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Experimental investigation of dynamic instability of the turning process

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ABSTRACT

Purpose: Purpose of this paper is consideration of dynamic instability in turning process. There are several sources which lead to instability in turning process (cyclic variation of depth of cutting, inadequate rigidity of machine tool, high passive force component F_p, small tool nose radius and small tool/workpiece contact length, non-uniform stress distribution over contact length). In hard turning, when depth of cutting and feed have low values, lead edge angle and passive force F_p are strongly depend on real time value of depth of cutting.

Design/methodology/approach: Experimental tests and numerical modeling of tool /workpiece contact line have been done to evaluate the rate of cutting instability while using and comparing different process monitoring sensors, and acquisition techniques. This data can be used for prediction and compensation of machining errors.

Findings: It was found that high chip thickness alteration occurs because of cutting depth vary for a value of some 60 %. Even higher alteration of F_p force signal is recorded when machine tool has inadequate stiffness.

Research limitations/implications: Results and findings presented in this paper are qualitative and might be slightly different in other cutting condition (e.g. if wiper inserts are used). Also there are no experiences with coated workpieces or with workpiece material with low deformation energy.

Practical implications: Assuming that a hard turning is a semi finishing or finishing process, surface finish is of big relevance. Surface roughness is a consequence of both cutting instability and of tool/workpiece loading condition. Results of test indicates an optimal cutting depth for final pass when minimum surface roughness can be achieved what can be valuable for cutting regime determination. Furthermore, more effective use of the machine tool performances might be achieved.

Originality/value: Originality of the paper is in analysis of sources of turning instability (variable depth of cutting combined with lead edge angle and tool nose radius) which lead primary to condition where F_p sensing data does not fit to the normal distribution and secondary to cyclic push-offs of the edge.

Keywords: Machining; Mechanical properties; Dynamic properties; Depth of cutting

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MANUFACTURING AND PROCESSING OF ENGINEERING MATERIALS

1. Introduction

Cutting edge is in hard turning exposed to very high mechanical and thermal loads with mostly continuous (uninterrupted) nature. But, if we consider real time value of uncut chip area and depth of cutting in particular, this process shifts to dynamic one. Additional irregularities of workpiece shape geometry from early process stages , and variations in depth of cut (DOC) resulting from prior tool pass scallops, feedrate, cutting velocity and effective lead angle, along the tool path produce large dynamic force variations. The components with cylindrical shape which are machined on turning machines are also associated with the eccentricity of the workpieces, what might lead to self-exited vibration in any component of lathe. Presence of that kind of vibration can lead to irregularity of machined shape as well as surface damage of machined workpiece. Application of other low removal rate processes (e.g. grinding) suffer of the same problems. To ensure precise and productive (efficient) machining process, vibration has to be controlled and process conditioned without self-exited vibration. In order to reduce or remove presence of sources of process instabilities, especially self-exited vibration, first step is to lower cutting width and cutting feed rate or tool geometry. These limitations implicate lower efficiency of machining process. Besides these consideration related with productivity and quality, vibrations can also lead to increased tool wearing [1] and tool breakage as well. Large tool nose radius ensures better surface finish, but also increases specific cutting energy [2].

Thereby, it is of great importance to become familiar with dynamic behavior of cutting process. If sources and condition which enhance dynamic instability are recognized, it is possible to maximize efficiency of machining process.

Machining of hard components with application of turn-milling process, when higher removal rate are possible to be reached, the appearance of vibrations as a result of process kinematics-variations in the chip-cross section, and especially by the entry-exit condition [3] is still present.

Dynamic instabilities of turning process are also caused by deflections in machining system (machine-tool-workpiece) [4]. The sources of these instabilities can be [5]: machine tool parameters - feed drive instabilities and dynamic behavior of the machine tool; tool parameters - geometrical variations caused with tool wear; workpiece parameters - geometrical deviations (diameter variations) , inhomogenities in workpiece material.

2. Description of the approach and assumptions

Depth of cutting and feed rate are very low in hard turning what implicate very narrow contact zone between tool and workpiece. Cutting edge is over this very short contact length exposed to very high specific pressures and loads. This contact length is dependant on both depth and feed rate values. As shown in Figure 1 tool/workpiece (T/W) contact is mostly within the tool nose radius.

