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Vibration and displacement analysis during turning of hardened steel

Agata Felusiak [a*]

[a] *Poznań University of Technology, Piotrowo 3, Poznań 61-138, Poland,*

[*] *Corresponding author, agata.z.felusiak@doctorate.put.poznan.pl, tel 690035682*

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ABSTRACT

This paper presents an analysis of the vibrations and displacements of the tool during the turning of hardened steel for various turning parameters. Studies have shown that an increase in feed from 0.1 to 0.35 mm / rev results in an almost two-fold increase in radial displacement of the tool. It has also been shown that the combination of high feeds and high rotational speed of the workpiece causes a rapid increase in vibration in all directions.

KEY WORDS

Hardened steel, displacements, turning, vibration, toolpath

1. INTODUCTION

Modern industry seeks to error minimization, but this cannot be achieved without the knowledge of the processes occurring during turning and their influence on precision. Turning accuracy is the exactness of the object received through the manufacturing process compared to the ideal object assumed by the constructor. Accuracy is influenced by many mechanical mechanisms such as: mechanical vibration, MGFT (machine-tool-grip-fixture-tool) system rigidity, machine tool accuracy, tool accuracy, heat deformation, residual stress [4,1].

Surface shaped during machining is irregular due to the impact of disruptions (vibrations, forces). The tool movement is affected by forces and heat so the tool movement is not parallel to the feed. The shape of a tool path is affected by: thermal properties of cutting tool material and the workpiece material, the rigidity of the MGFT system, the wear intensity of the cutting blade and the elastic deformations. Another cause of the tool path change is susceptibility of MGFT's mechanisms. It causes the tool to move relative to the workpiece, which results in shape errors of the surface[10]. Research shows that the position of the tool relative to the workpiece has a significant impact on the dynamics of the process. This affects changes in the maximum instantaneous forces and can affect milling vibration values and surface roughness[8].

Tool wear cannot be omitted, because it results in a shortening of the cutting edge radially, increasing cutting forces, increasing temperature in the cutting zone and changes in affecting of parameters to cutting force [2]. These factors affect the diameter of the final workpiece and the tool crushing or breaking. Studies have shown that flatness deviation is sensitive to flank wear, regardless of the type of milling process. An increase in the face mill tooth flank wear length leads to a significant increase in the torsional angle of the face mill, and to flatness deviation. Machining accuracy is also affected by the machining parameters used, their increase causes an increase in the flatness deviation [7].

Displacement also affects the durability of the cutting edge, especially made of brittle materials such as ceramic. The higher the displacement values, the greater the probability of cutting edge cracking is. It is particularly disadvantageous to use high feed rates and low cutting

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speeds because then the highest cutting forces occur which cause tool deflection [5].

The occurrence of mechanical vibrations during machining is always a disadvantage, they cause deformation of the workpiece and change in the path of the cutting tool, especially vibrations in the direction of cutting feed. Their intensity depends on the geometry of the cutting edge and on the cutting parameters [6]. Depending on the direction of the vibration, they have different effects on machining. Vibrations perpendicular to the surface have an influence on roughness and the waviness. Vibrations in line with the direction of the velocity vector, cause longitudinal section errors [9].

2. OBJECTIVE, SCOPE AND EXPERIMENTAL PROCEDURES

The aim of the study is to measure and analyse the displacement of the turning tool in the radial direction and the vibrations of the tool during turning the hardened steel, depending on the cutting parameters used.

2.1. Scope of research

The material used in the study was a 46mm diameter shaft made of hardened 100Cr6 steel of 62HRC hardness. It is a bearing steel for the production of roller bearings, shafts, rings, beads and general purpose of bearing needs. Not suitable for work at high temperatures and / or corrosive environments. The chemical composition of steel is shown in Table 1 [11].

Table 1. The chemical composition of steel [11]

element	C	Si	Mn	Cr	Ni	S	P	Cu
percent	0,95-1,1	0,15-0,35	0,25-0,45	1,3-1,65	to 0,3	to 0,025	to 0,025	to 0,3

MC2 Black Alloy Ceramic inserts (Al2O3 + TiC) were used for machining, this material is commonly used for hardened steel processing due to its high hardness, abrasion resistance and low coefficient of thermal expansion. Turning on TUR 560E lathe (Fig. 1).

