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ORIGINAL ARTICLE

# The dependence of tool overhang on surface quality and tool wear in the turning process

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**Abstract** In the turning process, the importance of machining parameter choice is increased, as it controls the surface quality required. Tool overhang is a cutting tool parameter that has not been investigated in as much detail as some of the better known ones. It is appropriate to keep the tool overhang as short as possible; however, a longer tool overhang may be required depending on the geometry of the workpiece and when using the hole-turning process in particular. In this study, we investigate the effects of changes in the tool overhang in the external turning process on both the surface quality of the workpiece and tool wear. For this purpose, we used workpieces of AISI 1050 material with diameters of 20, 30, and 40 mm; and the surface roughness of the workpiece and tool wear were determined through experiments using constant cutting speed and feed rates with different depth of cuts (DOCs) and tool overhangs. We observed that the effect of the DOC on the surface roughness is negligible, but tool overhang is more important. The deflection of the cutting tool increases with tool overhang. Two different analytical methods were compared to determine the dependence of tool deflection on the tool overhang. Also, the real tool deflection values were determined using a comparator. We observed that the tool deflection values were quite compatible with the tool deflection results obtained using the second analytical method.

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**Keywords** Tool overhang · Surface roughness · Tool wear · Tool deflection

**Nomenclature**

| | |
|---|---|
| b | Shank width |
| DOC | Depth of Cut |
| E | Modulus of Elasticity |
| $F_c$ | Cutting force |
| G | Shear modulus |
| h | Shank height |
| $I_{1,2}$ | Scalar moment of inertia |
| $I_{P1,P2}$ | Polar moment of inertia |
| k | Half of DOC |
| L | Tool overhang |
| $M_b$ | Torque |
| $M_e$ | Bending momentum |
| $R_a$ | Surface Roughness |
| U | Energy |
| $\alpha_0$ | Orthogonal clearance angle |
| $\gamma_0$ | Orthogonal rake angle |
| $\delta$ | Deflection |

## 1 Introduction

Machining processes are manufacturing methods for ensuring processing quality, usually within relatively short periods and at low cost. Several machining parameters, such as cutting speed, feed rate, workpiece material, and cutting tool geometry have significant effects on the process quality. Many researchers have studied the impact of these factors. The cutting tool overhang affects the surface quality, especially during the turning process, but this has not been reviewed much. Based on applications and theoretical approaches, it is known that cutting tools need to be clamped

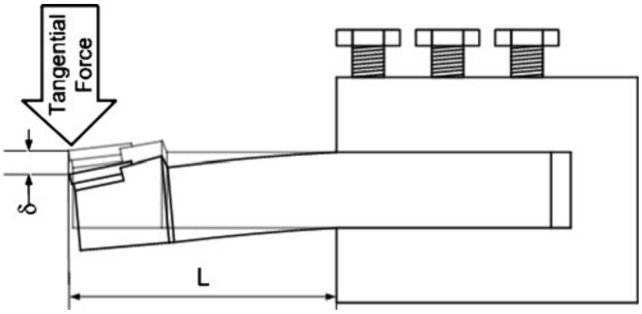


**Fig. 1** Tool holder undergoing deflection, $\delta$ due to the tangential force

as short as possible to achieve the desired surface quality of the workpiece. However, not much quantitative data about these exist besides the mentioned qualitative approaches. For the internal turning method in particular, the cutting tool should be attached with the proper length, not with the shortest distance. This situation may also be the case for external turning processes, depending on the workpiece geometry.

In this study, we investigate the effects of cutting tool overhang on both the surface quality and cutting tool wear in external turning processes. Because the tool holder is subject to bending and buckling depend on effect point of the cutting force (tangential force), cutting tool displaced. This situation has negative effects on the surface quality as shown in Fig. 1.

## 2 Literature review

In the experiments conducted in this study, although neither the theoretical nor the experimental measurements of the vibration effects were not performed, mostly the vibration effects of the tool overhang have been examined and the subjects were investigated together with the effect of the vibration in the relevant literature [1, 2]. Increasing tool overhang increases the vibration tendency of the overall system [1]. In machining processes, the measurement and effects of vibration have been studied for a long time. The first study on this topic was performed by Tobias-Fishwick

