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Correlations amongst process parameters in metal cutting and their use for establishing the optimum cutting speed

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Industrial summary

An investigation of the nature of the inherent variation of the tool life over a wide range of cutting speed for a turning process is presented. The objective of this work is to establish basic relationships amongst the process parameters in metal cutting in order to achieve better understanding of the process and, based on these relationships, to provide the guidelines for choosing the optimum (by the criterion of maximum area of the machined surface) cutting speed. The correlation amongst the cutting parameters is considered separately within each of four characteristic cutting-speed regions. The effect of watermix and oil-based cutting fluids on the cutting process is discussed.

Keywords: Metal cutting; Cutting speed; Process parameters

1. Introduction

The basic objective of contemporary turning operations is to generate desired reliable geometries at minimum cost consistent with the required quality levels and delivery schedules. The attainment of this seemingly straightforward objective can present challenges to those responsible for establishing and maintaining efficient production. The broad applicability of turning results in a wide variation in product requirements, materials, tolerances, lot sizes and shop facilities that, in turn, preclude simplified solutions [1].

Since the tool-life equation was discovered by Taylor, numerous research papers have been published throughout the world for better understanding of metal-cutting phenomena. Wear and tool life are so important from the economical point of view that many efforts have been made in order to identify those quantities analytically and/or experimentally [2–8]. During the cutting process many phenomena occur: plastic and other deformation; friction; thermal phenomena; abrasive, adhesion and diffusion wear; strain-hardening and loss of strain-hardening; phase transformation; adsorption; etc. All these phenomena influence each other to a greater or lesser degree [6–11]. However, the primary direct factor influencing production turning rates and process economics is the cutting speed. Therefore, the choice of the optimum cutting speed and the cutting fluid for a given combination of work/tool materials, shape of the workpiece, the machine tool used, etc., is a very important, but frequently unappreciated, stage in metal-cutting process design.

Unfortunately, the choice of the optimum cutting speed cannot be made using existing manufacturing data. In these data, the values of cutting speed are usually assigned to the tool/workpiece materials combination rather than to the particular cutting conditions. The recommended ranges of the cutting speed are very broad, which makes the proper choice of the cutting speed a heavily experience-dependent item. In most cases, such a choice is a matter of luck rather than a knowledge-based decision. Moreover, the wide spectrum of the tool and workpiece materials used in practice makes this problem even more complicated.

Such a non-optimistic result after more than one hundred year metal-cutting history is not a surprise.

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Two 'shores' of the metal cutting 'river', named cutting theory and experimental metal cutting, developed very independently, without any influence on each other. Their results never match each other but both are usually included in the student's text book. Even though the detailed analysis of metal-cutting history is beyond the scope of this paper and can be found in Refs. [1–5], one practical remark related to cutting speed should be made here. In the theory of metal cutting, the cutting speed does not appear in the main, constitutive equations relating the process parameters. Experimental studies usually present results that are valid only for the given set of cutting conditions without sufficient explanations as to why the particular value of the cutting speed was chosen and what would happen if another value were used. Therefore, the proper choice of the cutting speed cannot be made using the results of both of the above-mentioned approaches.

The objective of this work is to establish the basic relationship amongst the process parameters in metal cutting in order to achieve better understanding of this process and, based on these relationships, to provide the guidelines for choosing the optimal (by the criterion of maximum area of the machined surface) cutting speed.

2. Correlation amongst the metal-cutting phenomena

Because the cutting speed is the main concern of this study, consider the changes in the tool life, T, chip compression ratio, ζ, cutting force, R, and the cutting temperature, Θ, with the cutting speed.

It was found in experimental studies of cutting heat-resistant steels (0.2% C, 20% N, 25% Cr, 2% Si and 0.2% C, 18% N, 23% Cr) under different cutting regimes (feed, s, and depth of cut, t) that particular points on the curve $T=f(v)$ correspond to some specific points on curves $R=f(v)$, $\zeta=f(v)$, and $\Theta=f(v)$ [1–3] (Fig. 1). Furthermore, the specific interaction processes between the workpiece material and the tool correspond to these points.

It has been shown also in many experimental studies of metal cutting that the curve $T=f(v)$ has generally expressive extremes (Fig. 1(b), continuous line). It is also known [6–11] that in the turning of steels and alloys, the relationships $R=f(v)$, $\zeta=f(v)$ have extremes and the minimum tool life (point T_2, Fig. 1(b)) corresponds to the maxima of the cutting force and chip compression ratio. In the cutting of some alloys with special properties, the curves $R=f(v)$, $\zeta=f(v)$ do not have expressive extremes, but the left part (from point T_2) of the curve $T=f(v)$ (Fig. 1(b), dashed line) has a greater slope than its right part.

