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ORIGINAL ARTICLE

Experimental investigation of a novel machining strategy for rough turning using variable feed rate

Ali Oral[1] · **M. Cemal Cakir**[2] · **Demet Gonen**[3] · **A. Deniz Karaoglan**[3]

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Abstract The life of a tool is affected by many factors such as cutting speed, depth of cut, chip thickness, tool geometry, workpiece material, cutting fluid and the rigidity of the machine tool. This paper introduces the innovative turning strategy of variable feed turning. The workpiece material was AISI 1050, and two types of TiN-coated insert (CNMG-120408 (NC3020) and DNMG 150608-NM4 WPP20) were used as cutting tools in the machining tests. A thorough investigation was carried out on the effect on tool life of a gradual feed rate at a constant depth of cut and cutting speed with no cooling fluid. The feed rate was gradually increased twice every millimetre at the beginning of turning and kept constant for the rest of the cut. Turning experiments were conducted with both constant and variable feed rates. Brand new inserts were deployed in the experiments related with constant feed rate for each time period. Comparisons showed the significant influence of the variable feed rate. Apart from the reduction in initial wear, the new turning strategy produced very positive results regarding tool wear in the moderate wear zone, and a considerable increase of 32 % in tool life was achieved. Moreover, with the new strategy, total tool life was prolonged by up to 35 %.

Keywords Tool life · Initial wear · Variable feed rate

1 Introduction

Among the metal cutting methods used in industry, turning is a widely used material removal technique. Due to the normally high stress and shearing tension, chips removed from the material, once they are deformed, create friction as they slide on the surface, and tool wear occurs as a result [1, 2].

Tool wear is a time-related process and 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 one or more of them exerting predominant influence depending on the situation, identification of the dominant mechanism is far from simple [3]. As cutting proceeds and the cutting temperature increases, the amount of tool wear gradually increases.

Tool wear is generally considered to be the result of wear interactions between the tool and workpiece. These interactions can be categorised as mechanical wear, including thermo-dynamic wear which is mostly abrasion, and chemical wear, including thermo-chemical wear and diffusion [3, 4]. Primary tool wear, classified as flank wear, crater wear and nose wear, is an important factor affecting the smoothness of the product, the performance and the cost of operation.

The wear curve, which is the correlation of VB (flank wear) versus cutting time, is shown in Fig. 1. The wear curve line, which is straight in the central region with curved terminal

✉ Ali Oral
alioral@balikesir.edu.tr

M. Cemal Cakir
cemal@uludag.edu.tr

Demet Gonen
dgonen@balikesir.edu.tr

A. Deniz Karaoglan
deniz@balikesir.edu.tr

[1] Department of Mechanical Engineering, Balikesir University, 10145 Balikesir, Turkey

[2] Department of Mechanical Engineering, Uludag University, 16059 Bursa, Turkey

[3] Department of Industrial Engineering, Balikesir University, 10145 Balikesir, Turkey

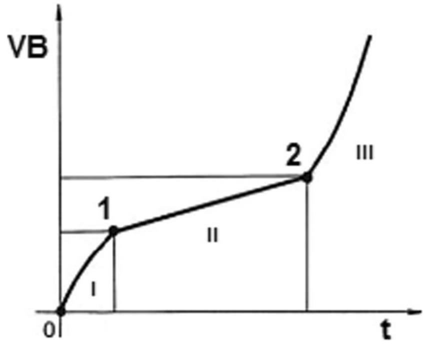


Fig. 1 Wear curve [5]

fragments, consists of three zones: initial wear, steady wear (moderate wear) and accelerated wear [5–7]. Tool wear shows a rapid increase at the very beginning of the cut (initial wear). Following this rapid increase, the wear rate slows down and keeps climbing steadily with a linear increase. As the tool life comes to an end, the wear rate accelerates, and therefore, the tool life expires as the cutting operation continues. In accordance with Standard ISO 3685, VB shall be used as a criterion for tool wear (Fig. 1). This standard defines the tool life value as a flank wear amount of 0.3 mm.

Hyrniewicz and Pluta (2012) presented a model of the entire wear curve, covering all of its characteristic segments relating to the cutting process from beginning to end. In their novel model, they presented the wear curve as four periods of time: (1) no detectable wear, (2) initial wear, (3) moderate wear and (4) accelerated wear [8]. In their model, they assumed that the first period of the curve had not always been determined univocally due to the fact that the measurements of the tool edge wear began after extended machining time, not allowing for the characterisation of geometric changes in the edge during the first period of operation.