Fig. 1. Location of displacement sensor

The shaft was turned longitudinally, dry at an unchanged cutting depth a_p = 0.1mm and with variable feed and rotation speed as in Table 2.

Table 2. Cutting parameters used in the tests

Parameter nr	n[rev/min]	f[mm/rev]
1.	900	0,1
2.	1120	0,1
3.	1400	0,1
4.	1800	0,1
5.	900	0,17
6.	1120	0,17
7.	1400	0,17
8.	1800	0,17
9.	900	0,26
10.	1120	0,26
11.	1400	0,26
12.	1800	0,26
13.	900	0,35
14.	1120	0,35
15.	1400	0,35
16.	1800	0,35

2.2. *Methodology of measurement*

Measurements of the turning tool displacement in the direction of the impact force were done by using the Micro-Epsilon optoNCDT 1700 laser displacement sensor. At the same time, mechanical vibration in three directions were measured by a piezoelectric vibration acceleration sensor fasten to the tool. The sampling frequency was equal 16384 Hz. The position of the sensor fix is shown in Figure 1. The diagram of the measurement path is shown in Fig. 2.

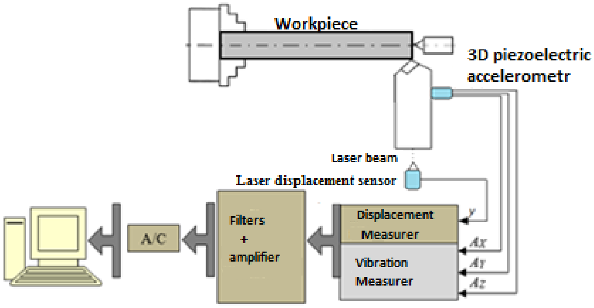

Fig. 2. Diagram of measurement set-up

Movements were recorded by an optical sensor. The working mechanism of the optoNCDT 1700 sensor is based on the triangulation principle (Fig. 3). A visible light spot is emitted by the laser diode on the surface of the measured element. Reflected light is received by the photosensitive element, through the optical system, the photosensitive element detects the position (CCD array). When an object changes its distance from the sensor, the light spot projection visible on CCD array is shifted, the displacement is captured by the sensor electronics. The sensor has a resolution of 0.005% FSO, linearity ± 0.08% FSO and a measurement frequency of 2.5kHz [12].

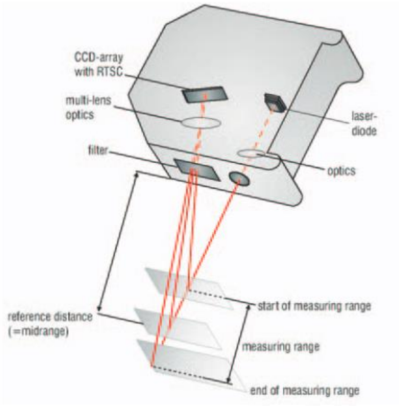

Fig. 3. Mechanism of working of optoNCDT sensor [12]

The signal from the sensor was passed to the voltage meter and then to the analogue-to-digital converter. Based on the graphs of the processed displacement and vibration signals, the RMS values of the vibration acceleration were determined. The displacement was calculated as the difference between the tool position before and after entering the workpiece. A low pass filter fd = 500 Hz was used in the displacement analysis.

2.3. *Measurement results and analysis*

3D graphs are showing the influence of the accepted cutting parameters on the acceleration of the oscillation resistance in the radial direction A_p (Figure 4) in the feed direction *Af* (figure 5) and in the main direction *Ac* (Figure 6). Based on the analysis of the following graphs, it can be said that increasing the cutting parameters (feed rate, cutting speed) leads to vibration increase in all directions. The highest values of vibration acceleration were observed in the direction of the Z axis, which corresponds to the direction of the velocity vector. Particularly unfavorable values, even three times larger than in the other directions, were noted at the highest feed rate, suggesting larger cross section errors with increased feed rate and cutting speed.

