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Tool life prediction in end milling using a combination of machining simulation and tool wear progress data

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Abstract

This study aims to establish a simple method for determining tool replacement timing based on tool wear progress. First, the relationship between machining conditions and tool wear progress was investigated via dry cutting experiments conducted using a 8.0dia. cobalt high-speed steel square end mill as the tool and a piece of SS400 steel as the work material under different spindle speeds, feed rates, and radial depths of cut. From the obtained results, a linear relationship was found between the cutting edge/workpiece contact length, and the flank wear width regardless of different cutting conditions. In this paper, a simple method for determining tool replacement timing based on this relationship and tool wear progress information is proposed. In this method tool replacement timing is determined based on correlations between the cutting edge/workpiece contact length as calculated by a machining simulation and the tool wear progress measured during machining operations. Since the correlation is determined during actual machining operations, tool wear prediction and tool replacement timing determinations are performed simultaneously, which means prior experiments are not necessary. In order to verify the validity of our proposed method, cutting experiments were conducted based on the premise of customized production, in which the machining conditions vary from one product to another. From these results, it was confirmed that the tool can be used up to its tool life based on tool wear predictions and tool replacement timing determinations.

Keywords : Tool life prediction, End-milling, Tool wear, Tool change, Machining simulation

1. Introduction

Although end mills are often used for machining dies and mechanical parts, the cutting tools used in those processes become progressively worn and become increasingly ineffective towards the end of their tool life. Since tool wear also creates adverse effects that degrade the finished surface properties of a product and reduce machining precision (Pimenov et al., 2018; Iwabe et al., 2003), tools need to be replaced before such adverse effects occur. Ideally, tool replacement timing should be based on tool wear, but in most machine shops, it is most often based on accumulated machining time. However, tool wear rates differ depending on the machining conditions, which means that while the machining time-based management method is useful for cases where cutting conditions are constant, such as in mass production, it is inappropriate in customized production cases where the cutting conditions differ between each of the pieces being machined.

Furthermore, since there are currently no effective methods for deciding tool replacement times by identifying the tool wear width, there have been reports that only 50 to 80% of the effective tool life is used prior to replacement (Salonitis and Kolios, 2003). This is important from the standpoint of realizing a sustainable society because, in order to reduce tool replacement time and cost, machining schedules and cutting conditions should be set so that the end of a tool's service life is reached after workpiece machining is finished. Because of this, there is a demand for a method that can predict the rate of tool wear of machining before the start of the job and thus make it possible to set the tool replacement timing appropriately.

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In previous tool wear studies, methods of estimating tool wear widths by monitoring machining states were proposed. These methods include estimating a tool wear width from the main spindle current (Doukasa et al., 2013) and cutting force (Nouri et al., 2015). However, since these two methods estimate the tool wear during machining, they cannot be used to set the tool replacement timing appropriately before the start of machining work. Additionally, prediction methods using actual cutting distance (Song and Aoyama, 2009). and cutting volume (Guo et al., 2018) have been proposed, but those methods utilize complicated prediction formulae, require multiple preliminary experiments to identify formulae parameters, and involve preliminary experiments for each set of cutting conditions. Separately, a machine learning-based wear prediction method (Ezuguwu et al., 1995) and a tool temperature-based prediction method (Usui et al., 1984) have been proposed for use during machining. However, the former method requires a massive amount of time for collection and analysis of supervision data, while the latter method requires preliminary tool temperature calculations using finite element method (FEM) analysis, etc., and is further complicated by the difficultly of correctly identifying analysis parameters.

In contrast to the methods above, this study proposes an easy-to-use tool life prediction method that uses on-machine tool diameter measurements taken after workpiece machining has finished. This method is based on experimental results showing that the tool flank face wear width is proportional to the tool cutting edge/workpiece contact length. A scheduling method for machining parts that is based on the tool life prediction results, thus preventing a tool from reaching its service life end during a machining process, is also proposed.

2. Tool wear prediction method

2.1 Experimental overview of relationship between cutting conditions and tool wear width

In this section, experiments performed to investigate the relationship between cutting conditions and tool wear width are discussed. In our experiments, a straight 100 mm cut made in the x-axis direction is defined as one pass, and tool flank face wear widths were measured after each pass. Tool wear progress states were investigated by changing the three cutting condition parameters of spindle speed S [rpm], feed rate f [mm/min], and radial depth of cut R_d [mm]. Note that the axial depth of cut A_d was fixed at 2 mm, and the cutting force during machining was measured using a dynamometer. Figure 1 shows a schematic outline of these experiments. Note that experiments were performed on both up- and down-cuts dry cuts without using cutting oil. Table 1 shows the machining conditions, while Table 2 shows the tool specifications used.

