THE INFLUENCE OF CUTTING PARAMETERS ON THE SURFACE TEXTURE OF 18CrMo4 HARDENED STEEL

Bogusław Pytlak

Summary

The experimental research of the influence of the cutting parameters on the chosen parameters of surface roughness for finishing hard turning of hardened 18CrMo4 steel with cubical boron nitride (CBN) inserts of Wiper geometry is presented in the work. For obtained results the assumed mathematical models illustrate the influence of the cutting parameters: v_c, f and a_p and cutting distance L on the chosen parameters of surface roughness: *Ra*, *Rz* and *Rmax*.

Keywords: hard turning, cubical boron nitride, surface texture

Wpływ parametrów skrawania na strukturę geometryczną powierzchni stali 18CrMo4 w stanie zahartowanym

Streszczenie

W pracy przedstawiono wyniki badań eksperymentalnych i ocenę wpływu parametrów skrawania na chropowatość powierzchni podczas toczenia wykończeniowego stali 18CrMo4 w stanie zahartowanym. Stosowano płytki z regularnego azotku boru (CBN) o geometrii typu Wiper. Opracowano modele matematyczne wpływu poszczególnych parametrów skrawania: v_c, f i a_p oraz długości drogi toczenia L na parametry chropowatości powierzchni: *Ra*, *Rz* i *Rmax*.

Słowa kluczowe: toczenie na twardo, regularny azotek boru, struktura geometryczna powierzchni

1. Introduction

The significant progress in the field of superhard materials for cutting tools, which took place in last years, contributed to situation, that more often hardened materials are machined [1, 2]. Hard turning considerably differs from traditional turning of soft materials [3]. It generates different type of surface texture, which was the research aim in works [4÷20]. In works [8÷11, 19, 20] the formula on average roughness $Ra = f^2/(32\ r_\varepsilon)$ was given, where: f – feed, mm/rev; r_ε – insert nose radius, mm. This equation has no practical application, because it does not

Address: Bogusław PYTLAK, Ph.D. Eng., University of Bielsko-Biała, Department of Manufacturing Technology and Automation, 43–309 Bielsko-Biała, Willowa 2, Poland, e-mail: bpytlak@ath.bielsko.pl

take into account such effects as: vibration, tool wear, hardness of machined material, which occur during real machining [9, 15]. In [7] it was suggested, that the specific segmented chip formation process and mostly catastrophic plastic strain influence the surface roughness, and can find "mirror image" in the surface texture. Therefore in works [10, 11, 18÷20] the empirical dependences in form of exponential models or polynomial models were proposed, which are more accurate in the prediction. The complex research of the influence of very small feed values on the surface roughness described by *Ra* parameter was presented in work [15]. The obtained research results show that hard turning is a quasi-deterministic process. To determine the surface roughness *Ra*, other variables as: tool defects, kind of tool material, tool wear rate, vibrations of machine tool must be taken into account. In particular, the variation of cutting edge defects in industry conditions is difficult to control, therefore in work [16] the graphical method was proposed. The important effect on the surface roughness has the machined material hardness [17÷20]. The rise of machined material hardness causes the value of *Ra* parameter to decline. For hard turning, the growth of the tool friction area on the machined material surface, which is a result of tool flank wear, causes the changes in the surface layer of machined elements described as "white layers" [5, 6, 8, 12, 14]. The "white layers" occur not only in case of hard turning, but very often in case of grinding too [4, 13].

The available literature lacks the research in the field of surface texture after machining of hardened steels with lower contents of carbon, which are used on the toothed elements in reducers and motoreducers [21]. The aim of the work is to determine the influence of cutting parameters on the chosen parameters of surface roughness during turning of 18CrMo4 hardened (59HRC) steel, taking into account the eventual mating of obtained surface with rotary shaft lipseal.

2. Methodology and scope of the tests

The research of finishing turning operation of 18CrMo4 steel, with CBN tools of Wiper geometry, include the influence of cutting speed v_c, feed f, depth of cut a_p and cutting distance L on the chosen parameters of surface roughness: average roughness *Ra*, mean roughness depth *Rz* and maximum roughness depth *Rmax* [22, 23]. These parameters mostly are assumed in assessment of the surface texture by leading manufacturers of rotary shaft lipseals and should be in the range: $Ra = 0.2÷0.8$ μm, $Rz = 1÷5$ μm, $Rmax < 6.3$ μm [24÷27]. In the research the specimens made of 18CrMo4 steel in the shape of steel bars with dimensions Ø60 × 300 mm in as-rolled condition are used. The specimens were next thermochemically treated: carburized on the depth 2 mm, hardened and tempered to hardness 59±2 HRC. Measurements of hardness $HV_{0.981}$ of carburized layer were carried out by means of the hardness tester Durimet 20K (Leitz Wetzlar Co.) under load of 0.981 N. The value of maximal depth of hardened layer was h_{max} = 1.44 mm. During the hard turning operation, the sum of particular passes for all specimens (shafts) did not exceed this value. The machining was carried out on the CNC lathe TUG 56-MN (AFM-Andrychów Co.). For finishing the monolithic CBN inserts TNGX1103085S-R-WZ of patented Crossbill™ Wiper geometry [28] are used (Fig. 1). The inserts are clamped in the tool holder CTJNR2525-M11. The inserts are made of the CBN100 grade, which is characterized by fine-grained structure and lower content of CBN. The fine-grained structure of CBN100 gives perfect quality of the cutting edge and lower content of CBN decreases the wear [28]. In the Table 1 a composition and property of CBN100 grade are given.

