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Cutting tool reliability analysis for variable feed milling of 17-4PH stainless steel

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Abstract

Variable feed machining has recently been proposed as a significant method to improve cutting tool life particularly for hard and diffucult to machine materials. This method, which is easy to apply in industry, has been shown to improve tool life in the order of 40% in certain cases. This paper presents a reliability model for the quantitative study of the effect of feed variation on tool wear and tool life. To better compare processes with two different wear modes, a reliability model taking simultaneously into account both flank and face wear has been developed. With this model, which is based on experiments, the tool life for the constant and variable feed cases was calculated from the reliability function. The mean time to failure, obtained from the reliability function, provides an accurate evaluation for any probabilistic distribution. The proposed method is therefore a general approach that can be used for analyzing cutting tool life under any conditions and for any equipment and material.

Keywords: Reliability; Cutting tool; Variable feed machining

1. Introduction

For machining, tool life is considered as a most important economic factor, particularly when heat-resistant alloys must be milled or turned. These hard and difficult to machine materials generate very high wear rates on both the flank and the face of the tool. In practice, a study carried out by Sakharov et al. [1] showed that the tooling cost in the case of flexible manufacturing systems represents approximately 25% of the total machining cost. Maccarini et al. [2] have also evaluated the productivity of flexible manufacturing systems with respect to their tooling costs and they proposed an analytical method to evaluate the tool properties to improve their reliability. On this topic, an original machining concept has been developed at École Polytechnique de Montréal. It consists of continuously varying the feed throughout the cutting process. Varying feed during machining changes the tool–chip contact area, reduces both the crater and the flank wear rate and consequently improves substantially the cutting tool life. This new rough machining concept has the advantage of maintaining the machining efficiency while improving the tool life [3–7]. Many researchers have indirectly addressed the qualitative influence of the cutting parameters and in particular of the feed on tool wear. Amongst others, Tlusty and Masood [8], Lee [9], Jemielniak et al. [10], Lentz et al. [11], and Brown [12] all studied this topic. From the previous research, it is clear that the change of feed during machining modifies the cutting tool wear modes.

Conclusive experimental results for various materials such as 17-4PH stainless steel, Inconel 600 and 4340 steel show that this original approach is extremely efficient. This simple method can also be immediately applied in industry without any capital investment on most numerically controlled machine-tools.

To evaluate the cutting tool life while applying the variable feed rate, reliability theory is proposed to model the random nature of the wear phenomena. Consequently, a quantitative estimate of the cutting tool improvement due to the variable feed was obtained. Many researchers have been interested in cutting tool reliability. Hitomi et al. [13] and Wager and Barash [14] have observed that the cutting tool life can be represented for the cases studied by the statistical normal distribution. To quantify the reliability of carbide tools, Negishi and Aoki [15] have studied the influence of feed on cutting tool life during intermittent cutting. Devor et al. [16] have also studied the variation of cutting tool life with the help of a model based on statistical tests of the particular cutting conditions for a finishing operation. Moreover, Ramalingam and Watson [17] have studied the probabilistic

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nature of the cutting tool life. Another probabilistic mathematical model was proposed by Devin and Vilgelm [18] which attempts to determine the minimum failure probability in turning. From these studies, a general understanding of the random nature of tool life became accepted.

The application of the reliability techniques for the analysis of the work of cutting tools enables the calculation of tool life by taking into account the empirical distribution of the operating times to faliure. Furthermore, the reliability function allows a more detailed analysis of the tool performance. In particular, it enables the evaluation of the probability of the failure-free working of a tool in a given time interval. For example, this knowledge can be used to better synchronize the replacement of tools for several machines working in series. In this case, it is most critical to properly manage tool replacement since machine downtime slows down the complete production line. Thus, the reliability function cannot only predict tool life but can also be used for production planning and tool management.