Normally, tool wear occurs on both the rake and flank faces. Rake face wear occurs due to friction with the chip, while flank face wear occurs due to friction with the finished surface. However, since the adverse effects caused by wear are mainly due to flank face wear, this research focuses on that factor, and all wear widths given hereinafter refer to flank face wear unless specifically otherwise noted. In this study, it is assumed that tool wear is uniform over the axial depth of cut and that chipping does not occur. Additionally, since it is preferable that wear width measurements be performed on-machine, we calculated flank wear width values from measured on-machine tool diameter reductions. Those tool diameter measurements were made using a non-contact tool position measurement instrument (Big Daishowa, DynaVision). This device measures the tool diameter by taking high-speed shutter images of the rotating tool with a CCD camera. In this experiment, 1 mm from the tool tip was used as the measurement point, and the average of five measurements was used.

As the tool flank face becomes worn, the tool diameter decreases, as shown in Fig. 2. The relationship between the flank face wear width and the reduction in the tool radius between the clearance angle γ [rad], flank wear width V_B [mm], and the reduction in tool diameter ΔD [mm] is given by Eq. 1 and shown in Fig. 3. Therefore, the flank wear width can be obtained by measuring the tool diameter and calculating its reduction.

$$V_B = \frac{\Delta D/2}{\tan\gamma} \tag{1}$$

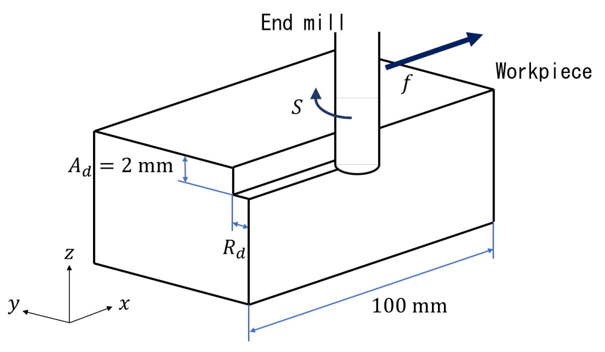

Fig. 1 Experimental cutting schematic.

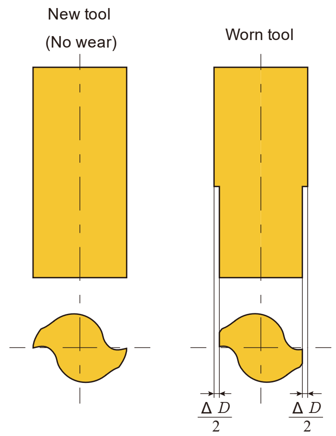

Fig. 2 Tool diameter reduction due to tool wear.

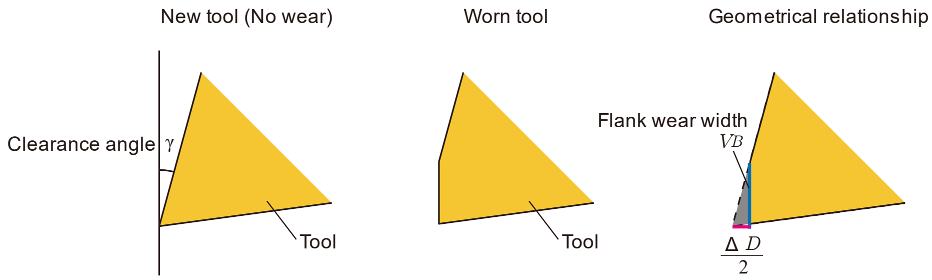

Fig. 3 Relationship between flank wear width and tool.

Table 1 Cutting conditions for cutting experiments.

Condition	A	B	C	D	E	F	G
Spindle speed [rpm]	1100	1100	1100	1100	1500	1900	1500
Cutting speed [m/min]	27.64	27.64	27.64	27.64	37.70	47.75	37.70
Feed rate [mm/min]	150	110	70	110	110	110	150
Feed per tooth [mm/tooth]	0.068	0.050	0.032	0.050	0.037	0.029	0.050
Radial depth of cut [mm]	3.0	3.0	3.0	1.5	3.0	3.0	3.0
Axial depth of cut [mm]	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Table 2 Specifications of cutting tools used in the experiments.

Helix angle [deg]	30
Clearance angle [deg]	5.5
Number of flutes	2
Flute length [mm]	20
Overall length [mm]	65
Tool diameter [mm]	8

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Table 3 Equipment and materials used in the experiment.

