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Effects of Random Aspects of Cutting Tool Wear on Surface Roughness and Tool Life

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The effects of random aspects of cutting tool flank wear on surface roughness and on tool lifetime, when turning the AISI 1045 carbon steel, were studied in this investigation. It was found that standard deviations corresponding to tool flank wear and to the surface roughness increase exponentially with cutting time. Under cutting conditions that correspond to finishing operations, no significant differences were found between the calculated values of the capability index C_p at the steady-state region of the tool flank wear, using the best-fit method or the Box-Cox transformation, or by making the assumption that the surface roughness data are normally distributed. Hence, a method to establish cutting tool lifetime could be established that simultaneously respects the desired average of surface roughness and the required capability index.

Keywords capability index, cutting tool lifetime, cutting tool wear, random aspects, surface roughness

1. Introduction

An essential part of machining in the unmanned factory is the ability to change out tools automatically when they are worn or damaged (Ref 1). Most tools fail by fracture or by gradual wear. Even within these two failure modes, there are various other types of wear (Ref 2). Fracture occurs more rapidly in brittle tools under interrupted cutting conditions. During gradual wear, the tool will reach its limit of life by either flank or crater wear. These are always present in a machining operation and have been considered to present regular cutting time-related growth characteristics. Due to these reasons, flank wear and crater wear have generally been the topics of most studies of cutting tool wear (Ref 3). In the gradual wear, only flank wear on the nose and the resulting recession of the cutting edge directly affect the workpiece dimensions and the generated surface quality. Therefore, the foremost type of wear that has drawn constant attention is flank wear.

Sensing methods of tool wear are divided into direct or indirect measurements. The first method, which is an off-line method, involves the tool wear measuring and evaluates the volumetric loss from the tool. The second method is based on the establishment of relationships between the tool wear and other parameters that can be measured on line. In this case, acoustic emission, vibration, or force sensing equipment was usually used (Ref 4-6). The main advantage from application of these techniques is their abilities to detect the tool wear state during the cutting operation. However, although good correlations between the used sensors output signals and the measured tool wear were generally found, the industrial applications of these techniques remain limited due to the induced extra costs and technical difficulties for sensor installation on the cutting machine. In addition, the sensor must be calibrated to correctly convert the original signal to tool wear. This task can only be achieved by the direct sensing method.

Examination of the literature related to the first method has particularly shown that the tool lifetime measurement is generally evaluated experimentally by establishing the relationship between the flank wear and the cutting time without taking into account random aspects of the tool wear (Ref 7, 8). By considering the efforts made in the last two decades to integrate the deployment of statistical process control for quality excellence, it seems unavoidable to consider the random aspects of the cutting tool wear. Indeed, the variation of the tool wear certainly induces variations in the workpiece's geometric and dimensional characteristics and in the finished surface quality. Therefore, the process capability is expected to be affected by random aspects of cutting tool wear regardless of desired specifications.

In this investigation, an attempt is made to characterize the random aspects of the cutting tool wear generated by the turning process. The effects of these random aspects on the variation of the surface roughness of turned workpieces and on the tool lifetime are discussed.

2. Experimental Procedures

All experiments were conducted using a REALMECA T400 (Clermont en Argonne, France) lathe having a power of 9 kW. The work material in use for the experiments is AISI 1045 carbon steel. This material is frequently used for mechanical parts that undergo heat treatment, such as hydraulic shafting, pump shafts, piston rods, and so on. The cutting tool used for the experiments is the Sandvik SNMG (Sweden) 120404-PM. Continuous cutting wear tests were conducted under dry cutting with constant values of depth of cut, $a = 2$ mm; feed rate, $f = 0.3$ mm/rev; $N = 1600$ rev/min; and cutting speed, $V_c = 191$ m/min. The cutting times were fixed to 1.5, 3, 4.5, 6, 7.5, 9, 12, 24, 36, 48, and 60 min. At the end of each cutting time,

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the test was stopped and the insert was changed. Flank wear at the worn insert (V_B) was, thereafter, measured using a toolmaker microscope (Fowler-Sylvac 25, Switzerland) having an accuracy of 0.001/0.001 mm. At the same time, the surface roughness parameters R_a (arithmetic surface roughness) and R_t (maximum depth of profile) were measured using a stylus-based instrument (Taylor Hobson, UK) having an accuracy of 0.1 μm. To investigate the random aspects of the tool wear, these operations were repeated 20 times for each cutting period.