Many researchers have indirectly addressed the influence of the cutting parameters and, in particular, the feed on tool wear. The basis of this method is the control of the contact length between chip and tool since it has been proven that the contact length is one of the most important control parameters [9–13]. Zadshakoyan and Pourmostaghimi (2013) developed a genetic equation for the tool–chip contact length with the use of the experimentally measured contact length values and genetic programming [14]. In their work, they concluded that the contact length shows a decreasing trend with increasing cutting speed due to the thermal softening effect and the decay of the apparent friction coefficient [15]. However, increasing the feed rate corresponds with increasing in the tool–chip contact length due to the increased chip thickness and cutting forces. Oral et al. indicated that an essential part of the initial wear zone was caused by the extreme cutting forces generated on first contact between the tool and the workpiece [16]. This suggests that, if the initial wear increases are due to the increase of cutting forces at first contact, then the initial wear will decrease if the forces are reduced.

Table 1 Chemical composition of AISI 1050

C	Mn	Si	P	S
0.52	0.80	0.25	0.035	0.035

Kim et al. (1995) suggested that improvements in tool life using variable feed are related to the shifting of the temperature peak at the tool–chip interface [17]. In their study, they investigated the effect of feed variation on tool wear and tool life using a reliability model for the quantitative study of variable feed milling of stainless steel 17-4PH. In their work, which is based on experiments, the tool life for the constant and variable feed cases was calculated from the reliability function. Both flank and crater wears have been taken into consideration.

Sikdar and Chen (2002) presented their experimental results and discussed in their study the use of polynomial equations to express the relationship between cutting forces and flank wear areas [18]. Yuefeng et al. (2010) performed a

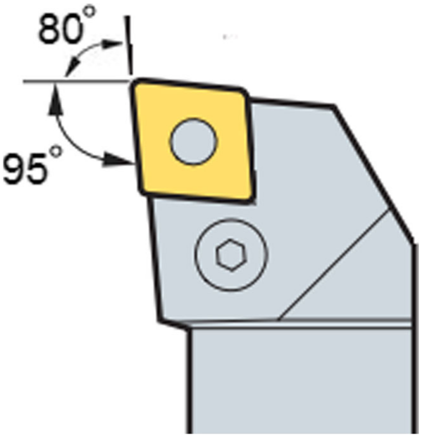


Fig. 2 Cutting tool angles used in the experiments

Fig. 3 CNC lathe used in the experiments

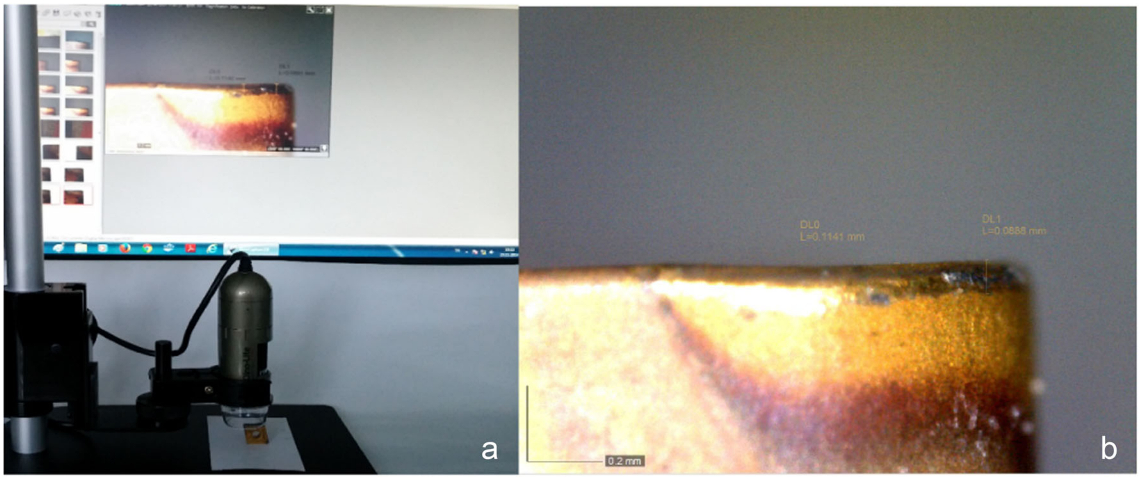


Fig. 4 **a** Dino-Lite AD4000 series microscope. **b** Wear measurements (240×)

Table 2 Cutting parameters for the constant feed turning operation

Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)
280	0.25	3

Table 3 Cutting parameters for the variable feed turning operation

Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)
280	$f_1 = 0.15$ for the first 1 mm; $f_2 = 0.20$ for the next 1 mm; $f_3 = 0.25$ for the rest	3

turning operation for a period of 2 min using various brands of cutting inserts and suggested that it was possible to establish a correlation between initial wear and uniform wear [19].