Tool/workpiece contact is within tool nose radius if:

$$a_p \le r_\varepsilon(1-\cos\kappa_r) \qquad (1)$$

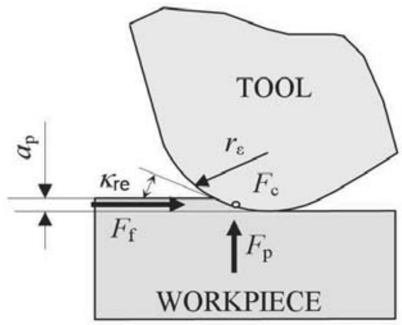

Fig. 1. Schematic presentation of tool/workpiece contact geometry

Table 1.
Conditions when T/W contact is over tool nose radius

r_ε, mm	a_{max}, mm
0.2	0.217421
0.4	0.434843
0.8	0.869686

what for turning condition where CNMA geometry of insert and PCLNR geometry of holder (while κ_r= 97°) are applied, means that depth of cutting is smaller than value given in table 1.

In soft turning, with relatively deep cuts, the effective lead angle is approximately equal to the lead angle κ_r. Otherwise in hard turning, effective lead angle is much more dependant on edge geometry (nose radius), depth of cutting and on feed rate. Therefore, with any variation in depth during cutting or in feed rate, effective lead angle will vary too, Figure 2.

Calculation of this effective lead angle is defined with equation as in [6]:

$$\tan \kappa re=0{,}5053 \tan \kappa r +1{,}0473 (f/r\varepsilon) + 0{,}4654 (r\varepsilon/ap) \qquad (2)$$

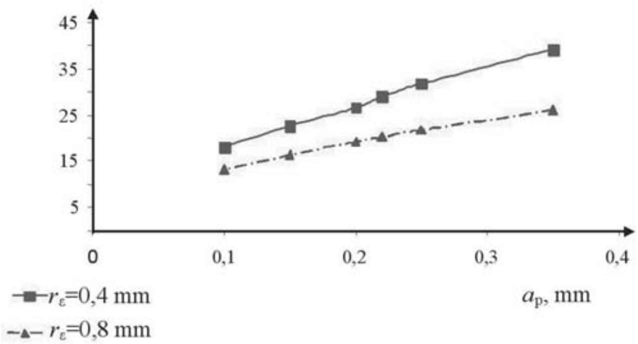

Fig. 2. Influence of DOC on effective lead angle

Lowering the depth, lead angle will decrease (fig 2) and passive force should increase. Passive force is also linearly dependant on depth of cutting what means that it will decrease because of lower depth. This theoretic consideration of dependence between forces and edge geometry is more complicated because of push-off effect (Figure 3) when edge is pushed off for small depth of cutting. This situation results with even narrower tool/workpiece contact and higher surface roughness what is derived by Brammertz (1961) [7]:

$$R_{tB} = \frac{f^2}{8 \cdot r_\varepsilon} + \frac{h_{\min}}{2}(1 + \frac{r_\varepsilon \cdot h_{\min}}{2}) \qquad (3)$$

where $h_{\min}$ is minimal chip thichness for push-off free cutting.

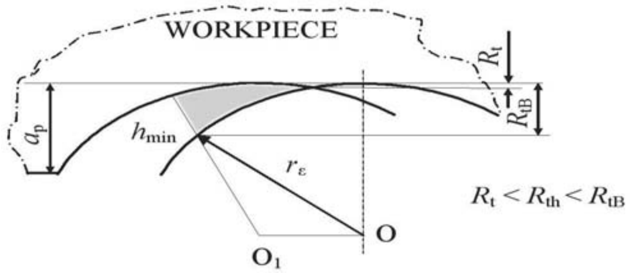

Fig. 3. Surface roughness in accordance with Brammertz (1961) [7]

Surface roughness R_{th} is therefore estimated within R_t and R_{tB}. Variation of cutting force, reported in [8], is a result of a nearly subcritical instability in the amplitude versus width-of-cut plane. Hua at all refere the effect of the finishing process on the subsurface residual stress profile related to cutting edge geometry [9].

