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ORIGINAL ARTICLE

Effects of the cutting feed, depth of cut, and workpiece (bore) diameter on the tool wear rate

Viktor P. Astakhov

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Abstract Most published studies on metal cutting regard the cutting speed as having the greatest influence on tool wear and, thus, tool life, while other parameters and characteristics of the cutting process have not attracted as much attention in this respect. This is because of the existence of a number of contradicting results on the influence of the cutting feed, depth of cut, and workpiece (bore) diameter. The present paper discusses the origin of the aforementioned contradicting results. It argues that, when the optimal cutting temperature is considered, the influence of the aforementioned parameters on tool wear becomes clear and straightforward. The obtained results reveal the true influence of the cutting feed, diameter of the workpiece, and diameter of the hole being bored on the tool wear rate. It was also found that the depth of cut does not have a significant influence on the tool wear rate. The obtained results provide methodological help in the experimental assessment and proper reporting of the tool wear rates studied under different cutting conditions.

Keywords Metal cutting · Tool wear · Optimal cutting temperature · Cutting feed · Depth of cut · Diameter of the workpiece

Nomenclature

C_v, C_h	Constants determined by the properties of the work material (Eqs. 3 and 4)
$C_{v\text{-}o}$	Constant in Eq. 7
D_w	Workpiece diameter
d_{cw}	Depth of cold working
d_w	Depth of cut
f	Cutting feed
h_h	Dimensional wear rate
h_r	Radial wear
$h_{r\text{-}i}$	Initial radial wear
h_s	Surface wear rate
$h_{s\text{-}opt}$	Optimal wear rate
L_w	Workpiece length
l	Total length of the tool path
l_i	Initial length of the tool path
S	Area of the machined surface
T	Tool life
T_{UD}	Specific dimensional tool life
$T_{UD\text{-}o}$	Optimal specific dimensional tool life
t_1	Uncut chip thickness
v	Cutting speed
v_{opt}	Optimal cutting speed
x_v, x_h	Powers determined by the specifics of the machining operation (Eqs. 3 and 4)
$x_{v\text{-}o}$	Power in Eq. 7
θ_{opt}	Optimal cutting temperature
ζ	Chip compression ratio

V. P. Astakhov (✉)
Production Service Management Inc.,
1777 Highland Drive, Suite E,
Ann Arbor, MI 48108, USA
e-mail: astvik@lycos.com

1 Introduction

In deforming processes used in manufacturing, concern over tool wear is often overshadowed by considerations of forces or material flow. Except for hot extrusion, die life is measured in hours and days, or in thousands of parts [1]. In metal cutting, however, tool wear is a dominant concern because process conditions are chosen to give maximum productivity or economy, often resulting in tool life measured in minutes. Central to the problem are: high contact temperatures at the tool–chip and tool–workpiece interfaces, which lead to softening of the tool material and promotes diffusion and chemical (oxidation) wear; high contact pressures at these interfaces and sliding of freshly formed (juvenile) surfaces of the work material layers promote abrasive and adhesion wear [2]; cyclic nature of the chip formation process, which can cause cracking due to thermal fatigue.

The nature of tool wear, unfortunately, is not yet clear enough, in spite of numerous investigations. Although various theories have been introduced hitherto to explain the wear mechanism, the complexity of the processes in the cutting zone hampers the formulation of a sound theory of cutting tool wear. Cutting tool wear is a result of complicated physical, chemical, and thermomechanical phenomena. Because different "simple" mechanisms of wear (adhesion, abrasion, diffusion, oxidation, etc.) act simultaneously with predominant influence of one or more of them in different situations, identification of the dominant mechanism is far from simple, and most interpretations are subject to controversy [1]. These interpretations are highly subjective and are based on the evaluation of the cutting conditions, possible temperature and contact stress levels, relative velocities, and many other process parameters and factors. As a result, experimental, or post-process methods, are still dominant in the known studies of tool wear [1–12] and only topological or, simply, geometrical parameters of tool wear are selected and, thus, reported on in tool wear and tool life studies.

As discussed in [13, 14], the cutting temperature is understood as the mean integral temperature at the tool–chip and tool–workpiece interfaces as measured by a tool-work thermocouple. As conclusively proven by Makarow [15], the temperature is the most suitable parameter to correlate the tribological conditions at the discussed interfaces with tool wear. Therefore, the correlation of the cutting temperature with parameters of the cutting system should be established.

Analyzing a great body of experimental data, Makarow [15] formulated the law which was presented as the first metal cutting law (Makarow's law) by Astakhov [13, 14]:

> For given combination of the tool and workpiece materials, there is the cutting temperature, referred to as the optimal cutting temperature θ_{opt}, at which the combination of minimum tool wear rate, minimum stabilized cutting force, and highest quality of the machined surface is achieved. This temperature is invariant to the way it has been achieved (whether the workpiece was cooled, pre-heated, etc).

It was discussed by Astakhov [13] that the pure geometrical characteristics of tool wear as the depth of the crater KT and relief face or flank wear VB are unsuitable for proper wear characterization. First, they do not account for the tool geometry (the flank angle, the rake angle, the cutting edge angle, etc.), so they are not suitable for comparing the wear parameters of cutting tools having different geometries. Second, they do not account for the cutting regime (the cutting speed and feed(s)) and, thus, they do not reflect the real amount of the work material removed by the tool during the tool operating time, which is defined as the time needed to achieve the chosen tool life criterion (KT or VB).