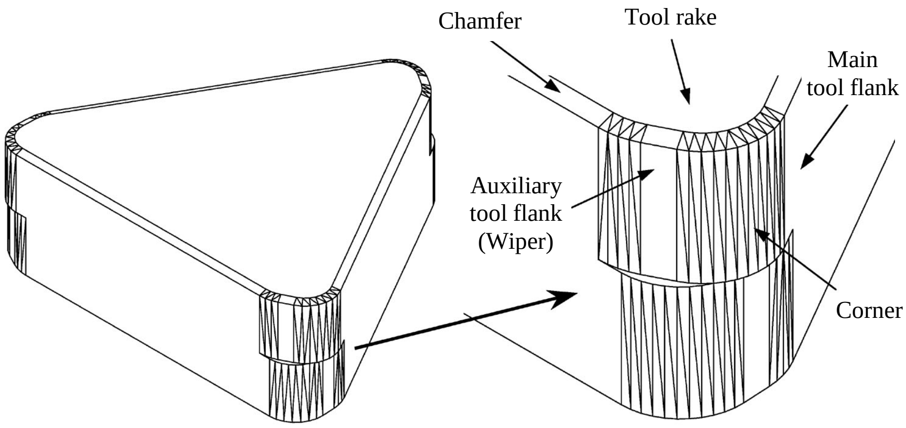

Fig. 1. The insert of Wiper geometry (TNGX1103085S-R-WZ) of Seco Co. [28]

Table 1. The composition and property of CBN100 grade [29]

Content of CBN	50%
Quantity of CBN grain	2 µm
Binder	TiC
Thermal conductivity	29 W/m·K, for 20ºC

The measurement of the surface roughness was made with the Mahr Pethometer Concept profilemeter. For measurements the stylus with radius 2 µm was used. The surface roughness was measured in the tree places, arranged uniformly on the shaft circumference every 120º. During measurement the original profile was recorded, from which the values of any parameters of surface roughness and waviness can be determined with the help of Pethometer Concept 7.0-19 software. The measurements were carried out with measuring length $lm = 4$ mm and sampling length $lr = 0.8$ mm, which is equal limiting wavelength λc (cut-off) for filter described in [30].

The evaluation of results was carried out using "Statistica" software. The verification of significance of mathematical models was performed by *F*-test. Whereas verification of significance of particular model coefficients was carried by Student's *t*-test [31]. In turn the test χ^2 for check the compatibility of the rest distribution with normal distribution was implemented.

3. Results and analysis of the test results

To describe chosen surface roughness parameters: *Ra*, *Rz* and *Rmax* in the function of cutting parameters and cutting distance *Ra*, *Rz*, *Rmax* = $g(v_c, f, a_p, L)$ the polynomial model of 2nd degree with interactions was assumed:

$$\begin{aligned} Ra, Rz, Rmax = {} & b_0 + b_1 \cdot v_c + b_2 \cdot f + b_3 \cdot a_p + b_4 \cdot L + b_{11} \cdot v_c^2 + b_{22} \cdot f^2 + \\ & b_{33} \cdot a_p^2 + b_{44} \cdot L^2 + b_{12} \cdot v_c \cdot f + b_{13} \cdot v_c \cdot a_p + b_{14} \cdot v_c \cdot L + \\ & b_{23} \cdot f \cdot a_p + b_{24} \cdot f \cdot L + b_{34} \cdot a_p \cdot L + b_{123} \cdot v_c \cdot f \cdot a_p + \\ & b_{234} \cdot f \cdot a_p \cdot L + b_{134} \cdot v_c \cdot a_p \cdot L + b_{1234} \cdot v_c \cdot f \cdot a_p \cdot L \end{aligned} \tag{1}$$

where: b_0, b_1, b_2, b_3, b_4, b_{11}, b_{22}, b_{33}, b_{44}, b_{12}, b_{13}, b_{14}, b_{23}, b_{24}, b_{34}, b_{123}, b_{234}, b_{134}, b_{1234} – constant coefficients of the model.

The values of cutting parameters of the finish turning of 18CrMo4 steel, with CBN tools of Wiper geometry were assumed according to complete multifactor experiment design (Table 2). Supposing, that tool wear have essential influence on the values of cutting forces, the additional quantity of cutting distance *L* was proposed.

Table 2. The values of cutting parameters: v_c, f and a_p and cutting length L

Investigated factors	**Values**
Cutting speed v_c, m/min	100; 150; 200
Feed f, mm/rev	0,1; 0,2; 0,3
Depth of cut a_p, mm	0,1; 0,2
Cutting distance L, m	200; 400; 600; 800; 1000; 1200; 1400; 1600; 1800; ...

For each from layouts of experiment design was made three repetitions

In the Tables 3÷5 are presented the values of cutting parameters and cutting length for particular layout of experiment design and mean values of the parameters: *Ra*, *Rz* and *Rmax*.

On the basis of the results of experimental research presented in the Tables 3÷5, by means of multiple regression, the values of constants coefficients of the models were calculated in the "Statistica" software. By inputting this coefficients into polynomial (1) the following forms of the mathematical models are obtained:

$$\begin{aligned} Ra = {} & 1.631510 - 0.005127 \cdot v_c - 1.007386 \cdot f - 16.241243 \cdot a_p + \\ & 0.000019 \cdot L + 0.000011 \cdot v_c^2 + 2.328053 \cdot f^2 + \\ & 49.446139 \cdot a_p^2 - 0.000000 \cdot L^2 + 0.007469 \cdot v_c \cdot f + \\ & 0.011817 \cdot v_c \cdot a_p + 0.000001 \cdot v_c \cdot L + 5.402884 \cdot f \cdot a_p - \\ & 0.000269 \cdot f \cdot L + 0.000229 \cdot a_p \cdot L - 0.047273 \cdot v_c \cdot f \cdot a_p + \\ & 0.001066 \cdot f \cdot a_p \cdot L - 0.000004 \cdot v_c \cdot a_p \cdot L + 0.000005 \cdot v_c \cdot f \cdot a_p \cdot L \end{aligned} \quad (2)$$

