Effect of fixing the pass-through turning tool in the tool holder on the roughness and surface macro deviations during turning

D Allenov*, K Deinova, V Konoplev and A Korzin
Peoples' Friendship University of Russia, Moscow, Russia

E-mail: allenov_dg@pfur.ru

Abstract. A study of the effect of the tool overhang length from the tool holder and cutting forces corresponding to different sizes of the removed layer on the formation of the quality of the surface layer of parts during turning is presented. Linear displacements arising in a stress-strain state and roughness parameters were used as estimated parameters. It is revealed that the quality of the surface layer improves with a decrease in vibration in the zone of contact between the workpiece and the tool.

Keywords: surface roughness, depth of cut, cutting force, tool overhang, static analysis.

1. Introduction
Currently, there are various methods of manufacturing machine parts and mechanisms, among which turning takes one of the main places. The main parameter of the geometric accuracy of product is the roughness – a set of irregularities forming the microrelief of the surface of the product because of plastic deformation of the workpiece during its processing due to friction and vibration of the tool, tearing material particles from the surface, irregularities of the cutting edges of the tool [1, 2]. The process of formation of the surface layer is influenced by a combination of simultaneously acting factors, the main of which can include processing methods, type and state of tooling, physicomechanical characteristics of the workpieces being machined, cutting modes (feed, depth and cutting speed, spindle rotation speed, length of the tool overhang of the tool holder, cutting power and cutting force), geometric abilities of the cutting plates of the tool, their cutting properties, rigidity technological system, the ability to absorb the energy of vibration (damping ability), the presence and quality of lubricating and cooling technological means and much more [1-6, 8]. Machining attachments, cutting modes, workpiece and tool material are specified by the technological process, but tool overhang is set arbitrarily. Therefore, there is a need to research the effect of tool overhang on the quality of the surface layer and macro deviation of the surface during processing. Among the quality parameters of the surface layer, roughness has a predominant effect on such performance properties of details as: wear resistance of rubbing surfaces, fatigue strength, corrosion resistance, therefore the study of this parameter is of great importance in assessing the quality of the surface of the product. [7].

2. Materials and methods
The paper investigates the influence of the depth of cut and the tool overhang on the quality of the surface layer of the part. The surface roughness parameters Ra and Rz were measured by the contact method [9]: with the model 130 profilometer. A right lathe straight-turning side-facing tool was used as a cutting tool for external turning with a mechanical fastener of the PCLNR2525M12 brand with replaceable inserts made of T15K6 hard alloy [10]. The three-dimensional, solid-state model was prepared in the student version of "Autodesk Inventor Professional" (Figure 1).
Steel cylindrical rolled products with a diameter of D = 40 mm (steel grade - St. 30) were used as workpieces. The processing of the workpieces was carried out on a 16K20 turning-cutting machine. The parts to be machined were mounted in a three-cam self-centering chuck with preloading of the rear center. This method of installation of machined parts on the machine allows you to reduce the negative impact on the quality of the surface layer of the vibration that occurs in the area of contact between the tool and the workpiece. In the tool holder, the tool was secured with two bolts. Workpiece processing was carried out at three different depths of cut $t_1 = 0.4$ mm, $t_2 = 1$ mm and $t_3 = 1.5$ mm. The feed rate and spindle speed did not change during the whole experiment and were equal to $s = 0.1$ mm / rev and $n = 1000$ rpm, respectively. Actual cutting speed was:

$$V_{\phi} = \frac{\pi D n}{1000} = 126 \text{ m/min}$$ (1)

Chip formation when cutting materials is carried out under the action of cutting force $P$, which is usually laid out on the following coordinate axes: tangential $P_z$, radial $P_y$ and axial $P_x$ [11, 12]. These components are interconnected by these relations: $P_y = (0.25 - 0.5) P_z$, $P_x = (0.1 - 0.25) P_z$. Numerous studies have established that in most cases the cutting force is approximately equal to the tangential component: $P_z \approx 0.9 P$, that is why practical calculations were made according to the force $P_z$ [11]. Cutting force $P_z$ was determined by the formula [11]:

$$N = 10C_p \cdot t^3 \cdot s^5 \cdot V_{\phi}^n \cdot K_p$$ (2)

In our case, the calculation was carried out for the material of the working part of the tool - T15K6 hard alloy, the type of treatment - external longitudinal turning and boring. The correction factor $K_p$, which takes into account the actual cutting conditions, is the product of a number of constant factors:

$$K_p = K_{np} \cdot K_{ap} \cdot K_{bp} \cdot K_{cp} \cdot K_{rp} = 0.846$$ (3)

According to the obtained values of the tangential force and the corresponding cutting modes (depth and cutting speed, as well as the feed rate), the cutting power was determined:

$$N = \frac{P_z V_{\phi}}{1020 \cdot 60}$$ (4)

The obtained values of the tangential component of the cutting force and power were recorded in Table 1:

| No. | Depth of cut (mm) | $P_z$ (N) | $V_{\phi}$ (m/min) | $N$ (kW) |
|-----|------------------|----------|-------------------|----------|
| 1   | 0.4              | 874      | 126               | 1.8      |
| 2   | 1                | 2185     |                   | 4.5      |
| 3   | 1.5              | 3277     |                   | 6.7      |
The power of the main drive motor is numerically equal to 10 kW. The calculated power at different depths of cut correspond to the given technical characteristics.

