EFFECTS OF THE CUTTING FEED AND WORKPIECE (BORE) DIAMETER ON THE TOOL WEAR RATE

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Abstract

The 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 did not attract much attention in this respect. As a result, the Taylor's tool life that correlated the tool life and the cutting speed is still in almost exclusive use today even at the level of National and International Standards. Among these neglected parameters the cutting feed and workpiece (bore) diameter are of prime importance. Unfortunately, the existence of a number of contradictive results on the influence of these parameters on tool life complicates the matter even further.

The present paper discusses the origin of the mentioned contradictive results. It argues, that, when the proper assessment (using the proposed metric) of cutting tool wear is used and the optimal cutting temperature is considered, the influence of the mentioned parameters on tool wear and thus on tool life becomes clear and straightforward. The obtained results reveal the true influence of the cutting feed and diameter of the workpiece and diameter of the hole being bored on the tool wear rate. It is shown that this influence is particularly significant when difficult-to-machine materials are machined. The obtained results also provide a methodological help in the experimental assessment and proper reporting of the tool wear rate studied under different cutting conditions.

Introduction

In deforming processes used in manufacturing, concern over the 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 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 clear enough yet in spite of numerous investigations. Although various theories have been introduced hitherto to explain the wear mechanism, the complicity of the processes in the cutting zone hampers formulation of a sound theory of cutting tool wear. Cutting tool wear is a result of complicated physical, chemical, and thermo-mechanical 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, the identification of the dominant mechanism is far from simple, and most interpretations are subject to controversy [1]. These interpretations are highly subjective and 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 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 tool-work thermocouple. As conclusively proven by Makarow [15], this temperature is the most suitable parameter to correlate the tribological conditions at the discussed interfaces with tool wear. Therefore, the correlation of this temperature with parameters of the cutting system should be established.

Analyzing a great body of experimental data, Makarow formulated the law [15] which was presented as the first metal cutting law (the 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 to compare 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 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 is the radial wear per 1000 cm^2 of the machined area (S) was introduced [13, 15] as follows

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

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

As follows from Equation (1), the surface wear rate is reverse 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, and workpiece (bore) diameter on the tool wear rate.

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 tool life [16].

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

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

$$T = \frac{48.36 \cdot 10^6}{v^4 f^{1.6} d_w^{0.48}} \qquad (2)$$

If the cutting speed $v = Const$ and the depth of cut $d_w = Const$ then it follow from Equation (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 Equation (2) can be found in literature on metal cutting although many researches, starting with Taylor [19], did not include the cutting feed in tool life equations because they did not considered this parameters as having significant influence on this life while other found that the experimentally obtained relation “tool wear-cutting feed” has a distinctive minimum. Such a great scatter in the experimental results can be explained by the fact that the cutting tests were carried out under invariable cutting speed that resulted in different cutting temperatures.

To gain understanding of the true influence of the cutting feed on tool wear, this influence should be considered in the context of 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 cutting feed increases (and $v = Const$), 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 the 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 the cutting temperature is lower than the optimal cutting temperature then an increase in the cutting feed leads to a decrease in tool wear rate, (b) if the current machining takes place using an “average” cutting speed so the cutting temperature passes its optimum with an increase in the cutting feed then 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 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 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 affect the cutting conditions on the current pass. Among other characteristic, 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 compare to those of the original work material. As such, 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 the 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 in much smaller rate compare 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 that 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, the operation that attracts 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 power of the machine tools used so the working cutting feed can be in a close proximity of the breaking feed.

Factor 5: Often, the intensity of vibrations that take place in machining reduces with the cutting feed. When it happens, 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.

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

Experimental Study

A series of turning tests were carried out. The test setup, methodology and conditions were the same as discussed earlier in [21]. The study aimed to reveal the influence of the cutting feed on the relative surface wear rate, h_s in machining AL610 alloy. AL610 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 of $(0.2..0.4)\,mm/rev$ with is commonly used in 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, 5 did not affect 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 tool wear rate with increasing the cutting feed. To study the influence of Factor 2, the cutting temperature was determined as function of the cutting regime. The result is shown in Figure 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*, *130* and $160\ m/\min$. As seen in Figure 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 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 an

