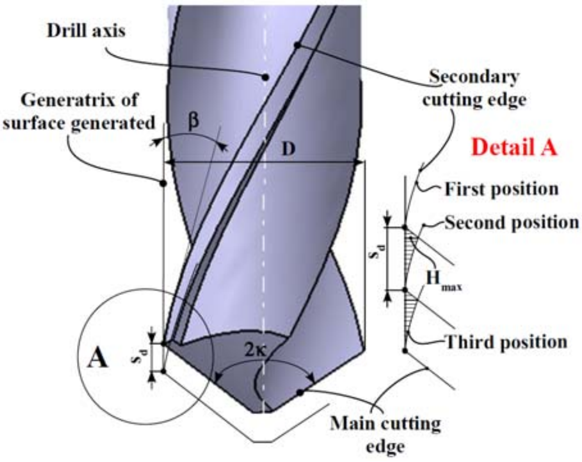


Fig. 2: Defining geometric roughness – straight main cutting edge drill

The following approximation is considered accepted, taking into account the feed size (s_d), the secondary cutting edge can be replaced with the tangent to this. Thus, for the drills with two straight lined cutting edges,

$$s_d = \frac{s}{2} \tag{1}$$

where, s –feed size [mm/rot];

Figure 3, presents a detail from the contact zone of the main cutting edge and the secondary cutting edge if the drill, detail A. the following notes are made: – fig. 3:

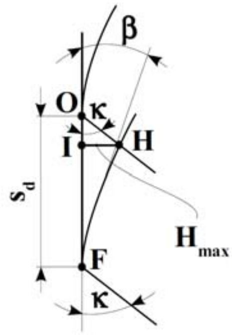


Fig. 3: Contact zone for cutting edges (Detail A)

$$\begin{aligned} OI &= X \\ FI &= Y \\ X + Y &= s_d \end{aligned} \tag{2}$$

$IH = H_{\max}$ - maximum size of the geometric roughness model and whether:

$$tg\beta = \frac{H_{\max}}{Y}; tg\kappa = \frac{H_{\max}}{X} \tag{3}$$

then:

$$s_d = X + Y = \frac{H_{\max}}{tg\beta} + \frac{H_{\max}}{tg\kappa}. \tag{4}$$

The maximum size of the geometric roughness can now be defined,

$$H_{\max} = s_d \cdot \frac{tg\beta \cdot tg\kappa}{tg\beta + tg\kappa} \tag{5}$$

But, the screw developed representing the secondary cutting edge, is defined by the function:

$$tg\beta = \frac{\pi \cdot D}{2\pi \cdot p} \tag{6}$$

where:
β is the helix angle (see figure 2);
D – diameter of drill;
p – helical parameter of drill screw.

The relation (5) is similar to the cylindrical cutting [15].

It is obvious, taking into account (6), relation (5) can also be written as

$$H_{\max} = s_d \cdot \frac{\frac{D}{2} \cdot \frac{1}{p} \cdot tg\kappa}{tg\beta + tg\kappa} = s_d \cdot \frac{D \cdot tg\kappa}{2p \cdot (tg\beta + tg\kappa)} \tag{7}$$

showing that:
- the geometric roughness increases at the same time with the feed advance;
- the geometric roughness increases at the same time with the size of the drill diameter;
- the geometric roughness decreases with the size of the helical pitch of the of the drill screw;
- decreasing the tool cutting edge angle leads to decreasing the geometric roughness.

It is obvious that this model of geometric roughness leads to roughness values not always comparable with the measured reality of the drilled surfaces.

2.2 Simplified geometric model for the surface roughness obtained with the three curved cutting edges drill

Similar to the information presented above, the geometric roughness to cutting with curved cutting edges drills it results that the winding of successive positions of the main edge assembly (circular curve) and secondary (helical line), in the relative movement with respect to the generatrix tool bore.

The model of maxim geometric roughness presupposes determining point C coordinates, see figure 4, at the intersection between a circular curve (main cutting edge) with a cylindrical helical line (secondary edge), which leads to a system of transcendent equations.

Simplifying hypothesis

In order to avoid inherent problems when solving a system of transcendent equations, the following approximation is proposed: the circular curve AV (part of the curved cutting edge) be replaced with the chord AV – fig. 4.