The maximum of the tool life (point T_3) corresponds to the point R_3 on the curves $R=f(v)$, $\zeta=f(v)$. In the vicinity of point R_3 these curves have the maximum curvature. Further to the right from this point, they gradually transform into the curves having a slight slope that reflects a small influence of the cutting speed (within the range considered) on the chip-compression ratio and cutting force. The maximum of the tool life (point T_3) also corresponds to point Θ_3 on the curve $\Theta=f(v)$ (Fig. 1(a)), which is the boundary point between the two parts of the curve $\Theta=f(v)$.

In order to analyze the correlation amongst the cutting phenomena, the whole range of the cutting speed is divided into four distinctive regions (I–IV).

Region I is characterized by an intensive increase in cutting temperature when cutting metals inclined to built-up formation. When the cutting speed is small, the built-up edge is stable, which results in low cutting temperatures and a small chip-compression ratio. With increasing cutting speed, the built-up edge becomes unstable and the adhesion-type of tool wear takes place. However, when cutting metals that are not inclined to built-up formation, region I is also characterized by adhesion wear, and the wear rate depends upon the combination of the cutting regime, the tool and workpiece material properties, and the presence of cutting fluid.

With further increase in the cutting speed (region II), the intensity of the adhesion wear, and the chip-compression ratio and cutting force decrease significantly, which result in an increase in tool life, whereas when cutting metals which are not inclined to built-up formation, the tool life continues to decrease but at a smaller

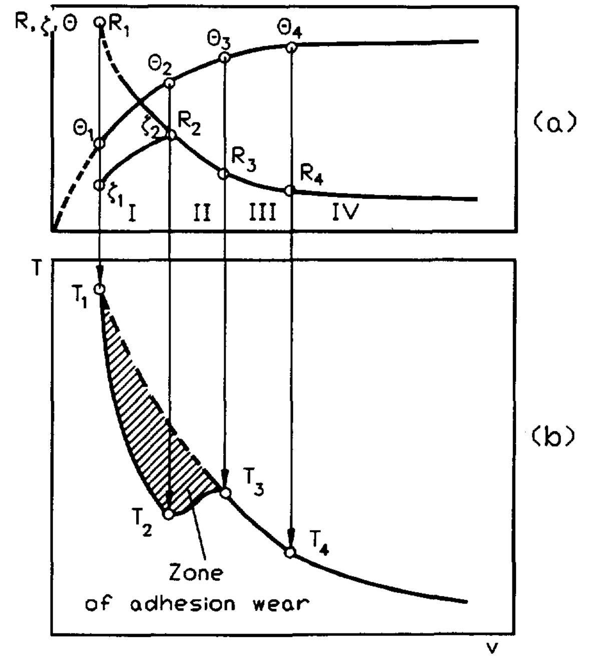


Fig. 1. Influence of cutting speed on cutting force, R, cutting temperature, Θ, chip compression ratio, ζ, and tool life T.

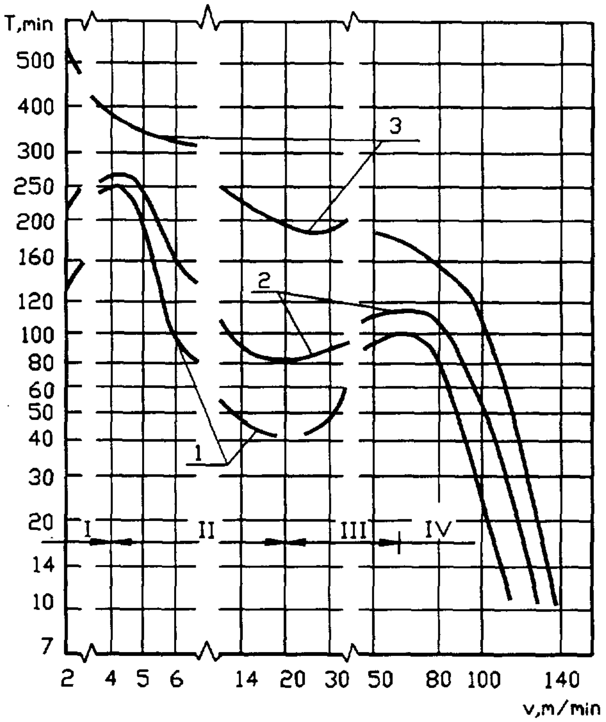


Fig. 2. Tool life vs. cutting speed ($t = 1.5$ mm, $s = 0.06$ mm/rev): (1) without cutting fluid; (2) with watermix cutting fluid, and (3) with the oil-based cutting fluid.

rate than in region I. Therefore, both regions I and II correspond to the predominance of adhesion wear.