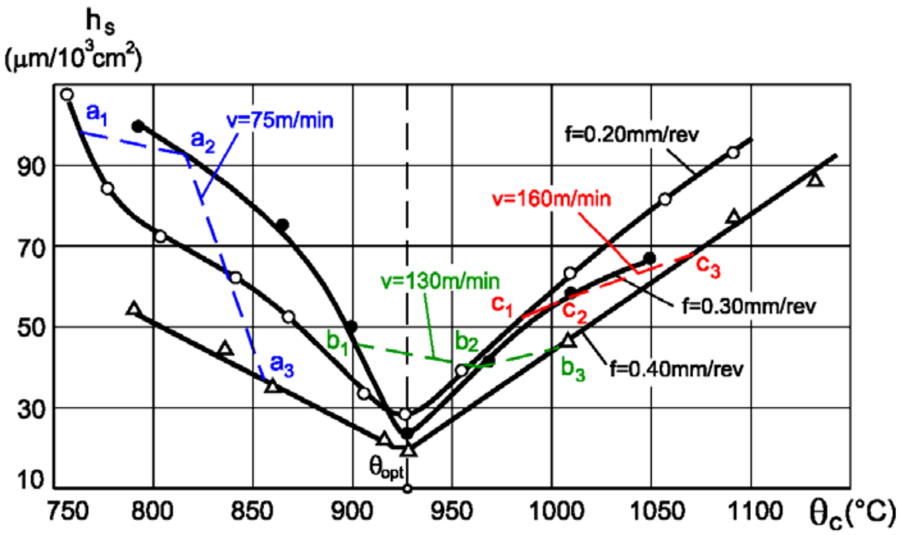

Fig. 1. The influence of the cutting temperature on the relative surface tool wear rate in turning AL 610 alloy. Tool material – carbide P10 (14%TiC,8%Co). Depth of cut $d_w = 1\ mm$.

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, a_3). Therefore, Factors 1 and 2 reduce tool wear rate with increasing the 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 the increase in the cutting temperature and reduction of 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 tool wear rate (points b_1, b_2, b_3). In the latter transition, Factors 1 and 2 work simultaneously but in opposite manner in terms of their influence on the tool wear rate. The influence of Factor 2 is stronger that causes an increase in tool wear rate. When the cutting speed is $v = 160\ m/\min$, any increase of the cutting feed leads to an increase of tool wear rate. Points c_1, c_2, 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.

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

Factor 3 is extremely important but 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 affect the cutting conditions on the current pass. Among other characteristic of strain hardening, the depth of cold working, d_{cw} with respect to the uncut chip thickness t_1 is of prime concern. 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 $d_{cv} > t_1$. When it happens, the major cutting edge cuts the cold worked work material characterized by a greater strength and higher hardness. As such, tool wear rate increases. Figure 2 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 that results in greater tool wear rate.

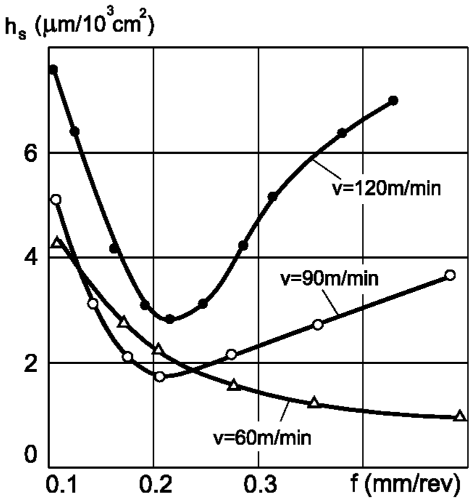

Fig. 2. Illustration of the depth of cold working of the transient surface (a) and influence of the feed on tool wear rate (Work materials – stainless steel AISI 303, tool material – carbide M10 ((97%WC,3%Co), depth of cut $d_w = 0.5\ mm$.

In the feed range of $(0.1...0.2)\ mm/rev$, the influence of Factor 1 leads to the reduction of tool wear rate. When the feed is increased further, the influence of Factor 2 becomes predominant that increases tool wear rate.

Influence of the cutting feed under the optimal cutting temperature

Understanding 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 proved [15] 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, C_h are constants determined by the properties of the work material, x_v, x_h are the powers determined by the specifics of the machining operation.