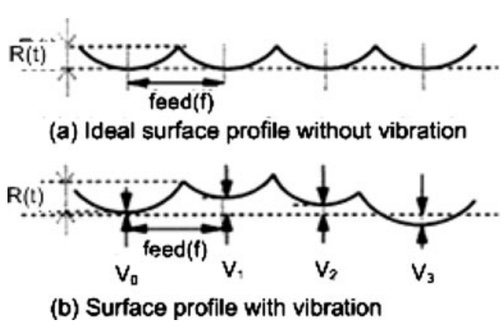


**Fig. 2** Surface profile modeling considering the relative vibration between the tool and workpiece [5]

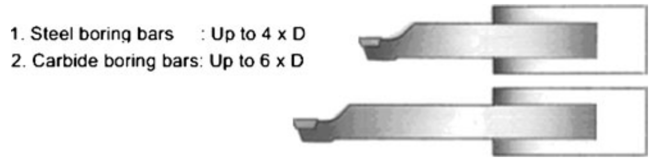


**Fig. 3** Recommended tool overhang for split sleeve holders in turning [11]

in 1958. This research was followed by the studies of Tlusty-Polacek in 1963 and Koenigsberger-Tlusty in 1971 [2].

Kassab and Khoshnaw [1] have determined the surface roughness of the workpiece by selecting tool overhangs at 25, 30, 35, and 40 mm at different cutting speeds, different depth of cuts (DOCs), and different feed rates. They studied this during the turning of workpieces made of carbon steel materials to determine the relevance between the tool vibration and the surface roughness. The results showed that the feed rate had the greatest effect on surface roughness and that both surface roughness and vibration increased in parallel with the tool overhang. As the tool overhang increases, so does the tendency of the system to vibrate. In all experiments, the surface roughness increased as the tool overhang increased.

Clancy and Shin [2] studied the wear and vibration of the cutting tool and the surface roughness of the workpiece during the face turning process. In experiments, they used an AISI 1018 steel bar as the workpiece material and cutting tools of 10° rake angle and 0.8 mm radius at different DOCs. They have indicated that the vibrations generated during the process had very negative effects on the surface quality and the dimensional accuracy of the workpiece. The vibrations accelerate tool wear lead to tool fracture, and may also have harmful effects on the machine tool and spindle. They noted that surface roughness was one of two basic methods applied in the determination of vibration.

Haddadi et al. [3] examined the impact of worn tools and brand new tools on vibration frequency in the turning process experimentally. They examined the effects of rake angle and tool overhang under orthogonal and oblique cutting conditions. In experiments, they used a workpiece made of low carbon steel and high-speed steel (HSS) tools. The tool overhangs used were 20, 30, and 50 mm. In the experimental studies that they conducted using different

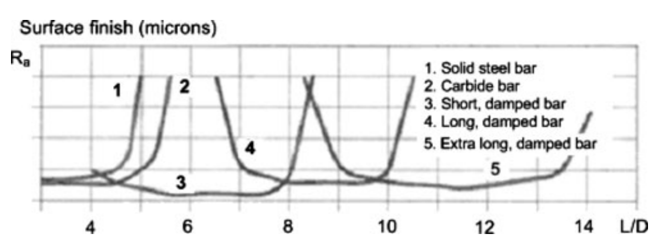


**Fig. 4** Changes of the surface roughness according to the tool overhang/cross-section ratio in turning [11]

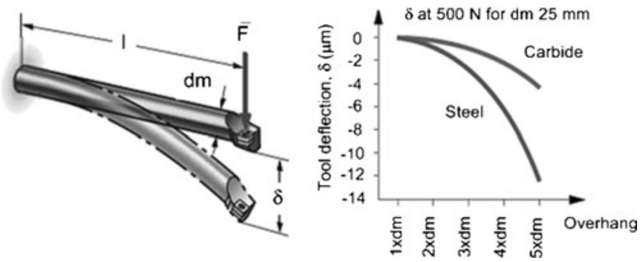


**Fig. 5** Displacement of the cutting tool under the influence of the cutting force [13]

DOCs, they found that the effect of the tool overhang was clearly dependent on the selected experimental parameters.

Tasdemir et al. [4] have studied the effects of tool geometry on the surface roughness, and they performed the experiments by using different types of inserts and different DOCs. The approach angle, cutting speed, and feed rate were constant. During the experiments, they accepted the cutting tool overhang as a variable, and afterwards, they determined the tool vibration. They implemented an artificial neural network and compared results from the theoretical approach and the experiments.

Lu [5] examined the determination of surface quality in machining processes. He presented, as reported by Jang et al., the surface profile modeling of the workpiece that occurs between the tool and workpiece with the effect of vibration, and the results are shown in Fig. 2.

