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Relationship Between Cutting-Edge Hardness and Tool Life for Alloy-Steel Bit in Machine Boring of MDF

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Tool-life tests in the machine boring of MDF were performed with four bits from an alloy-steel bit having the same tool geometry but different cutting-edge hardness from each other. The experimental data on the effects of the cutting-edge hardness of the bit upon both the progression of tool wear and the variation of cutting resistance (both torque and thrust) were obtained. Furthermore, cutting temperatures in the machine boring of MDF were estimated from the data for the cutting-edge hardnesses of the bits. After studying these data, the quantitative relationship between the cutting-edge hardness and tool life was determined by the extended Taylor's tool-life equation and some considerations were done about the application.

Key words : machine boring, spur machine-bit, tool wear, tool-life equation, MDF.

1. Introduction

Tool wear or tool life of wood machining tool is generally related to the hardness of its cutting edge, as reported already by various authors (1-12). In the previous study concerning tool lives of spur-machine bits in the machine boring of wood and wood-based materials (3), one of the authors performed some experiments on the relationships between cutting-edge hardness and tool wear for three different bits, such as alloy-steel bit, high-speed steel bit and cemented-carbide bit, and the wear characteristic of each bit was discussed from the results.

In this study, from the view point of that, it is very important for the determination of the optimum conditions of machine boring bits to understand quantitatively the relationship between the cutting-edge hardness of machine bit and tool life, we tried to conduct an experiment and an analysis. That is, tool-life tests of alloy-steel bits of 10mm in diameter with different cutting-edge hardnesses in the machine boring of MDF (Medium Density Fiberboard) were performed at four steps of spindle speed ranging from 1000 rpm to 4000 rpm. And we examined the effect of the cutting-edge hardness of alloy-steel bit on the tool-wear progression and Taylor's tool-life equation concerning the relationship between the tool life and cutting speed. Furthermore, we tried to establish the extended Taylor's tool-life equation including cutting-edge hardness besides cutting speed as variables.

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2. EXPERIMENT

2.1 Machine bits and work materials

Machine bits in this work had double-spur, double twist, and brad points which were made by the Leitz Company of Germany. The tool material was alloy steel. The shape of machine bit was illustrated in Figure 1 (diameter : 10 mm, overall length : 140 mm, helix angle : 24 deg). And the following four machine bits of the same alloy with different cutting-edge hardnesses were prepared for the experiment. One of them was non-tempered bit (original) and the others were heat treated bits which were tempered at 200℃, 300℃ and 400℃ respectively in a Muffle furnance in the air condition for 30 min and cooled in water after tempering.

The cutting-edge hardnesses of four kinds of machine bits were measured by the following method. Its method was the same in the previous study (2). The apparatus for measurement was shown in Figure 2. That is, after cutting off the brad point of the bit by a grinding machine, the bit was fixed vertically to the plate glass ① at the center of cylindrical glass ② of 25 mm in diameter, and then synthetic resin was flowed in this cylinder. After the resin became hard, cylindrical formed material in the solid state was removed from the glass, and was cross-cut as indicated by the dotted line ④, then the face ⑤ was polished with emery abrasive paper (#120～#2,000). After that, the hardnesses at the ten positions on the 50 μm inner face from outside face of the spur edges of both sides ⑥ were measured by use of micro-Vicker's hardness meter. The cutting-edge hardness in this report was represented by the average value of these ten measured values.

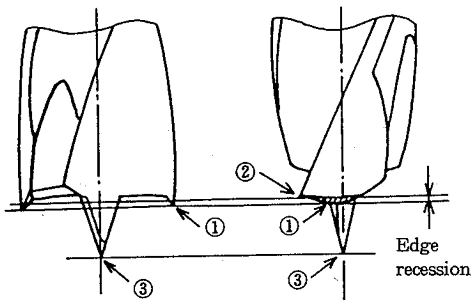

Figure 1. Shape of machine bit used in this test and representation of edge recession.
①Spur edge, ②Outer corner, ③Brad point

