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Turning conditions of Ck 45 steel with alternate hardness zones

A. Stoić [a], J. Kopač [b,*], T. Ergić [a], M. Duspar [a]
[a] Faculty of Mechanical Engineering, University of Osijek,
Trg I. B. Mažuranić 2, 35000 Slavonski Brod, Croatia
[b] Faculty of Mechanical Engineering, University of Ljubljana,
Aškerčeva 6, 1000 Ljubljana, Slovenia
* Corresponding author: E-mail janez.kopac@fs.uni-lj.si

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ABSTRACT

Purpose: of this paper is investigation of dynamic impacts on cutting edge during machining of locally hardened steel. Alteration of hardness on a single work piece is a source of impact on tool, which could lead to breakage of cutting tool and work piece surface damage in turning. Influence of material properties (primary hardness) is important when work piece is hardened locally by induction and part of material is soft annealed.

Design/methodology/approach: Experimental tests of cutting outputs have been done on specimens after induction hardening to evaluate the rate of variation of cutting forces, surface roughness and chip formation because of hardness alteration. Measured data of main cutting force were analyzed in frequency and time domain.

Findings: It was found that chip formation condition, chip thickness and chip shape depends on cutting forces alteration in transition areas in the range of 10 to 15%. Much higher alteration of force signal is recorded when machining is performed with low depth of cutting value as a result of backlash in system. The most important value of cutting force correlates with depth of cutting, and roughness correlates oppositely to the hardness.

Research limitations/implications: Results and findings presented in this paper are qualitative and might be slightly different in other cutting condition (e.g. other heat treatable steels or other hardening techniques or other single cutting point processes). There is evident force value alteration in the transition (hard to soft state) zone.

Practical implications: Surface roughness is a consequence of both cutting impacts and of tool/work piece loading condition.

Originality/value: Originality of the paper is in analysis for stability of turning to heat treatable steel influenced with alternating work piece hardness. It was recorded edge loading shock overcome from hard to soft machining. It was recorded and analyzed self-exited vibration. A new type of chips: horseshoe-type was found.

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

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1. Introduction

Work piece hardness as a mechanical property influencing energy consumption, tool wear and type of chip formation (continuous type of chips for soft materials and segments - saw typed for hard materials) is very important parameter of machining. Well selection of cutting conditions when hard materials are machined with conventional processes is of great interests for scientists and experts. Cutting process of hard materials with single point tools on lathe encompasses a relatively wide range of applications and wide range of work piece hardness values (from 45 to 70 HRC). Cutting edge is in hard turning exposed to high mechanical and thermal loads with mostly continuous (uninterrupted) nature. The components turning process with cylindrical geometry are locally hardened and machined later on, associated alternated cutting conditions which arise as a result of different hardness over the work piece. The variable conditions of cutting might lead to self-exited vibration in any component of lathe. Presence of that kind of vibration can lead to irregularity of machined surface geometry, as well as surface damage of machined work piece and tool breakage.