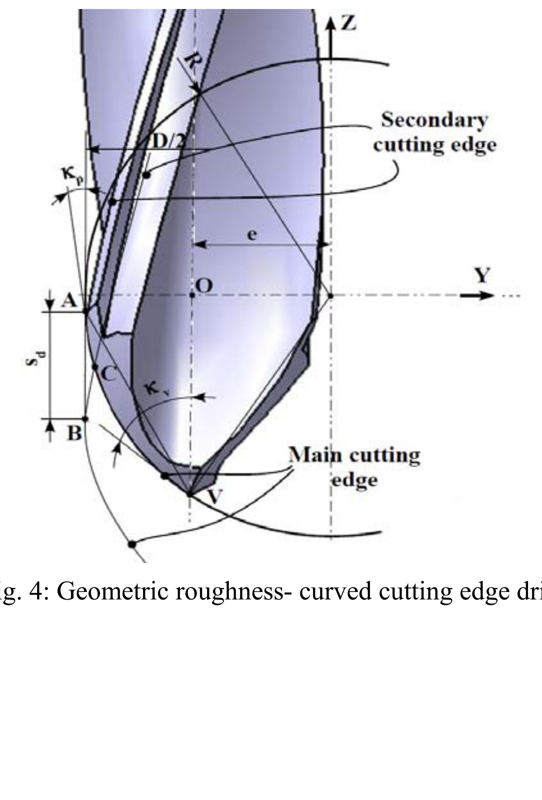


Fig. 4: Geometric roughness- curved cutting edge drill

The coordinates for extreme points A and V are defined:

$$A:\left\|\begin{array}{l} Y_1=-\dfrac{D}{2}; \\ Z_1=-R\cdot\sin\kappa_p; \end{array}\right. \quad V:\left\|\begin{array}{l} Y_2=0; \\ Z_2=-R\cdot\sin\kappa_v; \end{array}\right. \tag{8}$$

where κ_p and κ_v are the sizes of the tool cutting edge angles at the drill's lowest point and at its highest point.

The equation for the straight line written in dots is defined under the form

$$\frac{Y+\dfrac{D}{2}}{\dfrac{D}{2}}=\frac{Z+R\cdot\sin\kappa_p}{R\cdot\sin\kappa_p-R\cdot\sin\kappa_v} \tag{9}$$

The maximum size of the geometric roughness is defined as being shaped as a triangle, with sides AC and BC – fig. 5.

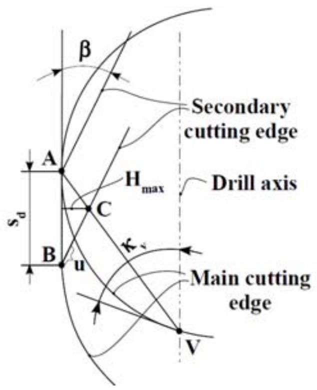


Fig. 5: Roughness size at the curved cutting edge drill

In this way it is accepted that the straight line where BC segment is situated (the screw is replaced with its tangent) has the parametric equations:

$$\begin{array}{l} Y=Y_B+u\cdot\sin\beta; \\ Z=Z_B+u\cdot\cos\beta, \end{array} \tag{10}$$

where Y_B, Z_B are point B coordinates B:

$$\begin{array}{l} Y_B=-D/2; \\ Z_B=-R\cdot\sin\kappa_p-s_d. \end{array} \tag{11}$$

From the intersection of BC line:

$$\begin{array}{l} Y=-D/2+u\cdot\sin\beta; \\ Z=-R\cdot\sin\kappa_p-s_d+u\cdot\cos\beta, \end{array} \tag{12}$$

u – variable parameter and β – helix angle of the secondary cutting edge, with AV line written in dots (10) – see figure 5:

$$\frac{-\frac{D}{2}+u\cdot\sin\beta+\frac{D}{2}}{\frac{D}{2}}=\frac{-R\cdot\sin\kappa_p-s_d+u\cdot\cos\beta+R\cdot\sin\kappa_p}{-R\cdot\sin\kappa_v+R\cdot\sin\kappa_p}, \quad (13)$$

or, finally after elaborations,

$$\frac{u\cdot\sin\beta+\frac{D}{2}}{\frac{D}{2}}=\frac{u\cdot\cos\beta-s_d}{R\cdot\left(\sin\kappa_v-\sin\kappa_p\right)} \quad (14)$$