Amin et al. [6] have performed studies aiming to determine chip form instability in the turning process experimentally. They used a CNMG120408 type insert and three workpiece materials (austenitic stainless steel and AISI 1020 and AISI 1040 carbon steels). To determine the impact of tool overhang, they selected overhang lengths of 40, 50, and 60 mm, and no significant chip form instability was observed when the tool overhang length was 40 mm. This situation has been referred to as the rigidity of the tool.

Audy [7] has conducted experiments using different cutting speeds and DOCs at a constant feed rate. During the experiments, the cutting forces were determined using a dynamometer. He evaluated the development of an adaptive control method to determine the process parameters in the machining. Audy also indicated that machine performance, workpiece and tool material selections, tool life, quality of machined surfaces, the geometry of cutting tool edges, and cutting conditions were closely related to the cutting forces. The deformation of the cutting tool during machining was calculated to demonstrate its effects on the dynamic variables (such as the cutting forces and amplitudes), and these depended on the cross-section of the cutting tool and the tool overhang. In addition, it was also shown that the elastic deformation of the cutting tool increased as the cross-section of the tool shank decreased and the tool overhang increased.

Abouelatta and Madl [8] indicated that it was quite important to determine the optimum set of machining parameters to achieve the required surface quality, and they performed studies to determine the relationship between the vibration and the surface roughness in the turning process. They selected 38 and 70 mm tool overhangs. Benefiting from the results obtained from these experiments, SPSS analyses were undertaken and empirical formulas derived.

Chiou and Liang [9] examined the effects of the slender cutting tool on flank wear in the turning process. They indicated that the vibration tendencies of the tool system increased as the tool wear increased. In this case, the effects of vibration were investigated using a brand new cutting tool and a worn tool. The vibration increased as the cutting speed increased.

Recently, Kotaiah et al. [10] progressively varied the cutting speed, feed rate, depth of cut, and tool overhang length to test their effect on the cutting forces, surface roughness, and critical chatter lengths of the workpiece. They used cutting tools made from HSS S-200 and three different types of steel and aluminum as the workpiece. They also selected ten different overhang lengths from 53 to 63 mm for the different workpiece materials. The results indicated that the tool overhang had a clear effect on the cutting forces. As the tool overhang increased, so did the cutting forces. They also determined that in all experiments, the surface roughness increased as the tool overhang increased.

After reviewing these studies, we examined the recommended values of the manufacturers who produce cutting tool inserts and tool holders (tool posts). The recommended maximum tool overhang values are given Fig. 3 according to the tool post material [11]. As seen in Fig. 3, for tool holders made of steel, it is specified that the maximum attaching (tool overhang) length may be up to four times