Tool degradation often appears under various wear modes and mechanisms, for example as flank wear, crater development and others. Tool life is therefore limited by all these wear modes and tool life assessment must take them into account simultaneously. Furthermore, the various wear mechanisms and corresponding tool degradations, which essentially depend on the cutting speed and on the tool and part materials, can generate different statistical distributions of the operating time to failure such as the normal, the log-normal or the Weibull distributions. Consequently, the use of a simple arithmetic mean, which is used most in practice to calculate tool life, is inadequate in certain cases. It can only be used when the distribution is normal. To evaluate the reliability of cutting tools in both variable and constant feed milling, a mathematical model based on the theory of probability is necessary. This stochastic model is related to the random variable associated with the operating time to failure of the cutting tool.

In this study, we propose an analysis method to quantify the tool life improvement due to the variable feed method. This mathematical approach is based on statistical distributions obtained from the experimental results and aims to estimate the reliability level of cutting tools working under variable feed conditions compared with constant feed conditions. It is therefore a stochastic model based on the theorem of total probability. The novelty of this model is that it simultaneously considers crater and rake face wear as tool failure criteria.

2. Reliability mathematical model of cutting tools

The cumulative simultaneous wear on the flank and on the face have been chosen as the observed modes of damage. This model is therefore characterized by its formulation that takes into account the standard ISO wear criteria: VB_{max} on

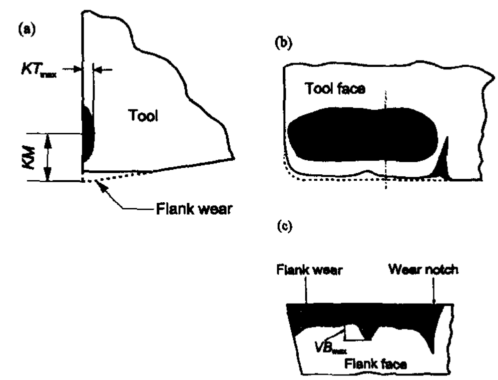

Fig. 1. Flank and crater wear parameters definition.

the flank and KT_{max} on the face, as critical failure criteria of the cutting edge (Fig. 1). The random variables of the time to failure are associated with these two processes of wear evolution.

2.1. Model description and definitions

For the reliability analysis, a cutting tool has two possible states: working state or failure state. In the working state, a tool possesses sufficient characteristics to properly fill its planned functions for machining. The failure state corresponds to the state where the tool is unable to cut properly and in terms of probability it is considered as an event opposed to the working state.

The transition of a tool from a working state to a failure state is defined as a failure. In practice, the failure of the cutting tool is observed as excessive wear or as a breakage. Often, the breakage of a cutting edge is due to an incompatible choice of the cutting parameters. However, for this comparative analysis of cutting tool reliability with and without variable feed, the failure by breakage has been eliminated and the wear only has been considered as a failure criteria. During the tests, no breakage failure was observed and therefore this hypothesis is valid.

For a cutting tool, the admissible wear is generally defined from geometrical, technological, physical, or economical criteria. The geometrical criteria take into account the geometry changes of the cutting edge, the technological criteria take into account the change of the machined surface roughness and its dimensions, the physical criteria take into account the cutting forces or the temperature variations and the economical criteria are based on the manufacturing costs.

In this study, the geometrical criteria were chosen to define the tool failure. From the few existing variables, the flank wear VB_{max} and the crater wear KT_{max} were adopted. Thus, overshoot of the wear critical values VB_{max} (flank wear) and KT_{max} (crater wear) are considered as failure of the cutting edge. Therefore, the criteria for the edge life correspond to the maximum values of the wear criteria representing the selected wear form.

2.2. Mathematical model

In a probability space formed by the triplet (Ω,H,P), a finite set A_i of events, incompatible two by two, is called a complete event system [19] if:

$$P\left(\bigcup_i A_i\right)=\sum_i P(A_i)=1 \tag{1}$$

where Ω is the set of observable events, H is the set of events, and P is a probability function.

For any event B of H, the probability of this event is given by:

$$P(B)=\sum_i P(B/A_i)P(A_i) \tag{2}$$

which is the theorem of total probability.