The final form is reached,

$$R\cdot u\cdot\sin\beta\left(\sin\kappa_v-\sin\kappa_p\right)=-\frac{D}{2}\cdot u\cdot\cos\beta+\frac{D}{2}\cdot s_d \quad (15)$$

Known as the acceptable form of the curved cutting line [1], where $R=1\cdot D$, it results that the equation (15) becomes:

$$u\cdot\sin\beta\left(\sin\kappa_v-\sin\kappa_p\right)+\frac{1}{2}\cdot u\cdot\cos\beta-s_d=0 \quad (16)$$

or

$$u=\frac{s_d}{\sin\beta\left(\sin\kappa_v-\sin\kappa_p\right)+0,5\cdot\cos\beta} \quad (17)$$

The maximum height of roughness,

$$H_{\max}=u\cdot\sin\beta \quad (18)$$

Or can be brought to the from

$$H_{\max}=\frac{s_d\cdot\sin\beta}{\sin\beta\left(\sin\kappa_v-\sin\kappa_p\right)+\frac{1}{2}\cdot\frac{1}{tg\beta}} \quad (19)$$

Taking into account (6), thus it results

$$H_{\max}=\frac{s_d\cdot\sin\beta}{\sin\beta\left(\sin\kappa_v-\sin\kappa_p\right)+\frac{p}{D}} \quad (20)$$

The geometric model of the roughness maximum height shows that:
- the geometric roughness depends on the feed size, $s_d = s/3$, for three cutting edge drills;
- increasing the pitch of the drill’s screw leads to decreasing the roughness;
- the roughness depends on the size of the peripheral cutting edge angle and peak of the drill;

Note
Another approximation can be accepted, according to which the main cutting edge forming geometric roughness is replaced with its tangent. Thus, the problem is reduced to form (7) where $\kappa=\kappa_p$ and:

$$tg\beta=\frac{H_{\max}}{X};\quad tg\kappa_p=\frac{H_{\max}}{Y} \quad (21)$$

thus,

$$s_d=X+Y=\frac{H_{\max}}{tg\beta}+\frac{H_{\max}}{tg\kappa_p} \quad (22)$$

resulting:

$$H_{\max}=\frac{s_d\cdot tg\beta\cdot tg\kappa_p}{tg\beta+tg\kappa_p}=\frac{s_d\cdot\frac{D}{2p}\cdot tg\kappa_p}{\frac{D}{2p}+tg\kappa_p} \quad (23)$$

It is obvious, this geometric expression of the maximum size of roughness is absolutely similar to the relation (5) or to what is known as surface finish [15].

The geometric roughness expressed through constructive parameters (D – drill diameter; p – helical parameter; κ_p - main working cutting edge), particularizing the general form (5) to the specific case of the drilling process.

3. EXPERIMENTAL ASPECTS REGARDING DRILLING ROUGHNESS

Comparative roughness tests were performed in order to establish the new geometrical proposed form of the main cutting edges while drilling using standard straight cutting edges drills and curved three cutting edges drills.

The experimental research made use of a set of four helical drills made of high-speed steel Rp3, two of which being standard HSS, with two straight cutting edges, and the other two curved three cutting edges, having the diameters of Ø20 mm and Ø18 mm. To perform the tests a general purpose carbon plate steel was used having the dimensions 350x350x50 mm, OL37 (A570, according to AISI and ASTM specifications), with the chemical composition, respectively the mechanical properties defined in tables 1 and 2 – SR EN 10025 (STAS 500/2-80).

Table1. Chemical composition A570 (OL37), [%]

C	Mn	Si	P	S	Cu
0,14÷0,25	0,30÷0,65	0,3	0,04	0,05	0,035

Table 2. Mechanical characteristics A570 (OL37)

Flow limit - σ_c (R_{eH}) [Mpa]	Resistance to tension - σ_c (R_m) [Mpa]	Breaking extension - ε (A) [%]	Hardness HB
210÷240	370÷440	25÷26	80÷140

The experimental research was performed in the machine-tool hall in the Department of Manufacturing Engineering, Mechanics Faculty, “Dunărea de Jos” University of Galați. The main working tools are: drilling machine with G16 column and Taylor Hobson Surtronic 3+ device; the working parameters, for the plates under testing, were established according to table 3.