$$\begin{aligned} Rz = {} & 5.591156 - 0.017289 \cdot v_c - 4.043564 \cdot f - 47.421215 \cdot a_p - \\ & 0.000141 \cdot L + 0.000028 \cdot v_c^2 + 3.985573 \cdot f^2 + \\ & 138.613867 \cdot a_p^2 + 0.000000 \cdot L^2 + 0.047363 \cdot v_c \cdot f + \\ & 0.042619 \cdot v_c \cdot a_p + 0.000001 \cdot v_c \cdot L + 29.945506 \cdot f \cdot a_p - \\ & 0.000068 \cdot f \cdot L + 0.002345 \cdot a_p \cdot L - 0.257162 \cdot v_c \cdot f \cdot a_p - \\ & 0.008685 \cdot f \cdot a_p \cdot L - 0.000008 \cdot v_c \cdot a_p \cdot L + 0.000054 \cdot v_c \cdot f \cdot a_p \cdot L \end{aligned} \quad (3)$$

$$\begin{aligned} Rt = {} & 5.990475 - 0.021941 \cdot v_c - 5.294663 \cdot f - 41.125959 \cdot a_p - \\ & 0.000193 \cdot L + 0.000043 \cdot v_c^2 + 5.590026 \cdot f^2 + \\ & 124.111799 \cdot a_p^2 + 0.000000 \cdot L^2 + 0.049506 \cdot v_c \cdot f + \\ & 0.026979 \cdot v_c \cdot a_p + 0.000001 \cdot v_c \cdot L + 21.447650 \cdot f \cdot a_p - \\ & 0.000049 \cdot f \cdot L + 0.000222 \cdot a_p \cdot L - 0.206423 \cdot v_c \cdot f \cdot a_p - \\ & 0.00227 \cdot f \cdot a_p \cdot L - 0.000007 \cdot v_c \cdot a_p \cdot L + 0.000002 \cdot v_c \cdot f \cdot a_p \cdot L \end{aligned} \quad (4)$$

The statistical analysis of the above regression equations confirmed, that this equations are significant and have high value of multiple correlation coefficient $R = 0.924 \div 0.940$. This equations have insignificant coefficients which in the next steps of analysis are eliminated. Exemplary detailed statistical analysis of the regression equation (2) for the *Ra* parameter is shown in the Table 6.

Table 3. The values of the average roughness Ra, μm

No.	Cutting speed v_c, m/min	Feed f, mm/rev	Depth of cut a_p, mm	Cutting distance L, m								
				200	400	600	800	1000	1200	1400	1600	1800
1	100	0.1	0.1	0.240	0.238	0.242	0.280	0.238	0.228	0.243	0.230	0.212
2	100	0.1	0.2	0.233	0.207	0.242	0.198	0.238	0.210	0.265	0.253	0.233
3	100	0.2	0.1	0.258	0.262	0.290	0.325	0.320	0.323	0.342	0.287	0.315
4	100	0.2	0.2	0.208	0.218	0.260	0.312	0.312	0.270	0.310	0.248	0.282
5	100	0.3	0.1	0.427	0.408	0.400	0.410	0.437	0.387	0.455	0.387	0.440
6	100	0.3	0.2	0.405	0.397	0.390	0.403	0.430	0.402	0.417	0.398	0.402
7	150	0.1	0.1	0.213	0.192	0.213	0.248	0.227	0.232	0.232	0.225	0.217
8	150	0.1	0.2	0.228	0.208	0.270	0.240	0.235	0.232	0.263	0.272	0.257
9	150	0.2	0.1	0.220	0.235	0.267	0.238	0.247	0.257	0.288	0.262	0.278
10	150	0.2	0.2	0.232	0.243	0.263	0.272	0.282	0.267	0.287	0.268	0.308
11	150	0.3	0.1	0.310	0.345	0.327	0.317	0.295	0.327	0.347	0.320	0.320
12	150	0.3	0.2	0.372	0.387	0.345	0.387	0.365	0.405	0.372	0.405	0.423
13	200	0.1	0.1	0.197	0.190	0.220	0.202	0.195	0.225	0.220	0.215	0.252
14	200	0.1	0.2	0.230	0.253	0.225	0.223	0.235	0.227	0.207	0.240	0.203
15	200	0.2	0.1	0.217	0.237	0.272	0.293	0.307	0.348	0.348	0.392	0.388
16	200	0.2	0.2	0.252	0.275	0.315	0.310	0.333	0.312	0.308	0.285	0.353
17	200	0.3	0.1	0.410	0.448	0.457	0.465	0.422	0.443	0.420	0.412	0.377
18	200	0.3	0.2	0.390	0.378	0.340	0.355	0.372	0.370	0.438	0.445	0.400

