INFLUENCE OF TOOL WEAR ON ULTRA-PRECISION CUTTING PROCESS OF ALUMINUM ALLOY

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Abstract Cutting edge wear of a single crystal diamond tool is a serious problem because the tool wear deteriorates accuracy and surface integrity of machined parts in ultra-precision cutting. The purpose of this study is to find out effective parameters for monitoring tool wear. The results obtained are as follows: (1) principal and thrust forces increased with increase in real cutting distance, respectively, but feed force continued to be about zero against increase of cutting distance, (2) rate of increase of thrust force with increase in cutting distance was larger than that of principal force, (3) RMS-values of AE-signals also increased with increase in real cutting distance, (4) AE-signal component between frequencies of 20 kHz and 30 kHz sharply increased just before tool life. As a result of consideration of these results, it is demonstrated that thrust force and AE-signals are effective parameters to detect tool wear of a single crystal tool.

Key Words Monitoring, Tool Wear, Ultra-Precision Cutting, Crystal Diamond Tool

1 INTRODUCTION

Ultra-precision cutting by a single crystal diamond tool is applied to machining of soft metals because this method can product mirror-like surface more easily than another methods such as grinding, polishing and buffing, etc. Therefore, it's used for manufacturing semiconductor, optical parts and so on. Since tool edge shape is closely duplicated onto work-piece surface in ultra-precision cutting, tool wear is a serious problem on precision and productivity of products. However, it is very difficult to detect tool wear during cutting on machine because the tool wear is extremely small. This prevents ultra-precision cutting operations from being automated and results in poor productivity. According to previous studies [1],[2] on conventional cutting, effective signals in indirect method for detecting tool wear are cutting forces and AE-signals. In this study, influence of tool wear on cutting forces, AE-signals and surface roughness is investigated in order to find out effective parameters for monitoring of tool wear in ultra-precision cutting.

2 EXPERIMENTAL METHOD

2.1 Experimental Apparatus

Experimental apparatus is schematically shown in Fig. 1. Aluminum alloy was cut by face-cutting with a single crystal diamond tool having large top corner radius on ultra-precision lathe (TOYOTA MACHINE WORKS, LTD AHN-60D). Cutting forces and AE-signals were measured by dynamometer (Kistler corp. 9256A) and AE-sensor (NF circuit design block corp. AE900S-WB) installed on the lathe, respectively. Tool wear was observed by a SEM (JOEL corp. JSM-6330F) and surface roughness was measured by an interferometer (Zygo corp. New View 5032).

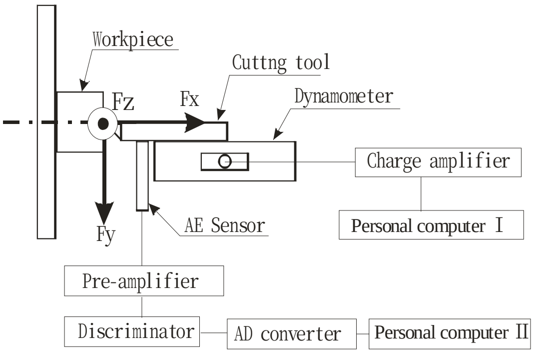

Fig. 1 Experimental apparatus

Table 1 Experimental conditions

Tool	Single crystal diamond tool Rake angle=0 ° Clearance angle=4 ° Nose radius=5mm (0.8mm)	
Work piece	Material Diameter Hardness	Al-Mg alloy (JIS A5056) 30mm, (197mm) 75Hv
Spindle speed	1000rpm	
Feed rate	50 μ m/rev **(**10～80 μ m/rev**)**	
Depth of cut	30 μ m **(**5～50 μ m**)**	
Cutting fluid	Kerosene(mist)	

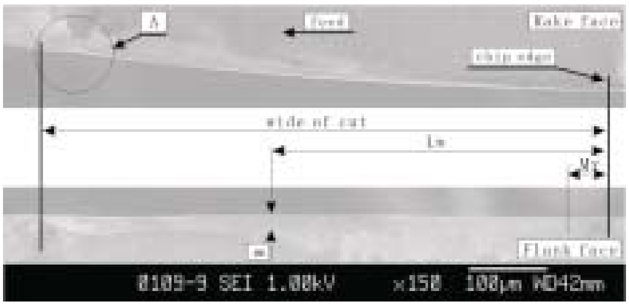

Fig.2 Typical tool wear (L=600km)