The most investigation of machining condition for high hardness work pieces has been conducted with turning tests. El Wardany et al. [1] have been investigating the effects of cutting conditions and tool wears on the chip formation mechanism in the hard turning of D2 tool steel. It was found that the saw toothed chip will only be formed when the cutting pressure in the direction of cutting speed exceeds a value of 4.000 MPa. Yallese et al [2] investigated the behavior of a CBN tool during hard turning of 100Cr6-tempered steel. Experiments were conducted to the study of tool wear, surface roughness, cutting forces and temperature changes in both the chip and the work piece. When cutting speed is beyond 280 m/min, the machining system becomes unstable and produces significant sparks and vibrations after few minutes of work. In the hard turning of D2 tool steel, Elbestawi et al. [3] indicated that the formation of saw-tooth chips could be related to the cutting force variation that reduces tool life. Poulachon and Moisan [4] have been investigating the relationship between the chip geometry and cutting conditions in the turning of 100Cr6 steel with five hardness values (180 to 720 HV). Saw-tooth chips type will occur if hardness value of work piece is over 402 HV. Özela et al. have been investigated surface finishing and tool flank wear in finish turning of AISI D2 steels (60 HRC) using ceramic wiper (multi-radii) design inserts [5]. Elbestawi et al. [6] Investigated the effects of different process parameters on the tool performances and the surface finish of H13 tool steel with hardness values of 45 and 55 HRC. The average cutting force was found to be much smaller for the 55 HRC tool steel than for the 45 HRC. The effect of cutting parameters (speed, feed rate and depth of cut) on cutting forces and surface roughness in hard turning of MDN250 managing steel using coated ceramic tool has been investigated by Lalwani et al. [7]. The results show that variations of cutting forces (feed force, thrust force and cutting force) are best fitted with a linear model dependence of cutting forces with feed rate and depth of cut. Depth of cut has the most dominant effect to the all three-force components, and in addition it interacts with feed rate. A non-linear quadratic model best describes the variation of surface roughness with the most significant parameter: feed rate and secondary depth of cut.

The cutting forces obtained in cutting soft steels are relatively high and decrease as the hardness increase. When the hardness exceeds 50 HRC (saw-tooth type of chips), the cutting forces suddenly increase. The force is lower when machining at higher cutting speed, when the energy consumption was higher. Variation of cutting force, refereed in [8], is a result of a nearly sub critical instability in the amplitude versus width-of-cut plane. Hua refers at the effect of finishing process on the subsurface residual stress profile related to innovative geometry [9]. Besides these considered relations with chip formation mechanism, vibrations of system components can also lead to increase tool wear [10] and tool breakage as well. The advantages of machining hard components with application of tangential turn-milling process, with higher removal rate are investigated by [11] with the normally available range of speed and feeds. The investigations have been mainly focused on surface roughness and timing process, while influence of cutting depth, feed rate and cutting speed considered Savas&Ozay [11].

The unstable cutting due to chatter vibration is one of the main limiting factors for improvement of productivity and worpiece quality and leads to economic losses. The prediction of stability limit and run the cutting process in condition close to the stability limit is absolutely necessary [12]. The sources of these instabilities can be [13]: machine tool parameters - feed drive instabilities and dynamic behavior of the machine tool; tool parameters - geometrical variations caused with tool wear; work piece parameters - geometrical deviations (diameter variations), in-homogeneities in work piece material.

2. Description of the problem

The sources of inefficiency during the manufacturing of relatively large diameter products incorporating the locally heat treated zones over the surface to be machined are: the alteration of mechanical properties of work piece (primary hardness), backlash of machining system and cutting regime.

Hard turning conditions (relatively small values of cutting speed and chip area in cross section, federate and depth of cutting) are favourable for disturbances, and are recognized by some other machining processes and not by conventional turning. Cutting insert is in hard turning exposed to cyclic loading conditions, which arise because of variation of uncut chip area and hardness in particular. Variations in depth of cut (DOC) because of prior pass valleys, feedrate, push–off effect, cutting speed and effective lead angle, along the tool path produce force variations and induce process disturbances.

The current method of producing e.g. bearing races surfaces involves annealing, rough turning, hardening (2 mm in depth on 56 +3 HRc) and hard turning. A technological problem, which disturbs hard machining, called hot spot (after induction hardening there is an arch length on surface of some tenth of mm with high hardness drop 750 to 200 HV), which is one source of load impact on cutting tool. Bearing rings are produced of Ck45N steel and in our case mounted on a heavy-duty machines (lifts, bulldozer, loader etc.). Chemical content and mechanical properties of steel are: content of C 0.42 – 0.5 %; contents of Mn 0.5 – 0.8 %; Si 0.15 – 0.35 %; P, S 0.35 %; hardness max. 207 HB (217 HV); yield strength $Rp_{0.2}$ – 420 N/mm^2; tensile strength 670 – 820 N/mm^2.