Five-axis machining center	NMV1500 (DMG MORI)
Tool (8 HSS square end mill)	2MSD0800 (MITSUBISHI MATERIALS)
Work material	SS400 (Daido Die & Mold Steel Solution)

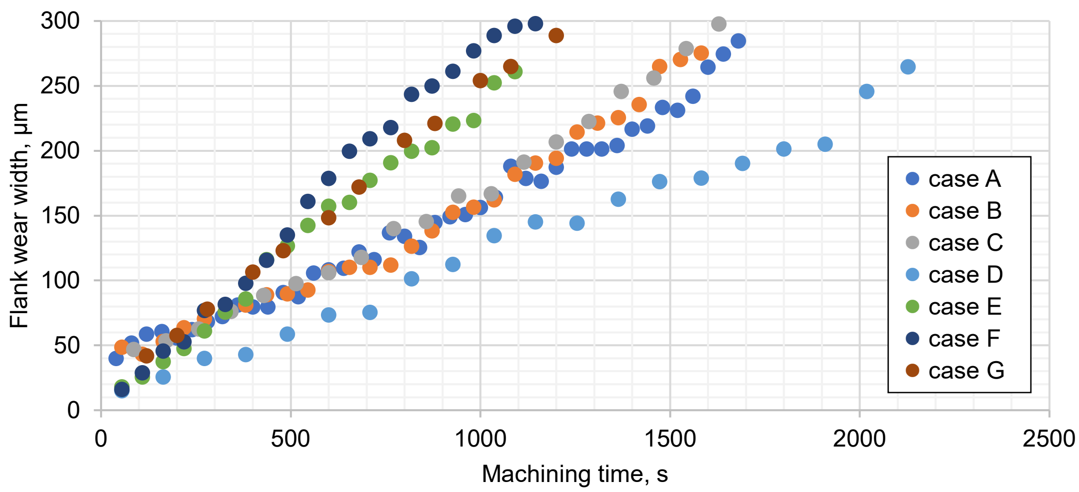
2.2 Experimental results

In Fig. 4, which shows the up-cut experimental results, the vertical axis represents the flank face wear width, and the horizontal axes in graphs (a) to (d) represent the machining time, machining distance, total cutting energy, and tool cutting edge/workpiece contact length, respectively. Note that the cutting energy in (c) is the product of the principle force of the cutting resistance (cutting force in the tangential direction) with the cutting speed multiplied by the cutting time, which is calculated from the cutting force measured by the dynamometer. Furthermore, the tool cutting edge/workpiece contact length in (d) is the contact distance between the tool cutting edge and the workpiece during cutting, as shown in Fig. 5, which can be calculated from Eqs. (2) and (3) shown below:

$$dl_c = \frac{\frac{d}{2}\theta S}{1000f}dl \tag{2}$$

$$l_c = \int dl_c = \int \frac{\frac{d}{2}\theta S}{1000f}dl \tag{3}$$

where l_c is the tool cutting edge/workpiece contact length [m], d is the tool diameter [mm], θ is the contact angle [rad], S is the main spindle speed [rpm], f is the feed rate [mm/min], and l is the cut length [mm].



(a) Tool wear progression in machining time.

Fig. 4 Measured flank wear progress in up-cut milling.