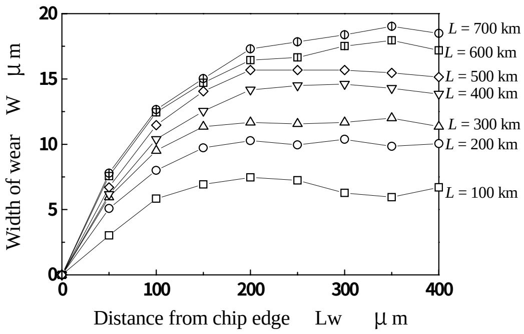

Fig.3 Relationship between distance from chip edge and width of flank wear

2.2 Experimental Conditions

Experimental conditions are shown in Table 1. These conditions were chosen to product mirror-like surface by results of preparatory experiment at feed rate (*f*=20~80 μ m/rev) and at depth of cut (*d*=5~50 μ m). In this preparatory experiment, it was confirmed that surface roughness did not depend on depth of cut, and the roughness almost coincided with theoretic surface roughness at the feed rate (*f*=20~80 μ m/rev).

3 EXPERIMENTAL RESULTS

3.1 Tool Wear

Typical tool wear observed at cutting distance *L* of 600 km is shown in Fig. 2. Tool wear was mainly abrasive wear on flank face, and it was confirmed from photo that large top corner radius of tool edge decreased. There is no chipping on tool edge. Temperature rise at cutting point measured by thermography was small (1~2 ℃). Tool wear on flank face was observed every real cutting distance *L*=100 km, and width of flank wear *W* in distance *Lw* from chip edge was measured. The relationship between *Lw* and *W* is shown in Fig. 3. At each real cutting distance, the width of wear is small and increases in proportion of *Lw* when *Lw*<200 μ m, and the wear is constant when *Lw*>200 μ m. The reason why the wear occurred is considered as follows. Chip thickness is nearly zero at chip edge point (*Lw*=0) and increases with increase of *Lw*. Tool wear is small near the chip edge, because cutting force is weak. Tool wear increases with increase of *Lw* because cutting force increases when *Lw*<200 μ m. And tool wear is constant when *Lw*>200 μ m, since contact width between flank face and work-piece is constant by clearance angle. Tool wear at *Lw*<50 μ m (Mr part in Fig. 2) is related with surface roughness because feed rate is *f*=50 μ m/rev in this experiment. Width of flank wear at *Lw*=50 μ m increases by 3 μ m from *L*=0 km to 100 km, and increases by 3 μ m from *L*=200 km to 700 km. Therefore, it is initial wear when *L*<100 km and it is uniform rate wear when *L*>200 km.