In the preliminary machining tests before the rings production started, both carbide and ceramic inserts were used. Big disadvantage of carbide insert is the decrease of hardness at high temperatures, while this problem is mainly annulated with ceramic inserts specially if it is improved with TiC, Ti(C, N),ZrO_2 and TiB_2 [14]. It is known that hardness of carbide inserts fails at higher temperature while ceramic material posses high melting point. When using ceramic cutting inserts, the cutting speed is increased, the processing is performed without coolant, and hereby-demanded quality of ring race surface is achieved.

During the preliminary tests, some types of ceramic inserts were broken. The reason for this breakage, we searched in impacts of the tool. Since the work piece has been pre-machined before hardening, there were no geometrically induced impacts on tool. The other reasons of impacts and breakage of tool could be associated with mechanical properties of work piece or weak rigidity of machine tool. Both of these possible impact sources were analyzed.

Considering the earlier phases of production, properties of work piece material have been changed with induction hardening. The main feature of induction heating is the transfer of heat directly from tool into the processed material. With the conventional procedures of heating, a heat flow is in the range from 0.5 to 20 W/cm^2, and with the induction tempering it measures from 10000 to 30000 W/cm^2.

Hardening process is performed to increase the life bearings and reduce its wear. After the process of induction hardening has been carried out, there is a soft spot left on the processed material due to technical reasons of conducted induction hardening with small tools. This hot spot on surface appears because hardening process on the circle has starting and end point. These starting and end point are the locations where hardness value alternates (Fig. 3). The hardness testing procedures have been carried out along the work piece material surface (conducted surface hardness tests by Vickers's method HV30) and radial (into the depth of the processed material by Vickers's method HV1), after the hardening. The aim of the preliminary hardness testing is to determine the differences in hardness of the soft and the hardened zone left on the processed material after the hardening induction.

Fig. 1. Hardening of inner ring race [15]

2.1. Surface hardness

Determination of hardness distribute along the machined surface of bearing race is primary performed for better prediction of exploitation life of bearings. Measuring data are also of relevance for hard machining condition determination. Surface hardness of the race measured a universal device for hardness testing (Brinell, Vickers, Rockwell), on the test sample Fig. 2. Substantial hardness deviation on the spot of 500 HV over the length of 30 mm is clearly visible on Fig. 3.

The following findings after the preliminary tests can be pointed out:

1. The measuring data of the surface hardness showed the significant decrease of hardness in the amount of 500 HV at the distance of cca. 30 mm. When the cutting tool is passing over the soft zone, the cutting insert is more inclined and penetrates "easier" into material due to lower thrust force. Passing over hardness transiting zone, cutting edge is exposed to higher dynamical stresses, which are transferred to the holder, as well as to the other parts of the machine. The expected result is higher radial deviation holder and free movement of backlash between the slide-ways and tailstock.
2. The achieved effective depth of the hardened layer does not fulfill the requested demand for hardness 56 +3 HRC at the depth of 2 mm. The reason for this could be the incorrect choice of hardening parameters. The expected result is the decrease of the hard layer depth as well as decreased bearing life.

Fig. 2. Outer bearing ring test sample

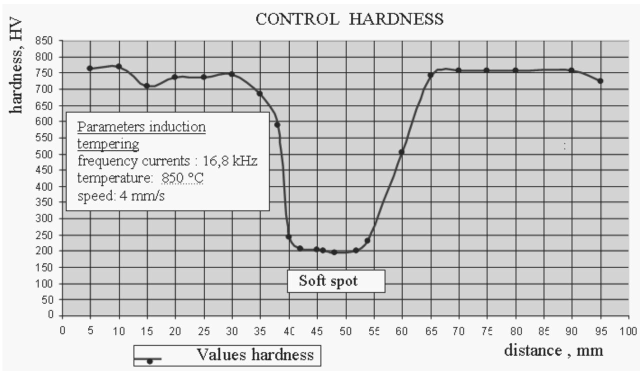


Fig. 3. Hardness profile of outer ring

3. Design of experiment

Experimental tests were conducted on the test sample produced of the same work piece material Ck 45 steel. The geometry of test sample is the bar with two diameters, shown in Fig. 4. Test sample was locally (approx. one quarter of magnitude) induction hardened (Fig. 5) to achieve alternate hardness over the cylindrical surface, which will be turned.