To evaluate tool wear objectively, the surface wear rate as the radial wear per 1,000 sm^2 of the machined area (S) was introduced [13, 15] as follows:

$$h_s = \frac{dh_r}{dS} = \frac{(h_r - h_{r-i})100}{(l - l_i)f} \quad \left(\mu m/10^3 sm^2\right) \tag{1}$$

where $h_{\text{r-i}}$ and l_{i} are the initial radial wear and the initial length of the tool path, respectively, and l is the total length of the tool path.

As follows from Eq. 1, the surface wear rate is inversely proportional to the overall machined area, and it does not depend on the selected wear criterion.

Using the notion of the optimal cutting temperature, the present work aims to reveal and clarify for practical use the influence of the cutting feed, depth of cut, and workpiece (bore) diameter on the tool wear rate.

2 Influence of the cutting feed

The cutting regime is understood as a particular combination of the cutting speed, cutting feed (feed rate), and depth of cut. It is well known that the listed parameters of the cutting regime affect the tool life [16].

2.1 Influence of the cutting feed in a wide range of cutting parameters

The uncut chip thickness or the cutting feed has a direct influence on the quality, productivity, and efficiency of machining. It is believed that the tool life decreases (and, thus, tool wear increases) with increasing cutting feed [5, 16–18]. Such a conclusion follows from the generally adopted equation for tool life. For example, generalizing the experimental data, Gorczyca proposed (Eq. 5.9 in [18]) the following relation:

$$T = \frac{48.36 \times 10^6}{v^4 f^{1.6} d_w^{0.48}} \tag{2}$$

If the cutting speed v and the depth of cut d_{w} are both constant, then it follows from Eq. 2 that tool life decreases when the cutting feed f is increased.

A great body of data to support the discussed point and, thus, the structure of Eq. 2 can be found in the literature on metal cutting, although many researches, starting with Taylor [19], did not include the cutting feed in their tool life equations because they did not consider this parameter as having a significant influence on tool life, while others found that the experimentally obtained relation “tool wear–cutting feed” has a distinctive minimum. Such a great variation in the experimental results can be explained by the fact that the cutting tests were carried out under variable cutting speeds, which resulted in different cutting temperatures.

To gain an understanding of the true influence of the cutting feed on tool wear, this influence should be considered in the context of the other parameters of the cutting process that make contributions to the cutting temperature. As such, the influence of the cutting feed (the uncut chip thickness) on the surface wear rate [13] is of prime interest while keeping invariable the area of the machined surface (or the volume of the removed work material) in contrary to the length of the cutting path. This is because the area of the machined surface (or the volume of the removed work material) does not change with the cutting feed, while the length of the tool path does.

Studying the influence of the cutting feed on the tool wear, the following factors should be considered [15]:

Factor 1 When the cutting feed increases (and v is constant), the length of the tool path decreases (for a given length of the workpiece). As a result, the cutting (contact) time decreases, as well as the corresponding tool wear. Therefore, the relative surface wear decreases.

Factor 2 Any change in the cutting feed leads to a corresponding change in the cutting temperature, so the cutting feed should influence the tool wear rate. As such, there are three basic cases: (a) if the current machining takes place using a relatively low cutting speed so that the cutting temperature is lower than the optimal cutting temperature, then an increase in the cutting feed leads to a decrease in the tool wear rate; (b) if the current machining takes place using an “average” cutting speed so that the cutting temperature passes its optimum with an increase in the cutting feed, then the relation h_s=(f) has a distinctive minimum. In other words, increasing the cutting feed until the cutting temperature remains below the optimal cutting temperature reduces the tool wear rate, while any further increase would increase this wear rate; (c) if the current machining takes place using a high cutting speed, i.e., when the cutting temperature is higher than the optimal cutting temperature, then any increase in the cutting feed should lead to an increase in the tool wear rate.

Factor 3 The tool actually cuts the transient surface (the surface being cut by the major cutting edge located between the surface to be machined and the machined surface). Because, in most practical machining operations, the tool cuts the part of the transient surface formed on the previous tool pass, the amount of cold working imposed by this tool on the previous pass affects the cutting conditions on the current pass. Among other characteristics, the depth of cold working, d_{cw}, with respect to the uncut chip thickness t_1 is of prime concern. When the cutting feed (the uncut chip thickness) is small, then it can happen that $d_{cw}>t_1$, so the major cutting edge cuts the cold-worked work material characterized by a greater strength and higher hardness compared to those of the original work material. As such, the tool wear rate increases. If, when this is the case, one increases the cutting feed, then the uncut chip thickness becomes greater than d_{cw}, so tool wear rate decreases.

Factor 4 Increasing the cutting feed leads to a corresponding increase in the normal contact stress at the tool–chip interface and in the tool–chip contact area (length) [20]. However, the contact area increases at much smaller rate compared to the normal contact stress [15]. When the level of the normal contact stress reaches a certain tool-material specific limit, the chipping of the cutting edge takes place, which eventually leads to tool breakage. Such a limit can be referred to as the breaking feed. Normally, the cutting feed used in machining common work materials is below the breaking feed. However, in hard turning, an operation that is attracting more and more attention in the automotive and aerospace industries, the breaking feed is normally well below those allowed by the surface finish of machined parts and by the power of the machine tools used, so the working cutting feed can be in close proximity of the breaking feed.