3. Results

3.1 Random Aspects

Examination of the cutting tool flank wear shows regular shapes (Fig. 1), and the wear could be measured with great accuracy. The experimental error was estimated to 2 μm. On the other hand, the random aspect of the collected data was studied by statistical tests. Statistical significance tests based on *P* value calculation were performed using a confidence level of $\alpha = 5\%$. It was supposed that, if the *P* value is higher than 0.05, then no statistical significant differences in the population of the collected data can be confirmed and the observed differences are only due to the experimental errors.

Accordingly, as seen in Table 1, no statistical significant differences in the data of the tool wear can be considered in the steady wear region corresponding to a cutting time between 5 and 48 min (not included). At the preliminary wear region corresponding to cutting time less than 3 min, the calculated *P* values are less than 0.05. This means that data of the cutting tool wear, measured at these cutting times, can be believed to be statistically different. The wear in this region is caused by microcracking, surface oxidation, and carbon loss layer, as well as by the microroughness at the cutting tool tip (Ref 2, 9). As the cutting operation progresses, the cutting edges wear out due to the small contact area and high contact pressure between the tool tip and the generated chips. Because the shapes and the geometries of these cutting edges are initially different, they wear out differently. This leads to significant differences between the data of the preliminary tool flank wear and the large dependency of tool wear on the initial state of the insert being used. On the other hand, cutting tool wear measured at cutting times higher than 48 min corresponds to the ultimate wear. When the wear size reaches a critical value at which the tool loses its cutting ability, the cutting force and temperature increase rapidly and the wear rate increases very sharply. At this stage, the behavior of the cutting edges becomes unpredictable and different behavior can be expected for each cutting edge that reaches this order of cutting time. Concerning the surface roughness parameter R_t, Table 1 shows that, for all the cutting times used in this investigation, no statistical differences can be observed between the collected data. However, the calculated *P* values for data corresponding to the arithmetic surface roughness parameter R_a indicate higher sensitivity of this parameter to the cutting time, as statistically significant differences can be established for cutting times higher than 36 min. It is important to notice that this time is close to the critical cutting period corresponding to the ultimate wear.

3.2 Flank Wear

The effects of the cutting time on the tool flank wear and on the corresponding standard deviation shown in Fig. 2. The

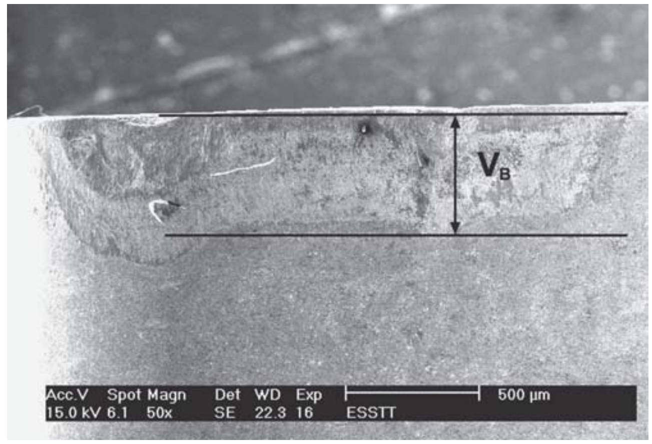

Fig. 1 SEM micrograph of the flank wear observed on the cutting edge after a cutting time of 60 min ($a = 2$ mm, $f = 0.3$mm/min, $V_c = 191$ m/min)

Table 1 Random aspects of the investigated characteristics at different cutting times

