Ultrasonic-Assisted on The Turning of Inconel 718 by Taguchi Method

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Abstract-*This paper presents an experimental investigation on the turning of Inconel 718 using tungsten carbide and cermet insert tools with ultrasonic-assisted. The Taguchi method as well as an L18 orthogonal array, signal-to-noise (S/N) ratio and analysis of variance (ANOVA) are employed to examine the performance characteristics of the turning operations. The effect of the machining parameters (cutting tool, depth of cut, cutting speed, feed rate, working temperature and ultrasonic power) on roundness and flank wear in the turning operations are studied. For roundness, depth of cut (σ = 38.40 %) and feed rate (σ = 22.59 %) were recognized to make significant contributions. For flank wear, the significant contribution order was cutting tools (σ = 51.16 %) for different materials, follow working temperature (σ=22.37 %), depth of cut (σ = 13.59 %), and ultrasonic power (σ = 5.79 %). Cutting with ultrasonic-assisted improves roundness by 17.78 % to 45.73 %, and improves flank wear by 26.52 % to 46.26 7%. Finally, turning experiments with 5-20 nm nano-particles cutting fluid were investigated. The experimental results indicated the cutter-workpiece friction force is noticeably reduced and cutter service life is prolonged.*

Keywords: Inconel 718; Ultrasonic-assisted; Flank wear; Roundness; Nano-particles.

I. INTRODUCTION

Nickel superalloy has been widely applied to escape valves, furnace equipment, petroleum, nuclear energy industries and corrosion resistant environments because of its superior properties. However, Inconel 718 is a well known difficult-to-cut material. Its low thermal conductivity and volume specific heat result in a high cutting temperature [1]. Good mechanical properties together with its severe work-hardening tendency lead to a high cutting force. In addition, the chips are easy to weld on the cutting tool to form a build-up edge (BUE). As a result, the cutting tool wears rapidly during machining.

The high temperatures generated in the cutting area when nickel-based alloy machining takes place are because of the low thermal conductivity and minimum chip thickness produced during the machining process [2]. Certain nickel-based alloy characteristics are responsible for poor machinability, as they have an austenitic matrix, and like stainless steel, rapidly work-harden during machining. Moreover, these alloys also tend to weld with the tool material at the high temperatures generated during machining. The tendency to form a BUE during machining and the hard abrasive carbide presence in their microstructure also deters machinability [3]. Precipitate hardening of γ'' secondary phase (Ni_3Nb) together with work-hardening during machining further worsens the cutting condition. All these difficulties lead to serious tool wear and a lower material removal rate [4].

The machinability performance study of Inconel 718 shows silicon nitride based material tool life mainly depends on flank wear. Tool life criterion for the silicon carbide whisker-reinforced alumina, however, is depth of cut notch wear [5]. Two types of coated cemented carbide inserts used with various combinations of side cutting edge angles, cutting speeds and feed rates were tested at a constant depth of cut. The cutting results indicate the side cutting edge angle, with the cutting speed and feed rate, play a significant role in determining insert tool life when machining Inconel 718 [6].

Ultrasonic vibrations have been extensively adopted in manufacturing processes. Babitsky et al. used high-frequency vibrations in radial directions to cut steel materials and found this approach could increase tool life [7]. Liu et al. proposed using ultrasonic-assisted vibrations to cut SiCp/Al thin-wall parts for precision processing [8]. Nath and Rahman examined the effect of cutting parameters on cutting performances in the cutting of Inconel 718 by applying both ultrasonic vibration cutting and conventional turning methods [9]. Compared with conventional cutting, this method has less cutting force and does not produce BUE.

This paper discusses Inconel 718 (Φ70 450 mm) machinability by applying a conventional lathe (YAM, CL4055) subjected to various machining parameters including cutting tools for different materials, depth of cut, cutting speed, feed rate, working temperature and ultrasonic power. Insert flank wear and workpiece roundness are also considered.