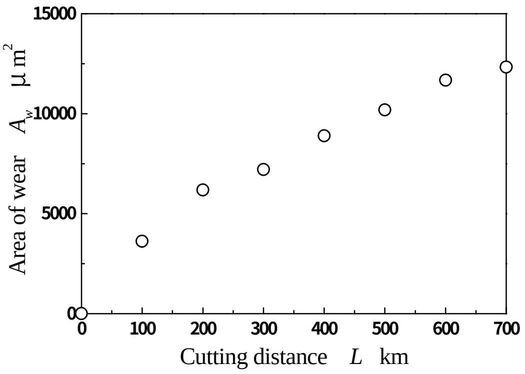

Fig.4 Relationship between cutting distance and area of wear

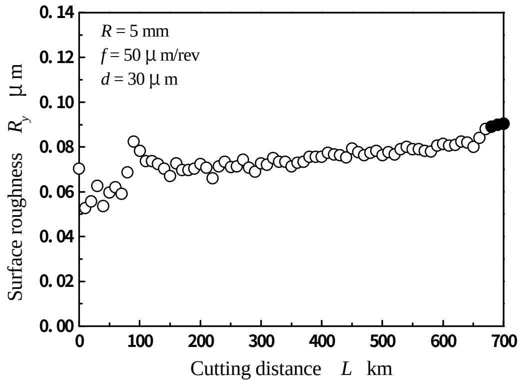

Fig.5 Relationship between cutting distance and surface roughness

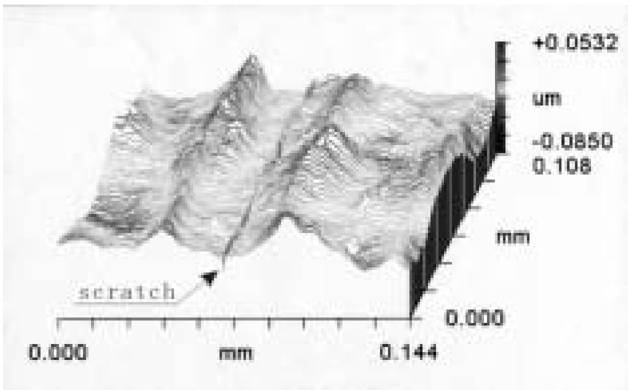

Fig.6 *S*cratch on bottom of cutter mark of surface

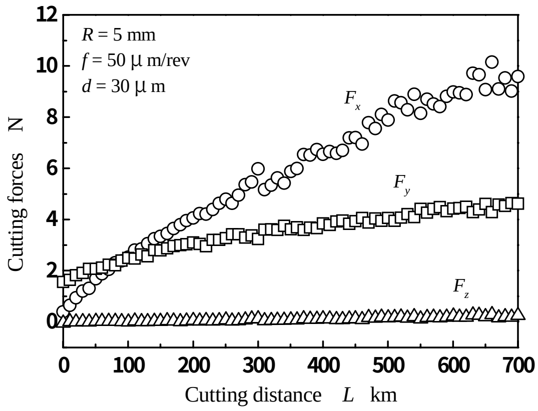

Fig.7 Relationship between cutting distance and cutting forces

Fig. 4 shows the relationship between real cutting distance L and whole wear area on flank face Aw calculated from data in Fig. 3. Tool wear increases monotonously, but increase rate of wear at L<100 km is larger than at L>200 km. Consequently, Fig. 4 also demonstrates that it is initial wear when L<100 km and it is uniform rate wear when L>200 km [3].

3.2 Surface Roughness

The relationship between real cutting distance L and surface roughness Ry is shown in Fig. 5. Black circles in this figure mean that small scratch was observed on bottom of cutter mark at the cutting distance (see Fig. 6) and it deteriorated machined surface. Since the scratch was observed at L=680 km, 680 km was defined as tool life in view of practical use. Surface roughness Ry fluctuates when L<100 km, and it increases monotonously when L>200 km. As mentioned in last section, initial wear progresses when L<100 km. Consequently, it can be considered that initial wear causes fluctuation of surface roughness when L<100 km. One reason why surface roughness increase monotonously can be considered that large top corner radius decreased by tool wear. This radius decreases nearly by 10 μ m at point A in Fig. 2. Surface roughness increase calculated is about 1 nm caused by decrease of corner radius. But surface roughness increases by 20 nm in Fig.5. Therefore, decrease of radius does not have much influence on surface roughness. On the other hand, the rate of wear increase is fast and surface roughness fluctuates when L<100 km, and the wear and surface roughness increase monotonously when L>200 km. Characteristics of surface roughness for cutting distance is similar to that of tool wear. Therefore, another reason why surface roughness increases monotonously can be considered that worn part on flank face causes large plastic deformation of work-piece surface.

3.3 Cutting Forces

The relationship between real cutting distance L and cutting forces Fx,Fy,Fz is shown in Fig. 7.