	P value		
		Surface roughness	
Cutting time, min	Tool wear V_B, mm	R_a	R_t
1.5	0.032	0.704	0.976
3	0.026	0.552	0.799
4.5	0.801	0.750	0.220
7.5	0.239	0.509	0.572
9	0.997	0.503	0.233
12	0.944	0.996	0.373
24	0.787	0.824	0.383
36	0.143	0.015	0.772
48	0.004	0.007	0.495
60	0.016	0.015	0.991

three regions characterizing the flank wear, i.e., preliminary wear region, steady-state region, and ultimate region, are observed in Fig. 2(a). Curves expressing the relationship between the cutting times and the standard deviations associated with the measured flank wear is given by Fig. 2(b). It is seen that this curve can be fitted accurately with an exponential function and that the standard deviation of the measured flank wear increases when the cutting time is increased. Because the machined surface quality is widely dependent on the wear state of the cutting tool, the scatter in tool wear introduces a high variation in the turned surface quality and, therefore, affects the process capability indices.

3.3 Surface Roughness

Effects of the cutting time on the surface roughness parameters R_t and R_a are given by Fig. 3(a) and (b) and by Fig. 4(a) and (b), respectively. These figures in particular show that the surface roughness parameters and their associated standard deviations increase with the cutting time. In this case also, curves expressing the relationship between the standard deviations of the surface roughness parameters R_t and R_a can be fitted by an exponential function. Thus, as indicated above, it can be expected that the capability indices decrease with the cutting time regardless of the surface roughness.

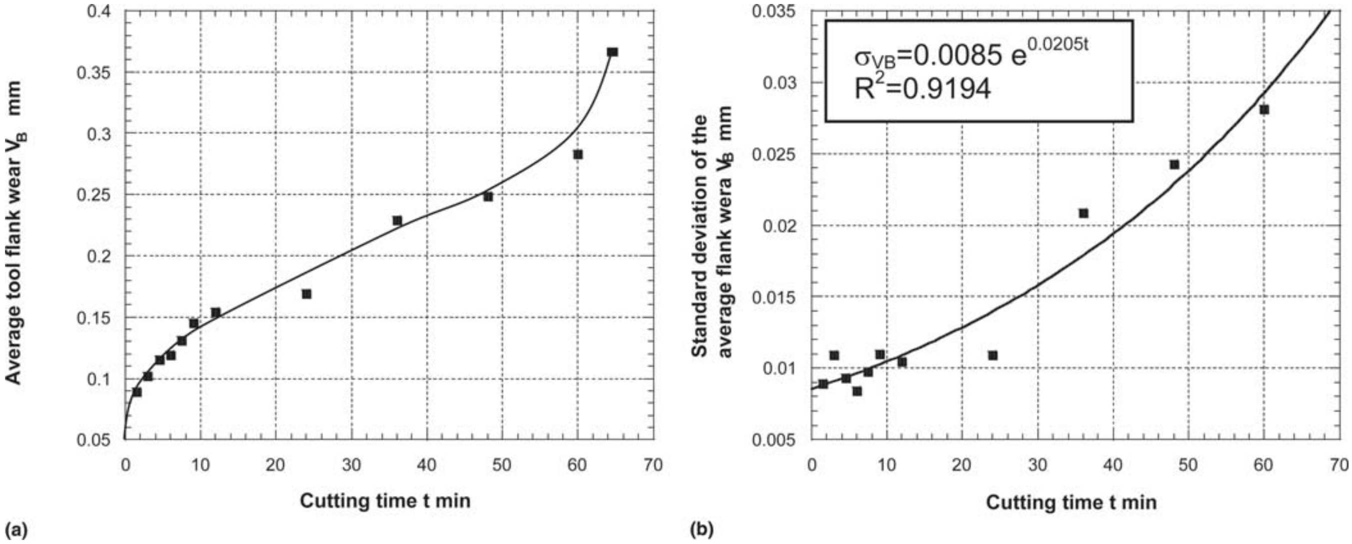

Fig. 2 Effects of the cutting time on the flank wear V_B: (a) average values; (b) standard deviation values