The most widely used tool life equation is the Taylor tool life equation [20], which relates the tool life to the cutting speed (V) through an empirical tool life constant (C_t):

$$VT^n = C_t \tag{1}$$

where T is specified in minutes and C_t is the cutting speed which yields one minute of tool life. The exponent n determines the slope of the tool life curve. Although Taylor's equation reflects the dominant influence of the cutting speed on tool life, it does not account for the less prominent but significant effects of feed rate and depth of the cut. For this reason, the extended Taylor equation is often used by Woldman and Gibbons (1951) [21].

$$VT^n f^a d^b = K_t \tag{2}$$

Values of K_t, n, a and b, for specific tool grades and common work materials, are sometimes tabulated in tooling catalogues.

As can be observed from the literature, much research has been conducted on the relations between cutting parameters and tool life in turning operations. However, apart from the works of Balanzinski [17, 22, 23], not many work has been reported in the literature concerning the reduction of wear, especially initial wear, by applying variable feed rates.

Table 4 Flank wear values at 2-s intervals for variable feed rate

Time (s)	Flank wear (mm)		
	0.15 mm/rev	0.20 mm/rev	0.25 mm/rev
2	0.0203	0.0210	0.0215
4	0.0215	0.0225	0.0265
6	0.0224	0.0246	0.0268
8	0.0245	0.0254	0.0275
10	0.0289	0.0268	0.0292

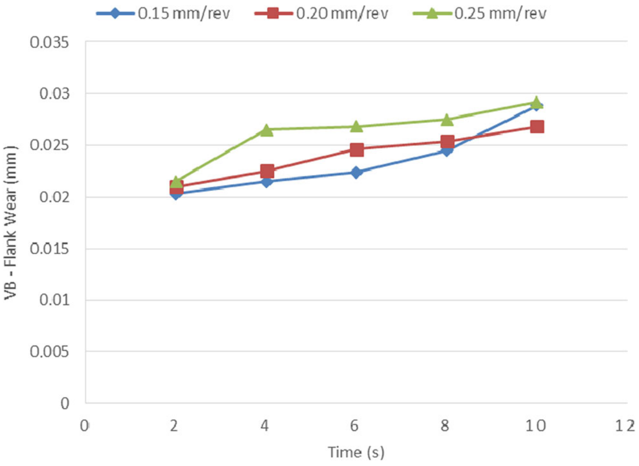


Fig. 5 Initial tool wear developments for the first 10 s

Table 5 Initial tool wear results for the first 10 s

Time (s)	Constant feed rate		Variable feed rate	
	Feed (mm/rev)	Flank wear VB (mm)	Feed (mm/rev)	Flank wear VB (mm)
2	0.25	0.0215	$f_1 = 0.15$ for the first 1 mm;	0.0133
4		0.0265	$f_2 = 0.20$ for the next 1 mm;	0.0164
6		0.0250	$f_3 = 0.25$ for the rest	0.0163
8		0.0275		0.0216
10		0.0290		0.0192