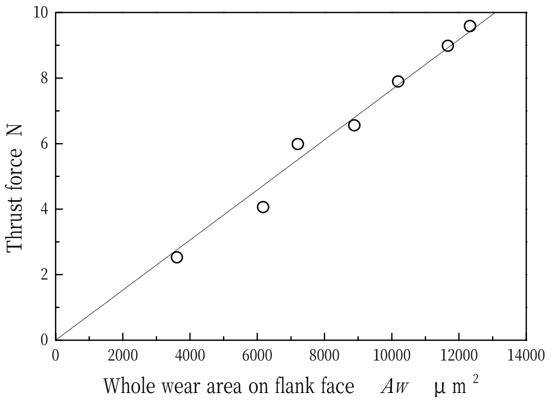

Fig.8 Relationship between whole wear area on flank face and Thrust force

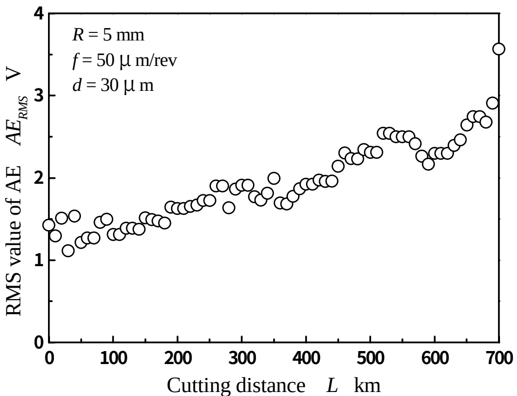

Fig.10 Relationship between cutting distance and RMS-value of AE

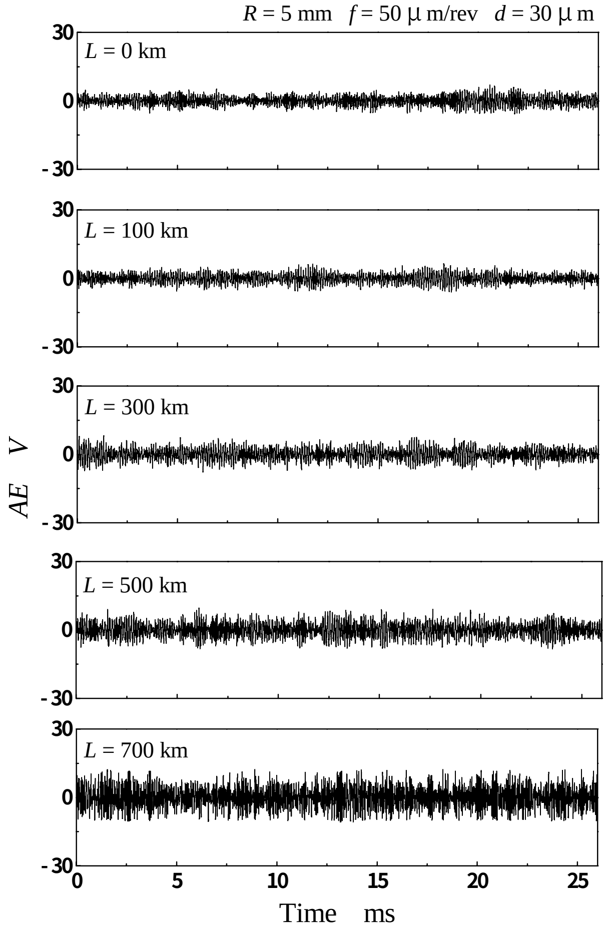

Fig.9 Sample of AE-signals

Principal and thrust forces increase with increase in real cutting distance, respectively, but feed force continued to be about zero against cutting distance. Rate of increase of thrust force with increase in real cutting distance is larger than that of principal force. Therefore, thrust force is expected to have good relation with tool wear. Fig. 8 shows the relationship between thrust force and whole wear area on flank face *Aw*. It is clear from this figure that thrust force is proportional to whole wear area on flank face *Aw*. Therefore, tool wear can be detected by monitoring thrust force, when threshold about wear area on flank face can be defined by preparatory experiment. But thrust force and wear area on flank face *Aw* are different by cutting conditions.

3.4 *AE*-Signals

A typical measured AE-signal is shown in Fig. 9. AE-signals are amplified and sampled at interval of 0.4 μ sec during 26 msec through A/D converter. Amplitude of AE-signal increases with increase of real cutting distance. RMS-value of AE-signal is represented by AE_{RMS}, and the relationship between real cutting distance L and AE_{RMS} is shown in Fig. 10. AE_{RMS} increases generally with increase of real cutting distance. Therefore, tool wear can be detected by monitoring AE_{RMS}, when threshold about AE_{RMS} can be defined by preparatory experiment. But *AE*-signals are different by cutting conditions. This means that preparatory experiment has to be done in advance of particular cutting condition, and it prevents from practical use.

FFT-analysis was carried out to find out characteristic parameter of spectra of AE-signal which is related with tool wear [4],[5],[6]. Results obtained are shown in Fig. 11. Two peaks exist at frequencies of about 8 kHz and 25 kHz at real cutting distance L of zero. Peak near 8 kHz does not have clear tendency because it fluctuates against increase of cutting distance. On the other hand, peak near 25 kHz increases with increase of real cutting distance. Area of spectrum between frequencies 5 kHz and