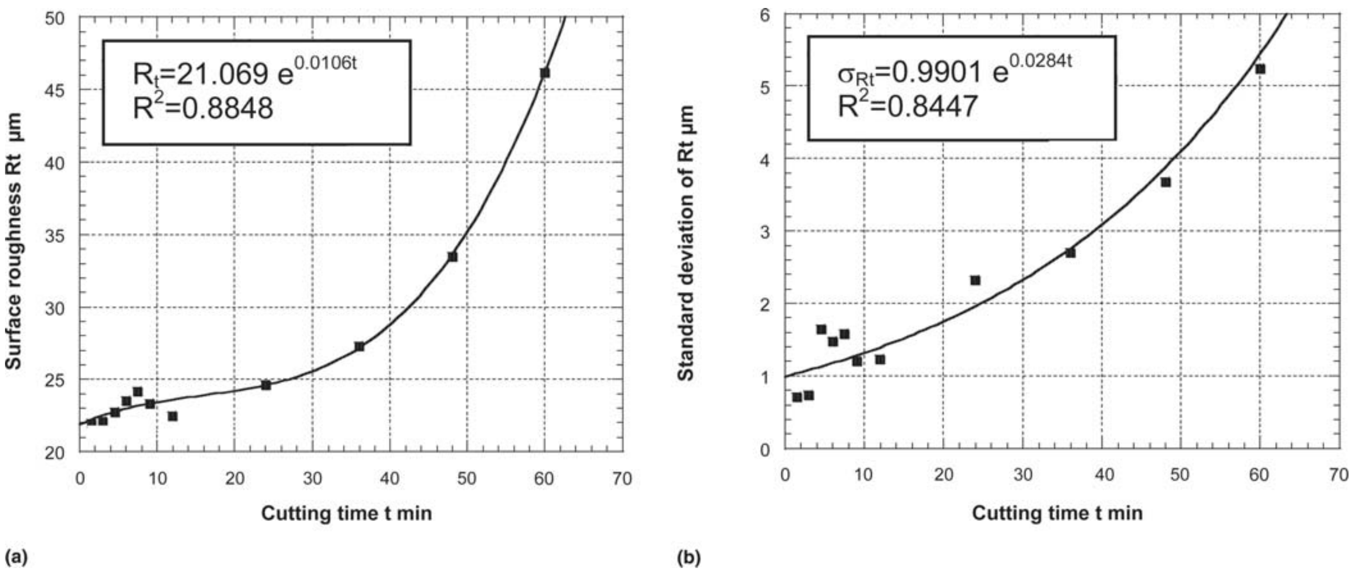

Fig. 3 Effects of the cutting time on the maximum depth of surface roughness profile: (a) average values; (b) standard deviation values

3.4 Capability Index Calculation

Various process capability indices, including C_p, C_{pk}, C_{pm}, and C_{pmk}, have been proposed to provide a unitless measure on whether the process is capable of producing products that meet the specifications preset by the product designer. Nevertheless, the most widely used indices in manufacturing industries are C_p and C_{pk} (Ref 10, 11). On the other hand, the use of these indices is partly based on the assumption that the process output monitored is normally distributed. If the process output is non-normally distributed, then the calculated indices (although normality of these distributions is assumed) and, consequently, the correspondingly expected proportions of nonconforming products are no longer proper (Ref 12). Therefore, the collected data for tool wear and surface roughness were checked for normality. The capability index C_p was calculated based on the work of Samuel et al. (Ref 11):

$$C_p = \frac{\mathrm{USL} - \mathrm{LSL}}{6\sigma} \qquad \text{(Eq 1)}$$

where USL, LSL, and σ are the upper and lower limit specification limits and the standard deviation associated with the measured specification limits.