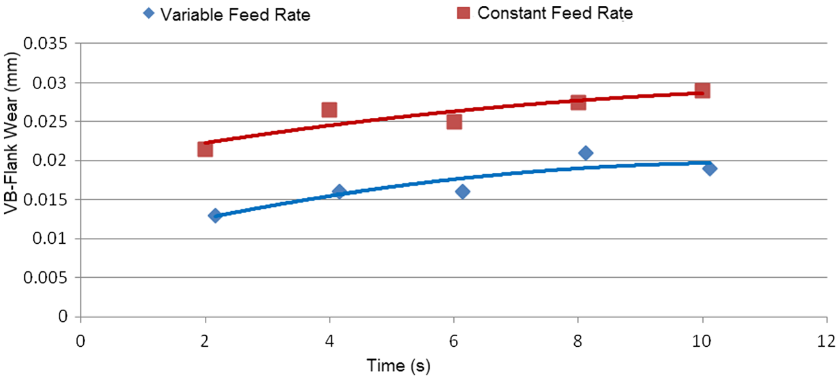


Fig. 6 Variable vs constant feed rates

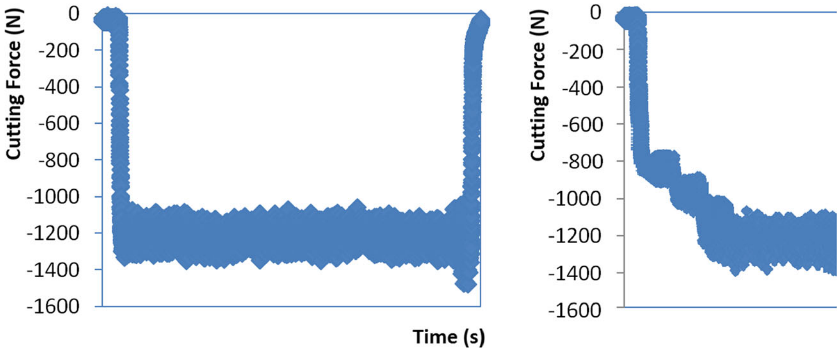
Balazinki's works mainly concentrated on improvement of tool life by varying feed during machining either by choosing discrete feed rates or using sinusoidal feed variation cycle or using reliability function. However, none of his works aim to investigate the initial wear. In this study, a series of machining tests was conducted in order to evaluate the effects of variable feeds on tool life in both the initial and moderate wear zones.

The tangential component of the cutting force can be specified as [24]:

$$F_c = K_s \cdot a_p \cdot f \qquad (3)$$

where K_s is the specific cutting force (N/mm^2), a_p is the depth of cut (mm) and f is the feed rate (mm/rev).

In order to reduce the cutting force and minimise its effect on tool life at the initial wear stage, either the feed rate or the depth of cut needs to be reduced. In the present work, the rapid increase of wear at the initial stage was considered to be the result of high cutting forces at first contact between the cutting tool and the workpiece. Thus, in order to reduce the forces, the turning operation was started with the lowest feed rate available and was increased gradually as the process continued. Depth of cut, the other parameter affecting the cutting force, was obviously kept constant in the longitudinal turning.



a- Constant feed rate

b- Variable feed rate

Fig. 7 Cutting forces for constant and variable feed turning. **a** Constant feed rate. **b** Variable feed rate

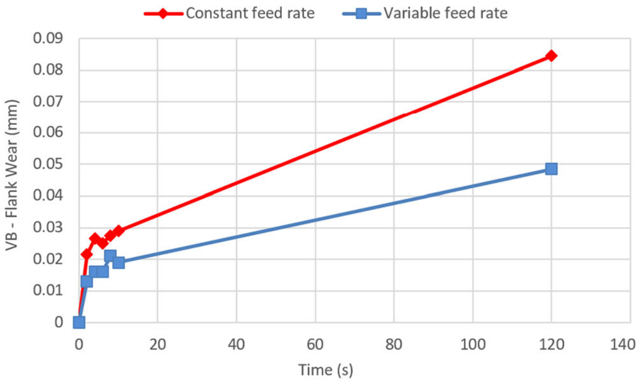


Fig. 8 Wear curve for 120 s of machining

2 Experimental procedures

The workpiece material was AISI 1050, and TiN-coated KORLOY CNMG-120408 (NC3020) (Fig. 2) was used for the cutting insert in the machining tests. The chemical composition of the workpiece material is given in Table 1. Machining tests were conducted on cylindrical samples (Ø80 × 200) in dry cutting conditions using a Goodway-GS-200 CNC lathe (Fig. 3). Cylindrical samples were 200-mm long. In each experiment, machining length was 125 mm in each pass for both constant and variable feed rates.

The aim of the paper was to investigate the tool wear in moderate wear zone as well as the initial wear zone and throughout the tool life. Therefore, three set of experiments were planned as follows: for the first 10 s, for 120 s and for the rest of the cut (up to 0.25 mm of flank wear). Experiments were repeated three times, and the mean values of tool wear were taken into consideration.