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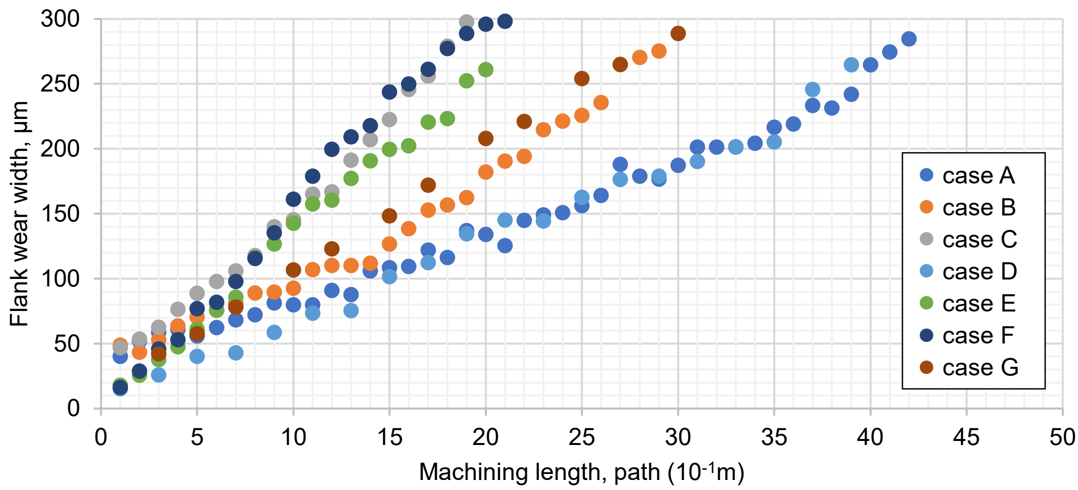
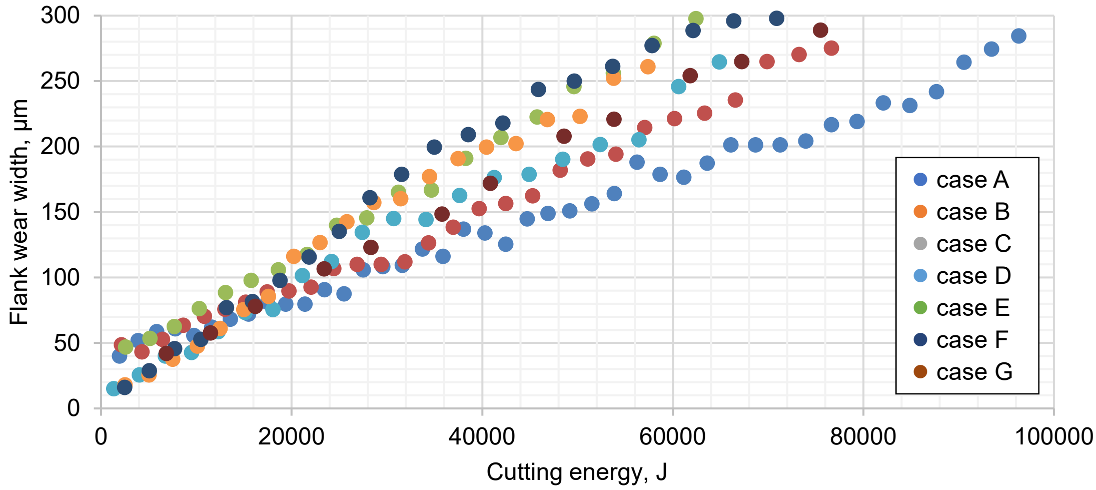
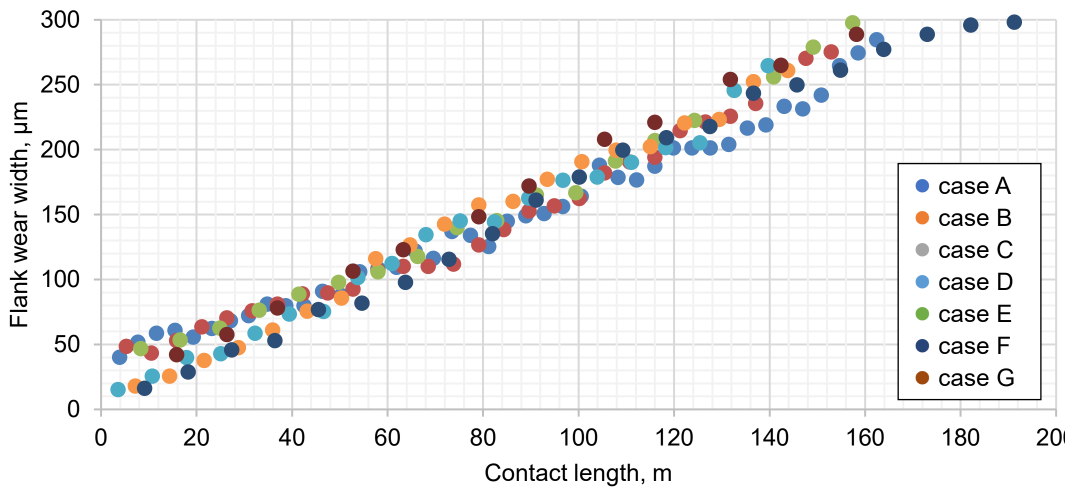


(b) Tool wear progression in machining length.



(c) Tool wear progression in cutting energy.



(d) Tool wear progression in tool cutting edge/workpiece contact length.

Fig. 4 Measured flank wear progress in up-cut milling. (continued)

Comparing the graphs in Figs. 4 (a) to (d), it is clear that the same linear relationship is formed between the tool wear width and the tool cutting edge/workpiece contact length regardless of cutting condition differences, and that relationship is also clearly found in the experimental down-cut results shown in Fig. 6. However, the results in Figs. 4 (a) and (b) show that the tool wear width cannot be determined by the machining time and machining distance when the tool is used under different cutting conditions.

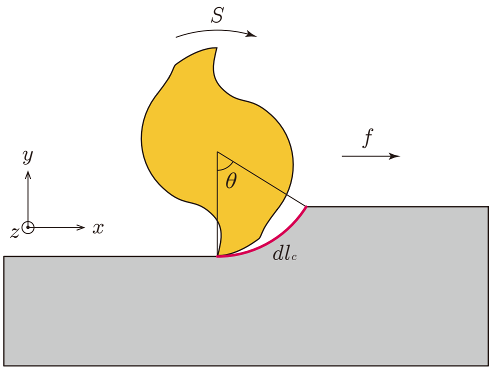


Fig. 5 Contact length is the contact distance between the tool cutting edge and the workpiece. (This represents a down-cut case.)