3. Results

3.1. The study of the deviation of the tool using computer simulation

Using the KOMPAS-3D and APM FEM three-dimensional modeling systems, a static calculation was made for five overhangs (the length of the first overhang was 35 mm, the others were made in 10 mm increments). The tool, whose dimensions of tool holder block are 25x25 mm, was fastened in a rotary tool holder with two bolts with a diameter of 16 mm.

Temperature equal to 20 degrees Celsius was applied to all surfaces of the created three-dimensional model of the tool under investigation. The tool was fastened in a rotary tool holder with two bolts, therefore, for the analysis, three surfaces were specified as matching (Fig. 2). When attaching the tool, the upper edge of tool holder block with two bolts is in contact (the distance from the working part of the cutter to the first bolt was 38 mm), and the lower edge - with the tool holder itself (the distance from the tool head is 30 mm). The scale of the image of forces that indicated the direction of interaction is numerically equal to 0.1.

To indicate the cutting force, a distributed specific force was applied to the tip of the tool. As the magnitude of the loading vector, the cutting forces were selected, shown in Table 1. Steel was set as the sample material.

The last step in creating a model was: the assignment of matching surfaces and the creation of a finite element mesh. The tool model was divided into four nodal tetrahedra. Operation parameters were set from practical considerations: the maximum length of the element side is 0.5, the thickening coefficient on the surface is 1, and the underpressure factor in a volume is 1.5. The resulting number of finite elements of the partition was equal to 5861, nodes - 1896.

In order to identify the relationship between the length of the tool overhang and the depth of cut from the tool deviation from the tool holder, a static calculation was performed. The number of elements selected by the system was 6235 (1896 knots), degrees of freedom - 5688 (443) [13]. It is necessary to pay attention to the increase in the number of selected elements of the system: compared with the stage of creating the finite element mesh, the number of finite elements has increased by 374 units. This is due to the fact that the created computational three-dimensional model, consisting of complex non-uniform geometric transitions, was subjected to additional adaptive splitting. In addition, during the analysis, an automatic calculation of displacements was performed, at which the stiffness matrix was formed and the results for loading were calculated.

The result of the analysis of the 5th sample with the greatest cutting force is presented in Figure 3.
**Figure 3.** The figure of deformed design of the tool with 5th overhang and the depth of cut of 1.5 mm wound.

The given maps are constructed in the form of iso-areas (the number of iso-levels is 16) on the basis of the deformed structure, while the values at the nodes are averaged. The scale factor (displacement scaling factor for rendering the deformed structure) is 100. For rods, plates, and volume elements, the total linear displacement parameters (USUM) were selected.

The dependences of the obtained linear displacements on the size of the removed layer from the workpiece and the length of the tool overhang from the tool holder are presented in Table 2.

**Table 2.** Table 2. Dependence of tangential force and power on cutting depth

| tool position | depth of cut t (mm) | cutting force P (N) | linear displacement (mm) |
|---------------|---------------------|---------------------|--------------------------|
| 1 tool position | 0.4 | 874 | 0.003497 |
|               | 1.0 | 2185 | 0.008553 |
|               | 1.5 | 3277 | 0.012990 |
|               | 0.4 | 874 | 0.003657 |
| 2 tool position | 1.0 | 2185 | 0.008960 |
|               | 1.5 | 3277 | 0.013710 |
|               | 0.4 | 874 | 0.004710 |
| 3 tool position | 1.0 | 2185 | 0.011660 |
|               | 1.5 | 3277 | 0.017660 |
|               | 0.4 | 874 | 0.006663 |
| 4 tool position | 1.0 | 2185 | 0.016500 |
|               | 1.5 | 3277 | 0.024980 |
|               | 0.4 | 874 | 0.008895 |
| 5 tool position | 1.0 | 2185 | 0.022240 |
|               | 1.5 | 3277 | 0.033350 |

Static analysis of the stress-strain state of the tool at different tool overhangs and cutting forces showed that linear displacements are directly dependent on the tool overhang and the depth of the layer being removed. Consequently, the tool was subjected to the greatest linear deformation equal to 0.03335 mm at the depth of cut of 1.5 mm, which corresponds to a cutting force of 3277 N, and the fifth tool overhang (Figure 3).