Tests were performed on turning machine TNP 160 A Prvomajska, main power 2.2 kW, n_{max} 4000 min^{-1} . Test sample was tightened into chuck. Cutting tool was carbide, with geometry CNMA 120404. Tool was nested into holder PCLNL 2525M12 - MED25100.

Influence of three input parameters of cutting regime during the experiment was observed (shown in Table 1):

Table 1.
Natural frequencies of components of lathe TNP 160A

Parameter/value	Minimum	Average	Maximum
No. Of revolution *n*, min^{-1}	560	800	1120
cutting depth a_p, mm	1	2	3
average hardness *HV 30*	270	-	640

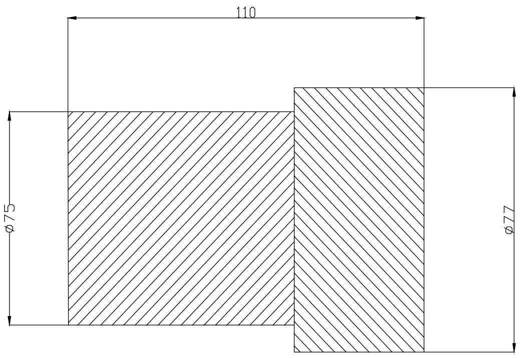


Fig. 4. Geometry of the test sample

Performing induction-hardening process, starting and stopping location of treatment is identified on surface as location with significantly smaller hardness – soft zones.

3.1. The results of machine tool stability measurements

The dynamic parameters of the machine tool components can be estimated with measurements of acceleration, force, displacement or other data from sensors mounted on machine tool, work piece or cutting tool. Measurements carried out during free runs of machine 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 work piece material. Various methods have been used to evaluate signal data including signal analysis (Fourier transformations - FFT) necessary to make decision upon the process stability/instability, and observation of work piece surface finish. The input signal in our tests is recorded with the data acquisition board. Signal data from force meter and accelerometer depends on time. The discrete amplitude spectrum S' (mΔf) of the recorded noise was calculated with the Fast Fourier Transform (FFT) technique:

$$S'(m\Delta f) = \frac{T}{N}\sum_{n=0}^{N-1} f(n\Delta t)\cdot e^{-j2\pi mn/N} \qquad (1)$$

Where m=1,2…1/2N; Δf is the frequency lines spacing, T is the time of recording, N is number of recorded data Δt is the time interval between samples, f (n Δt) is a digital value of a record at point n and j is $\sqrt{-1}$.