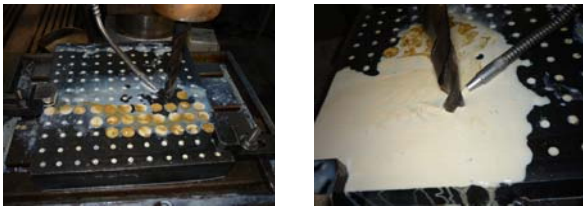
Table 3. Working parameters

(D) [mm]	(s) [mm/rot]	(v_c) [m/min]	(n) [rot/min]
TR-18	0,1; 0,16; 0,25	10,17; 25,43	180; 450
TR-20	0,1; 0,16; 0,25	11,3; 28,26	180; 450
TC-18	0,1; 0,16; 0,25	10,17; 25,43	180; 450
TC-20	0,1; 0,16; 0,25	11,3; 28,26	180; 450

The following notes are made:

TR – straight main cutting edge; TC – curved cutting edge.

The tests were performed under the same cutting conditions, without modifying the cross linear cutting edge of the standard drills or the three pyramidal cutting edges of the curved drills. Thus, the plate with the dimensions 350x350x50 mm was chucked with clamps – fig. 6a. The diluted soluble oil was an oil emulsion in water, type TRIM SC511, where 6÷7% from the mixture is synthetic oil and 93÷94% water, with a flow of 5 l/min. The constant flow of the diluted soluble oil was kept constant during tests. At the same time, a continuous flow of diluted soluble oil on the drill was taken into consideration during tests – fig. 6b.



a. b.

Fig. 6: Plate clamping system (a);
Cooling system (b)

The steel drilling depth with drills of diameters Ø18 and Ø20 mm, was limited to a value of 25÷30 mm (1,5·D), to avoid the risks of chip compaction in the drill slots. The profilometer Taylor Hobson Surtronic 3 was used to measure the parameters defining roughness – fig. 7. The sensitive element has the possibility to move on a distance from 1 to 40 mm. Measurements were performed with soft Talyprof (Taylor Hobson-®) device, allowing quantifying more basic parameters for the evaluated plate.

Fig. 7: Roughness measurement: (1) Taylor Hobson Surtronic 3+ Profilometer; (2) probe positioning

The evaluated roughness parameters were R_a and R_q [16]. The profile arithmetic mean deviation (R_a) – represents the arithmetic mean of profile deviation absolute values, y(x), to the median line, within the basic length limits, while R_q (profile root deviation) represents the root mean square of profile deviation, within the limit of basic length – fig. 8 [16], [9].

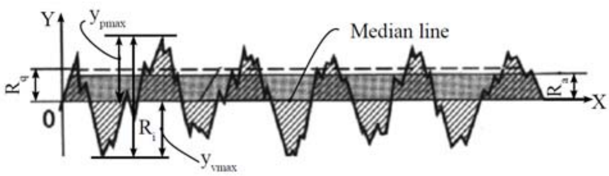


Fig. 8: Roughness parameters R_a and R_q

Relationally [16], [3],

$$R_a = \frac{1}{l}\int_o^l |\,y(x)\,|\,dx \quad \Rightarrow \quad R_a \approx \frac{1}{n}\sum_{j=1}^{n} |\,y_j\,| \qquad (22)$$

Due to the fact that with the help of R_a parameter, general variations can be detected in the profile height characteristic, this parameter can be used in monitoring a process of surface processing, but it has a limited efficiency because it cannot detect spacing differences or the presence/absence of high peaks or deep isolated gaps. Under these conditions, the R_q parameter is also used

For R_q the relation is defined [16], [3]:

$$R_q = \sqrt{\frac{1}{l}\int_o^l y^2(x)dx} \qquad (23)$$

The device calibration was made on a roughness reference standard test R_a = 0,6 μm. The parameters values R_a and R_q were defined for unfiltered profiles. for each processed tool bore profile measurements were taken in four areas, on an inspecting zone of 4 mm (l_n), on the same generatrix, from the bottom of the tool bore to the drill entry zone.

The profiles including the bottom and the edges of hole were eliminated from data analysis.

8000 values were recorded for each profile, two values for each micron.