Additionally, when displaying the results of the calculation, the deformed and non-deformed state of the tool were visualized to demonstrate noticeable linear displacements. The scale factor is chosen to be 100 in order to more clearly show the deflection of the tool that appears under the action of stresses.
The relationship between the linear displacements that occur during the cutting process, the tool overhang length and the depth of the layer being removed is shown in Figure 5.

The difference between the maximum and minimum values of the instrument deviations at \( t = 0.4 \) mm is 0.005 mm, at \( t = 1 \) mm - 0.015 mm, and at \( t = 1.5 \) mm - 0.016 mm. Such a distribution of deviations by depth of cut is related to the position of the tool in the tool holder: when the first tool overhang occurred, the tool holder block touched the tool holder with its entire edge, which had a slight effect on the tool deviation.

It can be seen from the graph that for each of the considered lengths of tool overhang from the tool holder, the total deviations increase with increasing depth of cut. However, when the first instrument overhang occurred, the linear displacements changed insignificantly with an increase in the size of the removed layer: the difference in linear displacements at \( t = 1 \) mm and \( t = 0.4 \) mm is approximately equal to the difference in linear displacements at \( t = 1.5 \) mm and \( t = 1 \) mm (this difference is 0.005 mm). The situation is different from the maximum tool overhang. The difference of linear displacements at \( t = 1 \) mm and \( t = 0.4 \) mm is 0.015 mm, and at \( t = 1.5 \) mm and \( t = 1 \) mm the tool was subjected to less linear deformation (0.006 mm). This is explained by the desire for steady-state elastic deformation, which is associated with the mechanical characteristics of the material. In other words,
when a certain value of linear displacements was reached, the tool began to resist the loads acting on it in order to prevent the onset of plastic deformation of its structure.

According to the obtained data, we can conclude that the length of the tool overhang and the depth of the layer removed from the workpiece significantly affect the tool deflection, that is, as the tool overhang length and cutting depth increase, the tool deviations in the tool holder increase.

3.2. Investigation of the influence of the tool overhang on the surface roughness
To confirm the direct relationship between the quality of the surface layer and cutting conditions by contact, the roughness parameters were measured using a profilometer. Graphs of roughness $R_a$ and $R_z$ on tool overhang and depth of cut are presented in figure 6.

![Figure 6](image)

**Figure 6.** Graphs of roughness parameters $R_a$ and $R_z$ depending on tool overhang and depth of cut: a - for roughness parameter $R_a$; b - for the roughness parameter $R_z$.

According to the data obtained, it can be concluded that the tool overhang significantly affects the surface roughness when machining steel grade 30. At the same time, with an increase in the length of the tool overhang from 0 to 50 mm, the surface roughness parameters increase by 30-40% (Figure 6, a). The visible sharp increase in roughness at a depth of cut of 1.5 mm with tool overhang 1 and 3 is due to the fact that when processing workpieces a drain ribbon-like confused chips occurred, which, when removed from the cutting zone, wrapped the treated surface, thereby scratching it [14]. The effect of the depth of cut on the surface roughness is directly proportional to the dependence, which is confirmed in [1, 15]. Similar dependences are observed for $R_z$. Since this parameter is used to normalize irregularities much less frequently, a more detailed assessment of the dependencies for it was not carried out.

To eliminate the effect of drainage chips on the surface roughness, intermittent cutting was used, that is, the alternation of the cutting process (chip formation) and idling: the chips were crushed into small and easily removable components. This cutting method allowed us to obtain roughness values that are more suitable for plotting (Figure 7).

![Figure 7](image)

**Figure 7.** Graph of the roughness parameter $R_a$ versus tool overhang and depth of cut with intermittent cutting.
This graph shows that the ratio of the maximum value of roughness to the minimum with a depth of cut of 0.4 mm is 1.3; with a depth of cut of 1 mm - 1.1; with a depth of cut 1.5 mm - 1.2. These relationships show that the effect of tool overhang on surface roughness at different depths of cut is uneven. Since, in conducting the study, the geometrical parameters of the cutting tool (for example, the cutter angles and the radius of the cutting wedge radius), the cutting conditions and the materials of the workpiece and the turning plate did not change, the main influence on the formation of irregularities was caused by the vibration that occurs during machining in the area of the workpiece and tool. At the same time, in the course of numerous experiments it was found that the surface roughness improves with decreasing vibration, which in turn will be the lower, the greater the cutting speed will be, the cross-sectional size of the cutting tool, the rigidity of the technological system and less depth of cut, feed, and overhang [1, 4, 6]. According to the data obtained, it can be concluded that with an increase in the length of the tool overhang, the amplitude of oscillations increases, which increases the surface roughness.