Table 4. The values of the mean roughness depth Rz, μm

No.	Cutting speed v_c, m/min	Feed f, mm/rev	Depth of cut a_p, mm	Cutting distance L, m								
				200	400	600	800	1000	1200	1400	1600	1800
1	100	0.1	0.1	1.216	1.400	1.435	1.540	1.322	1.482	1.432	1.623	1.523
2	100	0.1	0.2	1.270	1.195	1.333	1.275	1.542	1.612	1.562	1.503	1.520
3	100	0.2	0.1	1.543	1.677	1.787	1.727	1.763	1.760	1.766	1.725	1.670
4	100	0.2	0.2	1.407	1.510	1.558	1.705	1.750	1.653	1.688	1.683	1.943
5	100	0.3	0.1	1.998	1.860	1.952	2.022	1.883	1.918	1.905	2.157	2.172
6	100	0.3	0.2	1.948	1.912	1.837	1.822	2.045	1.978	2.122	2.043	1.887
7	150	0.1	0.1	1.327	1.202	1.250	1.383	1.435	1.412	1.282	1.385	1.375
8	150	0.1	0.2	1.252	1.383	1.553	1.490	1.478	1.587	1.660	1.690	1.830
9	150	0.2	0.1	1.460	1.663	1.758	1.708	1.555	1.592	1.732	1.620	1.690
10	150	0.2	0.2	1.457	1.497	1.602	1.605	1.527	1.548	1.658	1.622	1.890
11	150	0.3	0.1	1.907	1.918	1.827	1.882	1.755	1.788	1.832	2.078	2.057
12	150	0.3	0.2	1.973	1.882	1.879	1.827	1.858	1.958	1.912	2.252	2.205
13	200	0.1	0.1	1.223	1.200	1.282	1.175	1.263	1.250	1.462	1.398	1.480
14	200	0.1	0.2	1.175	1.150	1.255	1.332	1.452	1.495	1.475	1.528	1.472
15	200	0.2	0.1	1.390	1.449	1.562	1.672	1.710	1.948	1.918	2.107	2.005
16	200	0.2	0.2	1.367	1.530	1.557	1.758	1.850	1.730	1.925	1.858	2.180
17	200	0.3	0.1	2.355	2.195	2.232	2.483	2.390	2.508	2.428	2.480	2.450
18	200	0.3	0.2	1.827	1.893	1.765	1.998	1.995	2.060	2.260	2.395	2.327

Table 5. The values of the maximum roughness depth *Rmax*, μm

No.	**Cutting speed v_c, m/min**	**Feed f, mm/rev**	**Depth of cut a_p, mm**	**Cutting distance L, m**								
				200	**400**	**600**	**800**	**1000**	**1200**	**1400**	**1600**	**1800**
1	100	0.1	0.1	1.503	1.565	1.755	1.722	1.593	1.677	1.592	1.747	1.622
2	100	0.1	0.2	1.613	1.405	1.617	1.547	1.705	1.597	1.800	1.752	1.680
3	100	0.2	0.1	1.738	1.815	1.947	1.805	1.823	1.982	1.828	1.770	1.798
4	100	0.2	0.2	1.595	1.635	1.683	1.817	1.855	1.767	1.813	1.800	2.007
5	100	0.3	0.1	2.108	2.045	1.970	1.932	2.020	2.160	2.032	2.305	2.268
6	100	0.3	0.2	2.113	1.917	1.932	2.020	2.277	2.188	2.235	2.127	2.007
7	150	0.1	0.1	1.558	1.405	1.452	1.677	1.657	1.445	1.377	1.573	1.507
8	150	0.1	0.2	1.480	1.477	1.633	1.627	1.505	1.532	1.672	1.790	1.874
9	150	0.2	0.1	1.620	1.892	1.912	1.887	1.633	1.678	1.915	1.733	1.773
10	150	0.2	0.2	1.537	1.663	1.673	1.742	1.675	1.630	1.755	1.557	1.962
11	150	0.3	0.1	2.278	2.123	1.963	2.025	1.935	1.898	2.070	2.188	2.142
12	150	0.3	0.2	2.022	1.827	1.923	1.802	1.865	2.135	2.122	2.285	2.215
13	200	0.1	0.1	1.448	1.233	1.513	1.353	1.525	1.430	1.558	1.597	1.675
14	200	0.1	0.2	1.382	1.333	1.408	1.483	1.560	1.590	1.692	1.798	1.827
15	200	0.2	0.1	1.532	1.675	1.658	1.950	1.793	2.223	2.217	2.222	2.148
16	200	0.2	0.2	1.375	1.630	1.660	1.948	2.083	1.887	2.103	2.045	2.298
17	200	0.3	0.1	2.490	2.282	2.362	2.637	2.560	2.658	2.590	2.492	2.570
18	200	0.3	0.2	1.952	2.013	1.948	2.167	2.115	2.300	2.528	2.560	2.313

Table 6. The summary of the multiple regression results for the polynomial model

N = 162	**Regression summary for dependent variable: *Ra* (*Ra*) R = 0.92445496; R^2 = 0.85461697; Adjusted R^2 = 0.83631701; $F(18,143)$ = 46.700; p < 0.0000; Std. error of estimate: 0.02983**			
	b_i	Std. Err. of b_i	$t(143)$	p-level
Intercept	1.6315	0.48563	3.35959	0.001001
v_c	-0.0051	0.00084	-6.07992	0.000000
f	-1.0074	0.43570	-2.31213	0.022198
a_p	-16.2412	7.15030	-2.27141	0.024615
L	**0.0000**	**0.00007**	**0.27613**	**0.782848**
v_c^2	0.0000	0.00000	5.35063	0.000000
f^2	2.3281	0.49805	4.67435	0.000007
a_p^2	49.4461	23.84126	2.07397	0.039875
L^2	**-0.0000**	**0.00000**	**-1.75459**	**0.081471**
$v_c \cdot f$	0.0075	0.00223	3.35087	0.001031
$v_c \cdot a_p$	0.0118	0.00413	2.85805	0.004900
$v_c \cdot L$	**0.0000**	**0.00000**	**1.63902**	**0.103407**
$f\, a_p$	**5.4029**	**2.77028**	**1.95030**	**0.053096**
$f\, L$	**-0.0003**	**0.00018**	**-1.52750**	**0.128845**
$a_p \cdot L$	**0.0002**	**0.00049**	**0.47125**	**0.638183**
$v_c \cdot f\, a_p$	-0.0473	0.01651	-2.86332	0.004823
$f\, a_p \cdot L$	**0.0011**	**0.00172**	**0.62158**	**0.535209**
$v_c \cdot a_p \cdot L$	**-0.0000**	**0.00000**	**-1.31799**	**0.189614**
$v_c \cdot f\, a_p \cdot L$	**0.0000**	**0.00001**	**0.54761**	**0.584811**