A Dino-Lite Pro2 AD4000 microscope with a sensitivity of 0.0001 mm was employed for wear measurements (Fig. 4). In accordance with Standard ISO 3685, flank wear (VB) was used as a criterion for tool wear. Cutting parameters used in the experiments are given in Tables 2 and 3. In this study, two groups of flank wear values were acquired, one for the constant feed and one for the variable feed. Feed rate was the only cutting parameter that can be altered during longitudinal turning (where the workpiece diameter is constant). Thus, only its effect was evaluated in terms of tool wear and processing time.

3 Results and discussion

3.1 'Variable' vs 'constant' for the first 10 s (initial wear zone)

In the present work, flank wear measurements for 2, 4, 6, 8 and 10 s of machining at variable feed rates (0.15, 0.20 and 0.25 mm/rev), but constant cutting speed and depth of cut ($V_c = 280$ m/min; $a_p = 3$ mm) were conducted (Table 4). For all the machining trials, lower feed rates resulted in reduced tool wear, except 10 s of machining (Fig. 5). This was interpreted as being the result of the unbroken chip at the low feed rates that caused greater friction, heat and wear. Lower feed rates cause lower cutting force, and the lower cutting force leads to less flank wear. The greater the values in the flank wear area, the higher the friction of the tool on the workpiece material, which generates high heat [25].

In this study, the influences of variable feeds on the initial and moderate wear zones were investigated. Flank wear was measured and evaluated for 2-s-incremented machining periods of turning (first 2 s of machining time, then 4 s, then 6 s, etc.) with a constant feed rate. Brand new inserts were deployed in each machining period. In the next step, the same process was repeated for the variable feed that was increased from 0.15 to 0.20 mm/rev and then to 0.25 mm/rev at 1 mm of cutting intervals then kept constant for the rest of the cut. Initial tool wear results for both constant and variable feeds are listed in Table 5, and their comparison is given in Fig. 6. Flank wear values are mean values.

The cutting forces measured using KISTLER 9257B dynamometer are illustrated in Fig. 7. In Fig. 6a, as a result of the constant feed rate (0.25 mm/rev), the cutting force was constant. However, the cutting force increased gradually as the feed increased steadily from 0.15 to 0.25 mm/rev with an increment of 0.05 mm/rev (Fig. 7b). The increase in cutting force was proportional to the increase in feed rate, and the initial wear was significantly altered, based on the magnitude of these cutting forces.

Table 6 Tool wear values for the first 120 s

	Cutting speed (m/min)	Depth of cut (mm)	Feed (mm/rev)	Flank wear VB (mm)
Constant feed	280	3	0.25	0.0845
Variable feed	280	3	$f_1 = 0.15$ for the first 1 mm $f_2 = 0.20$ for the next 1 mm $f_3 = 0.25$ for the rest	0.0485

Table 7 Tool wear after feed increase to 0.26 mm/rev (variable feed 2)

Cutting speed (m/min)	Depth of cut (mm)	Feed (mm/rev)	Flank wear VB (mm)
280	3	$f_1 = 0.15$ $f_2 = 0.20$ $f_3 = 0.26$	0.0573