4. Discussion
During turning in the zone of contact of the cutting wedge and the work surface, vibrations are formed under the force of friction shavings on the cutter and the cutter on the workpiece. With an increasing of tool overhang, the rigidity of the technological system «machine – device – tool – detail» decreases, as a result the amplitude of the oscillations increases and negatively affects the quality of the surface. Increased vibration in the cutting zone also leads to a reduced service life of the cutting tool due to the increased wear of the cutting wedge [16, 17].

From the above it follows that during turning it is necessary to set the minimum tool overhang. In case of surface treatment at a distance, using a cutter with a long holder, it is necessary to set reduced cutting mode, or to perform processing in multiple passes.

Conclusions
Thus, it should be noted that the quality of the surface layer improves with a decrease in vibration in the zone of contact between the workpiece and the tool. In turn, the emergence of vibrations is influenced by numerous factors, such as, for example, the depth of cut and the tool overhang. With an increase in the size of the layer removed from the workpiece and the length of the tool overhang, an increase in the roughness parameters is observed, and, consequently, the quality of the surface layer deteriorates. In addition, it should be noted that the increase in the values of the above-mentioned cutting conditions adversely affect the occurrence of linear displacements (deviations of the tool in the tool holder). In other words, the strength and wear resistance of the tool, as well as the quality of machining of the parts directly depend on the depth of cut and the overhang of the tool.

References
[1] Suslov A G 2008 Inzheneriya poverykhnosti detalei [Part Surface Engineering] (Moscow: Publishing House Mashinostroenie) 320 p (in Russian)
[2] Merchant M E 1945 Journal of Applied Physics 16 pp 267–275 https://doi.org/10.1063/1.1707586
[3] Bez'yazychnyy V F 2000 Vliyaniye kachestva poverkhnostnogo sloya posle mekhanicheskoy obrabotki na eksplutatsionnye svoystva detalei mashin [The influence of the quality of the surface layer after machining on the performance properties of machine parts] Engineering Journal 4 pp 9-16 (in Russian)
[4] Kozochkin M, Allenov D and Andryushchenko I 2019 Proc. 4th International Conference on Industrial Engineering 2018 https://doi.org/10.1007/978-3-319-95630-5_143
[5] Allenov D G 2016 Issledovaniye vliyaniya iznosa rezhushchey kromki instrumenta na chistotu poverykhnosti [Study of the effect of wear of the cutting edge of the tool on the surface cleanliness] Mechanical Engineering 4(16) pp 12-16 (in Russian)
[6] Thomas M, et al 1996 Computers & Industrial Engineering 31(3-4) 637–644 https://doi.org/10.1016/s0360-8352(96)00235-5

[7] Allenov D G, et al 2018 Issledovaniye vliyania kachestva poverkhnostnogo sloya na ekspluatatsionnyye kharakteristiki detali [The study of the influence of the quality of the surface layer on the performance characteristics of the part] Scientific and Technical Bulletin of the Volga region 6 pp 30-34 (in Russian)

[8] Rogov V A and Gorbani S 2015 Influence of the handle design on a composite lathe cutter Russian Engineering Research https://doi.org/10.3103/s1068798x15010220

[9] Markova T V and Kryzhanovskaya I M 2006 Sherokhovatost poverkhnosti [Surface Roughness] (St. Petersburg: Polytechnic University Press) 32 p (in Russian)

[10] Lim T, et al 2001 International Journal of Production Research 39(6) pp 1239–1256

[11] Dalsky A M, et al 2003 Spravochnik tekhnologa-mashinostroitelya [Reference Book Technologist-Mechanical Engineering] (Moscow: Publishing House Mashinostroenie) 912 p (in Russian)

[12] Parfeneva I E 2012 Tekhnologiya konstruktsionnykh materialov. Obshchaya kharakteristika obrabotki rezaniem [Technology of construction materials. General characteristics of machining] (Moscow: Publishing House Mashinostroenie) 454 p (in Russian)

[13] Ambati R and Yuan H 2011 International Journal of Advanced Manufacturing Technology 53(1–4) 313–323 https://doi.org/10.1007/s00170-010-2818-9

[14] Wolf A M 1973 Rezaniye metallov [Metal cutting] (Leningrad: Publishing House Mashinostroenie) 496 p (in Russian)

[15] Korsakov V S 1961 Tochnost mekhanicheskoy obrabotki [Accuracy of machining] (Moscow, Publishing House Mashgiz) 397 p (in Russian)

[16] Allenov D, Kozochkin M and Andryushchenko I 2017 MATEC Web of Conferences 129 https://doi.org/10.1051/matecconf/201712901032

[17] Chen J C and Chen W L 1999 Journal of Intelligent Manufacturing 10(2) pp 187–197 https://doi.org/10.1023/A:1008980821787