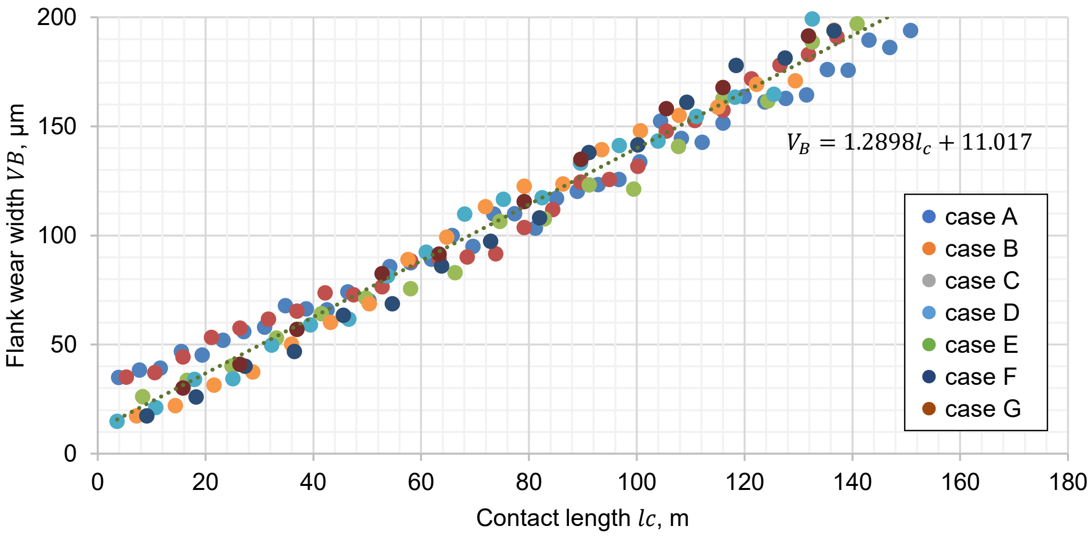


Fig. 6 Measured flank wear progression in down-cut milling.

2.3 Wear model and tool life prediction

The results of the previous section confirm that the same linear relationship exists between the tool wear width and the cutting edge/workpiece contact length regardless of cutting condition differences. Therefore, this research considers a tool wear model in which the flank face wear width is represented by a first-order equation of the cutting edge/workpiece contact length that creates tool life predictions based on the following equation:

$$V_B = C_1 l_c + C_2 \quad (4)$$

where C_1 and C_2 are parameters determined by the tool/workpiece combination and the up- and down-cut differences. For example, the C_1 and C_2 parameters can be identified by performing least-squares fitting to the experimental results shown in Fig. 4(d), as shown in Fig. 7. Moreover, based on the experimental result showing that the tool wear width is proportional to the cutting edge/workpiece contact length, the C_1 and C_2 parameters can be identified without advance

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experiments. This is accomplished by plotting the change in tool wear width from the results of on-machine tool diameter measurements performed each time a piece is finished.

Next, by taking the flank face wear width to set the tool life as V_{Bl}, the tool life l_{cl} converted from the tool cutting edge/workpiece contact length can be found using the following equation:

$$l_{cl} = \frac{V_{Bl} - C_2}{C_1} \tag{5}$$

If the cutting edge/workpiece contact length during machining is known in advance at the tool path creation stage, the post-machining cutting edge/workpiece contact length can be determined by adding the tool cutting edge/workpiece contact length during machining to the tool cutting edge/workpiece contact length before machining. If the cutting edge/workpiece contact length after machining is compared to the tool life l_{cl}, it becomes possible to determine whether or not the tool life will be reached while the machining is in progress.

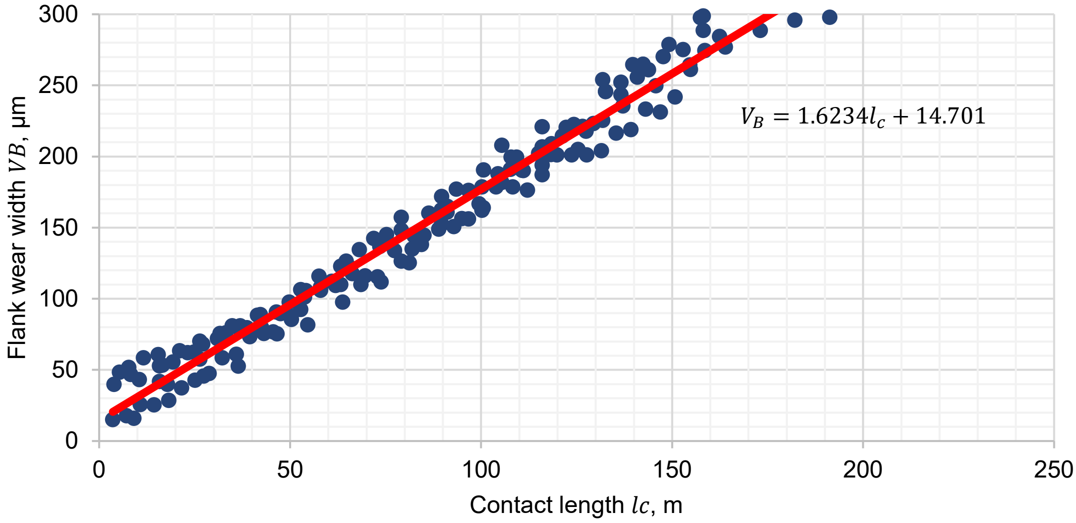

Fig. 7 Wear model identification parameters.