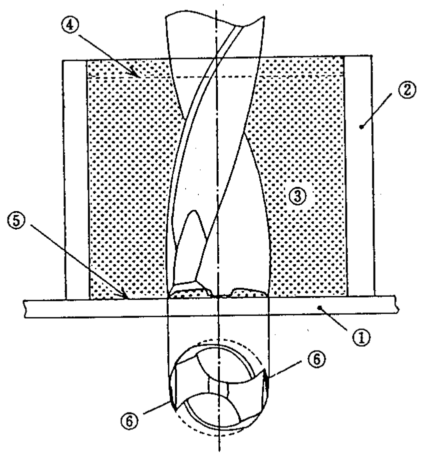

Figure 2. Preparation for measurement of Vicker's hardness of machine bit.
①Plate glass, ②Cylindrical glass
③Synthetic resin, ④Cutting face
⑤Polishing face, ⑥Inspecting face

The value of Vicker's hardness for non-tempered bit obtained by the method above-mentiond was 676. And also the values for tempered bits showed 595, 550 and 457 in the order of tempering temperature 200℃, 300℃ and 400℃, and they decreased with increases of tempering temperature as shown in Figure 3.

The work materials were 2-ply MDF (Medium Density Fiberboard, air-dried specific gravity : 0.74) 30mm total thick (two sheets of commercial 15 mm thick MDF were glued together with

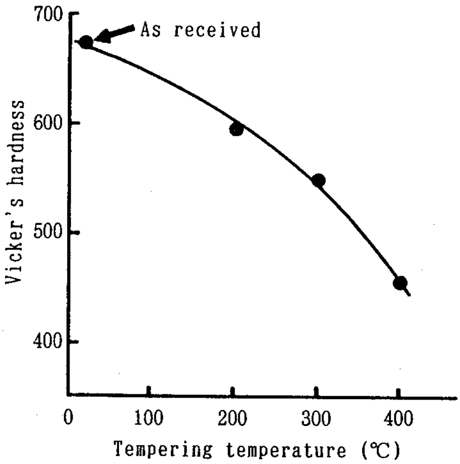

Figure 3. Relationship between tempering temperature and Vicker's hardness of machine bit.

Table 1. Boring conditions in this test.

Spindle speed	Cutting speed of bit	Axial feed speed	Feed per revolution of bit
(rpm)	(m/min)	(cm/min)	(mm/rev)
1,000	31.4	10	
2,000	62.8	20	0.1
3,000	94.2	30	
4,000	125.7	40	

polyvinyl-acetate adhesive). The workpieces were 24 mm in width and 300 mm in length, and the air-dried moisture content was approximately 8.2 %.

2.2 Experimental method

The test machine in this work was a drilling machine equipped with an auto-feeding apparatus and a tool-dynamometer. Tool-life tests of four kinds of machine bits with different cutting-edge hardnesses were performed at four steps of spindle speed keeping a constant feed per revolution as presented the details of boring conditions in Table 1. In each tool-life test, the workpiece which was clamped in a vise of tool dynamometer were bored throughout continuously until the number of machined holes were 300.

Every time a constant number of holes were bored, the amount of tool wear and cutting resistance (both torque and thrust) were measured, and the variations of these values with increases of the number of machined holes, accordingly total cutting-length and net boring-time were examined. Furthermore, Vicker's hardness of cutting edge for each machine bit was measured by the same method above-mentioned after boring 300 holes and the relationships between this value and spindle speed were also examined.

The amount of tool wear was represented by the recession of spur edge of the bit as illustrated in Figure 1. Recessions of two spur edges of the bit pararell to the central axis of the bit were meaured by use of tool microscope, and the average value of two edge recessions was adopted as the amount of tool wear.

Torque and thrust were measured with a tool dynamometer (Sato machinery, AST-BMS) attached on the table of the drilling machine. Their time waves were drawn on the display of analyzing recorder (Yokogawa, 3655E) through the strain amplifier (San-ei, 6M52), the maximum values at the entrance of the hole and the average values of the whole wave during boring one hole were obtained by using the calculating function of the recorder.