Factor 5 Often, the intensity of the vibrations that take place in machining reduces with the cutting feed. When this happens, the tool wear rate reduces. Moreover, increasing the cutting feed changes the ratio of the radial, F_y, and the axial (feed), F_x, forces that increases the dynamic rigidity of the machine tool.

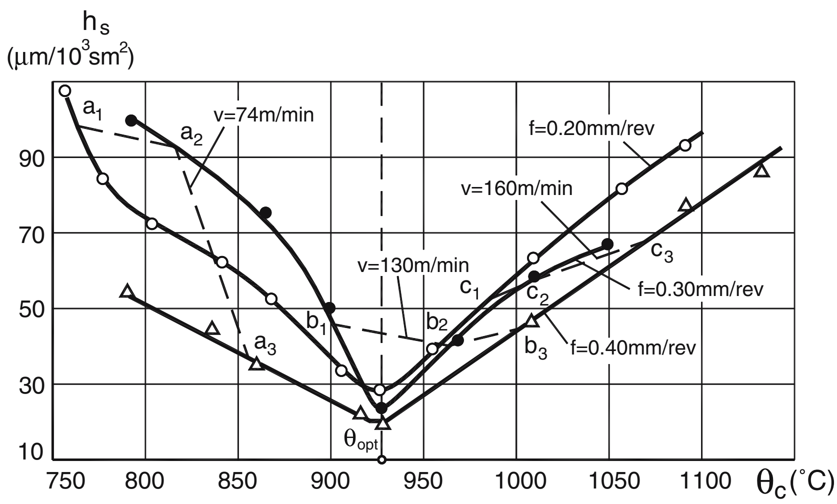

Fig. 1 Influence of the cutting temperature on the relative surface tool wear rate in turning AL 610 alloy, tool material: carbide P10 (14%TiC, 8% Co), depth of cut d_w=1 mm

Summarizing the above considerations, one should realize that, when the cutting feed increases, the cumulative effect of the discussed factors may affect the tool wear rate in considerably different ways, depending upon the many parameters and characteristics of a particular cutting system. Makarow [15] found that the effect of the cutting feed becomes more pronounced when machining difficult-to-machine materials having a great number of allying components.

2.2 Experimental study

A series of turning tests were carried out. The test setup, methodology, and conditions were the same as discussed earlier by Astakhov and Shvets [21]. The study aimed to reveal the influence of the cutting feed on the relative surface wear rate, h_s in machining AL 610 alloy. AL 610 is a low-carbon (less than 0.015 wt.%), silicon-containing (up to 4.3 wt.% Si), chromium (up to 18.5 wt.% Cr), nickel (up to 15.5 wt.% Ni) austenitic stainless steel. This alloy is typically used for applications in the chemical industry. The high silicon content provides good resistance to oxidizing environments, such as concentrated nitric acid, over a wide range of temperatures.

In the tests, the feed was selected to be in the range 0.2–0.4 mm/rev, which is commonly used in the industry for this alloy. As such, the uncut chip thickness is greater than the depth of cold working, there were no noticeable vibrations, no chipping of the cutting edge and tool breakages, so Factors 3, 4, and 5 did not affect the tool wear rate as the cutting feed was increased. Therefore, the relation h_s=(f) was determined only by Factors 1 and 2.

Factor 1 always reduces the tool wear rate with increasing cutting feed. To study the influence of Factor 2, the cutting temperature was determined as a function of the cutting regime. The result is shown in Fig. 1. The different cutting temperatures were obtained by varying the cutting speed.

Consider the change in the cutting temperature and tool wear rate when the cutting feed changes from 0.2 mm/rev to 0.4 mm/rev at three different cutting speeds, 75 m/min, 130 m/min, and 160 m/min. As seen in Fig. 1, when the cutting feed increases in a zone where the resulting cutting temperature is less than θ_{opt}, this increase leads to the reduction of the tool wear rate. The opposite happens then the cutting temperature exceeds θ_{opt}. When the cutting speed is v=75 m/min, an increase in the feed from 0.2 mm/rev to 0.4 mm/rev leads to the increase in the cutting temperature within the left branch of curve h_s=(f). As such, the higher the cutting feed, the higher the cutting temperature, the lower tool wear rate (points a_1, a_2, and a_3). Therefore, Factors 1 and 2 reduce tool wear rate with increasing cutting feed. When the cutting speed is v=130 m/min, increasing the feed from 0.2 mm/rev to 0.4 mm/rev causes the cutting temperature to pass its optimum. As such, the increase of the cutting feed from 0.2 mm/rev to 0.3 mm/rev leads to an increase in the cutting temperature and reduction of the tool wear rate, while the increase of the cutting feed from 0.3 mm/rev to 0.4 mm/rev leads to the increase of the tool wear rate (points b_1, b_2, and b_3). In the latter transition, Factors 1 and 2 work simultaneously, but in opposite manners in terms of their influence on the tool wear rate. The influence of Factor 2 is stronger, which causes an increase in the tool wear rate. When the cutting speed is v=160 m/min, any increase of the cutting feed leads to an increase of the tool wear rate. Points c_1, c_2, and c_3 show what happens when the cutting feed increases from 0.2 mm/rev to 0.3 mm/rev, and then to 0.4 mm/rev, respectively.