3. Case studies

3.1 Machining identical parts

A case study was conducted that simulated machining of an actual part in order to verify the proposed method. In this simulation, the tool life l_{cl} is converted from the cutting edge/workpiece contact length. The machine tool, tool, and work material used in the experiment are the same as those used in Chapter 2 and are shown in Table 3. In this example, the spindle speed was fixed at 1100 rpm, all cutting directions were up-cut, and the radial depth of cut, axial depth of cut, and feed rate changed while machining was in progress, and the cutting edge/workpiece contact length was calculated via a machining simulation. Figure 8 shows a computer-aided design (CAD) part model. Table 4 shows both the part dimensions, the cutting edge/workpiece contact length, and the cutting conditions.

The tool wear width was calculated from tool diameter on-machine measurement results after the machining of each piece was finished, and the tool life was predicted from the linear relationship between the tool wear width and the cutting edge/workpiece contact length. Table 5 and Figure 9 show the experimental results. Figure 9 also shows the predicted lines using the parameters identified from the data at the time of measurement after each part was machined. Assuming a flank face wear width of 300 μm as the tool life, the predicted tool life value converted from the tool cutting edge/workpiece contact length varies from 155.0 m after the machining of one piece to 205.7 m after machining of two pieces, 185.6 m after machining of three pieces, and 179.7 m after machining of four pieces, as shown in Table 5.

However, since the tool cutting edge/workpiece contact length after machining the fifth piece would be 214.20 m, which exceeds the 179.7 m predicted value of the tool life, we determined that the tool service life would end during the fifth piece machining process. In fact, the flank face wear width measured after fifth piece machining was found to be 376.2 μm, which exceeds the tool life flank face wear width of 300 μm. This shows that during actual part machining work, the tool should be replaced after machining four pieces.

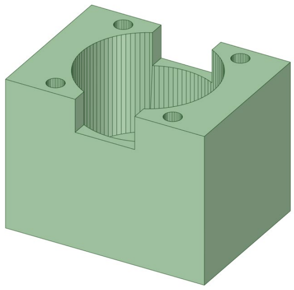

Fig. 8 Part shape to be machined in the experiment shown in Section 3.1.

Table 4 Part information in the experiment shown in Section 3.1.

Material		SS400
External dimensions		60 mm × 60 mm × 80 mm
Contact length		42.84 m
Cutting conditions	Radial depth of cut	1.0 mm – 8.0 mm
	Axial depth of cut	4.0 mm – 6.0 mm
	Feed rate	90 mm/min – 110 mm/min

Table 5 Results of the experiment shown in Section 3.1.

Machining times	Contact length [m]	Measured flank wear width [μm]	Predicted tool life [m] (Converted to contact length)
1st	42.84	82.9	155.0
2nd	85.68	140.3	205.7
3rd	128.52	214.8	185.6
4th	171.36	289.7	**179.7**
5th	**214.20**	376.2	174.6

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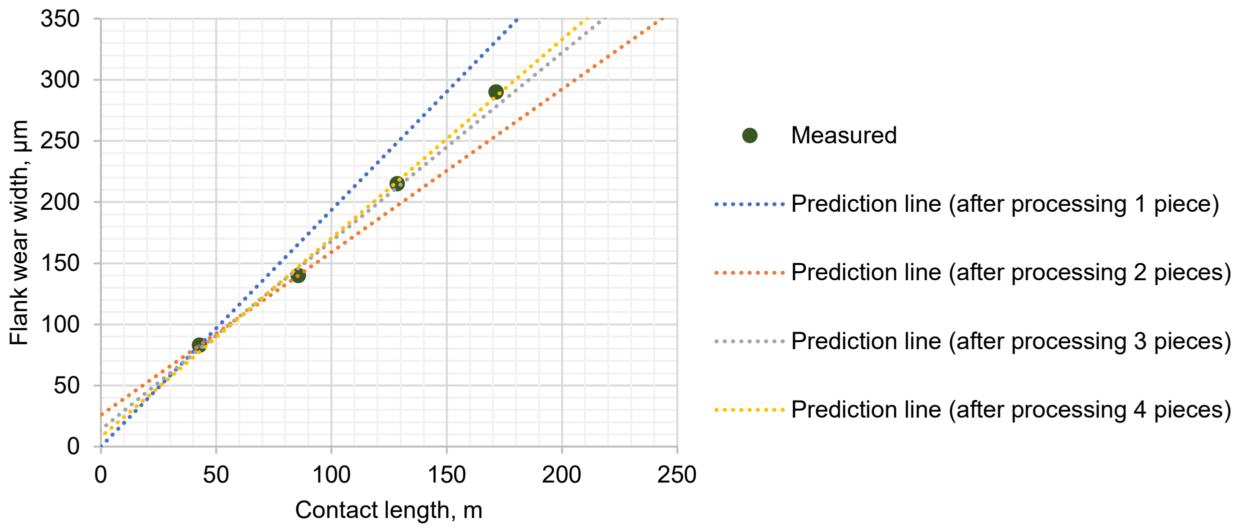