Total cutting-length L and net boring-time t were calculated with the following equations :

$$L = \frac{\pi \ D \ d}{1000 \ f_{rev}} \ m \quad \text{(Equation 1)}$$

$$t = \frac{d}{f_{rev} \ N} \ m \quad \text{(Equation 2)}$$

where L : total cutting-length (m), t : net boring-time (min), D : diameter of machine bit (mm), d : depth of boring hole (mm), f_{rev} : feed per revolution of machine bit (mm/rev), N : spindle speed (rpm), m : number of machined holes.

3. RESULTS AND DISCUSSION

3.1 Tool-wear progression of machine bit and cutting resistance

First, the difference of tool-wear progression by the cutting-edge hardness of machine bit, as examples, at 1,000 rpm and 4,000 rpm of spindle speeds is shown in Figure 4. As in this figure, the amount of tool wear increases parabolically with increases of number of machined holes, accordingly total cutting-length and net boring-time, and the tool-wear progressions for the two spindle speeds decrease with increases of cutting-edge hardness. And those for the other spindle speeds show the same tendency.

For the two machine bits with Vicker's hardnesses of 676 and 457, the difference of tool-wear progression by spindle speed is shown in Figure 5. As shown in this figure, the tool-wear progression increases with increasing spindle speeds, this tendency is similar to those for the other cutting-edge hardnesses.

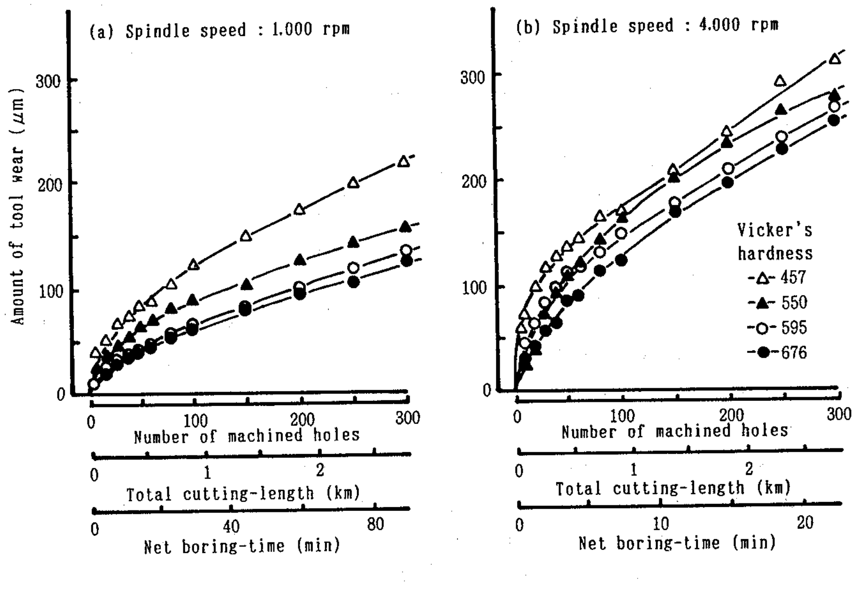

Figure 4. Progressions of tool wear for four machine bits having different Vicker's hardnesses at two spindle speeds.

Next, the variations of the amount of tool wear after boring 300 holes and cutting resistance (the maximum value at the entrance of hole and the average value of the whole of one hole) during boring the 300th hole with cutting-edge hardness at 1,000 rpm of spindle speed are shown in Figure 6 (a) and (b), (c). This figure indicates that the amount of tool wear and cutting resistance decrease with increases of cutting-edge hardness.

In general, the relation of the amount of tool wear after cutting a constant length to the cutting-edge hardness in the machining of wood-based materials is given as a minimum curve (11). That is, the amount of tool wear shows a decreasing tendency with increases of cutting-edge hardness within the relative lower range of the hardness, and after showing the minimum value, it shows increasing tendency conversly. It seems that the tool wear in the former range is caused