**Fig. 6** Modeling of a standard cutting tool according to Castigliano's Theorem

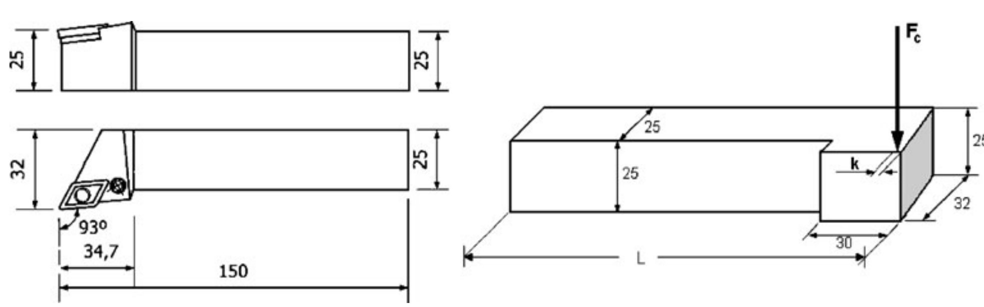

**Table 1** Test parameters

| Test number | Workpiece diameter (mm) | Depth of cut (mm) | Overhang (mm) |
|---|---|---|---|
| 1 | 20 | 0.5 | 50 |
| 2 | 20 | 1.0 | 50 |
| 3 | 20 | 0.5 | 60 |
| 4 | 20 | 1.0 | 60 |
| 5 | 20 | 0.5 | 80 |
| 6 | 20 | 1.0 | 80 |
| 7 | 20 | 0.5 | 90 |
| 8 | 20 | 1.0 | 90 |
| 9 | 30 | 0.5 | 50 |
| 10 | 30 | 1.0 | 50 |
| 11 | 30 | 0.5 | 60 |
| 12 | 30 | 1.0 | 60 |
| 13 | 30 | 0.5 | 80 |
| 14 | 30 | 1.0 | 80 |
| 15 | 30 | 0.5 | 90 |
| 16 | 30 | 1.0 | 90 |
| 17 | 40 | 0.5 | 50 |
| 18 | 40 | 1.0 | 50 |
| 19 | 40 | 0.5 | 60 |
| 20 | 40 | 1.0 | 60 |
| 21 | 40 | 0.5 | 80 |
| 22 | 40 | 1.0 | 80 |
| 23 | 40 | 0.5 | 90 |
| 24 | 40 | 1.0 | 90 |

that of the tool holder's cross-section. During the experiments performed during this study, these criteria were taken into consideration. In the literature review we conducted, we found empirical researches that used attaching lengths that were quite beyond this proposed ratio.

In addition, the achievable surface roughness values depended on the stiffness of the cutting tool (the ratio between the tool overhang and tool diameter) according to the properties of the tool material as provided in Fig. 4 [11].

## 3 A suggestion to determine the cutting tool deflection

In machining processes performed using a single cutting edge tool, a displacement of the tool edge occurs that depends on the magnitude of the cutting force and the tool overhang. It affects the surface quality and the tool wear during the machining.

In the literature on the subject [12], concerning the displacement calculations, it is considered that the tool