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

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

As discussed above, the lower the wear rate, h_s, the higher the specific dimension tool life, the greater number of parts can be machined without correction/compensation of the tool. The specific dimension tool life corresponding to the optimal surface wear can be referred as the optimal specific dimension tool life, T_{UD-o}. Therefore, the optimal specific dimension 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 $C_h = Const$ then, when $h_r = Const$, the dimension tool life is proportional to power x_h. The results of multiple cutting tests carried out by Makarow [15] allow to conclude that this power is in the range of $0.31-1.75$ 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 dimension tool life. The greater x_h, the stronger the influence of the feed on the dimension tool life, the greater increase of the dimension 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 M20 (94%WC,6%Co) carbide tool (power $x_h = 1.3$) led to the increase in the dimension tool life in 6.2 times while a 3.28-time increase was achieved in the same operation when P10 (30%TiC,66%WC,4%Co) tool was used (power $x_h = 0.88$) [15].

Influence of the workpiece diameter

The diameter of the workpiece affects the cutting process in various ways 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 boding bar or arbour and thus effects the static and dynamic stability of the machining system.
- The workpiece diameter affects the curvature on the surface being cut that, 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 as the shear angle and the length of the shear plane) change with the workpiece diameter.
- When the cutting speed in kept invariable, the rotational speed (r.p.m.) changes with the workpiece diameter that 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 that 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 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.

Experimental Study

Cutting tests were carried out where two diameters of the workpiece, 15 and 29 mm, were used. At first, the length of the workpiece was selected to keep the same rigidity ($51 \cdot 10^3 N/mm$), then the invariable workpiece diameter was used while the length (and thus rigidity) of the workpiece was varied. The test results are shown in Figure 3. As seen, when the rigidity is kept invariable (by 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 (curve 1 to curve 2 in Figure 3). However, if under the same conditions, L_w is not changed, the tool wear rate and surface roughness increase significantly (curve 1 to curve 3 in Figure 3).

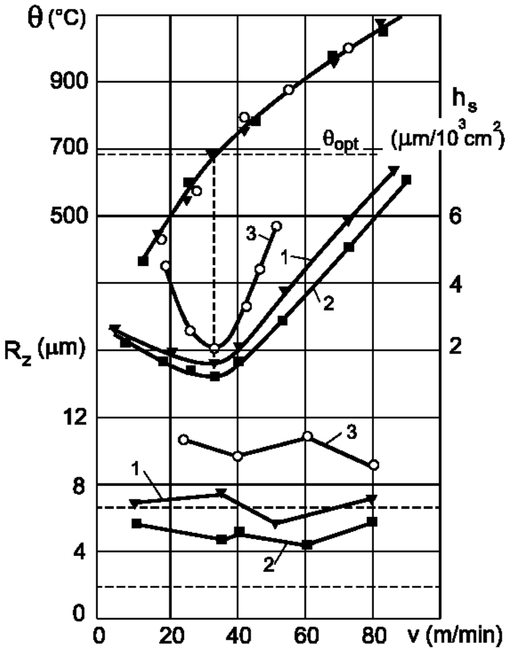

Fig. 3. Influence of the cutting speed and diameter of the workpiece in turning on the cutting temperature, tool wear rate and roughness of the machined surface. Work material – custom-modified Haynes 263 alloy (0.02%C,20%Cr, 2%Ti,2%Al) using cutting tool made of carbide M10 (94%WC,6%Co), depth of cut $d_w = 0.25\ mm$, cutting feed $f = 0.09\ mm/rev,$: 1 - $D_w = 29\ mm$, $L_w = 230\ mm$, 2 - $D_w = 15\ mm$, $L_w = 95\ mm$, 3 - $D_w = 15\ mm$, $L_w = 230\ mm$

Calculations show that the total length of the surface of the maximum combined stress (often referred as the shear angle and the length of the shear plane) insignificantly depends on the workpiece diameter. For example, changing this 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 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 Figure 4, 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]. It was proved by using the water-based (great 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].