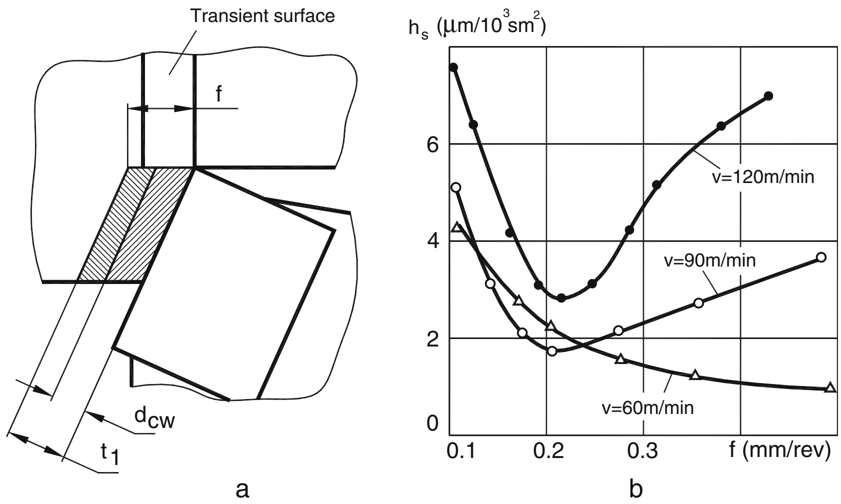

Fig. 2a, b Illustration of the depth of cold working of the transient surface (**a**) and influence of the feed on the tool wear rate (**b**), work material: stainless steel AISI 303, tool material: carbide M10 (97%WC, 3%Co), depth of cut d_w=0.5 mm

As follows from the above consideration, the influence of the cutting feed on the tool wear rate is different at different cutting speeds. In the considered case, the major factor affecting the tool wear rate is the cutting temperature.

Factor 3 is extremely important, but is practically always ignored in metal cutting theory and practice. As discussed above, the tool major cutting edge actually cuts the transient surface. Because, in most practical machining operations, the tool cuts the part of the transient surface formed on the previous tool pass, the amount of cold working imposed by this tool on the previous pass affects the cutting conditions on the current pass. Among the other characteristics of strainhardening, the depth of cold working, d_{cw} with respect to the uncut chip thickness t_1 is of prime concern (Fig. 2a). This is particularly important when cutting at low feeds, i.e., when the uncut chip thickness is smaller than the depth of cold working, i.e., when $d_{cw}>t_1$. When this happens, the major cutting edge cuts the cold-worked material, characterized by a greater strength and greater hardness. As such, the tool wear rate increases. Figure 2b illustrates this point. When the feed is 0.1 mm/rev, the depth of cold working is greater than the uncut chip thickness, so the cutting wedge cuts the cold-worked work material, which results in a greater tool wear rate. In the feed range of 0.1–0.2 mm/rev, the influence of Factor 1 leads to the reduction of the tool wear rate. When the feed is increased further, the influence of Factor 2 becomes predominant, which increases the tool wear rate.

2.3 Influence of the cutting feed under the optimal cutting temperature

Understanding the influence of the cutting feed under the optimal cutting temperature is important in the selection of the optimal cutting regime because the optimal combination of cutting speeds and feeds should be used in the practice of metal cutting.

Makarow [15] proved that the correlation between the optimal cutting speed and feed, as well between the optimal wear rate and feed can be established as:

$$v_{opt} = \frac{C_v}{f^{x_v}} \tag{3}$$

$$h_{s-opt} = \frac{C_h}{f^{x_h}} \tag{4}$$

where C_v and C_h are constants determined by the properties of the work material, and x_v and x_h are the powers determined by the specifics of the machining operation.

The dimensional tool life T_D can be represented as a product of the tool radial wear, h_r and the specific dimensional tool life, T_{UD} (defined in [13] as the area of the workpiece surface machined per 1 micrometers of the radial tool wear):

$$T_D = h_r T_{UD} \times 10^3 \left(sm^2\right) \tag{5}$$

As discussed above, the lower the wear rate, h_s, the higher the specific dimensional tool life, the greater the number of parts that can be machined without correction/compensation of the tool. The specific dimensional tool life corresponding to the optimal surface wear can be referred to as the optimal specific dimensional tool life, $T_{UD\text{-}o}$. Therefore, the optimal specific dimensional tool life can be represented as:

$$T_{D-o} = h_r T_{UD-o} = \frac{h_r}{C_h/f^{x_h}} = \frac{h_r}{C_h} f^{x_h} \tag{6}$$

Because C_h is constant, then, when h_r is constant, the dimensional tool life is proportional to the power x_h. The