With further increase in the cutting speed (region III), the rate of the adhesion wear decreases significantly whilst the diffusion wear becomes predominant. As a result, the tool life decreases.

Further increase in the cutting speed (region IV) results in a further increase in the cutting temperature, which leads to further increase of the diffusion wear.

The above-described phenomena correspond to the characteristic points in the curves $\zeta = f(v)$, $R = f(v)$, and $T = f(v)$ (Fig. 1). The presence of the cutting fluid does not change the characteristics of these relationships, but shifts their maxima relative to those obtained without cutting fluid.

3. Experimental

Experimental verification of the above-considered phenomena is shown in Figs. 2 and 3. The conditions of the tests were the following.

(i) *Workpiece material*: stainless steel (0.12% C, 18% Cr, 10% Ni). The composition, the elements limits and the deoxidation practice were chosen to be in agreement with the requirements of standard *ANSI/ASME B94.55M-1985*. The test bars were normalized to a Brinell hardness of 200 HB. The hardness of the work material was determined over the complete cross section of the end of each test bar and cutting tests were conducted only on the bars where the hardness was within the limits ± 10%. Special parameters such as the microstructure, grain size, inclusions count, etc., were checked using quantitative metallography.

(ii) *Cutting tool*: the normal rake angle $\gamma_N = 10°$, the normal clearance angle $\alpha_N = 10°$, the principal cutting edge angle $\phi_p = 30°$; the tool material is carbide BK8 (C-6) [12]. The dynamometer design, its static and dynamic calibrations, the method of the statistical design of experiments, and the method of the chip-compression-ratio determination were presented by the authors in Refs. [10,11]. The cutting speed varied within the limits of 2–150 m/min; the criterion for flank wear of 0.5 mm wear-land width, h_f, was used.

Referring to the tool life–cutting speed curves (Fig. 2) obtained with and without cutting fluids, the four characteristic regions corresponding to particular cutting-speed ranges can be recognized.

Region I corresponds to the turning with very small cutting speeds (2–4 m/min), within this region the tool life increases with increasing cutting speed: from 130 to 220 min in dry turning and from 215 to 255 min with the watermix-cutting fluid. Such a difference in the tool life can be explained by: (i) the change in adhesion under conditions of forming absorption films at the tool/workpiece contact area; (ii) deep penetration of the cutting fluid to the contact areas (for the cutting-speed range 2–3 m/min), and the protective function of the

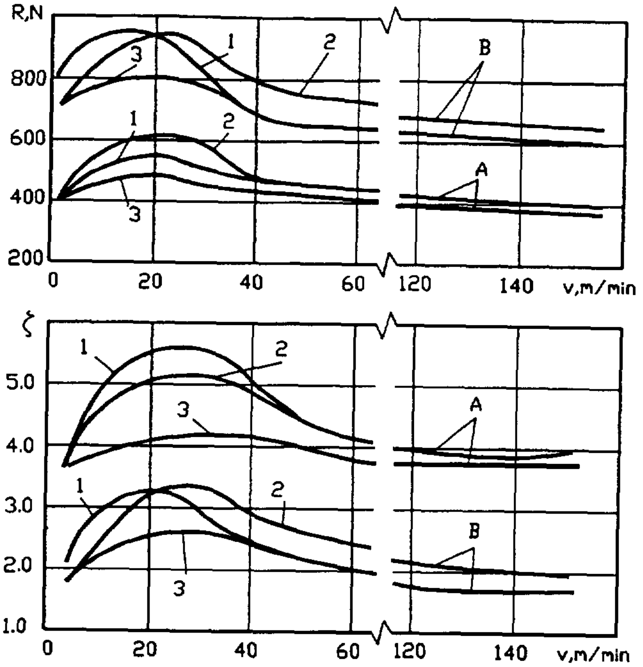
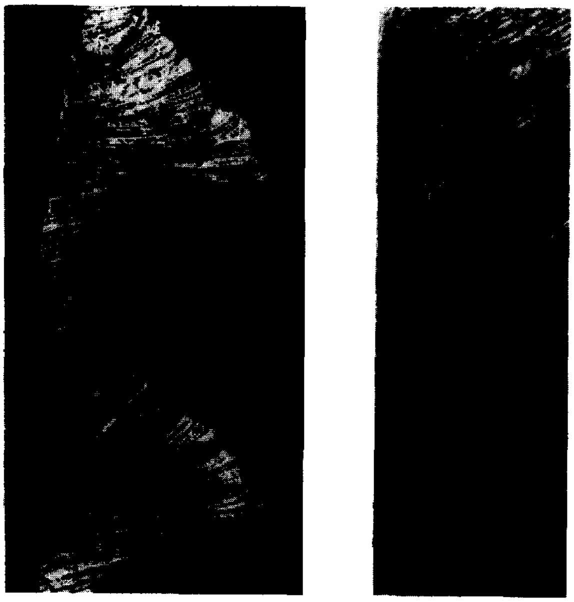