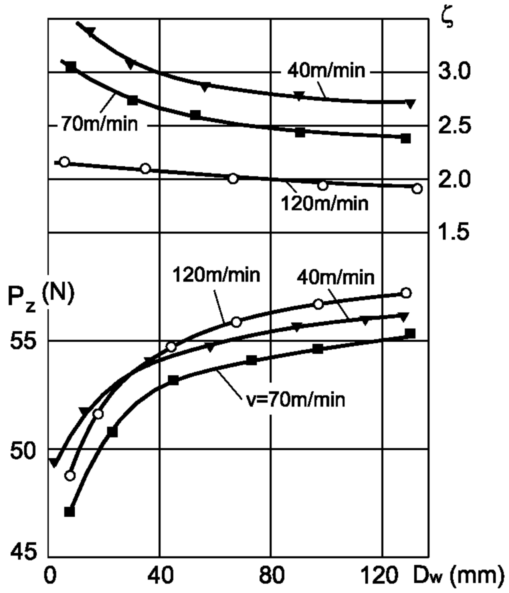

Fig. 4. Influence of the cutting speed and diameter of the workpiece in turning on the chip compression ratio and cutting force, work material - Haynes 263 alloy (29%Cr, 2.5%Ti), tool material – carbide M20 (92%WC,8%Co), depth of cut $d_w = 0.25\ mm$, cutting feed $f = 0.09\ mm/rev.$

The influence of the workpiece diameter shows up through the cutting temperature. When cutting with low cutting speeds ($v = 30\ m/\min$), increasing workpiece diameter lowers the cutting temperature bringing it down with respect to the optimal cutting temperature, the ratio of the contact stresses and tool wear rate increase as seen in Figure 5. When cutting with high cutting speeds ($v = 50\ m/\min$) 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 moderated 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 lowers below the optimal cutting temperature, however, increasing the workpiece diameter leads to increasing tool wear rate and contact stress ratio.

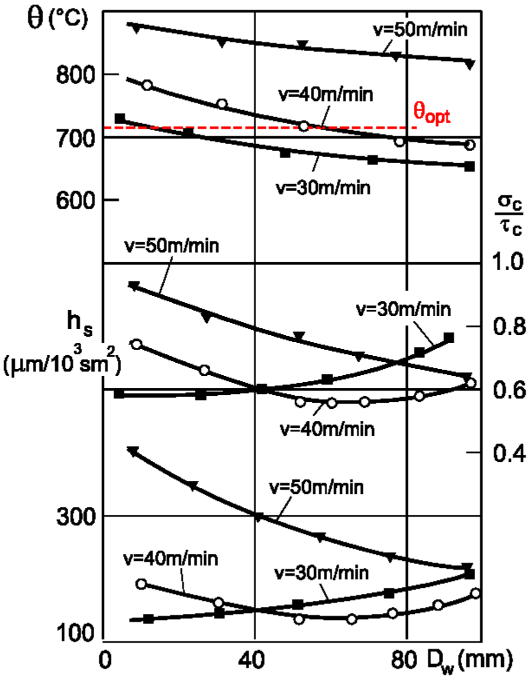

Fig. 5. Influence of the cutting speed and diameter of the workpiece on the cutting temperature, contact stress ratio at the tool-workpiece interface and optimal tool wear rate in turning, work material - Haynes 263 alloy (29%Cr, 2.5%Ti), tool material – micrograin carbide M10 (94%WC,6%Co) depth of cut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

Influence of the workpiece diameter under the optimal cutting temperature

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

$$v_{opt} = C_{v-o} D_w^{x_{v-o}} \tag{7}$$

Table 1 presents the value of C_{v-o} and x_{v-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*, *26*, and *37* mm. Cutting regime: depth of cut $d_w = 0.30\ mm$, cutting speed $v = (40-160)\ m/\min$, maximum radial tool wear rate $h_r = 50\ \mu m$. 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 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 the hole diameter, the optimal cutting speed increases and the tool wear rate and the chip compression ratio decrease. Figure 7 exemplifies these conclusions.