Bolded rows in the Table 6 indicate the insignificant coefficients, which are eliminated in the next steps of analysis, beginning from the most insignificant. The elimination of the insignificant coefficients caused minimal decrease of the adjusted multiple correlation coefficient R^2, which is not contrary to the decision of its elimination. The obtained regression equation has high multiple correlation coefficient $R = 0.918$ and is significant ($F_{10;151} = 81.118$, $p = 0.0000$). Finally after elimination of the insignificant coefficients (Table 7) the regression equation for the average roughness Ra has the following form:

$$\begin{aligned} Ra = {} & 0.634065 - 0.004599 v_c - 1.221571 f - 1.125925 a_p + 0.000010 v_c^2 + \\ & 2.265811 f^2 + 0.007205 v_c \cdot f + 0.007658 v_c \cdot a_p + 0.0000001 v_c \cdot L + \\ & 6.020526 f \cdot a_p - 0.039339 v_c \cdot f \cdot a_p \end{aligned} \tag{5}$$

Table 7. The summary of the multiple regression results for the polynomial model with eliminated insignificant coefficients

***N*=162**	**Regression summary for dependent variable: *Ra* (*Ra*) *R* = 0.91818585; *R*^{2} = 0.84306525; Adjusted *R*^{2} = 0.83267222; *F*(10,151) = 81.118; *p* < 0.0000; Std. error of estimate: 0.03016**			
	b_i	Std. Err. of b_i	t(151)	p-level
Intercept	0.634065	0.087837	7.21867	0.000000
v_c	-0.004599	0.000775	-5.93325	0.000000
F	-1.221571	0.403245	-3.02935	0.002884
a_p	-1.125925	0.476108	-2.36485	0.019308
v_c^2	0.000010	0.000002	5.15596	0.000001
f^2	2.265811	0.502649	4.50774	0.000013
$v_c \cdot f$	0.007205	0.002250	3.20215	0.001664
$v_c \cdot a_p$	0.007658	0.003070	2.49413	0.013704
$v_c \cdot L$	0.000000	0.000000	4.75580	0.000005
$f\ a_p$	6.020526	2.209307	2.72508	0.007188
$v_c \cdot f\ a_p$	-0.039339	0.014232	-2.76419	0.006417

The identical statistical analysis was made for remaining models (3) and (4) describing the parameters Rz and $Rmax$. It was shown, that they have the insignificant coefficients, which can be eliminated. The elimination of the insignificant coefficients caused minimal changes of the adjusted multiple correlation coefficient R^2, which confirms possibility of its elimination. Obtained regression equations have high multiple correlation coefficient $R = 0.938$ for Rz and $R = 0.920$ for $Rmax$ and are significant ($F_{12;149} = 91.124$, $p = 0.0000$) – Rz and ($F_{7;154} = 121.30$, $p = 0.0000$) – $Rmax$. Finally after elimination of the insignificant coefficients the regression equations for Rz and $Rmax$ take the following form:

$$Rz = 2.678195 - 0.015906v_c - 3.961551f - 4.844458a_p + 0.000027v_c^2 + 3.816645f^2 + 0.046635v_c \cdot f + 0.033541v_c \cdot a_p + 28.458806f \cdot a_p + 0.001495a_p \cdot L - 0.243340v_c \cdot f \cdot a_p - 0.008445f \cdot a_p \cdot L + 0.000049v_c \cdot f \cdot a_p \cdot L \quad (6)$$

$$Rmax = 2.775193 - 0.016948v_c - 2.123522f + 0.000042v_c^2 + 5.430604f^2 + 0.028112v_c \cdot f - 0.058322v_c \cdot f \cdot a_p + 0.000008v_c \cdot a_p \cdot L \quad (7)$$

The relation (5) was shown using three dimensional graph (Fig. 2) and depth contour graph (Fig. 3), in turn the relation (6) using graphs (Fig. 4) and (Fig. 5) and the relation (7) using graphs (Fig. 6) and (Fig. 7).

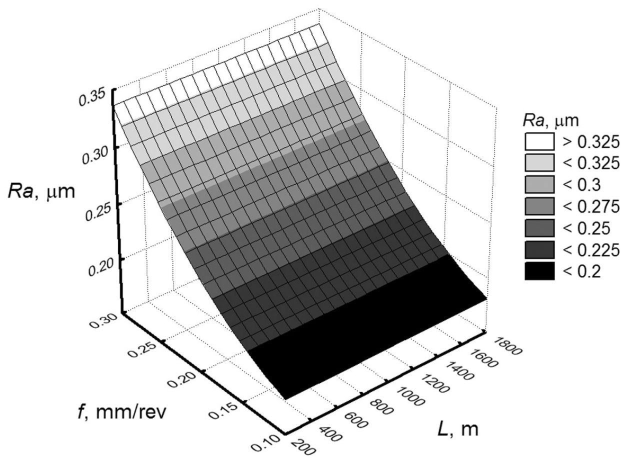

Fig. 2. Three dimensional graph depicting the influence of feed *f* and cutting distance *L* on the average roughness *Ra*, at constant values of v_c = 150 m/min and a_p = 0.1 mm

The analysis of the measured values of *Ra* (Table 3) indicates, that this values have significant scatter of results. But it should be marked, that only in sparse cases the value of the average roughness *Ra* exceeds the range *Ra* = 0.2÷0.8 µm. Moreover in the whole range of the cutting distance *L*, the change of cutting speed v_c does not influence in significant way the value of *Ra* parameter. The above tendency is confirmed by regression equation (5) (very small values of coefficients for components contained the cutting speed v_c).