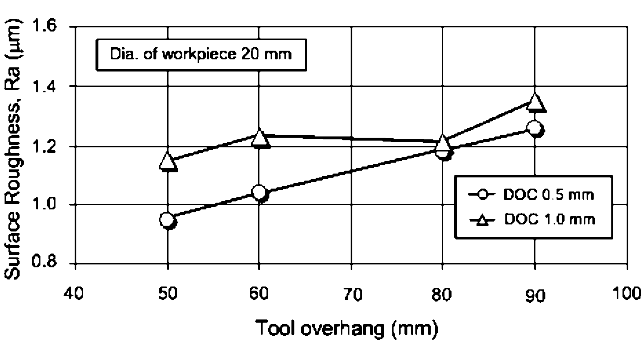


**Fig. 7** The effect of tool overhang and DOCs on surface roughness (workpiece diameter: 20 mm)

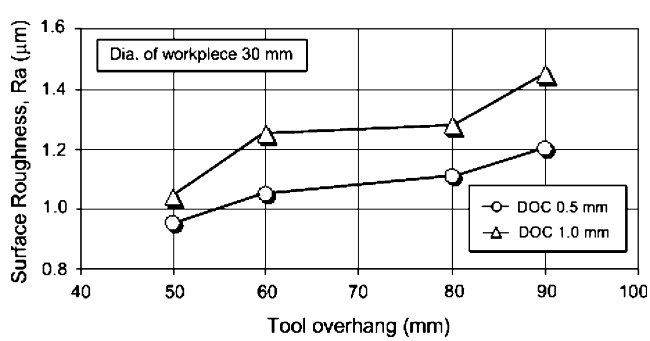


**Fig. 8** The effect of tool overhang and DOCs on surface roughness (workpiece diameter: 30 mm)

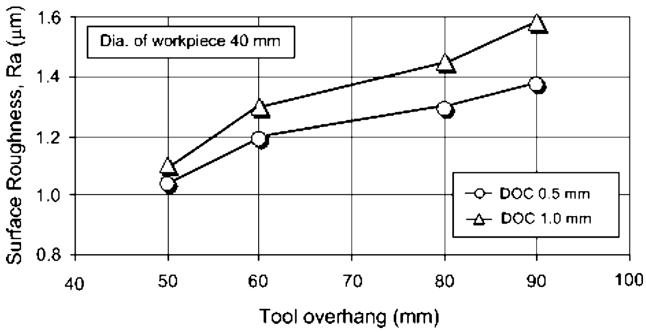


**Fig. 9** The effect of tool overhang and DOCs on surface roughness (workpiece diameter: 40 mm)

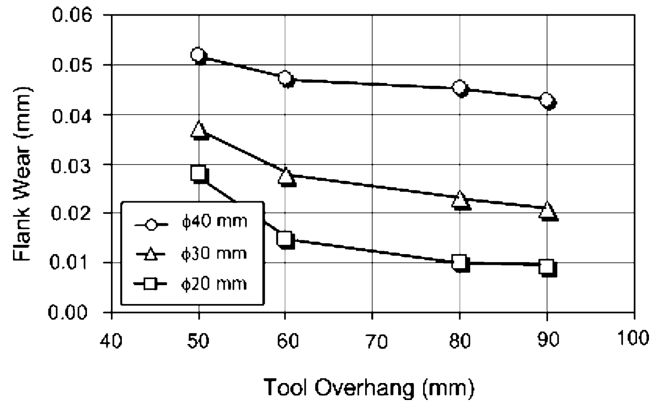


**Fig. 11** Changes of flank wear depend on the tool overhang and workpiece diameter

takes the form of a cantilever bar and that the cutting force ($F_c$) has an influence on the symmetry axis (Fig. 5). The commonly used tool deflection equality is given by Eq. 1, which belongs to the elastic curves produced by the Bending momentum (Me). $\delta$ is calculated as follows:

$$\delta = -\frac{F_c L^3}{3EI} \tag{1}$$

Here, $F_c$ is the cutting force, $L$ is the tool overhang, $E$ is the modulus of elasticity, and $I$ is the scalar moment of inertia. As can be seen, the tool deflection in Eq. 1 depends on $F_c$, $L$, $E$, and $I$.

The tool holder is also subjected to the effect of the bending momentum and the torque, as the cutting force is not applied in the symmetry axis. Therefore, the cutting tool has an elastic curve, which in turn generates a tool deflection, not only because of the bending momentum, but also because of the torque. For this reason, the above result Eq. 1 is not true, except approximately. To determine the displacement of the tool edge more accurately, Castigliano's Theorem (one of the energy methods) is used, so the effects of bending momentum and torque are taken into consideration. The second analytical method proposed is based on the following principle: "If an elastic structure is subjected to $n$ loads $\vec{F}_{c1}, \vec{F}_{c2}, \ldots, \vec{F}_{cn}$,the deflection $x_j$ of the point of application of $\vec{F}_{cj}$, measured along the line of action of $\vec{F}_{cj}$, can be expressed as the partial derivative of the strain energy of the structure with respect to the load $\vec{F}_{cj}$" [12].

$$i.e.,\ \delta = \frac{\partial U}{\partial F_{cj}} \tag{2}$$

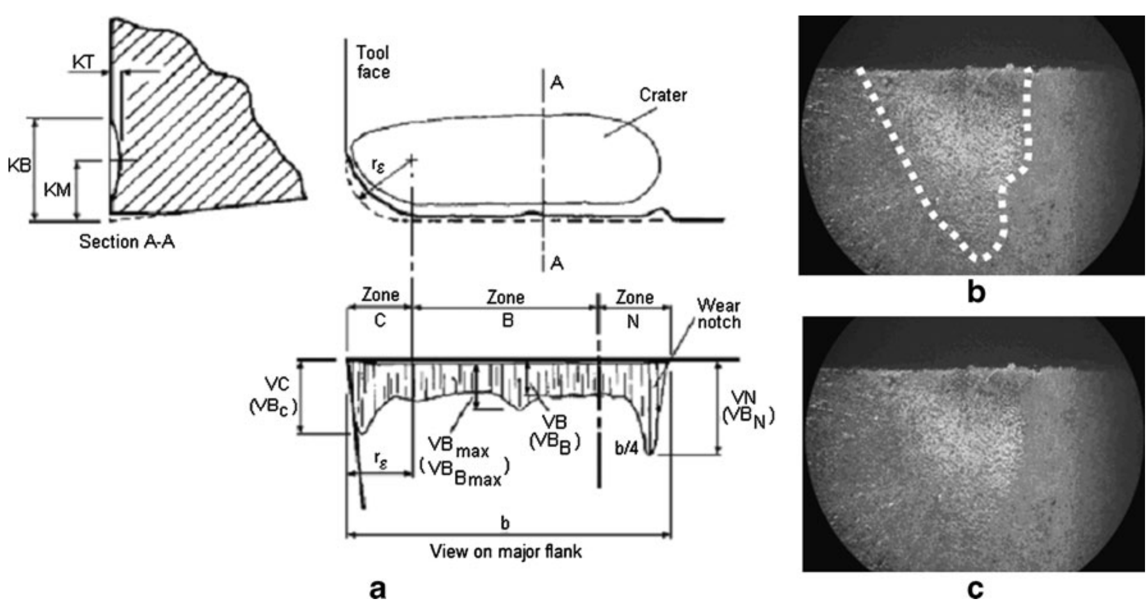


**Fig. 10** Crater wear and flank wear of a cutting tool: **a** according to the ISO 3685 standard [16], **b**, **c**: the tool/workpiece contact area (zone C) in test numbers 24 and 18, respectively