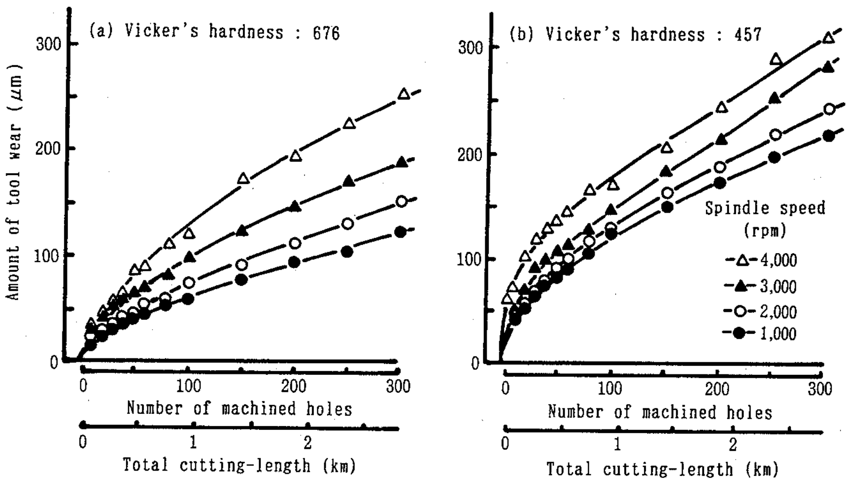

Figure 5. Progressions of tool wear for two machine bits having different Vicker's hardnesses at four spindle speeds.

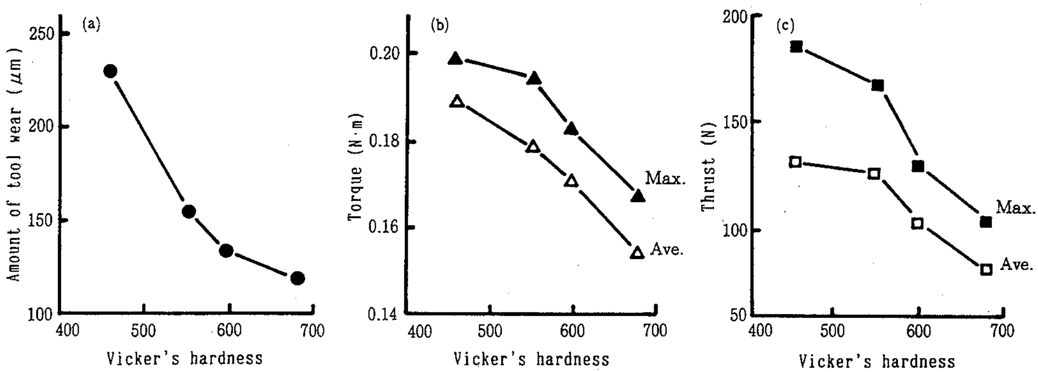

Figure 6. Variations of the amount of tool wear and cutting resistance (torque and thrust) at 300 machined holes with Vicker's hardness of cutting edge of machine bits.

chiefly by the thermal wear and that in the latter range is caused by the occurrence of large chipping or fracture at the cutting edge due to the lack of toughness of the tool material.

Although the amounts of tool wear of the bits tested have shown the decreasing tendency unilaterally with increase of cutting-edge hardness as in Figure 6(a), it is anticipated that the increasing tendency will appear in the higher range of the hardness beyond the range examined in the present test.

3.2 Cutting-edge hardness of machine bit and estimated tool temperature

The measured results of cutting-edge hardness for non-tempered bit after tool-life tests (after boring 300 holes) are shown in Figure 7, the dotted line in this figure indicates Vicker's hardness of the cutting edge before use. The reason why that value decreases with increasing spindle speeds as in Figure 7(a) is that the cutting edge is tempered by the higher cutting heat during boring as spindle speed becomes faster.

Generally speaking, it is difficult technically to measure the cutting temperature at the cutting edge of revolving wood machining tool during cutting. And so, we tried to estimate the cutting temperature by using the calibration curve indicating the relationship between cutting-edge hardness and tempering temperature as presented in Figure 2.

The estimated temperatures are presented in Figure 7(b). As in this figure, the temperature increases with increasing spindle speeds in the range of 120−230℃.