This theorem is proposed to evaluate the cutting tool reliability. In the case of cutting tools, the evaluation of the operating time probability is sought. Understanding that a failure corresponds to the maximum values of the wear criteria of VB_{max} or KT_{max}, the total probability theorem is expressed as follows from Eq. (2):

$$P(B)=P(B/\mathrm{VB})P(\mathrm{VB})+P(B/\mathrm{KT})P(\mathrm{KT}) \tag{3}$$

where $P(B)$ is the probability of an event comprising the non-failure of a cutting edge up to time t; $P(B/\mathrm{VB})$ is the probability of an event comprising the non-failure of a cutting edge up to time t, but calculated within the set of elementary events, such that $\mathrm{VB}\geq \mathrm{VB}_{max}$; $P(B/\mathrm{KT})$ is the probability of an event comprising the non-failure of a cutting edge up to time t, but calculated within the set of elementary events, such that $\mathrm{KT}\geq \mathrm{KT}_{max}$; $P(\mathrm{VB})$ is the probability of an event such as $\mathrm{VB}\geq \mathrm{VB}_{max}$; and $P(\mathrm{KT})$ is the probability of an event such as $\mathrm{KT}\geq \mathrm{KT}_{max}$.

To simplify the reliability model, the probabilities of two events, $P(\mathrm{VB})$ and $P(\mathrm{KT})$, are supposed independent and exclusive in the probability space. The dependence between $P(\mathrm{VB})$ and $P(\mathrm{KT})$ is not sufficiently clear and it is actually impossible to take it into account in the reliability model.

A continuous random variable τ, defined as the operating time, expresses the effective cutting time measured at the instant the maximum wear defined by the criteria is reached. Therefore, the probability of failure-free working of a tool in the time interval from 0 to t is written as $P(\tau>t)$. This implies that Eq. (3) is equivalent to:

$$P(\tau>t)=P[(\tau>t)/\mathrm{VB}]P(\mathrm{VB})+P[(\tau>t)/\mathrm{KT}]P(\mathrm{KT}) \tag{4}$$

The probability $P(\tau>t)$ represents the reliability function. From the definitions given above, the reliability of a tool cutting edge can be described by:

$$R(t)=R_{\mathrm{VB}}(t)P(\mathrm{VB})+R_{\mathrm{KT}}(t)P(\mathrm{KT}) \tag{5}$$

where $R(t)$ is the general reliability of a cutting edge, $R_{\mathrm{VB}}(t)$ is the cutting edge reliability evaluated from the failure defined as an event when $\mathrm{VB}\geq \mathrm{VB}_{max}$, and $R_{\mathrm{KT}}(t)$ is the cutting edge reliability evaluated from the failure defined as an event when $\mathrm{KT}\geq \mathrm{KT}_{max}$.

The reliability function is expressed as follows:

$$R(t)=\int_t^{\infty} f(t)\ \mathrm{d}t \tag{6}$$

where $f(t)$ is the failure probability density function, and the mean time to failure is obtained by:

$$\mathrm{MTTF}=\int_0^{\infty} R(t)\ \mathrm{d}t \tag{7}$$

From the experimental results measured on cutting tools in the same cutting conditions, the probabilities $P(\mathrm{VB})$ and $P(\mathrm{KT})$ can be evaluated. It is also possible to estimate the statistical laws associated with the random variable distributions of the tool operating time, calculated when the critical values VB_{max} or KT_{max} are reached.

3. Analysis of machining with variable feed rate

Variable feed machining is a new machining concept and until now its tool wear mechanism has not been precisely determined. We expect that improvements in tool life using variable feed machining are related to the shifting of the temperature peak at the tool–chip interface. Some explanations can be deduced based on the research efforts related to this topic.

According to Takeyama and Murata [20], we can distinguish two zones relating the temperature and the tool wear. In the first zone, up to a critical temperature of approximately 1200 °C, the flank and the crater wear increase slightly with the cutting edge temperature. After this critical temperature, in the second zone, the tool wear increases exponentially. This wear acceleration can be attributed to the domination of the diffusion wear mechanism which is strongly temperature dependent.