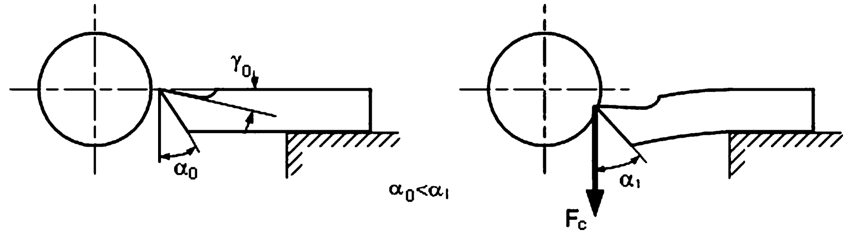


**Fig. 12** Change of the tool geometry in response to tangential force

For this purpose, we take the square cross-sectioned cutting tool holder used in the machining process into account, as seen in Fig. 6.

The cantilever cutting tool shown in Fig. 6 was considered in the calculations as two prismatic combined bodies having dimensions 252×30×7 and 25×25×L. The first part of combined prismatic body's symmetry axis is on the 30/2 mm. Therefore, the boundary value of integral was taken from 0 to L-15.

$$\delta=\int_0^7 \frac{M_e \frac{\partial M_e}{\partial F_c} dx}{EI_1}+\int_0^7 \frac{M_b \frac{\partial M_b}{\partial F_c} dx}{GI_{P_1}}+\int_0^{L-15} \frac{M_e \frac{\partial M_e}{\partial F_c} dx}{EI_2}+\int_0^{L-15} \frac{M_b \frac{\partial M_b}{\partial F_c} dx}{GI_{P_2}} \tag{3}$$

Substitution of the expressions for $M_e$ and $M_b$ into Eq. 3 gives:

$$\begin{aligned}\delta=&\int_0^7 \frac{F_c x^2}{\mathrm{EI}_1} dx+\int_0^7 \frac{F_c(15-k)(15-k)}{\mathrm{GI}_{P_1}} \mathrm{dx}\\&+\int_0^{L-15} \frac{F_c x^2+2F_c x(15-k)+F_c(15-k)^2}{\mathrm{EI}_2} dx+\int_0^{L-15} \frac{19.5^2 F_c}{\mathrm{GI}_{P_2}} \mathrm{dx}\end{aligned} \tag{4}$$

$$\begin{aligned}\delta=&P.F_c+Q.F_c(15-k)^2+\frac{F_c(L-15)^3}{R}\\&+\frac{F_c(15-k)(L-15)^2}{S}+\frac{F_c(15-k)^2(L-15)}{S}\\&+T.F_c(L-15)\end{aligned} \tag{5}$$

In Eq. 5, the expression for the deflection has been rearranged such that it depends on $F_c$, $k$, and $L$. By assuming that the $F_c$ is applied at the middle point of the DOC, the value of $k$ has been taken as half that of the DOC. The coefficients P, Q, R, S, and T include the values of $G$, $E$, $I_{P1}$, $I_{P2}$, $I_1$, and $I_2$. In the calculations, the modulus of elasticity E and the shear modulus G of the tool holder material have been taken as 210 and 80 GPa, respectively.

## 4 Experimental study

In this study, we selected the workpiece diameter, DOCs and tool overhang as variable experimental parameters and measured the surface roughness of the workpiece and cutting tool wear. Our experimental studies were carried using a CNC lathe. As the cutting tool, we used a P10 grade-coated sintered carbide inserts (the standard DNMG150608 and PDJNR2525 type tool holders). The workpieces used in the experiments were 20, 30, and 40 mm in diameter. The literature survey provided information about selection of the workpiece diameter, and these values lay in the range 25–100 mm. In the present study, we selected workpieces of materials and diameters that are widely used in industrial applications. We used a tailstock to prevent deflection of slender workpieces during machining operations, and the workpiece length was kept short to establish a more rigid setup. As the workpiece material, we selected the quite commonly preferred steel in the manufacturing industry, AISI 1050. This material contains 0.48–0.55% C, 0.17% Mn, and 0.69% Si, and has a hardness value of between 175 and 207 HV, depending on the applied heat treatment. The tool overhang lengths were 50, 60, 80, and 90 mm. The DOCs we selected were 0.5 and 1.0 mm. The cutting speed and feed rate were selected as 170 m/min and 0.17 mm/rev (at constant values), respectively. The external turning processes were carried out using the anticipated parameters. The selected processing parameters are given in Table 1.