3. Results of instability measurements

The dynamic parameters of the machine tool components can be estimate with measurements of acceleration, force, displacement or other data from sensors mounted on machine tool, workpiece or cutting tool. Measurements carried out during free runs of machines validate the condition of machine tool and environmental influence on measurements. Measurements carried out during machining validate interactions between the dynamic characteristics of machine tool, tool material and workpiece material. Various methods have been used to evaluate signal data including signal analysis (Fourier transformations - FFT) neccesary to make decision upon the process stability/instability, and observation of workpiece surface finish. Data from forcemeter and accelerometer were analyzed in our tests.

3.1. Natural frequency and damping of system

Identification of dynamic influences of irregularities on machining surface and measurement of dynamic parameters of machining system (workpiece, tool, tailstock, slideways, compound rest saddle, carriage and chuck) was performed. Different types of sensors were intended for such identification and different levels of measuring precision and parameters to be controled were analyzed by Lee and Dornfeld (1998) [10].

In our experiments, we have used accelerometer sensor Hottinger and Baldwin Messtechnik model B12. Data amplifier was also HBM model CWS-3082A and PC card PCI20428-3A was used as A/D converter. Tests were applied on bar shaped workpiece with diameter of 40 mm. Total distance from tailstock to headstock was 765 mm, and shape irregularities on machined surface were detected at distance of 190 mm from chuck - chattering was clearly emphasized.

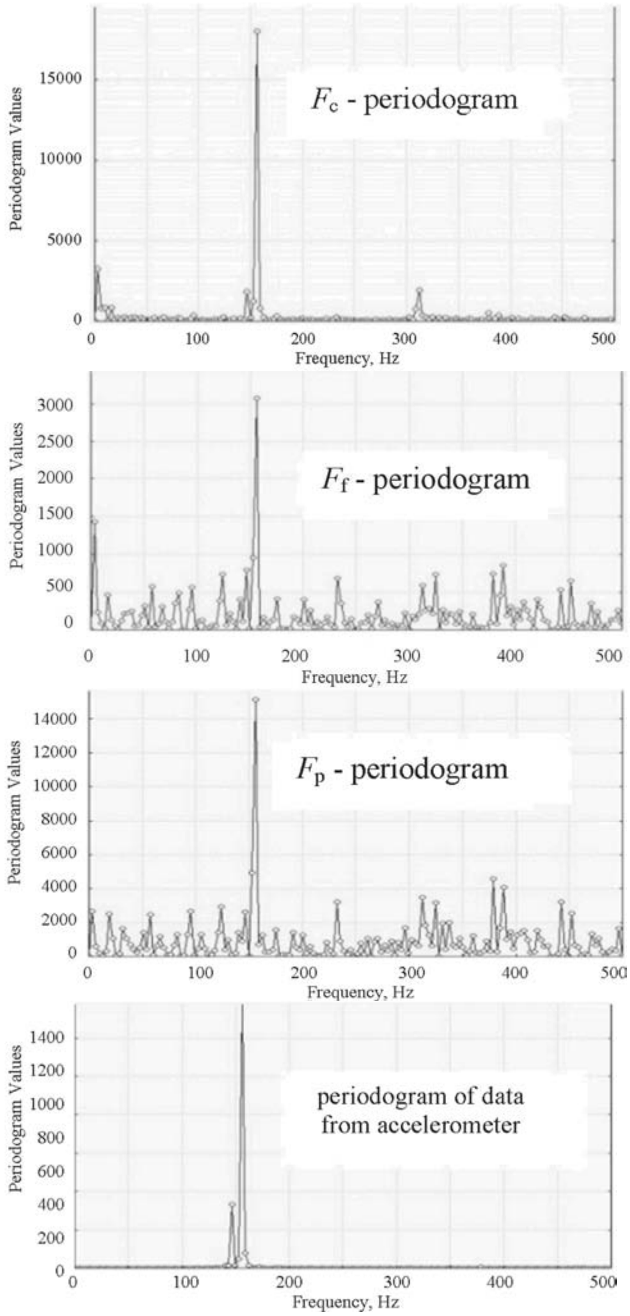

Fig. 4. Signals from accelerometers and force meters after FFT

Real time measured data from accelerometers were analyzed with software MATLAB to obtain natural frequencies and damping of machine tool components (shown in Table 2).