It has been shown by Chao et al. [21], while machining AINSI 1018 steel with a fixed speed and different feeds, that the increasing feed results in an increase of the tool–flank and tool–chip interface temperatures. There is also a gradual shift of the maximum peak of the temperature distribution curve away from the tool edge. On the rake face, the peak in the temperature distribution curve occurs at about 65% of the contact length measured from the cutting edge. As was shown by Brown [12], the contact length varies with the change of feed rate and therefore the temperature curve peak position changes. We therefore have a direct relation between the feed rate and the position of the maximum peak in the temperature curve. Therefore, the position of the crater axis KM is a linear

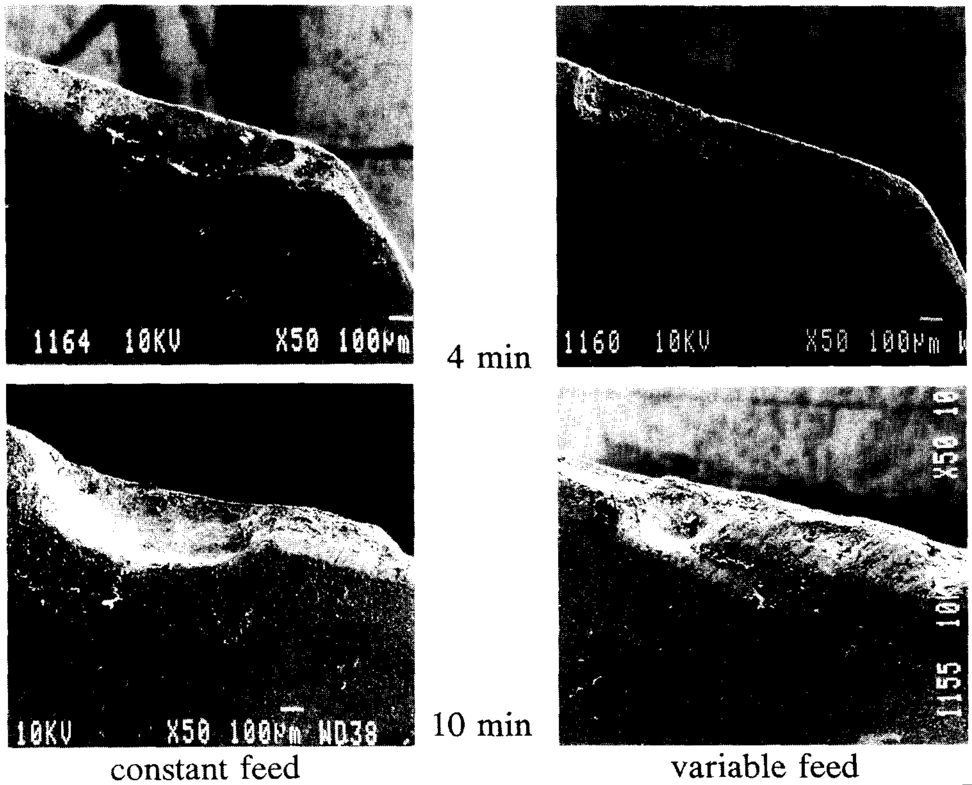

Fig. 2. Comparison of wear patterns for tool inserts under constant and variable feed cases.

function of the feed rate [4]. The characteristic function is approximated by the equation:

$$\mathrm{KM} = \mathrm{constant} \times f \tag{8}$$

This equation takes into account that the position of the crater axis is displaced as the feed is varied. According to Eq. (8), we can conclude that the feed variation, while machining according to a prescribed function, should cause the displacement of the crater center and of the temperature peak at the chip–tool interface. Taking into account the above information, it can be infered that with variable feed, the crater wear is spread throughout the whole surface instead of being concentrated at a single point. This probably prevents the temperature at any one given point from reaching the critical temperature that signals the beginning of the exponential increase in wear. Therefore, wear is spread out on the whole surface, but it is much less pronounced. It takes the shape of more numerous craters but of much smaller dimensions. This theory can be confirmed by the pictures in Fig. 2.