The capability index flow diagram given by Fig. 5 shows the method used in this investigation for C_p computation. The results of C_p calculations, using both the method given in Fig. 5, and by assuming the roughness data are normally distributed for the surface roughness parameters R_a and R_t, are given by Fig. 6(a) and (b), respectively. For C_p calculation, although only USL is usually required for the surface roughness parameters by the product designer, the LSL is usually imposed by the manufacturer to avoid the extra costs induced by overquality in the manufactured products. Thus, for the finishing operation considered in the case of Fig. 6(a) and (b), the selected specifications were LSL = 20 μm, USL = 40 μm for R_t and LSL = 2.5, USL = 6 μm for R_a. These figures do not show any significant difference between the value of C_p calculated by using the method indicated by Fig. 5 and by making the assumption that data of R_a and R_t are normally distributed for

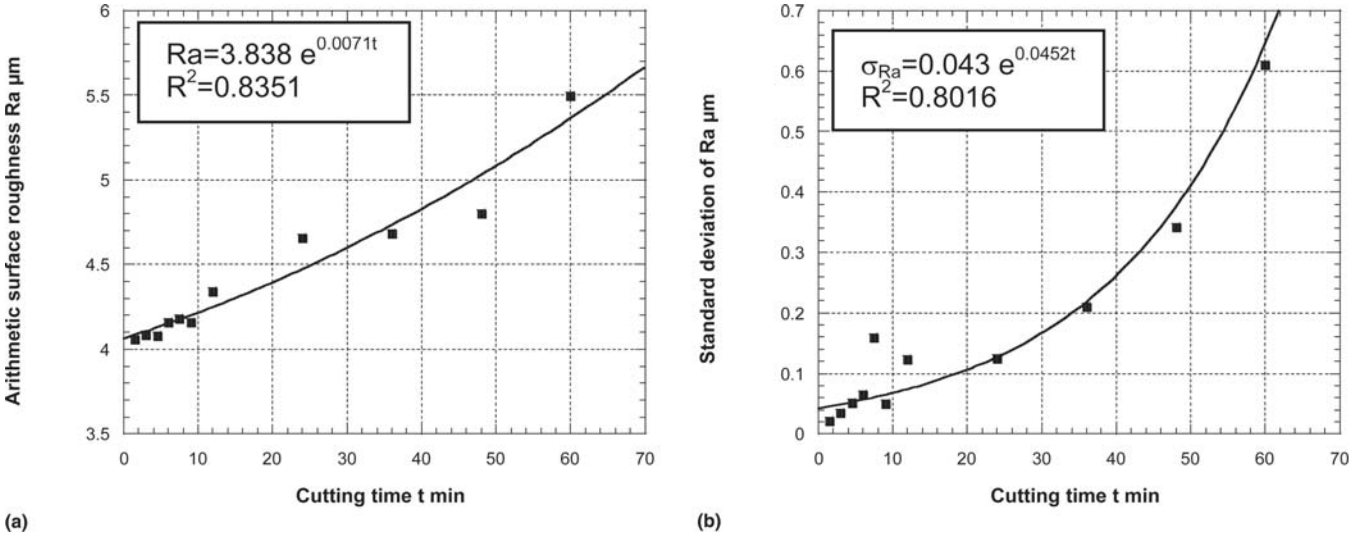

Fig. 4 Effects of the cutting time on the arithmetic surface roughness: (a) average values; (b) standard deviation values