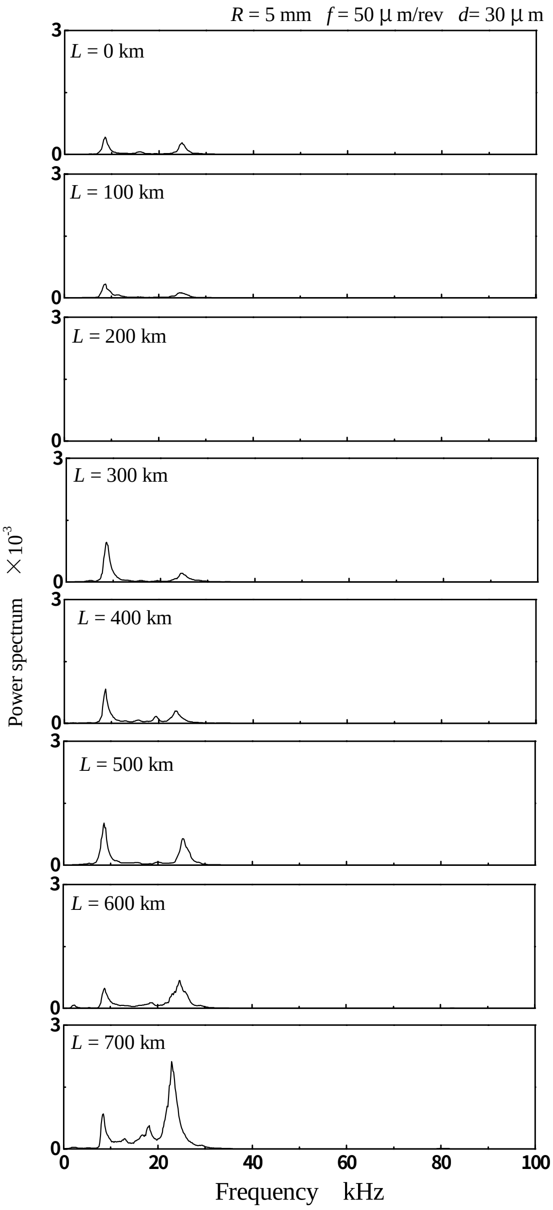

Fig.11 FFT analysis of AE-signals

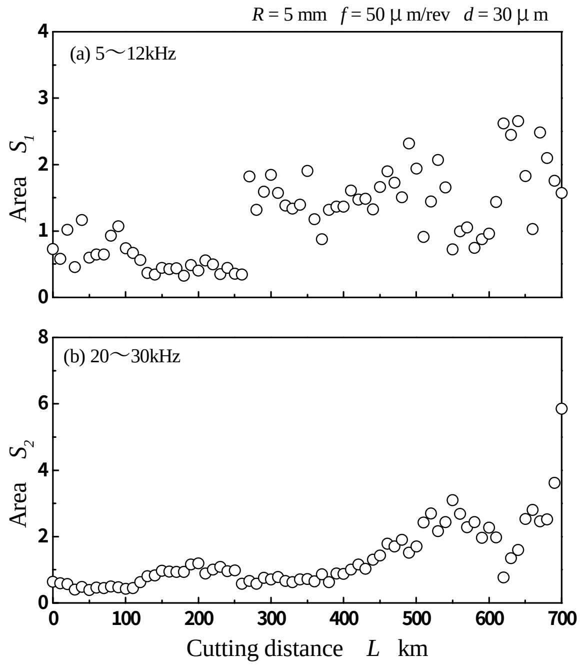

Fig.12 Relationship between cutting distance and peak area near *8kHz,25kHz*

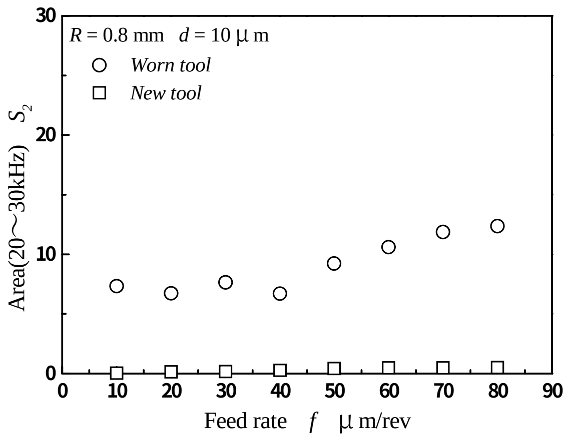

Fig.13 Relationship between feed rate and peak area near *25kHz*

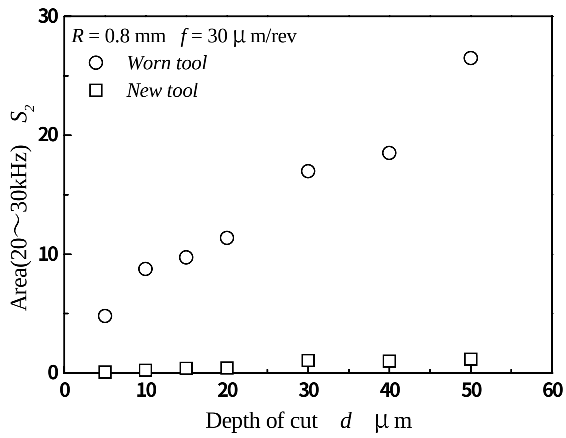

Fig.14 Relationship between depth of cut and peak area near *25kHz*

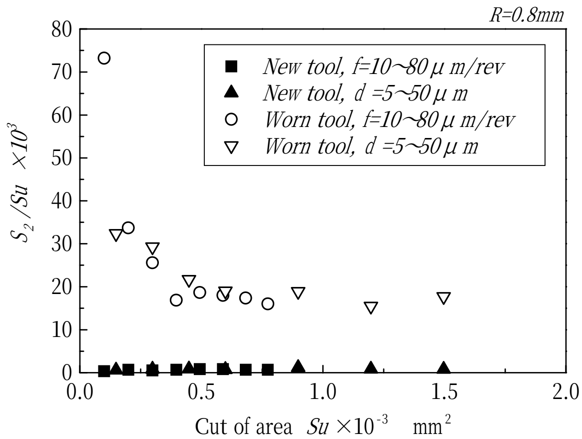

Fig.15 Relationship between area of cutting cross-section and peak area near *25kHz* per area of cutting cross-section

12 kHz is represented by S_1 and area between frequencies 20 kHz and 30kHz is represented by S_2. Area S_1 near 8kHz (5~12 kHz) and area S_2 near 25 kHz (20~30 kHz) are shown in Fig. 12. Area S_1 near 8 kHz has small dispersion when L<100 km but continues to be constant when 100 km <L<270 km and have large dispersion when L>270 km. Characteristics of area S_1 near 8 kHz doesn't coincide with that of tool wear. Area S_2 near 25 kHz continues to be constant when L<400 km, increases when 400 km<L<500 km, decreases slightly when 500 km<L<620 km, and increase sharply at L=620 km. Since occurrence of chatter vibration is verified by surface roughness measurement on bottom of cutter mark when L>700 km, it is considered that area S_2 near 25 kHz increased just before tool life.

For examine of this phenomenon on different cutting conditions, different large top corner radius R=0.8 mm is adapted, and experiments are performed on serial feed rates (f=10,20,••80 μm/rev) at constant depth of cut (d=10 μm) and serial depths of cut (d=5,10,15,20,30,40,50 μm) at constant feed rates (f=30 μm/rev) by using a new tool (L=0 km) and a worn tool (L=500 km). These results are shown in Fig. 13,14 , respectively. In case of constant depth of cut, area S_2 near 25 