One of the authors had estimated the temperatures of alloy-steel bits in the machine boring of several wood species and a wood-based material by the same method in the previous work (2), the results at the 4,000 rpm were as follows. That is, the estimated temperatures are 420 ℃ for shirakashi (*Querucus myrsinaefolia* Bl.), 350℃ for 3-layer particleboard, 280℃ for melapi (*Shorea sp.*)(Sabah) and 250℃ for kuri (*Castanea crenata* S. et Z.). Accordingly, the estimated temperature for MDF is lower somewhat than that for kuri.

The cutting-edge hardnesses after the tool-life tests for three kinds of tempered bits were also examined. The measured results are shown in Figure 8. Each dotted line is the cutting-edge hardness before use. Although the plots are scattered, the cutting-edge hardness of every machine bit decreases somewhat with increasing spindle speeds. The decrease at the 4,000 rpm of spindle speed is larger than those at the other spindle speeds.

3.3 Taylor's tool-life equations of machine bits

In this study, the tool life for machine bit was represented by the net boring-time until tool wear reached a critical amount, and the amount was set at 100 μm basing on the experimental result. And cutting speed was represented by the peripheral speed of the bit.

The tool lives at four steps of spindle speed for four machine bits with different cutting-edge hardnesses were estimated from the tool-wear progression curves presented such as in Figure 5. After plotting the estimated tool life versus cutting speed on a logarithmic graph, a nearly linear relationship was obtained for each bit as shown in Figure 9. Using the least squars method, each relationship was presented by the following Taylor's tool-life equation with a high coefficient of correlation.

$$V\,T^{n} = C \qquad \text{(Equation 3)}$$

where, V is cutting speed in m/min, T is tool life in min. The values of constant C are larger in the order of cutting-edge hardness and the values of n are scattered from 0.50 to 0.58 as presented in Table 2.

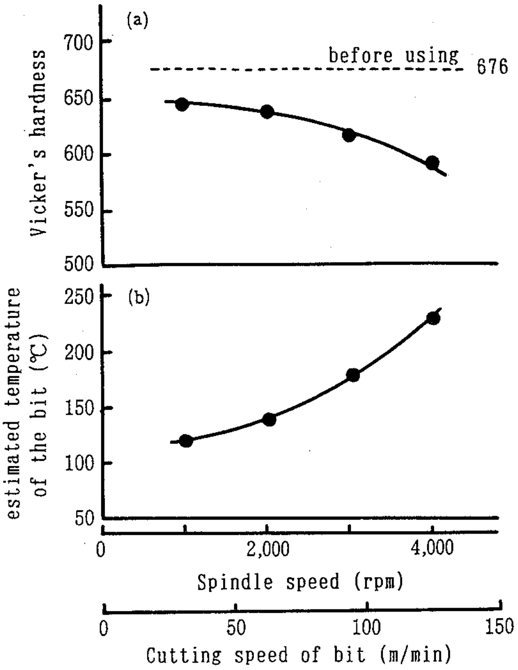

Figure 7. Relationships of spindle speed and cutting speed of bit to Vicker's hardness of cutting edge for non-tempered bit and estimated temperature of the bit at 300 holes.

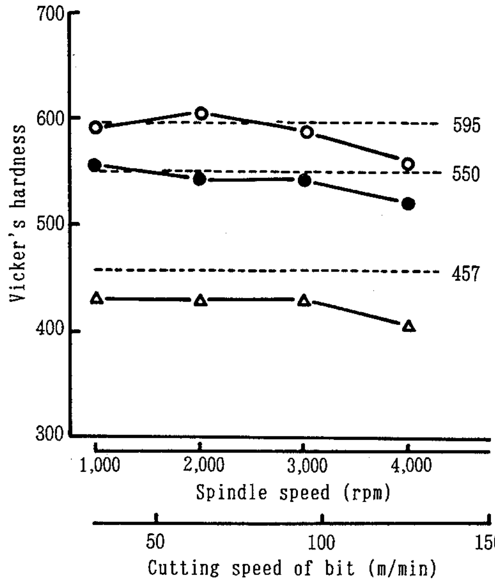

Figure 8. Relationships of spindle speed and cutting speed of bit to Vicker's hardness of cutting edge after boring 300 holes for three kinds of tempered bits.