In Fig. 2 [4], the differences in the tool wear for constant and variable feeds can be clearly seen. After 4 min of machining with constant feed, the tool wear quickly appears with the creation of a crater. While machining with a variable feed, the tool wear spreads more uniformly and there is no crater formation. However, we can see several very small craters beginning to take shape. After 10 min of machining with constant feed, a crater (about 0.15 mm) is formed. This crater depth is often sufficient to induce a catastrophic failure of the cutting edge. In the case of machining with variable feed, the tool wear is more uniform and appears as five smaller craters.

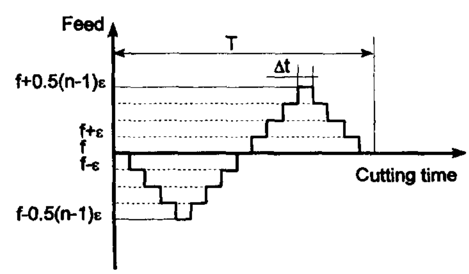

Fig. 3. Variable feed variation cycle.

The machining cycle with a variable feed rate is presented in Fig. 3, which displays the feed as a function of cutting time. The parameters of the feed variation sequence are: T, the time interval; f, the constant feed rate; ε, the increment of variable feed; n, the number of increments in a period; and Δt, the time interval in the variable feed rate sequence. These parameters were set so that the average process efficiency was constant for constant and variable feeds. The efficiency of this process can easily be measured in terms of the volume of material removed in a given time span [6].

The modeling of tool wear under variable feed conditions which takes into account the complex physico-chemical phenomena is presently under investigation by the authors.

4. Experimental procedures

The major goals in the experiments were to study the effect of the feed variation (during interrupted cutting) on the tool wear. The experiments were performed in two stages. First, a set of tests was performed to establish the range of the applicable cutting conditions while another set of tests was carried out to establish the effect of the feed variation on the tool wear.

All cutting tests were carried out under the following conditions (equipment, materials, and cutting conditions):
1. machine tool: NC Machining Center with a 7.5 kW motor;
2. microscopes: toolmaker microscope and scanning electron microscope, resolution 3.0 nm;
3. standard tool holder 45° pos/neg face mill diameter 2 in with 4 inserts, lead angle $\kappa_r = 45°$, cutting edge inclination $\lambda_s = 19°$, back rake angle $\gamma_p = +20°$, orthogonal rake angle $\gamma_o = 9°30'$, side rake angle $\gamma_f = 7°$;
4. inserts: SEM 43A (ANSI), triple coated;
5. workpiece material: stainless steel 17-4PH (630 AISI);
6. cutting conditions: depth of cut 1 mm, cutting speed $V=$ 92 m min^{-1}, feed 0.8 mm rev^{-1} or for variable sequence according to the cycle $\Delta t = 13.5$ s, $T = 2$ min, $\varepsilon = 0.025$, $n = 5$, as shown in Fig. 3;
7. type of milling operation: climb face milling.

The experimental results of the flank wear parameter VB_{max} and crater wear parameter KT_{max} were obtained in each case for both constant and variable feed. The tests were carried out in two series and the measurements of the wear parameters VB_{max} and KT_{max} were taken at time intervals of 2, 6, 10 and 14 min for the constant feed case and 2, 6, 10, 14 and 18 min for the variable feed case. For each series and for each time interval, 16 measurements were taken.

5. Results and discussion

As proposed in the ISO standards, critical values of crater wear KT_{max} of 0.10 mm and 0.15 mm and of flank wear VB_{max} of 0.3 mm and 0.35 mm were adopted. The tool operating times were obtained for each case from the set of wear curves for the limits adopted for KT_{max} and VB_{max} for both constant and variable feed experiments. Probability paper and a statistical package were used to find the best possible probability distribution from a set of observations. In all cases, the Weibull distribution with two parameters (b,θ) was adopted. To decide on the validity of the fit, the Kolmogorov–Smirnov test [19], with a 0.95 confidence level, was used.