Fig. 9 Predicted wear after machining each piece in the experiment shown in Section 3.1.

3.2 Machining dissimilar parts in sequence

In this section, a case study involving the sequential machining of dissimilar parts was conducted to simulate customized production. The parts shown in Table 6 and Fig. 10 were machined one at a time using the same tool, and the tool wear width was measured after each machining process. The tool cutting edge/workpiece contact length was calculated via a machining simulation, as shown in Table 6. As in the previous section, tool wear width was calculated from the measurement results taken after each machining process, and the tool life was predicted from the linear relationship between the tool wear width and the cutting edge/workpiece contact length. The machine tool, tool, and work material used in the experiment are the same as those used in Chapter 2 and are shown in Table 3. In this example, the spindle speed was fixed at 1100 rpm, all cutting directions were up-cut, and the radial cutting depth, axial cutting depth, and feed rate changed while machining was in progress, and the cutting edge/workpiece contact length was calculated via a machining simulation.

Table 7 and Figure 11 show the experimental results. Figure 11 also shows the predicted lines using the parameters identified from the data at the time of measurement after each part was machined. Assuming a flank face wear width of 300 µm as the tool life, the predicted value of tool life converted from the tool cutting edge/workpiece contact length varied from 158.8 m after machining Part ①, to 228.8 m after machining Part ②, 173.5 m after machining Part ③, and 170.7 m after machining Part ④, as shown in Table 7. Note that since the tool cutting edge/workpiece contact length after machining Part ⑤ would be 182.88 m, which exceeds the predicted value of tool life of 170.7 m, the tool service life would end when machining that part. However, if Part ⑥ were to be machined instead of Part ⑤ at this point, the tool cutting edge/workpiece contact length after machining would be 164.34 m, which does not exceed the predicted 170.7 m tool life value. The flank face wear width measured after machining Part ⑥ piece was actually 283.5 µm, which means the tool could be used up to the point immediately before exceeding the wear width of 300 µm that was set as its tool life.

These results show that it is possible to both prevent a tool from reaching its service life during a machining process and still use the tool up to immediately before its service life expires by flexibly scheduling part machining work based on tool life prediction results. Furthermore, our method tool life prediction method can flexibly handle tool life variabilities, such as the prediction differences used in the experiments outlined in Sections 3.1 and 3.2.

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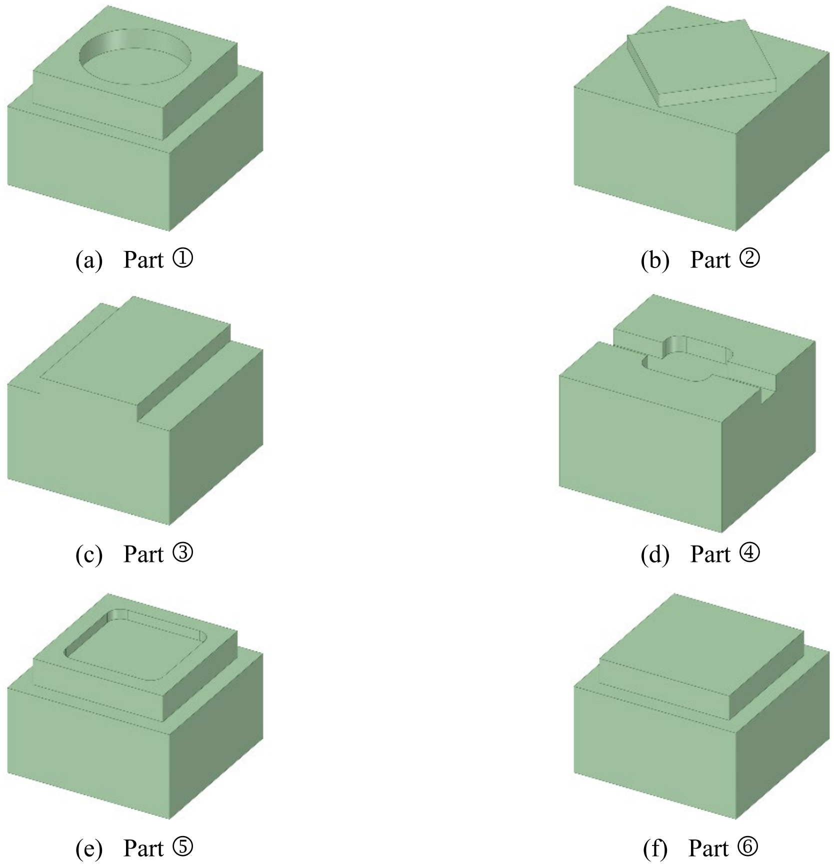