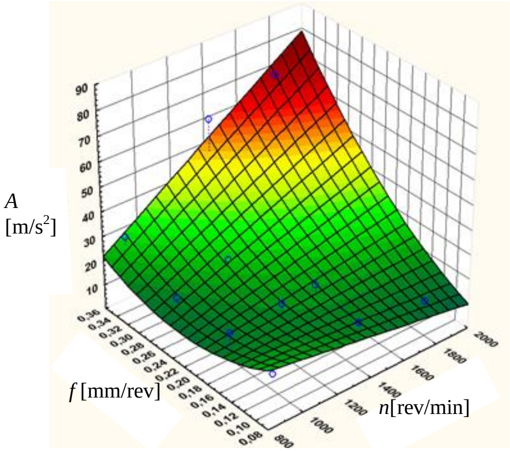

Fig. 4. Vibration diagram in the radial direction

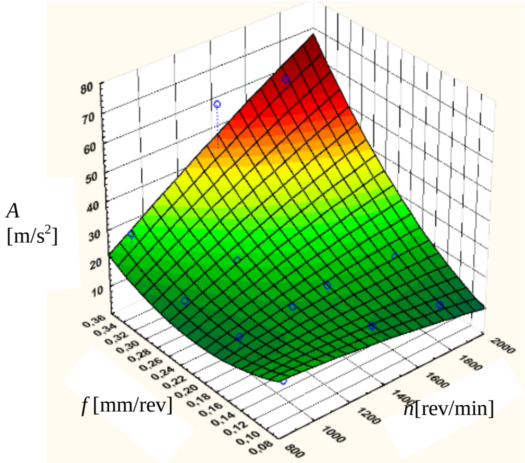

Fig. 5. Vibration diagram in the feed direction

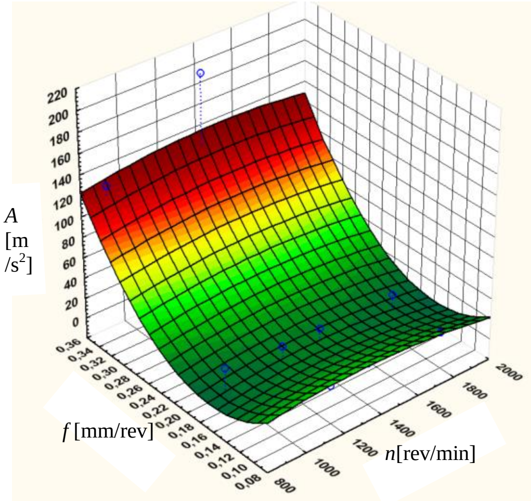

Fig. 6. Vibration diagram in the main direction

As it is shown in graph 6 and less clearly in the other graphs, because of the vibration level it is preferable to use a feed rate of *f*=0.17 mm/rev, since a decrease in vibration acceleration value is visible, the accuracy and the surface quality would be the highest with this feed rate. Vibrations in the main direction are largely dependent on the feed rate and the acceleration of the vibrations in the other directions depend equally on the cutting speed and feed rate. For each feed rate, the highest vibrations in the feed direction occur at the highest speed, and a higher roughness is expected.

It is noticeable from the vibration graph that the application of *f*=0.35 mm/rev is not suitable for ceramic tool because there is a significant increase in vibration acceleration, thus a significant deterioration in product quality should be expected. The graphs shown on figures 7 to 10 are showing the influence of the change of feed rate on the tool displacement values during cutting for different feeds. Fig. 11 shows the effect of the feed value on the amount of tool displacement in the radial direction.

Graphs 7-10 show the moment of the entry of the tool into the workpiece as a rapid decline. In the first case (Fig. 7), it can be seen that the tool gently delves into the material. This is a good situation because of the lack of a rapid load on the tool with the force of resistance and therefore the risk of crushing. As the feed rate increases, the value of the displacement of the tool relative to the object increases (Figure 11), and therefore the errors in the shape of the product are increasing. When the feed rate is increased, the tool insertion point in the material is clearly visible (Fig. 8-10).