Fig. 3. Cutting speed vs. tangential cutting force, R_T, and chip-compression ratio, ζ (workpiece material: stainless steel 0.12% C, 18% Cr, 10% Ni, 1% Ti; cutting regime: $t = 1.5$ mm, (A) $s = 0.06$ mm/rev, (B) $s = 0.16$ mm/rev). (1) without cutting fluid; (2) with watermix cutting fluid, and (3) with oil-based cutting fluid.



(a) (b)

Fig. 4. Shape of the chip in (a) region II, and (b) region III.

stable built-up edge formed when the cutting speed reaches 4 m/min.

Region II (corresponding to the cutting-speed range of 4–19 m/min) is characterized by a sharp decrease in tool life with increasing cutting speed; its cause is the transition of the build-up edge from the stable to unstable condition. Tool wear initially takes place by the crumbling-out of fine particles and then, increasing the cutting speed from 10 to 20 m/min, by rough particles of the tool carbide. The deformation of the layer being cut takes place non-uniformly and the chip has parts of different thickness along its length (Fig. 4(a)).

With further increase in cutting speed up to 60–70 m/min (region III), the tool life, in turning without cutting fluid increases from 40 to 100 min. On the other hand, in turning with cutting fluid, the tool life increases at a lower rate (from 90 to 118 min). The increase in the tool life within this speed range is explained by a gradual transition from the adhesion type of tool wear into the diffusion type. The deformation of the work material takes place uniformly and the thickness of the chip becomes uniform along its length (Fig. 4(b)).

Region IV corresponds to machining at high cutting speed. The decrease in the tool life within this region is explained by high cutting temperatures.

When using the oil-based cutting fluid in the cutting speed range of 2–80 m/min, the tool life–cutting speed curve does not have expressive maxima. i.e., the rate of the tool wear does not change significantly. The tool life in this case is found to be greater than in the case of turning with the watermix-cutting fluid. Thus, for the cutting speed range of 12–30 m/min when using the oil-based cutting fluid, the tool life is found to be 2.7–5 times greater than that with the watermixed-thing fluid. A uniformly deformed chip was produced over the entire range of cutting speeds used in this study and the crumbling-out of carbide was not observed. The chip-compression ratio and cutting force reduce significantly within the cutting speed range of 15–40 m/min, where adhesion wear is predominant.

The comparison of data from Figs. 2 and 3 shows that the characteristic regions of the relationships cutting speed–tangential force and cutting speed–chip-compression ratio have a particular correlation with the characteristic regions of the relation cutting speed–tool life. Specifically, in cutting without cutting fluid, the beginning of the tool-life increase (the transition from region II to III) at the cutting speed $v = 18$–20 m/min corresponds to the maxima of the tangential force, R_T, and the chip compression ratio, ζ. Continuing to refer to Fig. 2, the increase in tool life continues up to $v = 60$ m/min, which corresponds to the beginning of a small influence of the cutting speed on the tangential force and chip-compression ratio. When using the watermix and oil-based cutting fluids, the transition from region II to region III takes place at the cutting speed $v = 18$–20 m/min and the end of the region III corresponds to the cutting speed $v = 80$ m/min. According to Fig. 2, particularly to the curve corresponding to machining with the oil-based cutting fluid, the characteristic region corresponding to the cutting speed $v = 18$–20 m/min is not very obvious, which can be explained by the lower chip deformation (smaller chip-compression ratio) and smaller cutting force when compared with cutting at the same speed without the cutting fluid or with the watermix cutting fluid.