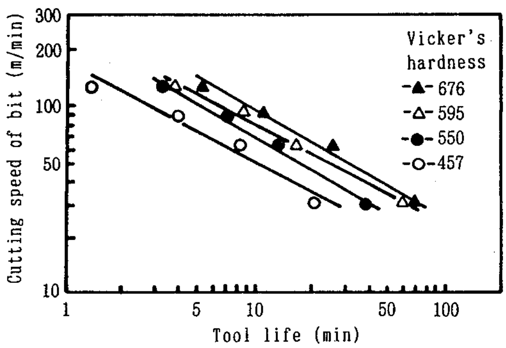

Figure 9. Relationships between tool life and cutting speed of bit with the critical amount of tool wear at 100 μm for four machine bits with different Vicker's hardnesses of cutting edge.

Table 2. Exponet n, constant C and coefficient correlation r in the tool-life equation of alloy-steel bit

Vicker's hardness	Tempering temperature	Values of n, C and r		
		n	C	r
	(℃)			
676	Non	0.54	325	0.988
595	200	0.51	261	0.995
550	300	0.59	278	0.991
457	400	0.50	165	0.972

3.4 Extended Taylor's tool-life equation

The Taylor's tool-life equations for the four machine bits were determined above. Furthermore, an attempt to establish an "extended Taylor's tool-life equation" including cutting-edge hardness of machine bit besides cutting speed as variables was tried. First, the next equation was assumed.

$$V\ T^{n'} Hv^{-\beta'} = C' \qquad \text{(Equation 4)}$$

where Hv is Vicker's hardness of cutting edge. The reason why the exponent for Hv is expressed by negative as $-\beta'$ is that tool life becomes longer as Hv is larger at a constant cutting speed as shown in Figure 9. If Equation 4 is valid, a linear relationship should exist between $VHv^{-\beta'}$ and T on a logarithmic scale coordinates. And so, next, to clarify whether the linear relationship is well-established or not, the following mathematical treatment was done by aid of a personal computer.

(1) Twelve values of T were set up randamly in the range of 5−50 min, and the corresponding values of V were calculated according to Equation 3.

(2) One hundred values of β' were set up in the range of 1.0−1.99 by every 0.01 as a matter of convinience, and one hundred values of $VHv^{-\beta'}$ were calculated.

(3) One hundred values of the coefficient of correlation related to the linear relationship between $VHv^{-\beta'}$ and T were calculated by the method of least squares.

(4) After plotting the values of coefficient of correlation versus the values of exponent β' on a graph, a maximum curve was given. It could be known from the curve that the coefficient of correlation showed the maximum value 0.997 when β' was 1.51.

(5) Plots of T versus $VHv^{-\beta'}$ in tha case of β' 1.51 on a logarithmic graph is presented in Figure 10, and the value of exponent n' and constant C' in this case are 0.54 and 1.752×10^{-2} respectively.

From above mathematical treatment, it becomes evident that Equation 4 is well-established with high confidence coefficient.

Then, some considerations were done about Equation 4. When T_1 and T_2 are an unknown and the already-known tool lives of the two machine bits under the same cutting speed, and Hv_1 and Hv_2 are their cutting-edge hardnesses respectively. According to Equation 5, the unknown tool life can be calculated by the next simple equation.

$$T_1 = T_2\,(Hv_1 / Hv_2)^{\beta'/n'} \quad \text{(Equation 5)}$$

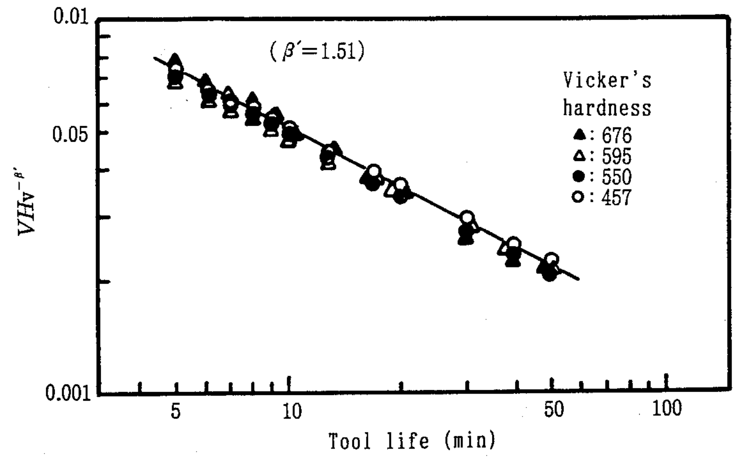

Figure 10. The related line for determining tool-life exponent and Taylor constant in Equation 4, when the value β' is chosen so that the absolute value of the coefficient correlation shows the highest.