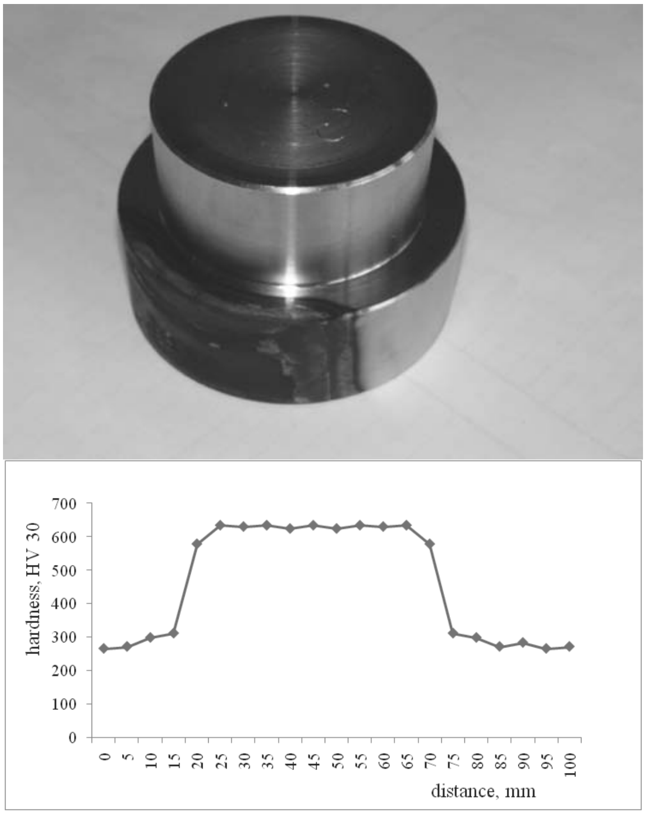


Fig. 5. The test sample after hardening, and the hardness profile

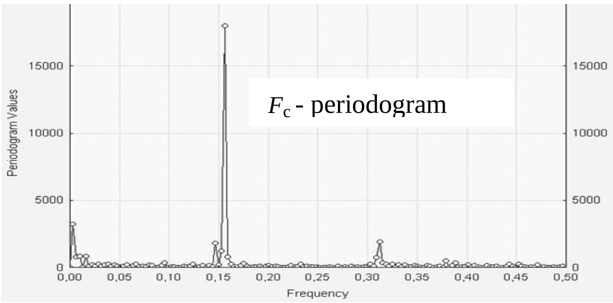
Real time measured data from accelerometers were analyzed with software MATLAB to obtain natural frequencies of machine tool components (shown in Table 2).

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

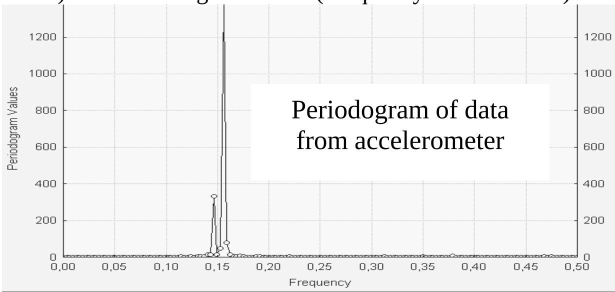
Object	Frequency, Hz
Chuck	315
Tailstock	277
Slide ways	163
Saddle	226
Headstock	326

During the experiments, emphasized irregularities are noticed on machined surface on the location on which appears resonance. Natural frequencies of slide ways and work piece have the same value on this location. Large amplitudes of signals in frequency domain, close to the natural frequency of the dominant mode, were derived also in [16], while this resonance is linked only with revolution frequency.

Fig. 6. shows cutting data signals from force meters and accelerometers with prominent peaks on certain frequencies.



a) Main cutting force data (Frequency values in kHz)



b) Accelerometer data (Frequency values in kHz)

Fig. 6. Signals from accelerometers and force meters after FFT

First peak correlates with natural frequencies of slide ways (obtained with measurement-shown in table 2) and second peak of natural frequencies of work piece (obtain with FEM model-shown in table 3), and therefore this value have dominant effect on dynamic behavior during machining [17].

3.2. FEM modeling and frequency analysis

In order to validate experimental results, finite element analysis is performed and ANSYS software [18] was used. Work piece was modeled as beam element, and cutting tool was represented with combined elements that include spring rigidity and damping [19]. 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 fig. 6. Mahdavinejad in [20] reports that natural frequency is related to certain components.

3.3. The force impact measurement result

Force was measured with three main strain gages (Fig. 7). Strain gages were 10/120 LY11. For signal amplification we used amplifier HBM-KWS-3082 A. As the A/D converter we used Multifunction Board PCI 20428-3A. Force components measurements were performed with new insert. The sample frequency on A/D board was adjusted to 500 samples /second per channel to address the variations of the cutting force components.

Table 3.
Natural frequencies of work piece 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

Input data for force components calculation are gages deformation on three locations (Figs. 7 and 8). Determination of equations for force components calculations is performed on eccentric bar specimen load.