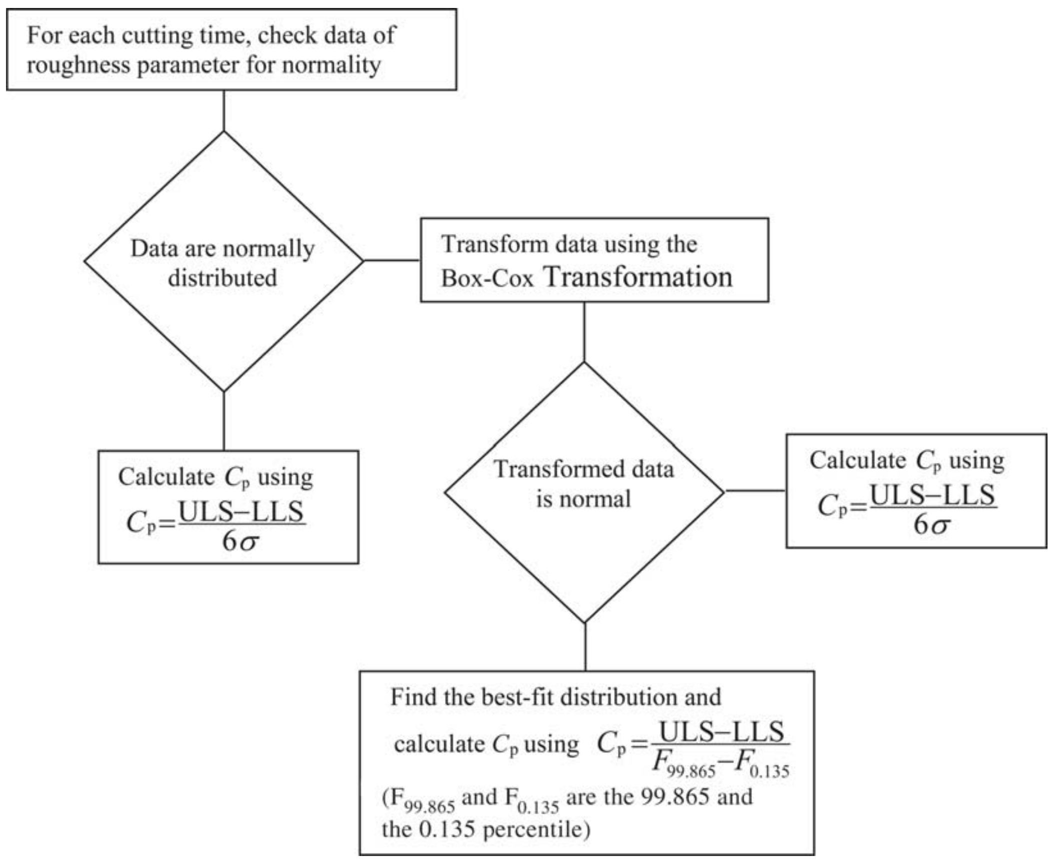

Fig. 5 Method for the calculation of the C_p capability index

cutting times more than 8 min. This period corresponds to the time required to reach cutting tool steady-state wear. It is important to note that the expression of the cutting tool lifetime is usually established in this region. Therefore, it can be concluded that, within the experimental conditions selected in this investigation, the assumption that C_p can be calculated using the following expression:

$$C_p = \frac{USL - LSL}{6\sigma_{\bar{R}_i}} \quad \text{(Eq 2)}$$

is valid in the steady-state region of the cutting tool wear. Here USL, LSL, and σ_{R_i} are the upper and lower limit specifications and the standard deviation of the surface roughness parameter.

3.5 Tool Life Prediction

To determine the cutting tool lifetime (T), which respects both the required surface roughness value and the imposed capability index C_p, the method shown in Fig. 7 was developed. This method points out that the cutting tool lifetime T is the lower value between t and t'. The first time, t, is the cutting