Fig. 10 Parts to be machined in the experiment shown in Section 3.2.

Table 6 Part information in the experiment shown in Section 3.2.

Part No.		①	②	③	④	⑤	⑥
Material		SS400					
External dimensions		50 mm × 50 mm × 35 mm					
Contact length		52.46 m	28.42 m	33.21 m	19.47 m	49.32 m	30.80 m
Cutting conditions	Radial depth of cut	1.0 mm – 8.0 mm					
	Axial depth of cut	4.0 mm – 6.0 mm					
	Feed rate	90 mm/min – 110 mm/min					

Table 7 Results of the experiment shown in Section 3.2.

Part No.	Contact length [m]	Measured flank wear width [μm]	Predicted tool life [m] (Converted to contact length)
①	52.46	100.2	158.8
②	80.88	132.4	228.8
③	114.09	204.1	173.5
④	133.56	236.8	**170.7**
⑤	**182.88**	not machined	**---**
⑥	**164.36**	283.5	172.7

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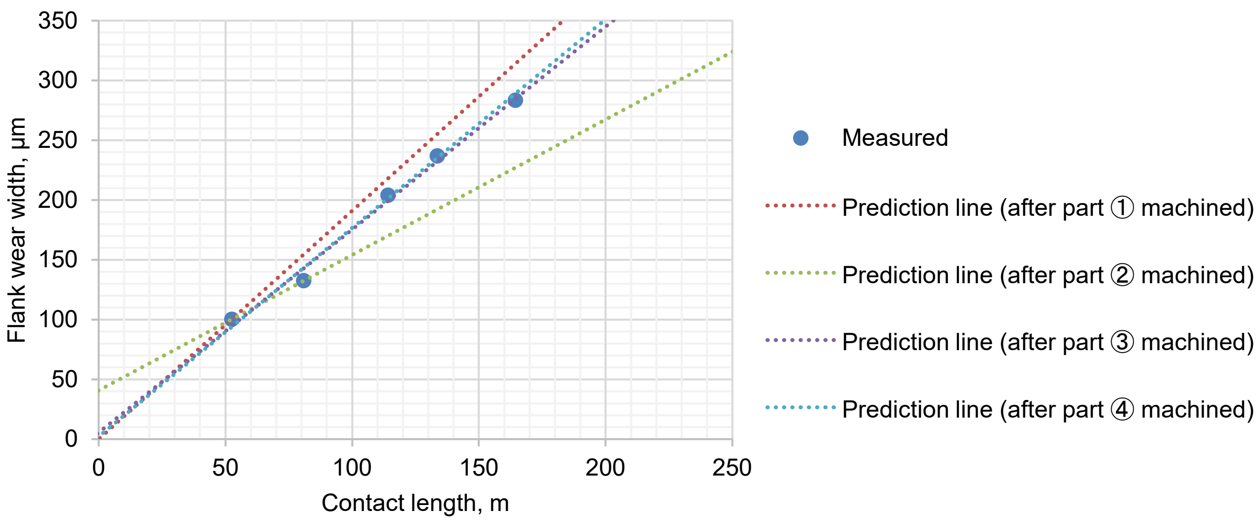

Fig. 11 Predicted wear after each piece machined in the experiment shown in Section 3.2.

4. Conclusions

This research proposed a method of easily predicting tool life from the results of on-machine tool diameter measurements taken when machining operation on a part is finished. The method is based on experimental results that show the tool flank face wear width is proportional to the tool cutting edge/workpiece contact length. Furthermore, a part machining scheduling method that prevents tools from reaching their service life end during machining work based on the tool life prediction results was proposed and the following points were clarified:

(a) It was found that the same linear relationship exists between the tool cutting edge/workpiece contact length and flank wear width under different cutting conditions.
(b) Based on the above relationship, our proposed method can easily predict tool lives by calculating the tool flank face wear width from the results of on-machine tool diameter measurements performed each time a part machining process has finished. The verification experiments performed in this study confirmed that tool life could be predicted without preliminary experiments.
(c) Verification experiments showed that when machining various part types, it is possible to use the tool up to its service life end by scheduling work by effectively using tool life prediction results.

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