Three force components (F_c – cutting force, F_f - feeding force, F_p- thrust force) are acquired and analyzed in time and frequency domain. Recording period shorter than one second was long enough to point out the transition from hard to soft zone. Two force diagrams are shown in Fig. 9.

During the measurement of cutting force, it is recognised the disturbance (emphesied in Fig. 9-b) visible in the shape of harmonic vibration which is a result of usage of machine tool.

The amplitude of this harmonics is in the all cuting condition (depth of cutting, speed of revolution) determined only on main cutting force which value is constant (F_c= 60 N). The frequency of this harmonics is one half of vibration excitation (Fig. 10).

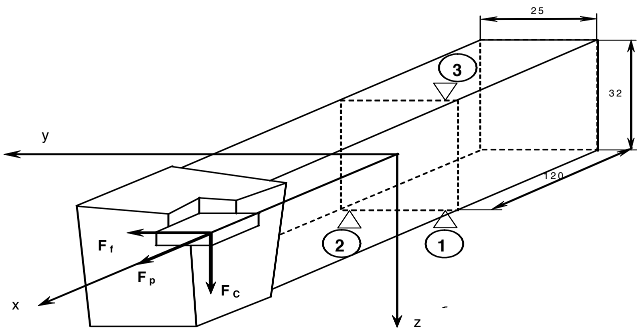


Fig. 7. Strain gages layout

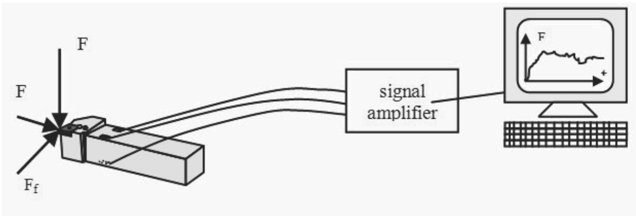
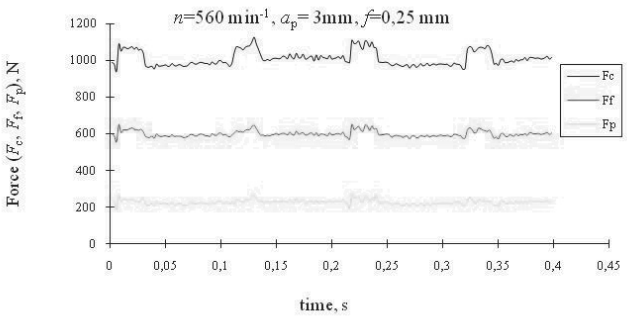
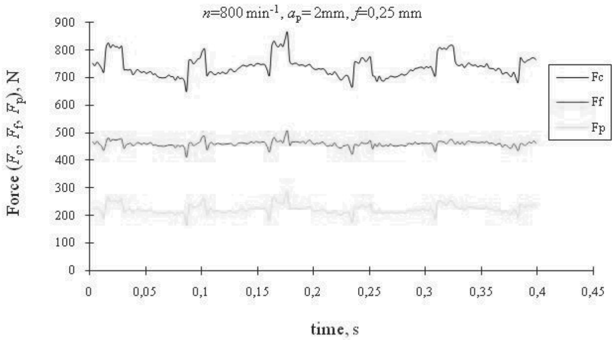


Fig. 8. Force measuring system

The rise of cutting force (F_c) transition from soft to hard cutting (from soft zone to hardened zone) has aproximately the same value for all loading conditions of cutting edge. The relative rise value is cca. 10 % of nominal soft zone loading force, although the hardness alteration (soft to hard) is multiplied by factor 2.5 (from 270 HV30 to 640 HV30- shown in Fig. 5.).