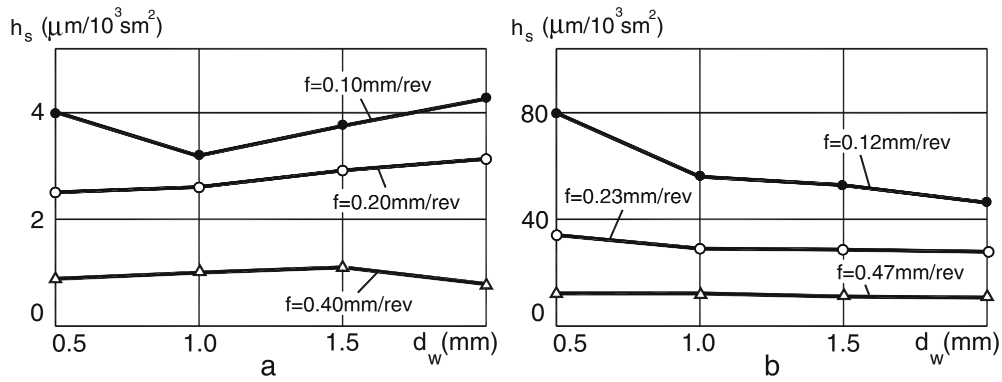

Fig. 3a, b Influence of the depth of cut on the tool wear rate. **a** Cutting with the invariable cutting speed optimal for d_w=0.5 mm, work material: stainless steel AISI 303, tool material: carbide M10 (97%WC, 3%Co). **b** Cutting with the invariable optimal cutting temperature determined for d_w=1.0 mm, work material: AL 610 alloy, tool material: carbide M20 (92%WC, 8%Co)

results of the multiple cutting tests carried out by Makarow [15] allowed him to conclude that this power is in the range 0.31–1.75 and is always positive. Therefore, in machining, if the optimal temperature is kept invariable, an increase in the cutting feed leads to an increase in the dimensional tool life. The greater the x_h, the stronger the influence of the feed on the dimensional tool life, the greater the increase of the dimensional tool life with the cutting feed. For example, a four-fold increase in the cutting feed (from 0.10 mm/rev to 0.40 mm/rev) in turning stainless steel AISI 303 using an M20 (94%WC, 6%Co) carbide tool (power x_h=1.3) led to the increase in the dimensional tool life of 6.2 times, while a 3.28-times increase was achieved in the same operation when a P10 (30%TiC, 66%WC, 4%Co) tool was used (power x_h=0.88) [15].

3 Influence of the depth of cut

When the depth of cut increases and the uncut chip thickness is kept the same, the specific contact stresses at the tool–chip interfaces, the chip compression ratio (defined as the radio of the chip and the uncut chip thicknesses [14, 16, 21]), and the average contact temperature remain unchanged. Therefore, an increase in the depth of cut should not change the tool wear rate if the machining is carried out at the optimum cutting regime.

Figure 3a shows the influence of the depth of cut on the tool wear rate. In the test, the cutting speed was determined to be optimal for the depth of cut d_w=0.5 mm, and was kept invariable for the other depths of cut. As seen, the depth of cut has very little influence on the tool wear rate. In other series of tests, the optimal cutting temperature was determined for d_w=1.0 mm, and was kept invariable in the test. The test results are shown in Fig. 3b. As seen, the depth of cut has little influence on the tool wear rate.

4 Influence of the workpiece diameter

The diameter of the workpiece affects the cutting process in various ways, such as:

- The static rigidity of the machining system depends on the workpiece diameter. In boring, the diameter of the hole being bored often determines the diameter of the boring bar or arbor, and, thus, effects the static and dynamic stability of the machining system.
- The workpiece diameter affects the curvature on the surface being cut, which, in turn, affects the stressed-deformed state of the layer being removed. As a result, the final inclination angle and the total length of the surface of the maximum combined stress (often referred to as the shear angle and the length of the shear plane) change with the workpiece diameter.
- When the cutting speed is kept invariable, the rotational speed (r.p.m.) changes with the workpiece diameter, which affects the dynamics of the process.
- As was discussed by Astakhov [22], the interaction of the thermal and deformation waves takes place in metal cutting. As such, if the cutting speed and feed are kept invariable, the time of one turn of the workpiece changes with its diameter, which greatly affects the discussed interactions. In more simple words, less residual thermal energy left by the previous tool pass is available at the current pass when the diameter of the workpiece increases.

In practical testing, it is important to separate the influence of each factor so as to conduct tests with different workpiece diameters to exclude the influence of the system rigidity. To do so, the workpiece diameter, D_w, and its length, L_w, were selected accordingly to keep the ratio L_w^3/D_w^4 invariable.

The cutting tests were carried out in which the two diameters of the workpiece, 15 mm and 29 mm, were used.