During the experiments, emphasized irregularities are noticed on machined surface on the location on which appears resonance. Natural frequencies of slideways and workpiece have the same value on this location. Very large amplitudes of signals in frequency domain, close to the natural frequency of the dominant mode, were derived also in [11], while this resonance is linked only with revolution frequency.

Figure 4. shows cutting data signals from force meters and accelerometers with prominent peaks on certain frequencies. First peak correlates with natural frequencies of workpiece, and therefore this value have dominant effect on dynamic behavior during machining. Similar findings were pointed out by Khanfir [12].

FEM modeling and frequency analysis

In order to validate experimental results, finite element analysis is performed and ANSYS software [13] was used. Workpiece was modeled as beam element, and cutting tool was represented with combined elements that include spring rigidity and damping [14]. Both supports are considered as elastic with high rigidity to include backlash in chuck. The FEM analysis results are shown in Table 3. Natural frequency data for one elastic support, including contact with cutting tool corresponds (shadowed cell in table 3) with frequency periodograms peaks shown in Figure 4. Mahdavinejad (2005) [15] in reports that natural frequency is related to certain component.

3.2. Importance of DOC value for cutting stability

To check depth of cutting variation over time, model of tool/workpiece interface was made (shown with valley in Figure 5), and DOC $a_{min}<a<a_{max}$ was calculated in different valley position according to previous tool pass (p≥0). This calculated DOC variation in Hard turning is in the range of 60% (Figure 6), while in soft steel turning this value is about 10%. This significant difference is related primary with length and geometry of contact between tool and workpiece. For Hard turning this contact length is multiple smaller. Depth variation in hard turning could be slightly lower 25-30% (for higher nose radius of priore tool pass, and for smaller feed rate), and slightle higher 10-15% (for other p values).

This DOC variation can be recorded also by forces measurement. As shown in Figure 7, passive force *F*p is the most sensitive on DOC variation and as a result *F*p force variation over 70% can be established [16]. This value is close to the previous consideration (60% variation of DOC), and confirm assumed facts on dynamic behavior of depth of cutting.

Table 2.
Natural frequencies of parts of lathe TNP 160A

Object	Frequency, Hz
Chuck	315
Tailstock	277
Slideways	163
Saddle	226
Headstock	326

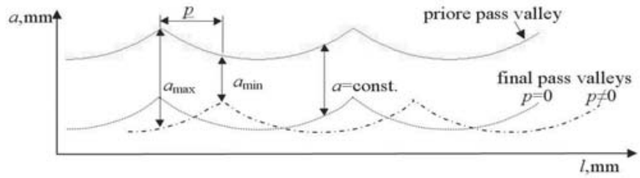

Fig. 5. Parameters for interface modeling and DOC computing

Depth variation in hard turning could be slightly lower 25-30% (for higher nose radius of priore tool pass, and for smaller feed rate), and slightle higher 10-15% (for other p values).

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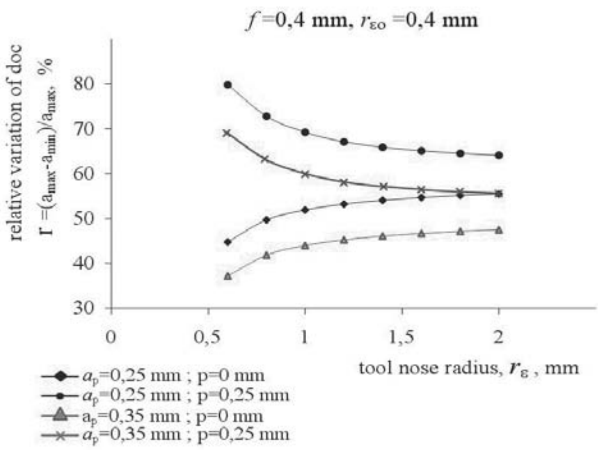