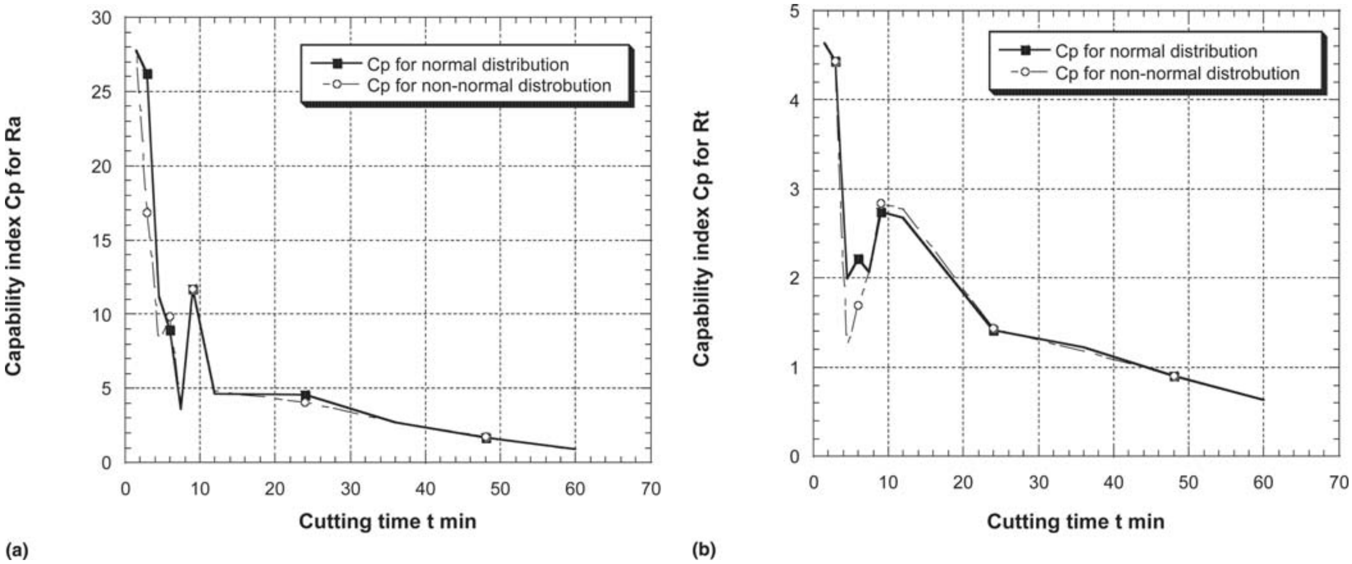

Fig. 6 Capability index C_p for different cutting times: (a) for arithmetic surface roughness, R_a; (b) for maximum depth of surface roughness profile, R_t

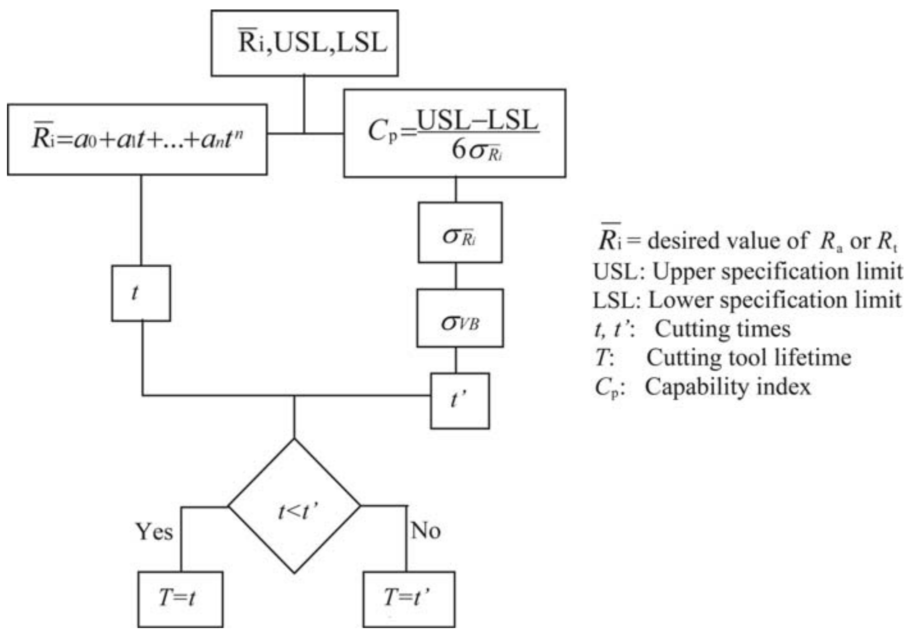

Fig. 7 Developed method to establish the lifetime of the cutting tool

tool life that respects the average value of the desired surface roughness. Time t' is the longest cutting time before the insert has to be changed to avoid a percentage of nonconforms higher than that of the tolerated value.

The cutting time t can be determined by using the graphs in Fig. 3(a) and 4(a) or by solving the polynomial equation yielding the relationship between the cutting time and desired average surface roughness, as indicated in Fig. 7. Concerning time t', it can be found by using Fig. 8. Here, the value of C_p fixes the highest tolerated value of the standard deviation of the surface roughness parameter $\sigma_{\overline{R}_i}$ (Eq 2). Therefore, the cutting time t' can correspond to the value of $\sigma_{\overline{R}_i}$.