In boring of holes using cutting tools made of carbide K10 (92%WC,8%Co) when work material is stainless steel AISI 303, at the above-indicated cutting regime, the optimal cutting speed and optimal tool wear rate correlated with the hole diameter, D_w as

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

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

Using these equations, one can calculate the optimal cutting speed and optimal tool wear rate for 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

Materials		Diameter of workpiece	C_{v-o}	x_{v-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

Table 1. Values of C_{v-o} and x_{v-o} in Equation (7) for the depth of cut $d_w = 0.25\ mm$, and feed $f = 0.09\ mm/rev$.

invariable, the dimension wear rate [13] correlates with the hole diameter as

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

the total tool life is

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

and the dimension tool life is

$$T_D = \frac{h_r}{h_{s-opt}} = 205 h_r D_w^{0.22} \qquad (cm^2) \qquad (13)$$

With increasing diameter of the hole being machined (when $\theta_{opt} = Const$), the total tool life decreases (the dimension wear rate increases) while the dimension tool life increases. This apparent contradiction is explained by the fact that if $\theta_{opt} = Const$, 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 a low cutting speeds ($v = 72\ m/\min$), increasing 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 lowers 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 the 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 $72\ m/\min$ (which is optimal for a hole of *17* mm dia.) then the dimension tool life reduces by *2.36* and the productivity of machining by *1*.5 compare to those obtained at the cutting speed $105\ m/\min$, which is the optimal cutting speed for the latter hole diameter.

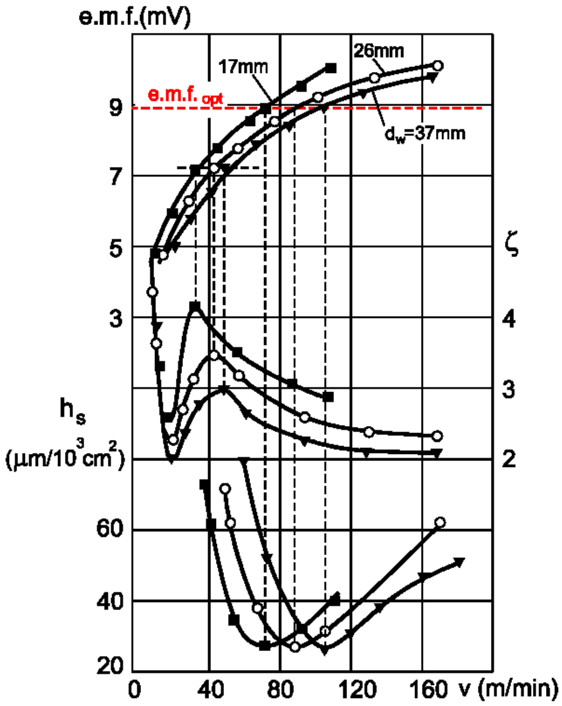

Fig. 6. Influence of the cutting speed and diameter of the hole being machined on the cutting temperature and tool wear rate, work material – stainless steel AISI 303, tool material – carbide M20 (92%WC,8%Co), depth of cut $d_w = 0.30\ mm$, cutting feed $f = 0.06\ mm/rev$.

Conclusions

1) The notion of the optimal cutting temperature resulted 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 5 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 tool wear rate is different at different cutting speeds.
3) As the cumulative effect of the discussed factors may affect 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 in the shop floor.
4) At optimal cutting temperature, the increase of the cutting feed leads to increased dimension tool life.
5) The diameter of the workpiece has strong influence on the cutting temperature and thus on the tool wear rate and the roughness of the machined surface. This is because this

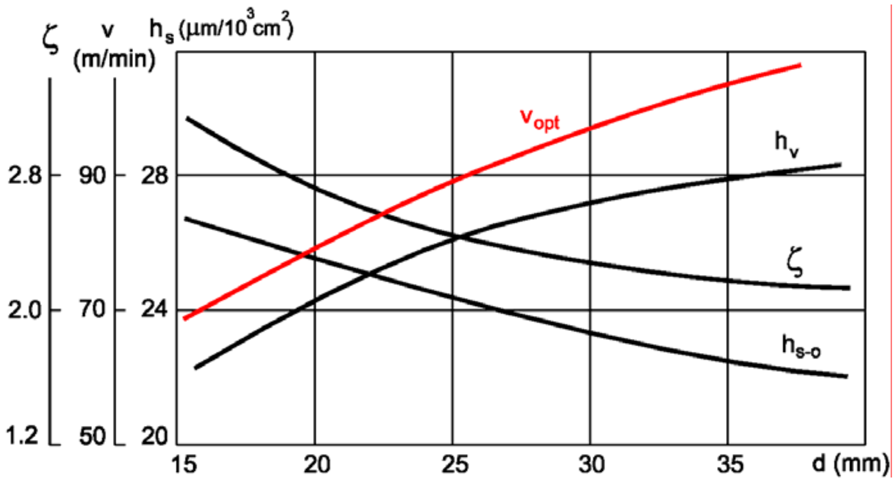

Fig. 7. Influence of the diameter of the hole being machined on h_{s-o}, v_{opt}, v_{ho} and ζ at the invariable optimal cutting temperature. Turning, work material – stainless steel AISI 303, tool material – carbide M20 (92%WC,8%Co).

diameter affects the static and dynamic rigidity of the machining system, curvature on the surface being cut, interaction of the thermal and deformation waves in the layer being removed.