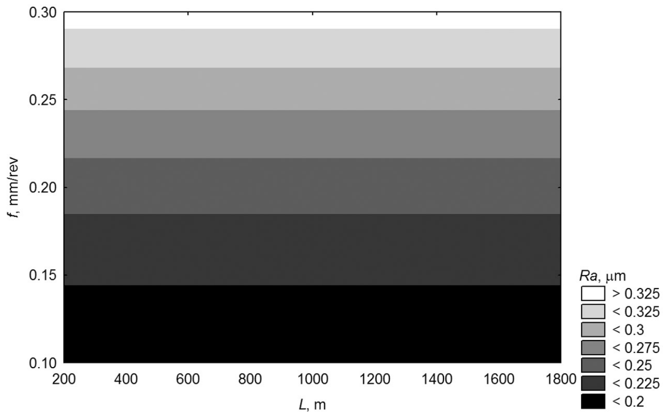

Fig. 3. Depth contour graph depicting the influence of feed *f* and cutting distance *L* on the average roughness *Ra*, at constant values of v_c = 150 m/min and a_p = 0.1 mm

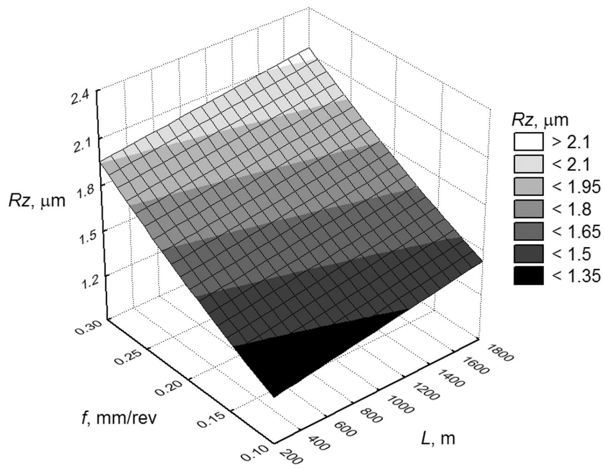

Fig. 4. Three dimensional graph depicting the influence of feed *f* and cutting distance *L* on the mean roughness depth *Rz*, at constant values of v_c = 150 m/min and a_p = 0.1 mm

The influence of feed *f* on the value of *Ra* parameter is very clear. The increasing of feed *f* from 0.1 mm/rev to 0.3 mm/rev causes the increasing of values *Ra* parameters from 0.1 μm to 0.2 μm. The increasing values of cutting speed v_c and cutting depth a_p contribute to the minimal increasing of the influence of feed *f* on values of *Ra* parameters. Likewise in a case of cutting speed v_c the change of depth of cut a_p does not change in a significant way the value of *Ra* parameter. In the investigated range the value of *Ra* parameter was not influenced by the cutting distance *L*.

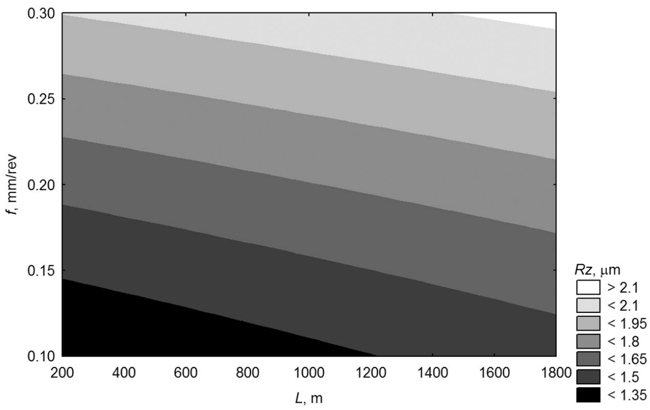

Fig. 5. Depth contour graph depicting the influence of feed *f* and cutting distance *L* on the mean roughness depth *Rz*, at constant values of v_c = 150 m/min and a_p = 0.1 mm

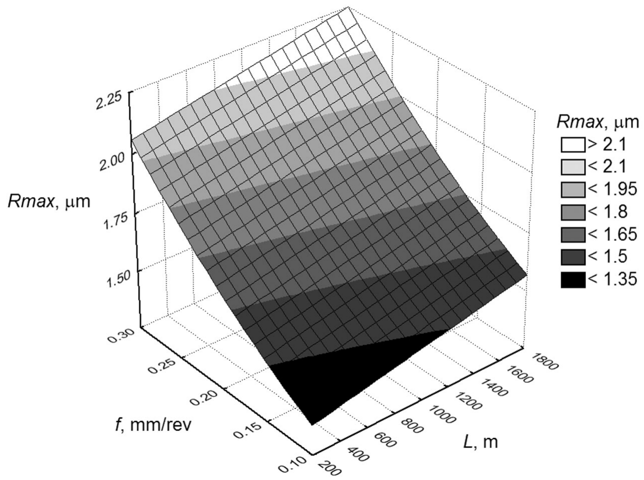

Fig. 6. Three dimensional graph depicting the influence of feed *f* and cutting distance *L* on the maximum roughness depth *Rmax*, at constant values of v_c = 150 m/min and a_p = 0.1 mm

Likewise in a case of *Ra* parameter, also for *Rz* parameter a significant scatter of measuring results was observed. The analysis of values *Rz* parameter (Table 4) did not indicate that the increase of cutting speed v_c influences in a significant way the value of *Rz* parameter. Whereas for selected association of cutting parameters, the increasing of a cutting distance *L* causes a little rise of values of *Rz* parameter. This effect can be explained by progressive tool wear. The biggest influence on the value *Rz* has the feed *f*. The increase of values of feed f in a significant way contributes to the rise of values of *Rz* parameter. The increase of feed f from value 0.1 mm/rev do 0.3 mm/rev causes the rise of values of *Rz* parameter on average about 0.7 μm. This dependence changes with the variation of cutting speed v_c and depth of cut a_p. The depth of cut a_p likewise cutting speed v_c practically does not influence the value of *Rz* parameter. Obtained results of measurements of the mean roughness depth *Rz* are in the range recommended by manufacturers of rotary shaft lipseals i.e. 1÷4 μm. Only in a few cases exceeded this range and are smaller than 1 μm.