Fig. 6. Variation of DOC during hard turning

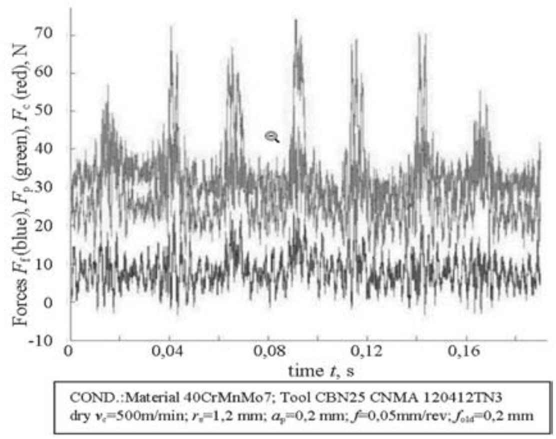

Fig. 7. Cutting forces data

Force signals in frequency domain (signal data shown in Figure 7) shows peaks only in the range below 2 kHz (observed range was up to 40 kHz), and high power peak at the frequency which correspond to frequency when tool is passing over valley peaks of previous pass. On accelerometer signal (sensor was oriented in the same direction as passive force) frequency peaks diverse over range 5 and 45 kHz (with not so high dominant peaks at 17 and 31 kHz). This diverse is influenced with cutting speed as well as chip formation and segmentation [17].

Table 3.
Natural frequencies of workpiece obtained by finite element analysis

WORKPIECE	FEM Model :One elastic support, in contact with cutting tool
1. natural frequency	30.8 Hz
2. natural frequency	165.8 Hz
3. natural frequency	224.4 Hz
4. natural frequency	445 Hz
5. natural frequency	728.4 Hz

3.3. Influence of tool nose radius on cutting dynamics

Tool nose radius has, as mentioned above, strong influence on DOC variation, and on lead angle what implicate cutting dynamics. It seems reasonable to verify influence of nose radius on cutting dynamic in frequency domain.

During the turning of heat treatable steel (Č1431 HRN C.B9.021 or Ck 35 DIN or C35E EN WNr1.118 ; hardness HRC=50 +- 2) with cutting inserts (CBN, geometry CNMA 1204 TN3) the resulting acceleration of tool holder in X-axis were measured.

The concept and arrangement of measurements is shown in Figure 8. One can see from Figure 8 that direction of accelerometer sensitivity is coincided with direction of passive force in X-axis. It is also evident that the applied CNC lathe (Mori Seiki SL-153) has a relatively large revolver head where our experimental tool holder with accelerometer at one end and with cutting insert (geometry CNMA 1204 TN3) at another end was fixed.

As shown in Figure 8 the useful length of a test workpiece (heat treatable steel Ck35 E) was slightly less than 350 millimeters. This length was divided into several sections and for each two neighboring sections machining was performed under the same conditions (the same cutting parameters). For each section 10 single signals for acceleration in X-axis were recorded and after that transformed and averaged in frequency domain. Thus, the presented results are average spectra of 10 single spectra, obtained with discrete Fast Fourier Transformation. Sampling frequency during the signal recording was 100 kHz and number of discrete points was 8192. According to relations between sampling frequency, number of discrete points and time of recording, the latter was 0.08192 s. This means that frequency resolution of average frequency spectra was approximately 12.207 Hz .

Figure 9 shows the effect of nose radius (r_ε) on accelerometer data signal. One can see that smaller r_ε means higher amplitudes, in general. The analysis of the effect of nose radius shows that the amplitude peak at 4 kHz is inversely proportional to the nose radius r_ε. Therefore, one can conclude that the amplitude peak at 4 kHz is a reliable criterion for identification of cutting nose radius.

From Figure 9 one can see that there is an additional prominent peak at 10 kHz, however its amplitude is higher for larger nose radius, which is not in agreement with conclusions from the first amplitude peak (see above). Therefore, it is reasonable to conclude that only the first resonant peak has physically logical meaning: Smaller nose radius results in smaller tool holder stability (stronger vibrations) at this frequency in comparison to larger nose radius.