4. EXPERIMENTAL RESULTS

The drilling processing of a pate with dimensions 350x350x50 mm made of OL37, using helical drills with two straight cutting edges and three curved cutting edges and varying the cutting parameters according to table 3, after processing the data recorded in MSExcel, the most important values were grouped in a table and graphically according to the influences imposed by the working conditions and the cutting parameters, taking special notice to: processing advance, cutting speed and the cutting tools geometry.

The graphic representation of roughness profile contains the testing length (l_n) and the height of the profile irregularities (R_i), as sum between a peak height and the adjacent gap line. This represents the distance, vertically measured, between the profile peak line and the profile gap line within the limits of the basic length – fig. 8. Mathematically, the parameter R_i can be calculated using the relation

$$R_i = y_{p\max} + y_{v\max} \tag{24}$$

Tables 4 and 5 contain the values recorded for the roughness parameters R_a şi R_q, at processing with drill having a diameter of Ø18 mm, for $n = 180$ *rot/min*, respectively $n = 450$ *rot/min*.

Table 4. Values for R_a and R_q - drills Ø18 mm

(D) [mm]	s [mm/rot]	v [m/min]	R_a [μm]	R_q [μm]
TR-18	0,1	10,17	3,26	4,16
TC-18	0,1	10,17	2,67	3,47
TR-18	0,16	10,17	3,56	5,42
TC-18	0,16	10,17	3,07	4,09
TR-18	0,25	10,17	4,46	6,19
TC-18	0,25	10,17	3,77	4,71

Table 5. Values for R_a and R_q -drills Ø18 mm

(D) [mm]	s [mm/rot]	v [m/min]	R_a [μm]	R_q [μm]
TR-18	0,1	25,43	5,91	7,6
TC-18	0,1	25,43	3,36	4,39
TR-18	0,16	25,43	7,73	9,4
TC-18	0,16	25,43	3,71	5,17
TR-18	0,25	25,43	8,17	10
TC-18	0,25	25,43	4,31	5,73

Similarly, for the same revolution regime, tables 6 and 7 present the recorded values for roughness parameters R_a and R_q, at working with drill with a diameter of Ø20 mm.

Table 6. Values for R_a and R_q - drills Ø20 mm

(D) [mm]	s [mm/rot]	v [m/min]	R_a [μm]	R_q [μm]
TR-20	0,1	11,3	4,04	4,95
TC-20	0,1	11,3	3,62	4,6
TR-20	0,16	11,3	4,31	5,5
TC-20	0,16	11,3	3,95	4,84
TR-20	0,25	11,3	4,67	5,83
TC-20	0,25	11,3	4,01	5,16

Table 7. Values for R_a and R_q - drills Ø20 mm

(D) [mm]	s [mm/rot]	v [m/min]	R_a [μm]	R_q [μm]
TR-20	0,1	28,26	5,05	6
TC-20	0,1	28,26	3,91	5,49
TR-20	0,16	28,26	6,01	6,91
TC-20	0,16	28,26	4,1	5,68
TR-20	0,25	28,26	6,82	8,4
TC-20	0,25	28,26	4,94	6,2

Figures 9÷12 present comparatively some prophilograms.