For applications, see Table 2. In these cases, the LSL were fixed to the nil theoretical value. As can be seen in Table 2, the tool life, which has to be selected, significantly depends not only on the desired surface roughness but also on the required capability index C_p.

4. Conclusions

In this study, the effects of the random aspects of the cutting tool wear on lifetime as a function of the machined surface roughness were investigated using AISI 1045. In particular, it was established that standard deviations in the cutting tool flank wear, arithmetic surface roughness (R_a), and maximum depth of roughness profile (R_t) increase exponentially with the cutting time. On the other hand, for cutting times that correspond to the steady-state region of the cutting tool flank wear,

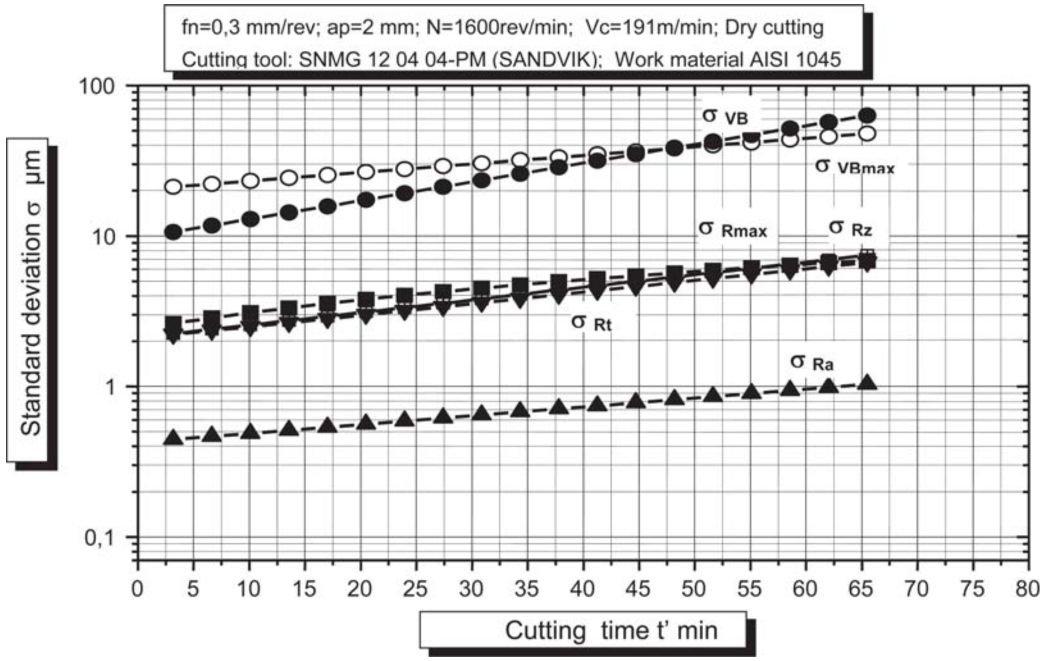

Fig. 8 Abacus for cutting time determination depending on the tolerated standard deviation of the considered surface roughness parameter

Table 2 Examples of application of the proposed method given by Fig. 7

Roughness parameter	Desired value, µm	Required C_p index	t, min	$\sigma_{\bar{R}_i}$, µm	t', min	T, min
R_t	40	1.33	55	5	45	45
		2	55	3.33	37	37
	25	1.33	28	3.1	33	28
		2	28	2	<5	<5
R_a	5.5	1.33	65	0.689	38	38
		2	65	0.45	<5	<5
	4.5	1.33	26	0.563	22	22
		2	26	0.375	<5	<5

no significant differences were observed with respect to the calculated capability indices (C_p) using the best-fit distribution, the Box-Cox transformation, or assuming that data of roughness parameters are normally distributed. Thus, a method for cutting tool lifetime establishment that takes into account both the required roughness and the imposed capability index was proposed. Application of this method could make evident the high sensitivity of the cutting tool lifetime to these requirements that cannot be ignored for accurate determination of the cutting tool life.

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