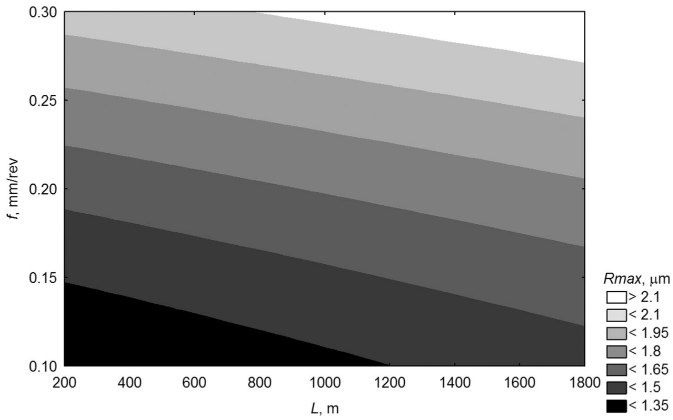

Fig. 7. Depth contour graph depicting the influence of feed f and cutting distance L on the maximum roughness depth *Rmax*, at constant values of v_c = 150 m/min and a_p = 0.1 mm

The analysis of values of *Rmax* parameter (Table 5) indicate especially large scatter of measuring results. But it should be marked, that all values of *Rmax* parameter are less than 6.3 μm, which is the maximal acceptable maximum roughness depth *Rmax* value for surfaces mating with rotary shaft lipseal. The maximum values of *Rmax* parameter oscillate around 3 μm and only in a few cases exceed this vale. For all layouts of experiment design, no significant influence of cutting speed v_c on the value *Rmax* parameter was observed. Whereas for sparse associations of cutting parameters, a tendency for slight rise of value of *Rmax* parameter with increasing of cutting distance L can be observed, which was visible in the case of analysis of influence of cutting parameters and cutting distance on value of *Rz* parameter. From all cutting parameters the biggest influence on maximum roughness depth *Rmax* has feed f. The increasing values of feed f in a significant way causes the rise of maximum roughness depth *Rmax*. This dependence does not practically change with variation of cutting speed v_c and depth of cut a_p. The increasing of feed f by

0.1 mm/rev causes the rise of *Rmax* parameter about 0.4 µm. The depth of cut a_p does not practically influence the value of *Rmax* parameter.

In order to visualise the surface texture after finishing hard turning, the examples of surface roughness profiles and material ratio curve for different values of feed *f* were shown (Fig. 8).

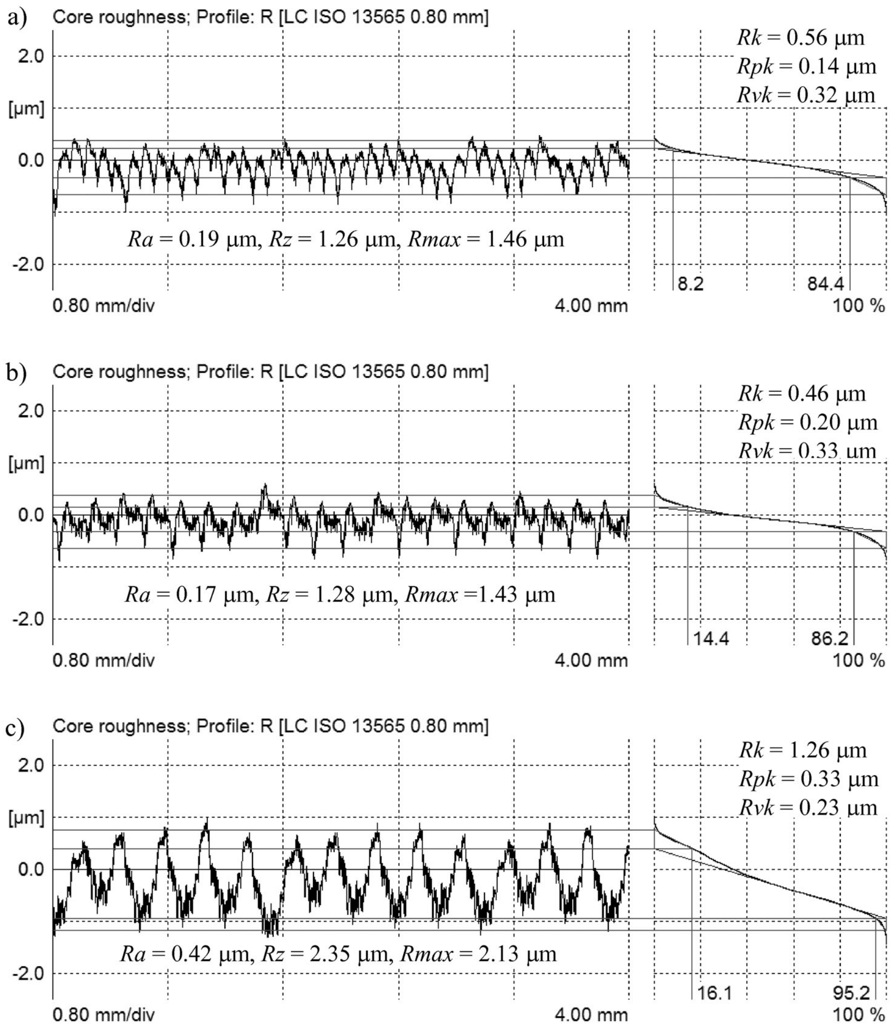

Fig. 8. Roughness profiles and material ratio curve of surface finishing hard turning of hardened (59HRC) steel 18CrMo4, for different values of feed *f*: a) $f = 0.1$ mm/rev, b) $f = 0.2$ mm/rev, c) $f = 0.3$ mm/rev, at constant values of $v_c = 100$ m/min, $a_p = 0.2$ mm and $L = 200$ m

4. Summary

Presented research results indicate the possibility of obtaining surface texture conforming requirements for mating with rotary shaft lipseal, after hard turning of 18CrMo4 steel hardened to 59±2 HRC with CBN tools of Wiper geometry

On the basis of the above research results, including the influence of cutting parameters on chosen parameters of surface roughness, one can see, that the most significant factor is feed f. It confirms the fact, that surface roughness is primarily formed by imaging of edge geometry in machined material. The increase of the feed f value causes only slight rise of above parameters of surface roughness. This is the result of application of CBN inserts with Wiper geometry.