a) result- no. 1



b) result- no. 2

Fig. 9. Force measuring results

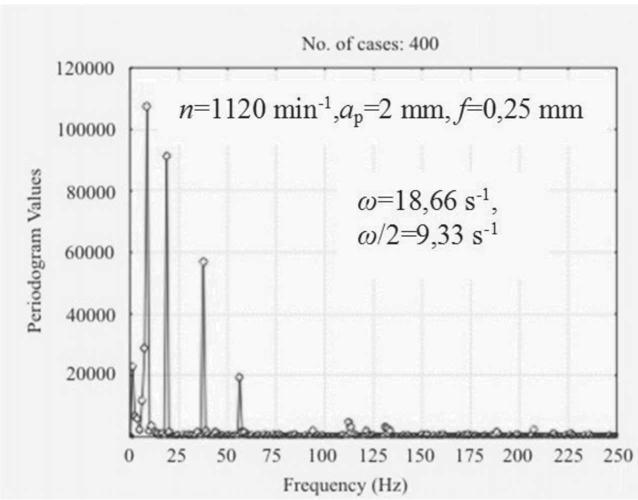


Fig. 10. FFT diagram of force measurement

Measuring data shown on diagram (Fig .11 and Fig. 12) comprises 18 key points measurement, selected from the force diagrams over time (Fig. 9.). These 18 data include three representative revolutions.

The depth of cut is the most influential factor. Influence of cutting depth (ap = 1 ; 2; 3 mm) is significant and visible identified. Cutting force value is proportional to the depth of cutting, and the highest cutting force has been measured by highest depth of cutting (Fig. 11.). When the cut of depth is increased, chip thickness became significant what caused the growth of the volume from deformed metal and that required enormous cutting force to cut the chip. The analysis of some mathematical models from literature confirms that the increase in cutting speed leads to the reduction in cutting forces and the increase in chip section (f×a_p) induces the cutting forces growth. Dependance of cutting force and revolutional speed has not been clearly identified (Fig. 12.).

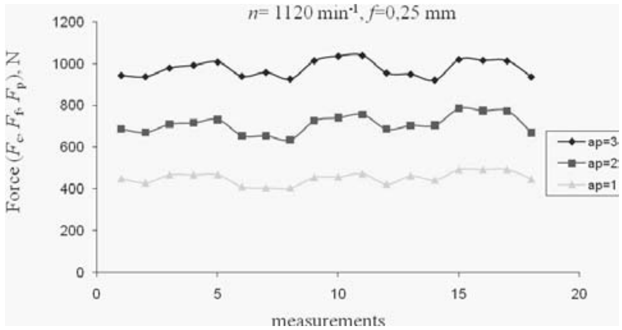


Fig. 11. Force vs. depth of cutting diagram

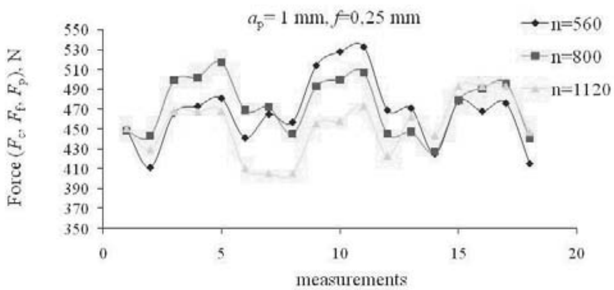


Fig. 12. Force vs. cutting speed diagram

3.4. the results of roughness measurements

The surface roughness of materials finished by turning is determined by the contact geometry of cutting tools and work piece, composing of a tool nose radius and end- and side-cutting-edge angles and the rate of feed. The surface roughness also depends on the depth of cut and the side-cutting-edge angle when a cutting tool of a small nose radius machines it.

The mathematically/geometrical models, confirm that the feed rate is the most influential factor on different criteria of surface roughness. The second parameter that influences the roughness is cutting speed. Effect of the depth of cut on roughness is not very significant. But, in accordance with Brammertz theory and push-off effect depth becomes more significant. Apart from regime influence, hardness of the work piece has also significant influence on the roughness what was confirmed with the results of our measurements (Fig. 13).

Roughness was in our experiments measured with device type SURTRONIC 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 measured values of *Ra*, *Rt* and *Rz* (DIN 4762, DIN 4768 and ISO 4287/1).