After the experiments were carried out using the selected processing parameters, we determined the surface roughness of the workpiece and tool wear.

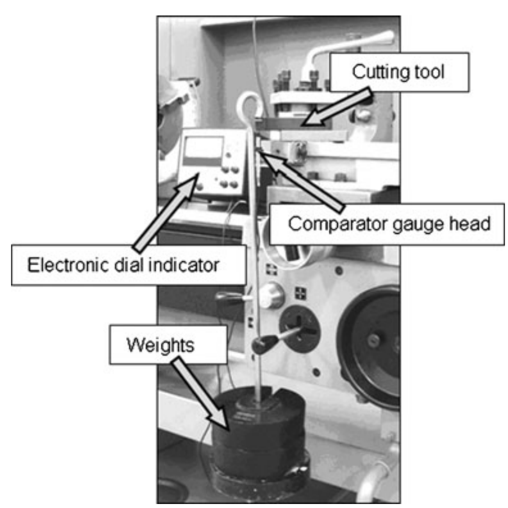


**Fig. 13** The experimental set-up

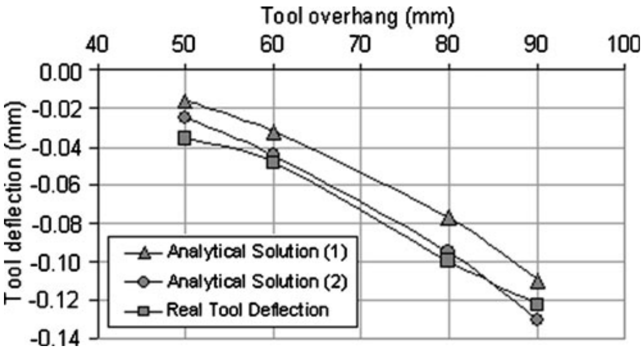


**Fig. 14** Comparison of the deflection values obtained analytically and experimentally ($F$=315N, DOC=1.0 mm)

## 5 Experimental results

### 5.1 The surface roughness of the workpiece

After the machining process, the surface roughness of the machined surfaces was determined using a Perthen brand Perthometer model profilometer. The cut-off length was selected as 2.5 mm. The surface roughness was determined as an arithmetic average of the surface roughness ($R_a$), as is commonly used as a quantitative measurement of the quality of machined surfaces. These measurements values are shown graphically in Figs. 7, 8, and 9. The results show that the surface roughness of the workpiece increases with the length of the tool overhang. This is due to the tendency of the tool system to vibrate more as the tool overhang increases, so that the surface quality becomes damaged. Apart from this, it is seen that for the same tool overhang, an increase in the DOC causes a slight increase in the surface roughness of the workpiece. This situation is directly related to the mechanism of chip formation and the workpiece material.

As seen in Fig. 7, the surface roughness values observed using a machining depth of 0.5 mm and a workpiece diameter of 20 mm are 0.95, 1.04, 1.18, and 1.26 µm with tool overhang lengths of 50, 60, 80, and 90 mm, respectively. When machining at a 1.0-mm depth in the same workpiece, the corresponding surface roughness values are 1.15, 1.23, 1.21, and 1.35 µm, respectively. A similar upward trend can also be seen in Figs. 8 and 9. The surface roughness of the workpiece increased as the workpiece diameter increased. This result indicates that the surface roughness of the workpiece has increased with the increase in the DOC and is compatible with the literature [14, 15]. In addition, it can be observed in the same figures that the surface roughness values of the workpiece have a tendency to increase with increasing tool overhang.

### 5.2 Cutting tool wear values

The crater and flank wear zones of a cutting tool are shown in Fig. 10a of reference [16]. Optical photographs of the flank wear zones that occurred under machining conditions corresponding to numbers 24 and 18 in Table 1 are provided as examples in Fig. 10b and c, respectively.

The contact areas between the cutting insert and workpiece have been identified using a SOIF brand 2B model XJP optical microscope equipped with an ocular micrometer. Flank wear will develop in these contact areas. The measured values of flank wear are shown graphically in Fig. 11. As the cutting tool inserts used in the experiments were coated and the total machining length was 100 mm, complete formation of flank wear could not be observed for all of the tests. The flank wears categorized as VC ($VB_c$) were determined according to the literature [16] as ISO 3685. After the machining operations, it was observed that zone C (in Fig. 12a) occurred in accordance with the related standard on the flank surface of the cutting tool insert.