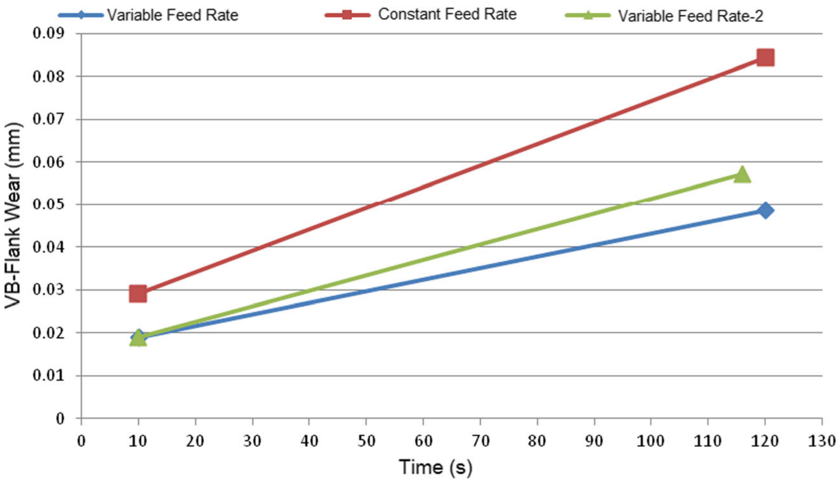


Fig. 9 Variations in tool wear for constant and variable feeds

Table 8 Tool wear values for total tool life at variable and constant feed rates

Machining period (s)	Flank wear (mm)	
	Variable feed rate	Constant feed rate
2	0.0131	0.0215
4	0.0162	0.0265
6	0.0161	0.0250
8	0.0210	0.0275
10	0.0190	0.0290
55	0.0220	0.0370
106	0.0285	0.0480
152	0.0383	0.0500
194	0.0381	0.0730
231	0.0472	0.0840
263	0.0573	0.0880
291	0.0651	0.1150
315	0.0725	0.1230
370	0.0755	0.1700
421	0.0811	0.1850
467	0.0880	0.2540
508	0.1122	
545	0.1713	
578	0.2141	
608	0.2350	
631	0.2520	

3.2 Comparison of feed types on the moderate wear zone

In the present work, in order to investigate the effects of the variable feed on the moderate wear zone, the tool wear was observed for 120 s of machining, and comparisons between constant and variable feed rates were made. First, a volume of 436,404.9 mm^3 was turned at three cutting depths with a constant feed rate. The wear curve for 120 s is given in Fig. 8 and the tool wear values in Table 6. Flank wear for the variable feed was determined as half of the wear for the constant feed.

Next, the same amount of material (436,404.9 mm^3) was machined using a variable feed rate for each depth of cut (see Table 6). This time, the machining process was completed in 120.7 s, which means that although the wear was halved, there

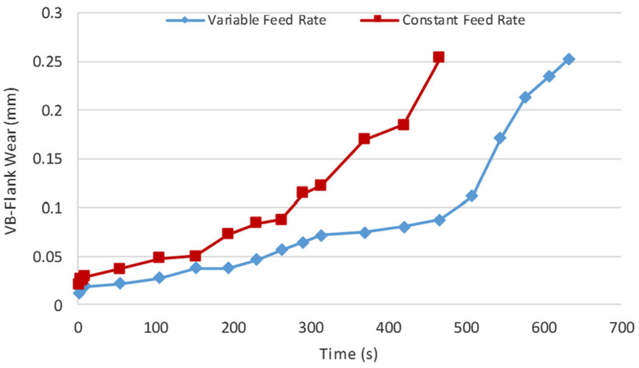


Fig. 10 Wear development throughout the tool life

Table 9 Cutting parameters and initial tool wear results in the first 10 s for DNMG 150608-NM4 WPP20 insert

Time (s)	Cutting speed (m/min)	Dept of cut (mm)	Constant feed rate		Variable feed rate	
			Feed (mm/rev)	Flank wear VB (mm)	Feed (mm/rev)	Flank wear VB (mm)
2	280	3	0.30	0.016	$f_1 = 0.20$ for the first 1 mm; $f_2 = 0.25$ for the next 1 mm; $f_3 = 0.30$ for the rest	0.014
4				0.019		0.017
6				0.023		0.019
8				0.024		0.022
10				0.028		0.024

was extra machining time (0.7 s) that had to be eliminated. Thus, the feed at the last part of turning was increased to 0.26 mm/rev. Consequently, the machining process was completed in 116.1 s, removing the same amount of material. The tool wear resulting from the increment in feed is given in Table 7, and the wear values for the first 120 s can be seen in Fig. 9.

3.3 Comparisons for the entire tool life

In the experiments for the entire tool life, machining tests were carried on until the flank wear reached 0.25 mm, which took 467 and 631 s for the constant feed and the variable feed, respectively. Machining tests were repeated using a new cutting insert for each machining period. Thus, 21 sets of flank wear values (which are mean values of the three trials) were congregated. According to the test results, the difference between the cutting tool lives was 35 %. Wear measurement results are given in Table 8, and the wear curves of these machining processes are shown in Fig. 10.

At the constant feed rate, 0.254 mm of flank wear was observed in 467 s. However, this wear was only 0.08 mm for the variable feed rate, and the flank wear reached 0.252 mm after 631 s of machining. Since the proposed novel strategy is for rough turning, no surface roughness measurements were conducted. Besides, a new set of experiment was deployed with different tool geometry (DNMG 150608 and 93° of approach angle) and cutting parameters. For this new setup, initial tool wear results in the first 10 s for both constant and variable feeds are listed in Table 9, and their comparison is given in Fig. 11.