kHz obtained by a worn tool is clearly larger than that by a new tool. Area S_2 by a new tool continue to be about zero against increase of feed rate. Area S_2 obtained by a worn tool is almost constant when f<40 μm/rev, and it increases with increase of feed rates when f>40 μm/rev. In case of constant feed rate, area S_2 obtained near 25 kHz by a worn tool is also larger than that by a new tool. Area S_2 obtained by a new tool continues to be about zero against increase of depth of cut. Area S_2 obtained by a worn tool increases with increase of depth of cut. Real area of cutting cross-section is represented by Su. In case of changing feed rate and depth of cut, the relationship between area per real area of cutting cross-section S_2/Su and real area of cutting cross-section Su is shown in Fig. 15. Value of S_2/Su on a new tool continues to be about zero, but value of S_2/Su on a worn tool is larger than 10,000 on all cutting conditions. Value of S_2/Su is nearly constant when Su>0.5E-3, value of S_2/Su increases with decrease of Su when Su<0.5E-3. It is possible to detect tool wear by using parameter S_2/Su, when feed rate and depth of cut are changed.

4 CONCLUSIONS

(1) Principal and thrust forces increase with increase in real cutting distance, respectively, but feed force continued to be about zero against increase of cutting distance.
(2) Rate of increase of thrust force with increases in cutting distance is larger than that of principal force.
(3) RMS-values of AE-signals increase with increase in real cutting distances.
(4) AE-signal between frequencies of 20 kHz and 30 kHz sharply increased just before tool life.

Thrust force and AE-signals are effective parameters to detect tool wear of single crystal diamond tool in ultra-precision cutting.

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