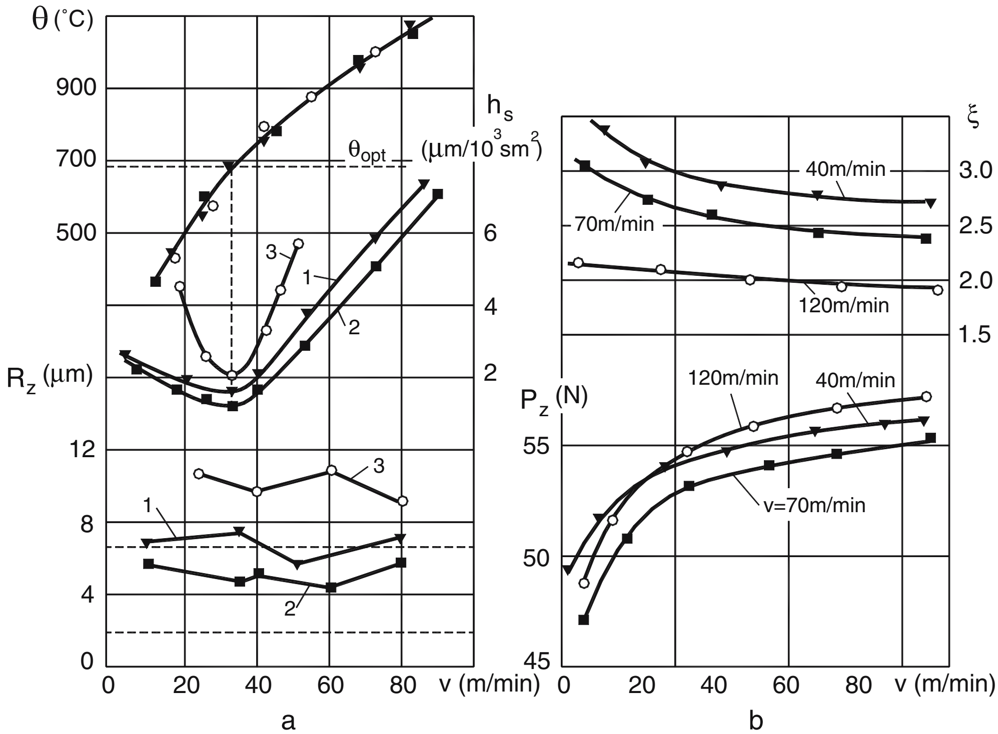

Fig. 4a, b Influence of the cutting speed and diameter of the workpiece in turning: (**a**) on the cutting temperature, tool wear rate, and roughness of the machined surface, work material: custom-modified Haynes 263 alloy (0.02%C, 20%Cr, 2%Ti, 2%Al) using a cutting tool made of carbide M10 (94%WC, 6% Co), depth of cut d_w=0.25 mm, cutting feed f=0.09 mm/rev, 1: D_w=29 mm, L_w=230 mm, 2: D_w=16 mm, L_w=95 mm, 3: D_w=15 mm, L_w=230 mm; (**b**) on the chip compression ratio and cutting force, work material: Haynes 263 alloy (29%Cr, 2.5% Ti), tool material: carbide M20 (92%WC, 8%Co), depth of cut d_w=0.25 mm, cutting feed f=0.09 mm/rev

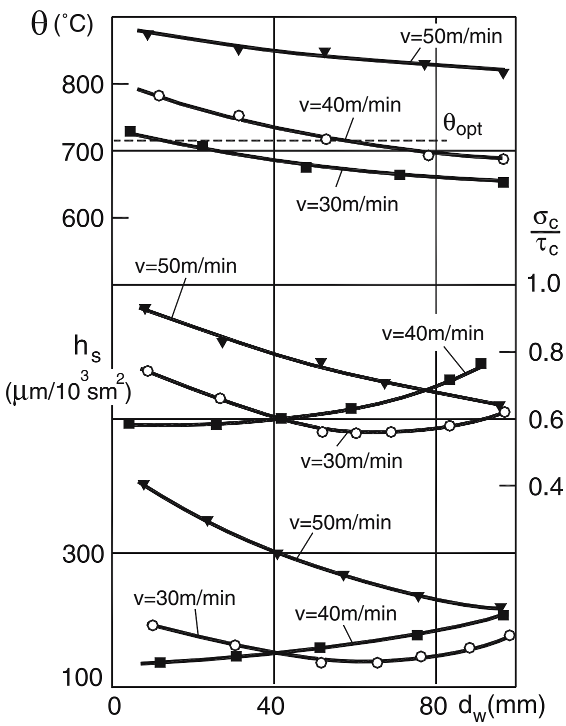

Fig. 5 Influence of the cutting speed and diameter of the workpiece on the cutting temperature, contact stress ratio at the tool–workpiece interface, and optimal tool wear rate in turning, work material: Haynes 263 alloy (29%Cr, 2.5%Ti), tool material: micrograin carbide M10 (94% WC, 6%Co), depth of cut d_w=0.25 mm, cutting feed f=0.09 mm/rev

At first, the length of the workpiece was selected to keep the same rigidity (51×10^3 N/mm). Then, the invariable workpiece diameter was used while the length (and, thus, rigidity) of the workpiece was varied. The test results are shown in Fig. 4a. As seen, when the rigidity is kept invariable (by a corresponding reduction in L_w), decreasing the workpiece diameters leads to a certain reduction in the tool wear rate, as well in the roughness of the machined surface. However, if, under the same conditions, L_w is not changed, the tool wear rate and surface roughness increase significantly.

Calculations show that the total length of the surface of the maximum combined stress (often referred to as the length of the shear plane) insignificantly depends on the workpiece diameter. For example, changing the diameter from 10 mm to 500 mm leads to a 5–7% increase in the total length of the surface of the maximum combined stress (shear plane), depending upon the rake angle and the uncut chip thickness. On this basis, one should expect some reduction in the chip compression ratio when the diameter of the workpiece decreases. The test results, however, do not support this hypothesis. As seen in Fig. 4b, with decreasing diameter, a certain increase of the chip compression ratio is the case. This is explained by the reduction in the energy required for the fracture of the layer being removed due to the increased amount of residual thermal energy (higher temperature) from the previous tool pass [22].