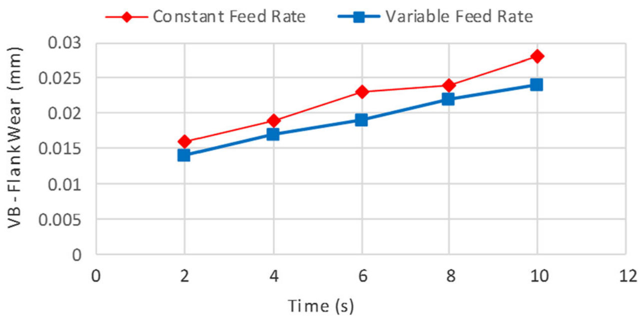


Fig. 11 Flank wear in 10 s for the new set of experiments

For the moderate wear zone, machining tests were carried on until the flank wear reached 0.30 mm. At the constant feed rate, 0.300 mm of flank wear was observed in approximately 400 s. However, this wear was only 0.222 mm for the variable feed rate, and the flank wear reached to 0.298 mm after 500 s of machining.

According to the test results, the difference between the cutting tool lives was 25 %. Wear measurement results are given in Table 10, and the wear curves of these machining processes are shown in Fig. 12.

4 Conclusions

Main objective of our work was to investigate the effect of incremental feed rate and present a new machining strategy

Table 10 Tool wear values for total tool life at variable and constant feed rates for DNMG 150608 insert

Machining period (s)	Flank wear (mm)	
	Variable feed rate	Constant feed rate
2	0.016	0.014
4	0.019	0.017
6	0.023	0.019
8	0.024	0.022
10	0.028	0.024
20	0.030	0.027
50	0.076	0.054
100	0.114	0.104
200	0.178	0.166
300	0.215	0.182
400	0.293	0.222
500	0.357	0.298

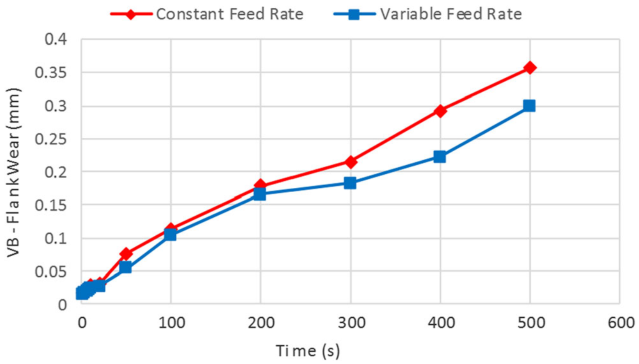


Fig. 12 Wear development throughout the tool life for the new setup

based on incremental feed rate; therefore, the effect cutting speed or depth of cut was not taken into consideration.

This paper introduces variable feed turning as a new approach for turning operations. Machining tests using both constant and variable feeds were performed in order to emphasise the gain in tool life at the variable feed rate for both the initial and moderate wear zones. In the machining tests, the cutting speed and depth of cut were kept constant, and only the effect of the variable feed rate was taken into consideration. Consequently, it was concluded that the gradual increase in the feed rate had a substantial effect in both wear stages owing to the lower cutting forces resulting from lower feeds at the workpiece interface.

Apart from the reduction in initial wear, the new turning strategy produced very positive results regarding tool wear in the moderate wear zone and a considerable 35 % increase in tool life.

In order to compensate for the 0.58 % increase in machining time resulting from the variable feed, the feed rate was increased by a slight amount (4 %) at the last part of the machining. These results showed not only significant reduction in wear (32 %) but also reduction in machining time (3 %) as well. Moreover, the new strategy provided tool life extension (at an increase of up to 35 %) throughout the total life of the tool. Furthermore, similar results were obtained in repeated experiments with different tool geometry and feed rate.

At last but not the least, it can be concluded that the proposed simple method can be immediately applied in industry without any capital investment on most numerically controlled machine-tools. This means, further research is planned which will involve incorporating the variable feed rate into CAM software.

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Further scope

In the present work, machining tests were carried out under dry cutting conditions. For future studies, cutting fluid is to be included in the machining in order to investigate its effect on the wear mechanisms. Furthermore, hard, difficult-to-machine materials and CBN inserts will be considered as the next challenge. Since CBN inserts are costly, the effect of the variable feed rate on tool wear could be a significant contribution.