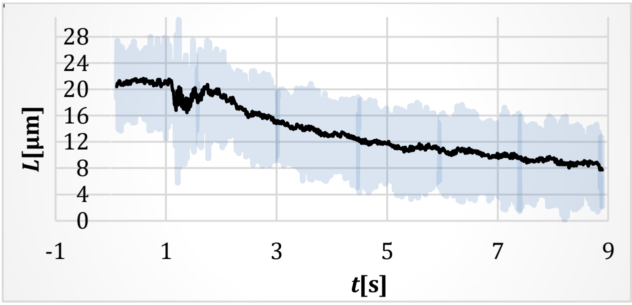

Fig. 7. Displacement graph for turning at a turning speed n = 1400 rpm and feed rate f = 0.1mm / rev

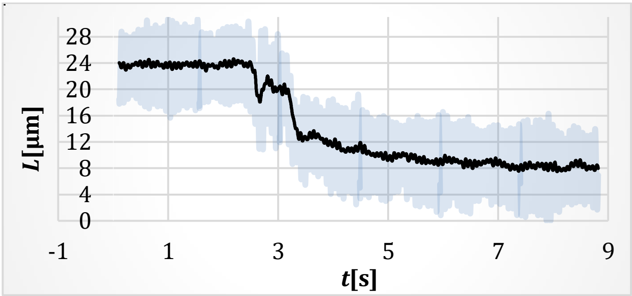

Fig. 8. Displacement graph for turning at a turning speed n = 1400 rpm and feed rate f = 0.17 mm / rev

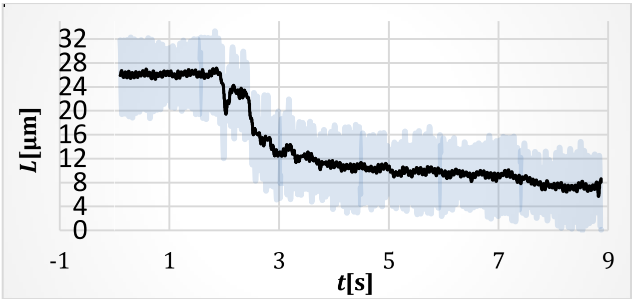

Fig. 9. Displacement graph for turning at a turning speed n = 1400 rpm and feed rate f = 0.26 mm / rev

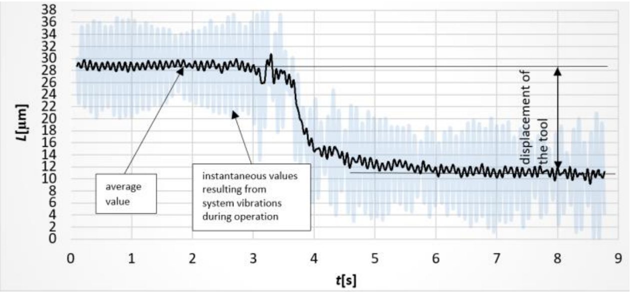

Fig. 10. Displacement graph for turning at a turning speed n = 1400 rpm and feed rate f = 0.35mm / rev

According to the literature, cutting force values are strongly affected by cutting parameters such as depth of cut, feed rate, cutting speed, and tool wear, among others. It is usually the change in cutting force that affects the elastic displacement of the machine elements and tool clamping system and the resulting error.

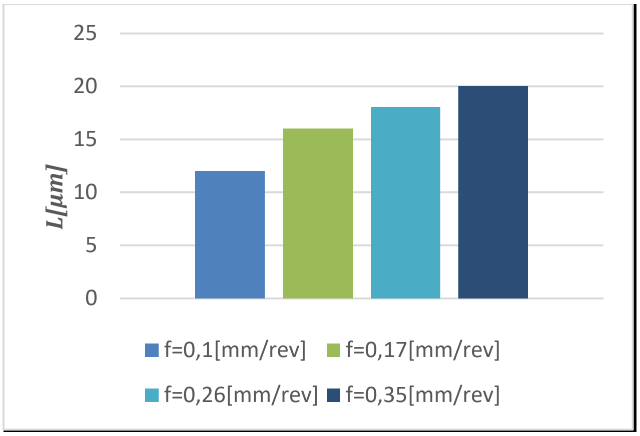

Fig. 11. Comparison of displacements for various feed rates at rotational speed n = 1400rpm

Graph 12 shows that the displacement of the tool is mainly affected by the rotational speed of the workpiece. This may be related to the temperature increase in the cutting area at increasing cutting speed. Only at higher values of the rotational speed, the increased feed is also important, because it results in an increased displacement of the tool. The increasing value of displacement and rapid loading of the tool during the entering to the material increases the risk of breakage or chipping, that occurred during the test. Displacement analysis is easier way to evaluate the magnitude of deviation of the shape than the vibration analysis.