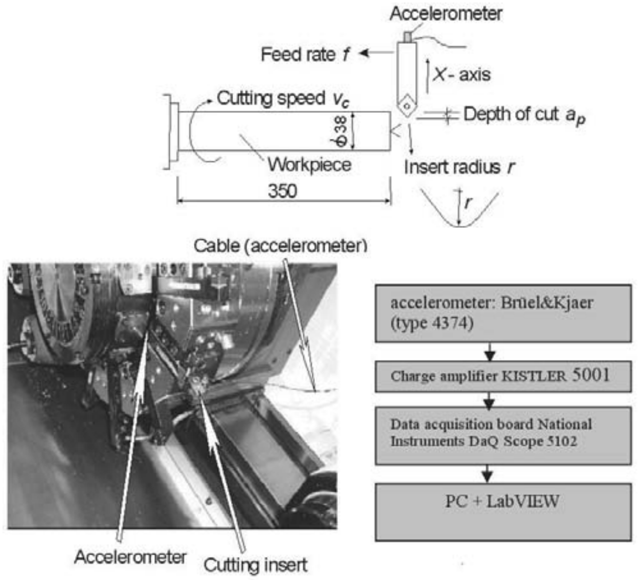

Fig. 8. Testing of significance of nose radius on dynamic characteristics of hard turning

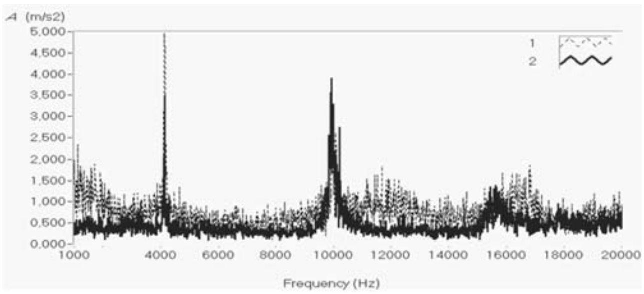

Fig. 9. The influence of tool nose radius on acceleration data, v_c = 450 m/min, a_p =0.2 mm, f =0.2 mm/rev (1- r_ε =0.4 mm, 2 – r_ε =1.2 mm)

3.4. Influence of cutting speed on cutting dynamics

The effect of cutting speed on accelerometer signals is shown in Figure 10. It has to be noted that in this figure because of practical reasons the amplitudes at frequency 4 kHz are not completely presented. Namely, for cutting speed 550 m/s the real values of amplitudes acceleration at 4 kHz are approximately 100 m/s^2.

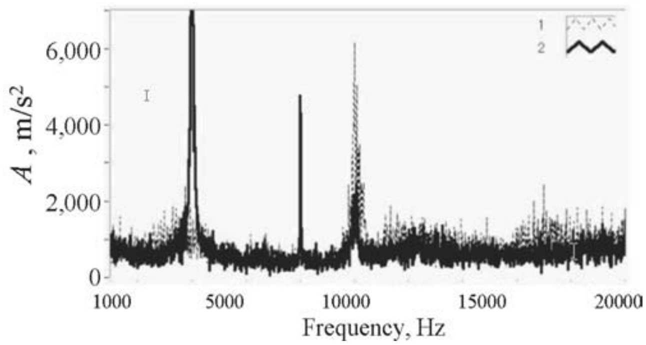

Fig. 10. The influence of cutting speed on acceleration data, r_ε =0.4 mm, a_p = 0.2 mm, f = 0.1 mm/rev (1- v_c = 450 m/min, 2 – v_c = 550 m/min)

The above conclusions from the analysis of the effect of insert radius can be directly applicable in the following analysis of the effect of cutting speed. Under the given circumstances the larger amplitude at this frequency corresponds to the higher cutting speed. In addition, it is interesting that the increase in cutting speed from 450 to 550 m/s results in excitation of second resonant peak of system machine tool – workpiece – tool at 8 kHz (see Figure 10) which is obviously the second harmonic component of 4 kHz. This is not surprising because it is reasonable to expect that higher cutting velocity is related to higher energy input into the system machine tool – workpiece – tool. Consequently, this results in higher amplitudes of vibrations for the corresponding amplitude peaks. For acceleration, another conclusion is that the amplitude of the peak at 10 kHz is inversely proportional to that one of 4 kHz. Thus, if the amplitude at 4 kHz is relatively high then the amplitude at 10 kHz is relatively low, which can most probably also be used in identification of process parameters.