5.1. Estimation of the reliability function and tool life for a Weibull distribution

In this specific case, the probability density function is represented by the relation:

$$f(t) = \frac{b}{\theta}\left(\frac{t}{\theta}\right)^{(b-1)} \exp\left[-\left(\frac{t}{\theta}\right)^{b}\right],\ b,\theta > 0;\ \ t \geq 0 \tag{9}$$

where b is the shape parameter and θ is the scale parameter.

Table 1
Weibull law parameters

	VB_{max}, KT_{max}	Variable feed		Constant feed	
		b	Θ	b	Θ
1	VB = 0.30	3.8	11.8	2.2	10.0
2	VB = 0.35	4.4	16.5	4.5	13.0
3	KT = 0.10	2.4	10.0	1.4	6.0
4	KT = 0.15	3.6	16.0	3.4	11.0

The corresponding reliability function is:

$$R(t) = \exp\left[-\left(\frac{t}{\theta}\right)^{b}\right] \tag{10}$$

and the mean time to failure is obtained by:

$$\mathrm{MTTF} = \theta\Gamma\left(1 + \frac{1}{b}\right) \tag{11}$$

where $\Gamma(x)$ is the Gamma function.

The Weibull distribution parameters for the various cases have been estimated and are presented in Table 1.

From the following equations, the probabilities of events $P'(\mathrm{VB})$ and $P'(\mathrm{KT})$ were estimated as the ratio of the observed number of events over the total possible number of elementary events:

$$P'(\mathrm{VB}) = \frac{n_{\mathrm{VB}}}{n_{\mathrm{VB}} + n_{\mathrm{KT}}} \quad P'(\mathrm{KT}) = \frac{n_{\mathrm{KT}}}{n_{\mathrm{VB}} + n_{\mathrm{KT}}} \tag{12}$$

where n_{VB} is number of failures up to time t, such as $\mathrm{VB} \geq \mathrm{VB}_{max}$, and n_{KT} is number of failures up to time t, such as $\mathrm{KT} \geq \mathrm{KT}_{max}$.

The probabilities $P(\mathrm{VB})$ and $P(\mathrm{KT})$ used in Eq. (13) have been calculated as average values of probabilities $P'(\mathrm{VB})$ and $P'(\mathrm{KT})$ in the test's time interval, e.g. for 14 min in the case of constant feed and for 18 min in the case of variable feed. This process has been adopted due to the limited data available and the necessity to estimate $P(\mathrm{VB})$ and $P(\mathrm{KT})$ in the initial cutting period (0–4 min) where no failure was observed. The numerical results of probabilities $P(\mathrm{VB})$ and $P(\mathrm{KT})$ are presented in Table 2.

To determine the reliability function, Eq. (5) and Eq. (10) were combined. Therefore, the general reliability of a cutting edge is obtained from the following equation:

$$R(t) = \exp\left[-\left(\frac{t}{\theta_{\mathrm{VB}}}\right)^{b_{\mathrm{VB}}}\right]P(\mathrm{VB}) + \exp\left[-\left(\frac{t}{\theta_{\mathrm{KT}}}\right)^{b_{\mathrm{KT}}}\right]P(\mathrm{KT}) \tag{13}$$

The results for the constant and variable feed cases for two of the four combinations of the critical flank and crater wear magnitudes VB_{max} and KT_{max} analyzed are presented in Figs. 4 and 5.