Table 1 Values of $C_{v\text{-}o}$ and $X_{v\text{-}o}$ in Eq. 7 for the depth of cut d_w=0.25 mm and feed f=0.09 mm/rev

Materials		Diameter of workpiece	$C_{v\text{-}o}$	$x_{v\text{-}o}$
Workpiece	Tool			
Steel AISI 1045	P20 (15%TiC, 6%Co, 79%WC)	35–130	141	0.125
Custom-modified Haynes 263 alloy (0.02%C, 20%Cr, 2%Ti, 2%Al)	Micrograin carbide M10 (94%WC, 6%Co)	20–50	20.4	0.200
Haynes 263 alloy (29%Cr, 2.5%Ti)	Micrograin carbide M10 (94%WC, 6%Co)	22–90	17.9	0.175

This was proved by using a water-based (greater cooling ability) cutting fluid for the same test conditions. When such a fluid was used, the chip compression ratio increases with decreasing workpiece diameter, although such a reduction is poorly correlated with the test conditions. This is due to the variations in the interaction of the thermal and deformation waves, which also depends on the workpiece diameter [22].

The influence of the workpiece diameter shows up through the cutting temperature. When cutting with low cutting speeds (v=30 m/min), increasing the workpiece diameter lowers the cutting temperature, reducing it with respect to the optimal cutting temperature, the ratio of the contact stresses, and the tool wear rate increase, as seen in Fig. 5. When cutting with high cutting speeds (v=70 m/min), increasing the workpiece diameter reduces the cutting temperature, bringing it closer to the optimal cutting temperature, so the contact stress ratio and tool wear rate reduce. When cutting with moderate cutting speeds (v=40 m/min), increasing the workpiece diameter first leads to decreasing tool wear rate and contact stress ratio when the cutting temperature reduced to the optimal cutting temperature. When the cutting temperature reduces to below the optimal cutting temperature, however, increasing the workpiece diameter leads to increasing tool wear rate and contact stress ratio.

The influence of the workpiece diameter at the optimal cutting speed can be expressed by the following empirical relation:

$$v_{opt} = C_{v-o} D_w^{x_{v-o}} \qquad (7)$$

Table 1 presents the value of $C_{v\text{-}o}$ and $x_{v\text{-}o}$ for some work conditions and materials.

The diameter of the hole being machined affects the cutting process significantly in boring operations. The smaller the diameter of the hole being machined (when the cutting speed is kept invariable), the greater the chip compression ratio and, thus, the work of plastic deformation [21]. As a result, the cutting temperature increases.

The influence of the diameter of the hole being machined in boring was studied experimentally. In the boring tests, stainless steel AISI 303 was used as the workpiece material, the diameters of the bored holes were 17 mm, 26 mm, and 37 mm. The cutting regime was as follows: depth of cut d_w=0.30 mm, cutting speed v=40–160 mm/min, maximum radial tool wear h_r=50 μm. Figure 6 shows the influence of the cutting speed on the electromotive force (e.m.f.), chip compression ratio, and tool wear rate in boring. As can be seen, the optimal tool wear rate depends on the diameter of the hole being machined (when the optimal cutting temperature is kept invariable). As such, with increasing hole diameter, the optimal cutting speed increases and the tool wear rate and the chip compression ratio decrease. Figure 7 exemplifies these conclusions.

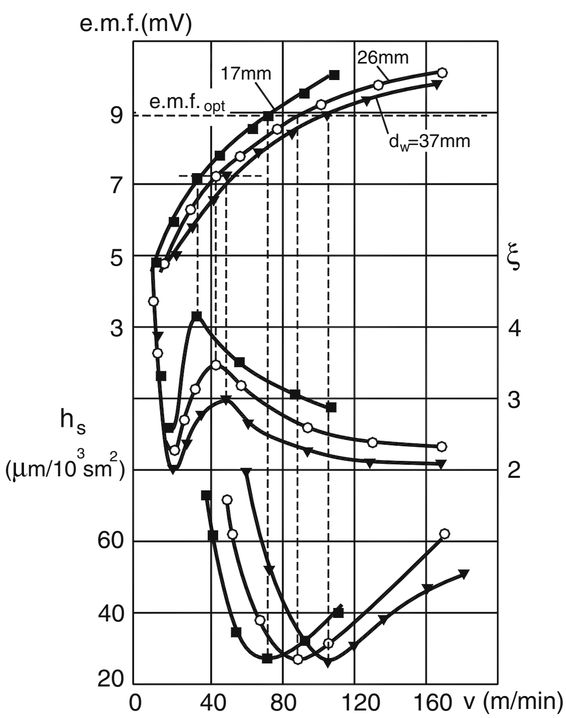

Fig. 6 Influence of the cutting speed and diameter of the hole being machined on the cutting temperature and the tool wear rate, work material: stainless steel AISI 303, tool material: carbide M20 (92% WC, 8%Co), depth of cut d_w=0.30 mm, cutting feed f=0.06 mm/rev

In the boring of holes using cutting tools made of carbide K10 (92%WC, 8%Co) when the work material is