3.5. Influence of cutting parameters on surface roughness

Assumptions of cutting parameters influence on surface roughness (explored in heading 2) especially in push-off effect were experimentally verified.

Tests were performed on CNC turning machine Boeringer, main power 7,5 kW, n_{max} 4000 min^{-1}. Test sample was tightened into chuck and supported with tip cone. Cutting tool was CBN 25, with geometry CNMA 1204__** TN3 (** - depending on tool radii). Tool was nested into holder PCLNL 2525M12 - MED25100. Roughness was measured with table type device PERTHOMETER S8P 4.51 with head feeding into range 1,5-60 mm. Accuracy of head feeding was 0,2 µm/60 mm, referent profile length l_e=0,8 mm and observed length l_m=4mm (DIN 4762). Used filter had 75% filtering. It were measured values of *Ra* (DIN 4762, DIN 4768 and ISO 4287/1) and *Rmax* (DIN 4768).

Identification of influence was done with four independent (input) variables : cutting speed (v_c), depth of cutting (a_p), feed (f) and insert radius (r_ε). Preliminary tests were carried out to determine suitable parameter range. Max. possible speed in our condition was 2500 m/min but at speeds higher than 800 m/min tool wear was too high and therefore two speed level were adopted (450 and 600 m/min). Depth of cut and feed were, because of physical properties of material, kept low (f_{min}=0,1 mm, f_{max}=0,2 mm, $a_{p\ min}$=0,2 mm and a_{pmax}=0,35 mm). Insert radius r_ε was varied between range 0,4 and 1,2 mm. Experiment design was central composite design 2^4 with 32 measurements (8 measurements in centre). All the experiments were conducted without cooling.

Two output variables were measured to indicate surface roughness (*Ra*, *Rmax*) and results are given in table 4. After the regression analysis was done, mathematical models (4 & 5) as output functions were obtained.

The analysis of the experimental data starts with an analysis of variance, which shows a significancy of influence of the machining parameters and their interaction on the measured value. After that, extended analysis of variance was made to give information about the polynomial effects of input variables (cutting parameters) on measured values. The significancy level of 5% provides information about what polynomial element in equasion will take a part in mathematical model.

One can say that there are several criteria (ecological, feasibility, etc.) which can be analyzed; e.g. passive component of cutting force could be an on-line indirect indicator of the machined surface quality; the higher the force (consequence of higher productivity rate during cutting) the lower the quality. But there is no well known uniform dependence force vs. roughness vs. productivity. It is also well known that economical goal of the fine cutting process is achievement of acceptable roughness with higher productivity. Figure 11 shows that demanded surface roughness lower the productivity (by means of feed rate), but also that there is optimal depth of cut which result with smallest surface roughness. This relation of surface roughness and DOC confirm the theoretic consideration of both effects given in heading 2 (DOC influence on lead angle and push off effect). This optimal value of DOC is of great interest for technologists during regime determination.

$$Ra = 4,829001 - 0,006326\,v_c - 7,280413\,a_p + 1,554342\,f - 3,567335\,r_e + 4,314476\cdot10^{-6}\,v_c^2 + 15,833074\,a_p^2 + 20,124416\,f^2 + 1,776459\,r_\varepsilon^2 \quad (4)$$

$$Rmax = 22,90518 - 0,031697\,v_c - 40,28705\,a_p + 12,75832\,f - 14,26172\,r_\varepsilon + 0,000023\,v_c^2 + 89,81484\,a_p^2 + 43,083389\,f^2 + 7,466528\,r_\varepsilon^2 \quad (5)$$