The cutting speed v_c and depth of cut a_p practically do not influence the surface roughness. The influence of cutting distance L in case of Ra parameter is not observable, while in case of residual two parameters Rz and $Rmax$ a minimal rise of their values along with progressive tool wear was observed.

References

[1] K.E. OCZOŚ: Relacja toczenia na twardo do szlifowania. *Mechanik*, **78**(2005), 5-13.

[2] D.P. SOROKA: Hard turning and the machine tool. www.hardinge.com.

[3] M. KAWALEC: Efekty technologiczne obróbki na twardo materiałów metalowych. *Mechanik*, **79**(2006)1, 20-25.

[4] A. BARBACKI, M. KAWALEC, A. HAMROL: Turning and grinding as a source of microstructural changes in the surface layer of hardened steel. *Journal of Material Processing Technology*, **133**(2003), 21-25.

[5] Y.K. CHOU, C.J. EVANS: Process effects on white layer formation in hard turning. *Transactions of NAMRI/SME*, **26**(1998), 117-122.

[6] Y.K. CHOU, C.J. EVANS: White layers and thermal modeling of hard turned surfaces. *Journal of Machine Tools & Manufacture*, **39**(1999), 1863-1881.

[7] M.A. DAVIES, Y.K. CHOU, C.J. EVANS: On chip morphology, tool wear and cutting mechanics in finish hard turning. *Annals of the CIRP*, **45**(1996)1, 77-82.

[8] T.G. DAWSON: Machining hardened steel with polycrystalline cubic boron nitride cutting tools. PhD thesis, Georgia Institute of Technology, Georgia 2002.

[9] T.G. DAWSON, T.R. KURFESS: Tool life, wear rates, and surface quality in hard turning. www.hardinge.com.

[10] J. FENG: An experimental study of the impact of turning parameters on surface roughness. Proc. of the 2001 Industrial Engineering Research Conference, Dallas 2001.

[11] J. FENG, D. WANG: Development of empirical models for surface roughness prediction in finish turning. *Journal of Advanced Manufacturing Technology*, **20**(2002), 348-356.

[12] W. GRZESIK, T. WANAT: Hard part machining of quenched alloy steel of 60 HRC hardness using conventional and wiper ceramic inserts. Proc. "Strojárska Technológia 2004", VI Medzinárodná Vedecká Konferenci, Súľov 2004.
[13] Y.B. GUO, J. SAHNI: A comparative study of hard turned and cylindrically ground white layers. *Journal of Machine Tools & Manufacture*, **44**(2004), 135-145.
[14] K. JÓŹWIAK, T. KACHLICKI, A. BARBACKI: Struktura i właściwości warstwy wierzchniej po skrawaniu zahartowanej stali C38. *Archiwum Technologii Maszyn i Automatyzacji*, **24**(2004)2, 83-91.
[15] M.M.W. KNÜFERMANN: Machining surfaces of optical quality by hard turning. PhD Thesis Cranfield University, 2004.
[16] M.M.W. KNÜFERMANN, M.A. FLEMING: Optimierung des Bearbeitungs-prozesses beim Hartdrehen. *Verfahren*, **38**(2004), 113-120
[17] P. KOSHY, P. DUMITRESCU: A simple technique to characterize the role of work hardness in hard part machining. *Journal of Engineering Manufacture*, **217**(2003)10, 1485-1489.
[18] T. ÖZEL, T. HSU, E. ZEREN: Effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and forces in finish turning of hardened ANSI H13 Steel. *Journal of Advanced Manufacturing Technology*, **25**(2005), 262-269.
[19] T. ÖZEL, Y. KARPAT: Prediction of surface roughness and tool wear in finish dry hard turning using back propagation neural networks. Proc. 17th Inter. Conf. on Production Research, Blacksburg 2003.
[20] A. VERNON, T. ÖZEL: Factors affecting surface roughness in finish hard turning. Report MARL-03-01, Rutgers University, Piscataway 2003.
[21] B. PYTLAK: Optymalizacja wielokryterialna operacji toczenia stali 18CrMo4 w stanie zahartowanym. Praca doktorska, Akademia Techniczno-Humanistyczna w Bielsku Białej, 2007.
[22] DIN EN ISO 4287: Geometrical product specifications (GPS) – surface texture: Profile method – terms, definitions and surface texture parameters.
[23] K.J. STOUT, L. BLUNT: Three dimensional surface topography. Penton Press, London.
[24] Simrit: Materiały informacyjne firmy Freudenberg-Simrit GmbH.
[25] DIN 3760: 1996: Rotary shaft lip type seals.
[26] DIN 3761: 1984: Rotary shaft lip type seals for automobiles.
[27] ISO 6194: 1990: Rotary shaft lip type seals
[28] Wkładki ostrzowe SECOMAX PCBN zdecydowanie intensyfikują obróbkę skrawaniem. *Mechanik*, **76**(2003)11, 649-652.
[29] Information materials of Seco Tools AB.
[30] ISO 13565-1: 1996: Geometric product specification (GPS) – surface texture: profile method – surfaces having stratified functional properties – Part 1. Filtering and general conditions.
[31] M. DOBOSZ: Wspomagana komputerowo statystyczna analiza wyników badań. Akademicka Oficyna Wydawnicza EXIT, Warszawa 2004.

Received in June 2010