When the graphs are examined, it is apparent that the wear values of the cutting tools are reduced as the tool overhangs increase. In tools subject to the tangential force effect, the tool geometry varies and the orthogonal rake angle ($\gamma_0$) and orthogonal clearance angle ($\alpha_0$) are subject to change due to the increase of the tool overhang and the changing position of the tool. The flank wear is reduced because the friction distance decreases due to the increase of the orthogonal clearance angle (Fig. 12).

### 5.3 Comparison of the tool deflection values obtained from analytical solutions with the experimental results

In the experimental study, we used a PDJNR2525 type tool holder to find the exact tool deflection values to compare the results obtained from the two analytical solutions. A photograph of the calibration mechanism is given in Fig. 13. The theoretically calculated cutting force depends on the workpiece material and the DOC has been identified as 315 N. Based on this value, the calibration weights on the tool holder were suspended and the exact values of tool deflection were identified using a Mercer 122L brand electronic comparator.

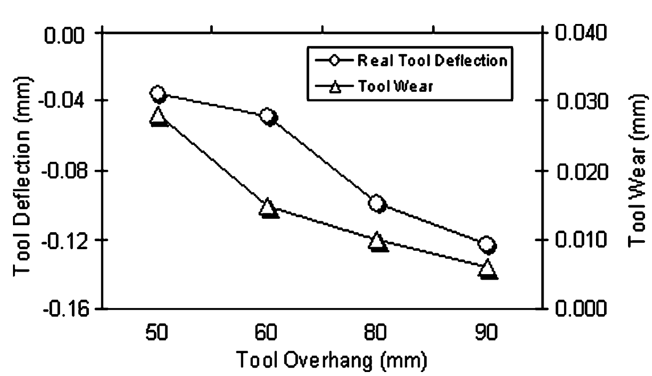


**Fig. 15** The relationship between tool wear and real deflection depend on the tool overhang (DOC: 1 mm)

In the graph shown in Fig. 14, in the determination of the tool deflection values that would be generated by the cutting force according to the tool overhang, we compared the values of the tool deflection obtained from two different analytical solutions with the results obtained from the experimental studies. We determined that the second analytical solution provides a better approach under anticipated working conditions.

Therefore, we observed that the results obtained from Eq. 1 provide less displacement than the results obtained from the second analytical solution under all experimental conditions.

For 1-mm DOCs, the difference between two approaches for a 50-mm tool overhang is 0.0093 mm and the deviation is 58.2%, whereas for a 90-mm tool overhang, the difference is 0.02 mm and the deviation is 18.8%. For 0.5-mm DOCs, the difference between two approaches for a 50-mm tool overhang is 0.0056 mm and the deviation is 52.0%, whereas for a 90-mm tool overhang, the difference is 0.011 mm and the deviation is 18.6%. The tool deflection decreases as the tool overhang reduces in both solutions, but the tool deflection deviation increases in the second analytical solution.

The relationship between the tool wear and displacement that was determined from the calibration is shown in Fig. 15. When we tested the 30 mm diameter workpiece for the possible development of tool wear at the tool contact areas described above and in Figs. 10 and 11, we observed that there is a relationship between the real tool deflection values of the tool and the wear tendency of the tool.

## 6 Conclusions

In this study, we investigated the effects of the changes in tool overhang on the surface quality of the workpiece and tool wear both experimentally and analytically. The tip of the cutting edge position of the tool under the influence of the cutting force was studied using two different analytical methods.

1. From the experiments performed on the anticipated machining parameters, we observed that the surface roughness of workpiece increases as the tool overhang increases. Using the same tool overhang, the surface roughness of the workpiece increases as the DOC increases. These results are compatible with the literature.
2. In the measurements performed after the experiments were complete, we observed that the cutting tool wear values decreased as the tool overhang increased, based on the determined wear values. The tool wear decreases as a result of the change in the geometry of the tool due to the displacement and the increment of the orthogonal clearance angle.
3. When the two analytical solutions for the deflection of the tool are compared, the tool deflection decreases as the tool overhang reduces in both of the solutions.
4. We observed that the second analytical solution in which the torque has been taken into account provides a better approach to real deflections than the other analytical solution under the selected working conditions.

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