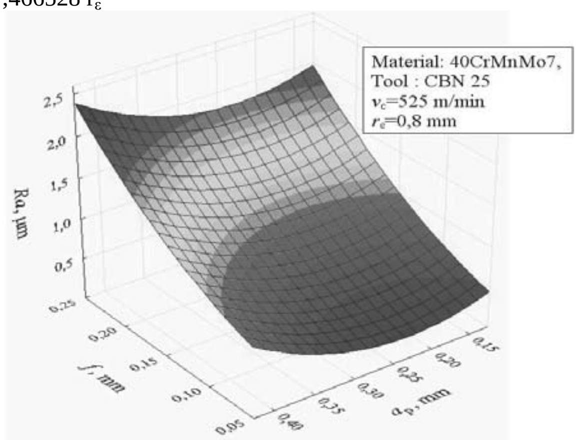

Fig. 11. The influence of cutting speed on acceleration signals

Table 4.
Roghness measurement results

Red br.	v_c, m/min	a_p, mm	*f*, mm	r_ε, mm	*Ra*, µm	*Rmax*, µm
1.	450	0.2	0.1	0.4	1.22	6.02
2.	600	0.2	0.1	0.4	0.96	4.9
3.	450	0.35	0.1	0.4	1.44	7.38
4.	600	0.35	0.1	0.4	1.77	6.27
5.	450	0.2	0.2	0.4	2.03	8.65
6.	600	0.2	0.2	0.4	1.76	7.54
7.	450	0.35	0.2	0.4	2.24	10.02
8.	600	0.35	0.2	0.4	1.97	8.91
9.	450	0.2	0.1	1.2	0.69	4.34
10.	600	0.2	0.1	1.2	0.42	3.23
11.	450	0.35	0.1	1.2	0.9	5.71
12.	600	0.35	0.1	1.2	0.63	4.6
13.	450	0.2	0.2	1.2	1.49	6.98
14.	600	0.2	0.2	1.2	1.22	5.86
15.	450	0.35	0.2	1.2	1.71	8.34
16.	600	0.35	0.2	1.2	1.44	7.23
17.	375	0.275	0.15	0.8	1.37	6.92
18.	675	0.275	0.15	0.8	0.65	3.96
19.	525	0.125	0.15	0.8	0.96	5.1
20.	525	0.425	0.15	0.8	1.39	7.83
21.	525	0.275	0.05	0.8	0.35	2.44
22.	525	0.275	0.25	0.8	1.69	7.31
23.	525	0.275	0.15	0.4	1.44	6.79
24.	525	0.275	0.15	1.2	0.51	3.52
25.	525	0.275	0.15	0.8	0.89	4.65
26.	525	0.275	0.15	0.8	0.9	4.72
27.	525	0.275	0.15	0.8	0.89	4.67
28.	525	0.275	0.15	0.8	0.91	5.06
29.	525	0.275	0.15	0.8	0.87	4.58
30.	525	0.275	0.15	0.8	0.88	4.63
31.	525	0.275	0.15	0.8	0.89	4.7
32.	525	0.275	0.15	0.8	0.88	4.66

4. Conclusions

An approach for identification of dynamic instability in hard turning process has been presented in this paper. This approach is based on determination of natural frequencies of machine tool components on different positions in work area and position of resonance frequency determination. Experimental results confirme that the resonance is located on position where several machine tool components oscillates with the same frequences. It was found DOC variation over time, by tool/workpiece interface modeling and confirmed with passive force measurement. DOC variation is specific and of big relevance for processes where short contact length between tool and workpiece is present. Under the given circumstances the amplitude peak at 4 kHz is a reliable criterion for identification of cutting nose radius and cutting speed influence, and acceleration amplitude at this frequency was inversely proportional to the tool nose radius r_ε. The results indicate the importance of DOC rate and its instability on surface roughness. Test results suggested that it is possible to achieve minimum roughness on machined surface if cutting instability and push off effect do not have dominant influence. Technologically, for hard turning, it means that DOC in final pass should not be as smaller as possible. Exerimental results and numerical modelling predict and shows a great potential in improving the efficiency and quality of hard turned parts. The achievements can be employed to increase productivity by guiding the judicious choice of cutting conditions and tooling geometry, and/or by regulating the spindle speed.

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