Table 2
Numerical values of probabilities $P(VB)$ and $P(KT)$

$P(A_i)$	Variable feed				Constant feed			
	VB = 0.30 KT = 0.10	VB = 0.30 KT = 0.15	VB = 0.35 KT = 0.10	VB = 0.35 KT = 0.15	VB = 0.30 KT = 0.10	VB = 0.30 KT = 0.15	VB = 0.35 KT = 0.10	VB = 0.35 KT = 0.15
$P(VB)$	0.38	0.61	0.31	0.48	0.35	0.53	0.46	0.44
$P(KT)$	0.62	0.39	0.69	0.52	0.65	0.47	0.54	0.56

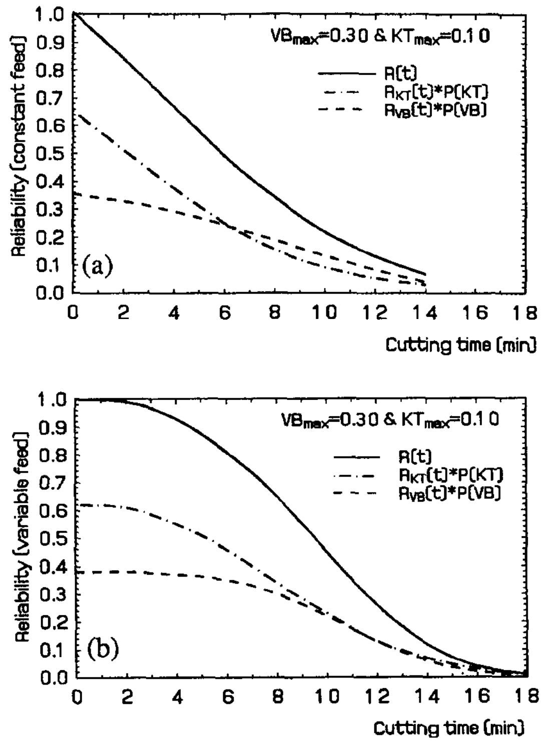

Fig. 4. Reliability of a cutting tool for $VB_{max} = 0.30$ mm and $KT_{max} = 0.1$ mm for constant and variable feed machining.

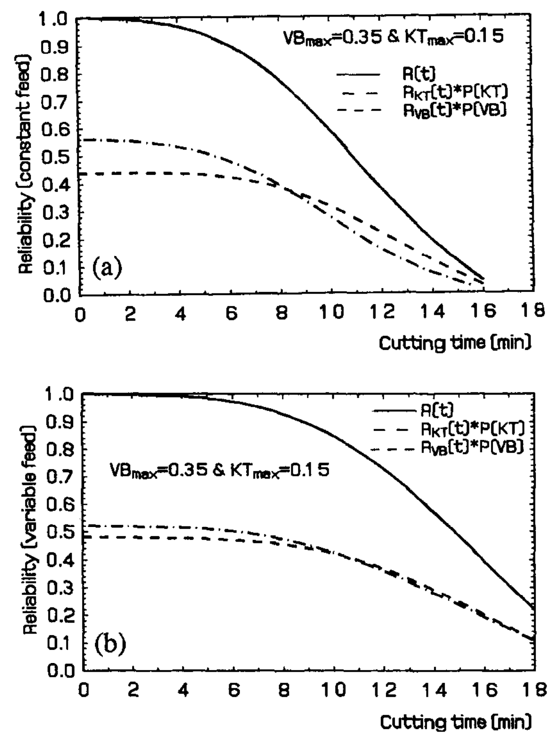

Fig. 5. Reliability of a cutting tool for $VB_{max} = 0.35$ mm and $KT_{max} = 0.15$ mm for constant and variable feed machining.

By combining Eq. (7) and Eq. (13), the life of a cutting edge can be evaluated from the following mean time to failure expression:

$$MTTF = P(VB)\int_0^\infty \exp\left[-\left(\frac{t}{\theta_{VB}}\right)^{b_{VB}}\right] + P(KT)\int_0^\infty \exp\left[-\left(\frac{t}{\theta_{KT}}\right)^{b_{KT}}\right] \qquad (14)$$

This expression effectively calculates the area under the reliability curves and generates information that is more usable by tool management systems. The integration can be calculated by numerical methods. However, in the particular case of the Weibull function, the MTTF can be simplified to Eq. (11) and, in this case, the MTTF is obtained by:

$$\mathrm{MTTF} = P(VB)\,\theta_{VB}\Gamma\left(1+\frac{1}{b_{VB}}\right) + P(KT)\,\theta_{KT}\Gamma\left(1+\frac{1}{b_{KT}}\right) \qquad (15)$$

The calculated MTTFs for all analyzed critical values are presented in Table 3.