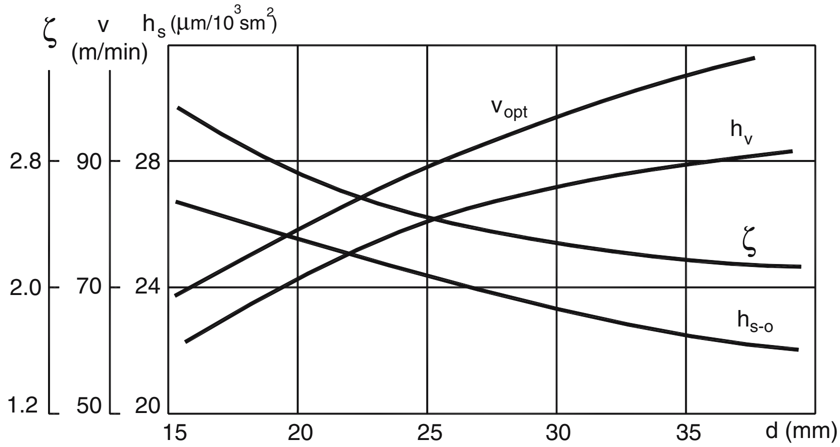

Fig. 7 Influence of the diameter of the hole being machined on $h_{s\text{-}o}$, v_{opt}, v_{ho}, and ζ at the invariable optimal cutting temperature. Turning, work material: stainless steel AISI 303, tool material: carbide M20 (92%WC, 8%Co)

stainless steel AISI 303 using the above-indicated cutting regime, the optimal cutting speed and optimal tool wear rate correlated with the hole diameter, D_w as:

$$v_{opt} = 16.6 D_w^{0.52} \ (m/min) \tag{8}$$

$$h_{s-opt} = \frac{48.8}{D_w^{0.22}} \ \left(\mu m/10^3 \ \ sm^2\right) \tag{9}$$

Using these equations, one can calculate the optimal cutting speed and the optimal tool wear rate for a wide range of diameters of the machined hole.

When the diameter of the machined hole increases and the cutting temperature is kept invariant and equal to the optimal cutting temperature, the chip compression ratio, ζ, increases. Under this condition, it can be calculated as:

$$\zeta = \frac{9}{D_w^{0.4}} \tag{10}$$

When the optimal cutting temperature is kept invariant, the dimensional wear rate [13] correlates with the hole diameter as:

$$h_h = 0.486 D_w^{0.30} \ (\mu m/min) \tag{11}$$

the total tool life is:

$$T = \frac{h_r}{h_h} = \frac{2.06 h_r}{D_w^{0.30}} \ (min) \tag{12}$$

and the dimensional tool life is:

$$T_D = \frac{h_r}{h_{s-opt}} = 205 h_r D_w^{0.22} \ \left(sm^2\right) \tag{13}$$

With increasing diameter of the hole being machined (when θ_{opt} is constant), the total tool life decreases (the dimensional wear rate increases), while the dimensional tool life increases. This apparent contradiction is explained by the fact that, if θ_{opt} is constant, the boring of holes of greater diameters requires higher cutting speeds, so, for a shorter total tool life, the tool would machine a greater area.

When boring with low cutting speed (v=72 m/min), increasing the workpiece diameter leads to a significant increase in the tool wear rate. This happens because the cutting temperature at v=72 m/min for diameter D_w=37 mm is below the optimal cutting temperature. When boring with a moderate cutting speed (v=90 m/min), increasing the diameter of the hole being machined in boring first leads to decreasing the tool wear rate, as the cutting temperature reduces, becoming closer to the optimal cutting temperature, then, reaching its minimum at the optimal cutting temperature, the tool wear rate increases as the cutting temperature becomes lower than the optimal cutting temperature. When machining with a high cutting speed (v=110 m/min), the tool wear rate reduces monotonely with increasing hole diameter. This is because the cutting temperature is high, so increasing the hole diameter leads to its reduction, so it becomes closer to the optimal cutting temperature.

The foregoing analysis shows that, in boring, the established optimal cutting speed for a certain diameter of hole being machined cannot be used if this diameter is changed. For example, if a hole of 37-mm diameter is bored at the cutting speed of 72 m/min (which is optimal for a hole of 17-mm diameter), then the dimensional tool life reduces by 2.36 and the productivity of machining reduces by 1.5, compared to those obtained at the cutting speed of 105 m/min, which is the optimal cutting speed for the latter hole diameter.

5 Conclusions

1. The notion of optimal cutting temperature resulting in the formulation of the first metal cutting law is very useful in the analysis of the influence of various parameters of the cutting process on tool wear, as it makes such an analysis simple and straightforward.

2. There are least five independent factors that determine the influence of the cutting feed on tool wear. Among them, the length of the tool path and the cutting temperature are of prime importance. As a result, the influence of the cutting feed on the tool wear rate is different at different cutting speeds.
3. As the cumulative effect of the discussed factors may affect the tool wear rate in considerably different ways depending upon many parameters and characteristics of a particular cutting system, these factors must be considered in any metal cutting testing and/or in the implementation of cutting tools on the shop floor.
4. At the optimal cutting temperature, the increase of the cutting feed leads to increased dimensional tool life.
5. Influence of the depth of cut on the tool wear rate is negligibly small if the machining is carried out at the optimum cutting regime.
6. The diameter of the workpiece has a strong influence on the cutting temperature and, thus, on the tool wear rate and the roughness of the machined surface. This is because this diameter affects the static and dynamic rigidity of the machining system, curvature of the surface being cut, and interaction of the thermal and deformation waves in the layer being removed.
7. The diameter of the hole being machined affects the cutting process significantly in boring operations. In the range of optimum cutting speeds, the smaller the diameter of the hole being machined, the smaller the optimum cutting speed, the greater the chip compression ratio, and, thus, the work of plastic deformation, the greater the tool wear rate.

Apart from being of particular practical significance, the obtained experimental results should be considered as methodological help in the experimental assessment and proper reporting of the tool wear rates studied under different cutting conditions.

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