6) 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.

Keywords

Metal cutting; tool wear; optimal cutting temperature; cutting feed; diameter of the workpiece, diameter of the hole being machined.

Bibliography

[1] Schey J.A., 1983, Tribology in Metalworking, American Society for Metals, Metals Park, Ohio.

[2] Olson M., Stridh, B., Söderberg S., 1988, Sliding wear of hard materials - the importance of a fresh countermaterial surface, Wear, 124/195-216.

[3] Stenphenson D.A., Agapiou J.S., 1996, Metal Cutting Theory and Practice, Marcel Dekker,

[4] Trent E.M., Wright, P.K., 2000, Metal Cutting, 4 Ed., Dutterworth-Heinemann, Boston.

[5] Childs T.H.C., Maekawa, K., Obikawa, T., Yamane, Y., 2000, Metal Machining. Theory and Application, Arnold, London.

[6] Jawahir I.S., Van Luttervelt C.A., 1993, Recent Developments in Chip Control Research and Applications, Annals of the CIRP, 42/2: 659-693.

[7] Loladze T.N., 1958, Strength and Wear of Cutting Tools (in Russian), Mashgiz, Moscow.

[8] Gordon M.B., 1967, The applicability of binomial law to the process of friction in the cutting of metals, Wear, 10/274-290.

[9] Usui E., Shirakashi T., 1982, Mechanics of Metal Cutting - From "Description" to "Predictive" Theory, On the Art of Cutting Metals - 75 Years later, Phoenix, USA, Edited by S.R. L. Kops, Production Engineering Division (PED), ASME, 7: 13-15.

[10] Luttervelt C.A., Childs T.H.C., Jawahir I.S., Klocke F., Venuvinod P.K., 1998, Present Situation and Future Trends in Modelling of Machining Operations. Progress Report of the CIRP Working Group 'Modelling of Machining Operations', Annals of the CIRP, 74/2: 587-626.

[11] Shuster L.S.H., 1988, Adhesion Processes at the Tool-Work Material Interface (em Russo), Mashinostroenie, Moscovo, Russia,

[12] Marinov V., 1996, Experimental study on the abrasive wear in metal cutting, Wear, 197/242-247.

[13] Astakhov V.P., 2004, The assessment of cutting tool wear, International Journal of Machine Tools and Manufacture, 44/637-647.

[14] Astakhov V.P., 1998, Metal Cutting Mechanics, CRC Press, Boca Raton, USA.

[15] Makarow A.D., 1976, Optimization of Cutting Processes (in Russian), Mashinostroenie, Moscow.

[16] Zorev N.N., 1966, Metal Cutting Mechanics, Edited by M.C. Shaw, Pergamon Press, Oxford.

[17] Kronenberg M., 1966, Machining Science and Application. Theory and Practice for Operation and Development of Machining Processes, Pergamon Press,

[18] Gorczyca F.Y., 1987, Application of Metal Cutting Theory, Industrial Press, New York.

[19] Taylor F.W., 1907, On the Art of Cutting Metals, Transactions of ASME, 28/70-350.

[20] Astakhov V.P., 2004, "Tribology of Metal Cutting", Mechanical Tribology. Material Characterization and Application., Edited by G. Totten e H. Liang, Marcel Dekker, 10-50.

[21] Astakhov V.P., Shvets, S., 2004, The assessment of plastic deformation in metal cutting, Journal of Materials Processing Technology, 146/193-202.

[22] Astakhov V.P., Shvets S.V., 2001, A Novel Approach to Operating Force Evaluation in High Strain Rate Metal-Deforming Technological Processes, Journal of Materials Processing Technology, 117/1-2: 226-237.