We concentrated on the hardness influence on the surface roughness measurement results (Fig 13.). It is evident in figure that roughness of the hard zone is significantly better than that of the soft zone. The results indicate the importance of rate of cutting depth and its instability on surface roughness.

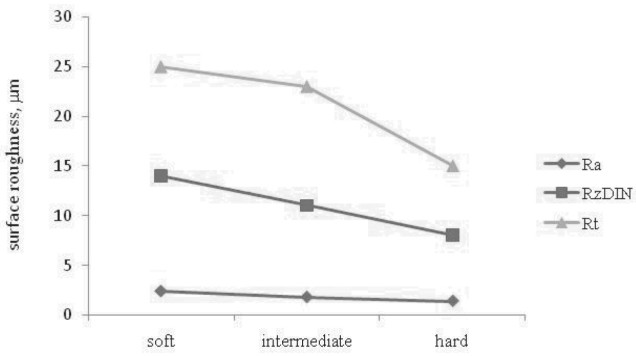


Fig.13. Roughness measuring results

3.5. The chip forms

Chip types in machining are determined by the combined effects of work piece material properties, cutting speed, and tool geometry. The chips produced in each cutting experiment were collected and visually analyzed. The shape of chips looks like horse-shoe (Fig. 14.).

Fig. 14. Horseshoe-type of chips

Generally, the forms of chips are significantly different for soft zone and hard zone. Deformation of chips from hard zone is stronger in comparison with chips from soft zone. Saw-toothed types of chips have been identified in hard zone. Since the length of hardened zone is cca 60 mm, chip has been broken at least once. When there was higher depth of cut, the length of chip correlates with peripheral work piece wheel length.

4. Conclusions

This paper presents the results of the research of machining conditions with heat-treated Ck 45 steel. Heat treatment is in experiment conducted to achieve two hardness zones (640 *HV30* and 270 *HV30*) on surface that will be fine machined after. These two hardness zones usually appear in induction hardening of rotational surface when relatively big work pieces are treated with relatively small heating tool. The experimental results show that all the cutting outputs detect hard to soft zone surface overcomes. Within hard zone, higher cutting and frictional energies are required for the chip shearing and smaller surface roughness as well. The higher cutting energy is connected with the severely deformed, shorter, and thicker chips than obtained for the softer zone. Surface roughness of the hard zone is shown to be considerably better than that of the soft zone at all cutting speeds and is independent of cutting speed, whereas the surface roughness of the softer zone is significantly improved with increasing cutting speed. Depth of cutting influence on surface roughness is identified in hard surface zone turning, where better roughness is achieved for higher depts. Technologically, for hard turning, it means that DOC in final pass should not be as smaller as possible.

The following conclusions can be drawn from force measurement:

- Under the different cutting parameters, the cutting force change with work piece hardness change is in accordance with traditional metal cutting theory. The cutting force has an increasing tendency with the increase of the work piece hardness, but the changing extent is different at the two zones of the work piece hardness. The rise of cutting force (F_c) by transition from soft to hard cutting (from soft zone to hardened zone) has approximately the same value for all loading conditions of cutting edge. The relative rise value is only cca. 10 % of nominal loading force, although the hardness alteration (soft to hard) is multiplied by factor 2.5 (from 270 HV30 to 640 HV30).
- Deformation of chips from hard zone is stronger in comparison with chips from soft zone. Due to its higher ductility, chips of the soft zone are more deformed with the higher chip thickness. The specific shearing energies for the two zones do not reflect as much difference as in their chip compression ratios, which could be explained by the lower yield strength of the soft zone. Saw-toothed types of chips have been identified in hard zone. Since the length of hardened zone is cca 60 mm, chip has been broken at least once. For the higher depth of cut, the length of chip correlates with peripheral work piece wheel length.

Experimental results and numerical modeling of cutting process offers a great potential in improving the efficiency and quality of hard turned parts.

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