The following equation can be also obtained by substituting the values of β' and n' into above equation,

$$T_1 = T_2 \,(Hv_1 / Hv_2)^{2.80} \qquad \text{(Equation 5')}$$

This equation indicates that an unknown tool life is given by the product of the known tool life and the value of the ratio of the two cutting-edge hardness of bits to the 2.8th power. For example, when the cutting-edge hardness of a bit is 1.48 times that of the other, the tool life will increase about three fold that of the other (this example corresponds to the case of two bits having Vicker's hardness 676 and 457 in Figure 9). Thus, tool life is closely related to cutting-edge hardness.

The equation derived will be useful to understand the quantitative relationship of cutting speed and cutting-egde hardness to tool life in the machine boring of MDF with this alloy-steel bit, and they will be applicable within such range as tool wear of bit is caused chiefly by thermal wear but not by large chipping or fracture.

4. Conclusions

For the purpose of determining the relationship between the cutting-edge hardness of spur machine-bit and tool life, continuous boring tests of MDF were performed with alloy-steel bits on a drilling machine at four steps of spindle speeds in the range of 1,000－4,000rpm keeping feed per revolution at 0.1 mm／rev constant. The bits prepared for the tests were consisted of the four same alloy bits having the same shape but different cutting-edge hardnesses each other, one of them was non-temperd (Vicker's hardness : 676), and the others were tempered under three different temperatures (Vicker's hardness : 457－595).

As the result of the tests, the data for the progression of tool wear and for the variation of cutting resistance (both torque and thrust) were obtained. Furthermore, cutting temperatures in the machine boring were estimated from the data for the cutting-edge hardnesses. After studying these data, the quantitative relationship between cutting-edge hardness and tool life was expresed by an equation.

The conclusions obtained in the present study are as follows.

(1) The amount of tool wear increases parabolically with net boring-time, and these wear progressions become faster as cutting-edge hardness becomes lower and as spindle speed becomes faster.

(2) The amount of tool wear and cutting resistance after boring a constant number of holes decrease unilaterally with increases of cutting-edge hardness.

(3) The cutting-edge hardness for each bit after continuous boring becomes lower than the initial one, and the lowering degree is larger in the case of the faster spindle speed for each bit. The apparent tool temperature during boring becomes higher as spindle speed is faster in the range of 120－230℃ based upon hardness.

(4) Tool life was represented by the net boring-time until the amount of tool wear reaches the given critical amount (100 μm) and could be estimated from the progression curve. Analyzing the relationship between cutting speed and the estimated tool life, Taylor's tool-life equations are determined for each bit. Furthermore, by mathematical treatment of these equations, the following extended Taylor's tool-life equation including cutting-edge hardness besides cutting speed as variables is established.

$$V\ T^{n'} Hv^{-\beta'} = C'$$

where T is tool life in min, V is cutting speed in m／min, Hv is Vicker's hardness of cutting edge. The exponent n' is 0.54, β' is 1.51, and constant number C' is 1.752×10^{-2}. Then, according to the above equation, the equation which can estimate an unknown tool life of these bits is derived as follows.

$$T_1 = T_2\ (Hv_1 / Hv_2)^{2.80}$$

where T_1 and T_2 are an unknown and the already known tool lives for the two bits, Hv_1 and Hv_2 are their cutting-edge hardnesses respectively.

The equations derived will be useful to understand the quantitative relatioship of cutting speed and cutting-edge hardness to tool life in the machine boring with alloy-steel bits and they will be applicable within such range as tool wear of machine bit is caused chiefly by thermal wear but not by large chipping or fracture.

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