Table 3
Cutting tool life in minutes

	VB = 0.30 KT = 0.10	VB = 0.30 KT = 0.15	VB = 0.35 KT = 0.10	VB = 0.35 KT = 0.15
Variable feed	9.54	12.11	10.11	14.46
Constant feed	6.65	9.34	8.41	10.76
$MTTF_{VAR}/MTTF_{CON}$	1.43	1.30	1.20	1.34

5.2. Discussion

The general reliability of the cutting edges $R(t)$ calculated from both crater and flank wear measurements Eq. (13) is shown on the upper solid curve in Fig. 4 and Fig. 5. The individual crater and flank reliability curves are shown in the same figures as separate dotted curves.

The general reliability of the cutting edges used under variable feed conditions is always superior to the constant feed case. One can also observe that the reliability stays high for a longer time under variable feed comparative to constant feed conditions. On the basis of these curves, tool replacement policies can be formulated. For example, if it is decided in a machine shop to replace tools when they are less than 70% reliable (probability of failure-free working of 70%), the tool change times would be 4 min under constant feed and 8 min under variable feed conditions (Fig. 4). In this case, the tool life increases by 100% for the variable feed condition. When comparing the MTTF parameters, which represent the area under the reliability function (Table 3), the variable feed MTTFs are also higher than the constant feed MTTFs. In those terms, the increase in tool life is at least 20% and can be as much as 43% depending on the combination of the critical failure values selected.

In machine-shop practice, both VB_{max} and KT_{max} parameters must be used. The first parameter controls the surface roughness and dimensional accuracy, the second controls tool breakage. When only VB_{max} is taken into consideration, one can clearly see in Fig. 4 for the variable feed case that the tool reliability is near constant for 8 min. In the constant feed case, the reliability decreases constantly from the onset of machining. This information can be essential for tool replacement policies in the case of high-precision machining where dimensional accuracy and surface quality are paramount. When simultaneously taking into account both wear parameters, one can notice that initially the more probable tool failure is on the flank face for both constant and variable feed machining cases. Later, both resultant probabilities are similar. When the critical wear parameter values are increased to $VB_{max}=0.35$ mm and $KT_{max}=0.15$ mm, which could be applied for rough machining, the tool failure probabilities are close to each other and therefore both VB_{max} or KT_{max} could be effectively used for tool replacement policies as shown in Fig. 5.

The current study therefore shows that both modes of failure must be considered for any reliability analysis of the machining process.

6. Conclusion

A new approach to the analysis of cutting tool life including a new reliability model has been developed. The proposed method shows that a more realistic tool failure criterion, taking simultaneously into account both the flank and the face wear, can be used for the analysis of cutting tool reliability. This method can be very useful to quantify the cutting tool reliability for tool manufacturers and manufacturing firms as well as for researchers.

From this research the following conclusions can be drawn:

1. The developed method permits a more detailed analysis of the tool performance under constant and variable feed conditions.
2. The reliability function can not only predict the tool life accurately but can also be used for production planning and tool management.
3. The results show a considerable reliability improvement of cutting tools working under variable feed conditions. Their mean life span is 20% to 43% longer than the mean life span of tools working under constant feed conditions. Moreover, when using the 70% reliability criterion, the increase can be as high as 100%.
4. The developed reliability analysis based on the two criteria can be used to compare tool life for specific machining applications such as high-precision and rough machining.

7. Future work

Future studies will focus on an in-depth analysis of the cutting tool reliability based on different feed variation cycles and materials. The increase in the number of tools studied should allow a more detailed analysis of the edge life limited by flank and face wear. The development of the above proposed model in order to incorporate catastrophic failures should also prove valuable.

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