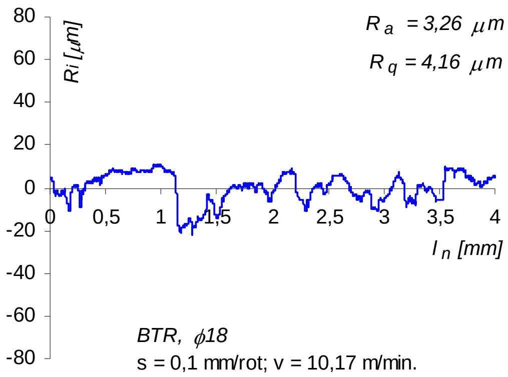


Fig. 9: Prophilogram, roughness R_a - TR Ø18, s=0,1mm/rot, v=10,17 m/min

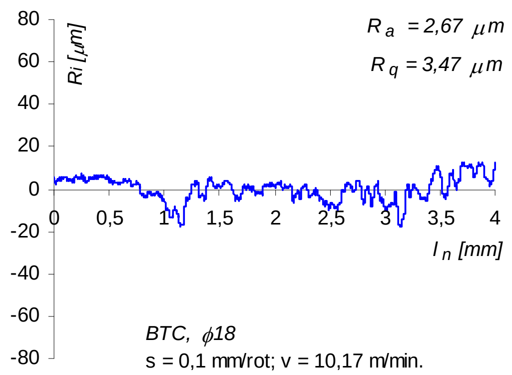


Fig. 10: Prophilogram, roughness R_a - TC Ø18, s=0,1mm/rot, v=10,17 m/min

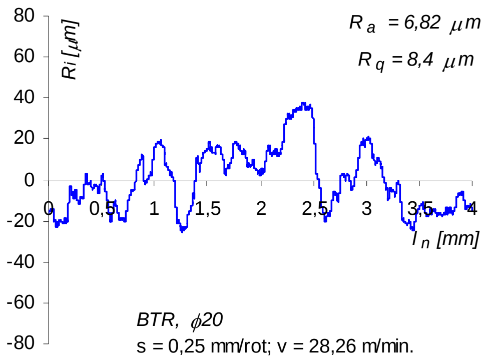


Fig. 11: Prophilogram, roughness R_a - TR Ø20, s=0,25mm/rot, v=28,26 m/min

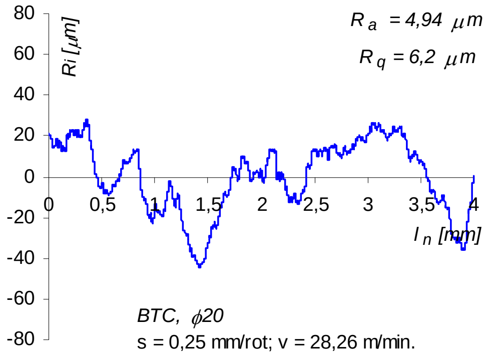


Fig. 12: Prophilogram, roughness R_a - TC Ø20, s=0,25mm/rot, v=28,26 m/min

In order to evaluate the influence of drill geometry and working parameters on the roughness of processed surfaces, the experimentally obtained values are presented in figures 13÷20.