4. Optimum cutting speed

The established basic correlations amongst the process variables in metal cutting provide the possibility for a quick determination of the cutting speed corresponding to the maximum machined area of the workpiece before the chosen wear limit of the tool is achieved. To do this, the experimental determination of relationships $\zeta = f(v)$ (for ductile materials) or $R_\mathrm{T} = f(v)$ (for brittle materials) should be completed in order to determine the maximum value of the chip-compression ratio, $\zeta_{\max}$, or of the tangential force $R_{T_{\max}}$. The cutting tests conducted on a broad spectrum of engineering materials show that the optimum cutting speed, v_{opt}, can be determined using the experimentally obtained relationships $\zeta = f(v)$ or $R_\mathrm{T} = f(v)$, as follows: (i) in the cutting of ductile materials, the optimum cutting speed is the speed corresponding to the chip compression ratio $\zeta_{v0} = (0.7–0.8)\zeta_{\max}$, and (ii) in the cutting of brittle materials, the optimum cutting speed is the speed corresponding to cutting force $R_{Tv_0} = (0.7–0.9)R_{T_{\max}}$.

It follows from the above considerations that $v_0 > v_{\zeta_{\max}}$ or $v_0 > v_{R_{\max}}$, where $v_{\zeta_{\max}}$ and $v_{R_{\max}}$ are the cutting speeds corresponding to the maxima of the chip-compression ratio and the tangential force, respectively.

The optimum cutting speed for the case considered in Fig. 3 lies in the speed range corresponding to the beginning of a small influence of the cutting speed on the tangential force and chip-compression ratio.

5. Conclusions

The characteristic regions of the relationships cutting speed–cutting force and cutting speed–chip-compression ratio have a particular correlation with the relationship cutting speed–tool life. In dry turning, the starting point of the increase in tool life (i.e., the transition of region II to region III at the cutting speed $v = 18$–20 m/min) corresponds to the maximum of the cutting force R and the chip-compression ratio ζ. The curve for the tool life T increases monotonously with increase in cutting speed, lasting up to $v = 60$ m/min, this speed corresponding in Fig. 3 to the beginning of a weak influence of the cutting speed on the cutting force and chip-compression ratio (i.e., to the transition of region III to region IV). In turning with both the watermix and oil-based cutting fluids, the starting points of regions II and IV correspond to cutting speeds of 18–20 and 80 m/min, respectively. In turning with the oil-based cutting fluid, the transition between regions II and III, which corresponds to the cutting speed range of 18–20 m/min, is not very impressive, which can be explained by the significantly smaller chip compression ratio and cutting force in the case considered, when compared with dry turning (or with the use of watermix cutting fluids) at the same cutting speed. This observation shows that the oil-based cutting fluids form solid protective films on the tool contact areas, making the adhesion weaker and, thus, preventing the formation of deposits. The basic relationships established amongst the process variables in metal cutting provide the possibility for a quick determination of the cutting speed corresponding to the maximum machined area of workpiece before the chosen wear limit is achieved.

Acknowledgements

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References

[1] R. King (ed.), *Handbook of High-speed Machining Technology*, Chapman and Hall, London, 1985.
[2] I. Timme, *Resistance of Metals and Wood to Cutting*, Dermacov, St. Petersburg, 1870 (in Russian).
[3] H. Ernst and E. Merchant, *Trans. ASME, 29* (1941) 229.
[4] N.N. Zorev, *Metal Cutting Mechanics*, Pergamon, London, 1966.
[5] E. Usui, *JSME Int., 31* (1988) 363.
[6] A.M. Rozenberg, *Metal Cutting and Tools*, Machinostroenie, Moscow, 1964 (in Russian).
[7] T.N. Loladze, *Wear of Cutting Tools*, Mashgis, Moscow, 1958 (in Russian).
[8] E.M. Trent, *Metal Cutting*, Butterworths, London, 2nd edn., 1984.
[9] E. Usui, T. Shirakashi and T. Kitagawa, *Bull. Jpn. Soc. Prec. Eng., 15* (1981) 237.
[10] V. Astakhov, *Metal Cutting Theory and Practice*, OPU, Odessa, 1992 (in Russian).
[11] V. Astakhov, *Metallorezushie stanky, 25* (1994) 35 (in Russian).
[12] A. Bhattachryya and I. Ham, *Design of Cutting Tools, Use of Metal Cutting Theory*, American Society for Mechanical Engineers, Dearborn, MI, USA, 1969, pp. 28–33.