The graphs shown in Figures 13, 14, which present the frequency analysis, show that the radial displacement of the main tool is affected by a frequency of approximately 23Hz, as shown by the formula (1), this is radial runout frequency.

$$f_b = \frac{n}{60} = \frac{1400}{60} = 23[Hz] \qquad (1)$$

where: f_b–radial runout [Hz], n - rotational speed [rpm];

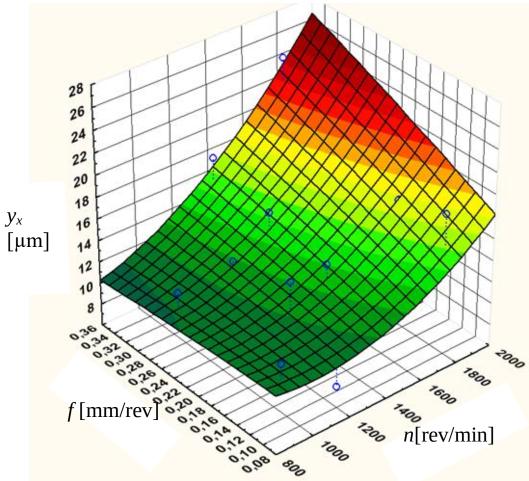

Fig. 12. The radial displacement of the tool in function of the rotation speed and feed rate

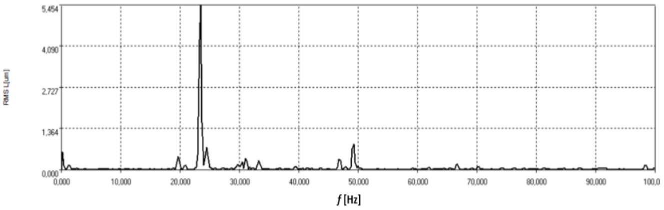

Fig. 13. Spectral analysis of the tool during turning at rotational speed n = 1400 rpm and feed rate f = 0.1 mm / rev

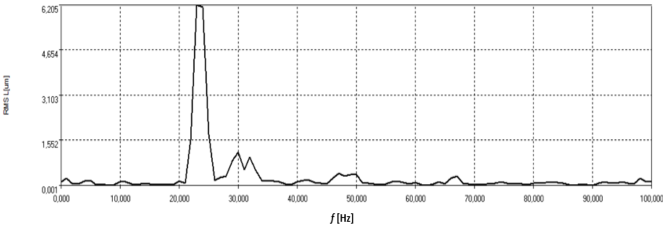

Fig.14. Spectral analysis of the tool during turning at rotational speed n = 1400 rpm and feed rate f = 0.35mm / rev

Thus, the radial displacement of the tool results mainly from the eccentric rotation of the workpiece.

3. SUMMARY AND CONCLUSIONS

Tool displacement and vibration cause machining inaccuracies, shape errors. The displacement of the tool, i.e. the deviation of its path from the path parallel to the feed direction is the result of the radial force acting on the tool. Prior to the machining process, radial displacement of the tool must be taken into account when designing the tool and planned to prevent it from occurring by applying the compensation.

The tests show that the value of the feed rate affects the more efficient generation of vibration and displacement, i.e. the increase in the feed rate is the cause of the increase in the cutting force, which directly affects the pushing away of the tool by elastic displacement of the machine elements. Higher feed rate also causes the increase in cutting section, thus increasing the heat generated in the cutting area, which also affects the toolpath.

It would be beneficial to extend the study to measure the temperature in the cutting area, which would allow us to ascertain how high the change in the trajectory of the tool with the temperature increase is.

When planning and carrying out the process, the workpiece must be mounted as accurately as possible to avoid radial runout which generates large displacements.

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