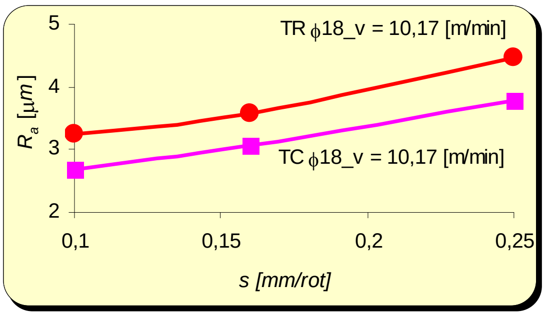


Fig. 13: Variation of roughness size R_a for TR Ø18 -TC Ø18, v_1 = 10,17 m/min

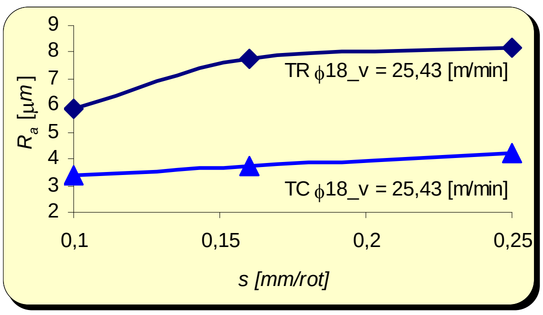


Fig. 14: Variation of roughness size R_a for TR Ø18 -TC Ø18, v_2 = 25,43 m/min

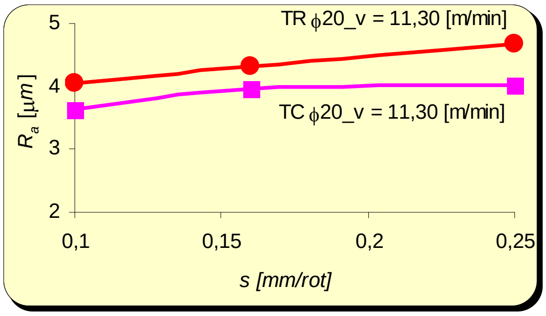


Fig. 15: Variation of roughness size R_a for TR Ø20 -TC Ø20, v_1 = 11,30 m/min

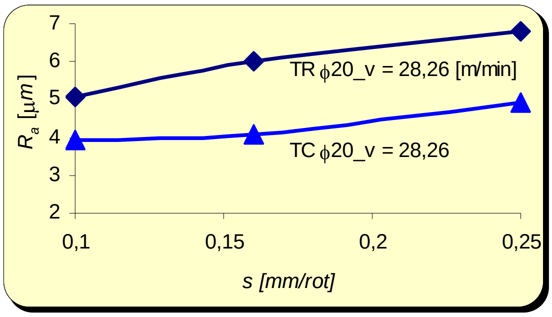


Fig. 16: Variation of roughness size R_a for TR Ø20 -TC Ø20, v_2 = 28,26 m/min

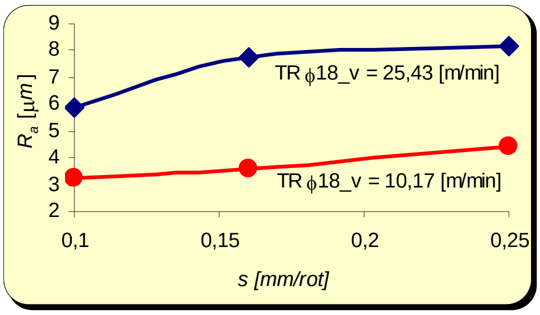


Fig. 17: Variation of roughness size R_a for TR Ø18, according to speed

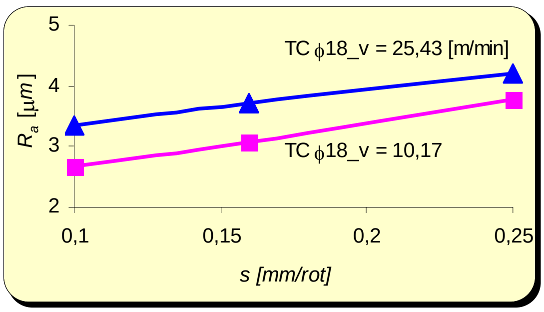


Fig. 18: Variation of roughness size R_a for TC Ø18, according to speed

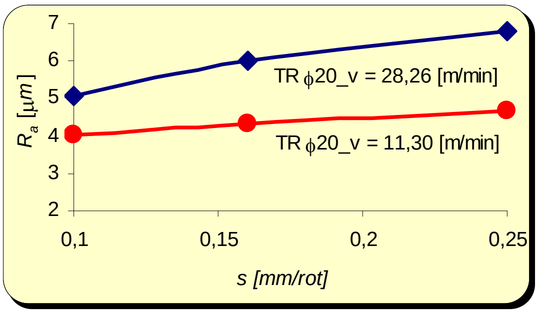


Fig. 19: Variation of roughness size R_a for TR Ø20, according to speed

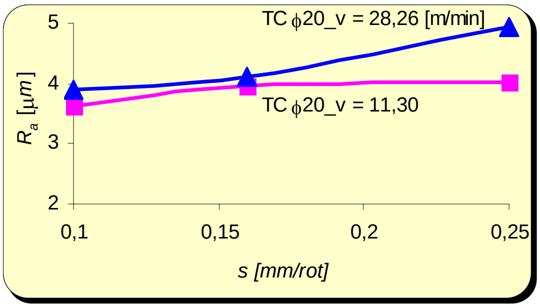


Fig. 20: Variation of roughness size R_a for TC Ø20, according to speed

5. CONCLUSION

The experiment carried out for the two types of drills having different geometry, for three advances s_1=0,1mm/rot, s_2=0,16mm/rot and s_3=0,16mm/rot, and two work rotation sizes (n_2=180rot/min and n_2=450rot/min), lead to the following conclusions:

1. feed (*s*) is the factor influencing more the surface roughness, confirming that its growth leads to an aggravation of surface quality – which is valid for both types of geometries;
2. from a geometrical point of view, the drills with curved cutting edges present a decreased roughness, explained both by increasing the number of cutting edges and the substantial decrease of chip thickness in the peripheral area of the curved cut;
3. at both types of drills, the surface roughness increases with increasing the working speed. Nevertheless it is known that there is a speed interval v=20÷30m/min, where a maximum roughness is obtained and after that it decreases [15].

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