II. EXPERIMENTAL DESIGN

Machinability is the difficulty or ease of machining a material. According to AISI specifications, the machinability rating for free machining steel (B1112) is 100 % and the machinability rating for nickel-based alloy is 6~15 %, reflecting free machining steel difficulty. Machinability ratings for various metals are shown in Table 1. Tests conducted in several laboratories determine the practicability of artificially heating the workpiece surface just before a cut is made. While the method does not appear to be of general interest, it may prove particularly valuable in high temperature alloy machining with serious strain hardening [10]. This study employs a gas torch to heat the workpiece. The object is to supply enough heat to the surface to raise the layer temperature to be equal to the depth of cut to desired value. An infrared thermovision mechanism (Flir, Therma CAM S60) was used to measure the cutting temperature.

The amount of nickel in a nickel-based high-temperature alloy is very important for cutting speed. An alloy with a nickel content of about 60 % and a recommended carbide tool speed of 13 m/min are adopted. This cutting speed increases to 20 m/min when machining alloys contain about 50 % Ni, and to 26 m/min when machining alloys contain 45 % Ni [10]. This study employs a high cutting speed with cutting tools for different materials, and combines hot machining with ultrasonic-assisted cutting, to analyze machining behavior and increase machining efficiency in nickel-based Inconel 718 alloys. The current investigation, based on relevant literatures [5-6] probes and practical cutting tests, selects three cutting tools, TN35 (Tungsten carbide coating Al_2O_3), CT3000 (Cermet, bending-resistance strength is 1.59 GPa) and NX2525 (Cermet, bending-resistance strength is 2.0 GPa), as listed in Table 2. This study uses a tangent direction as the ultrasonic vibration direction to assist cutting.

The Taguchi method is a powerful tool for designing high quality systems [11]. This work uses the orthogonal array in the Taguchi quality design to determine significant machining factors for increasing experimental efficiency. The experiment selects six influential machining parameters, such as different cutting tool materials, depth of cut, cutting speed, feed rate, working temperature and ultrasonic power, each of which is assigned 3 levels, as shown in Table 3. The machining characteristics studied include workpiece roundness and tool flank wear. This work seeks optimum cutting parameters by adjusting experimental combinations and analyzing experimental results. Roundness was measured using the roundness tester (Mitutoyo, RA-112). This work uses an optical microscope (Olympus, SZ-PT) and Optimas software to inspect tool flank wear. Considering the experimental precision, roundness and flank wear were was an average taken from three measurements.

III. EXPERIMENT RESULTS AND ANALYSIS

A. Analysis of the S/N ratio

Classical experimental design methods are too complex and difficult to use. To solve this problem, the Taguchi method uses a special orthogonal array design to study the entire parameter space with a small number of experiments [12]. The Taguchi method employs a generic S/N ratio to quantify the present variation. Depending on the particular type of characteristics, different S/N ratios may be applicable, including "lower is better" (LB), "nominal is best" (NB), and "higher is better" (HB). In general, a low value is positively correlated as better for roundness and flank wear, or the lower-is-better characteristic in the Taguchi method. The S/N ratio of the lower-is-better characteristic is calculated using the following equations [13]:

$$\eta = 10\log(\frac{S}{N} ratio) \qquad (1)$$

$$\text{LB}: (\frac{S}{N} ratio) = \frac{1}{\sigma_{LB}^2} \quad \sigma_{LB}^2 = \frac{1}{n}(y_1^2 + y_2^2 + ... + y_n^2) \qquad (2)$$

where η denotes the observed value, i.e., the calculated value of the S/N ratio (unit: dB), y_n represents the observed value and n is the repeated number.

Table 4(a) lists the experimental results for roundness and the corresponding S/N ratio using Equations (1) and (2). The mean S/N ratio for each cutting parameter level is summarized and called the S/N response table for roundness. The L_{18} experiments are also calculated and illustrated in Table 4(b). Figure 1 shows the S/N response graph for roundness, and indicates roundness without cutting tool influence, larger depth of cut, working temperature and ultrasonic power, and a smaller feed rate can obtain better roundness.

To examine ultrasonic-assisted cutting influence on roundness, two level conjunctions of No.17 and No.18, listed in Table 4(a), are used for the experiment, and represent the maximum and minimum roundness combinations, respectively, among 18 experimental combinations. In Table 4(c), the experimental conditions of No.17 and No.18, No.17-1 and No.18-1 are cutting with and without ultrasonic-assisted, obtaining average roundness values of 10.03 μm and 1.97 μm, 12.20 μm and 3.63 μm, respectively. The experimental results show that ultrasonic vibration application can significantly improve roundness quality. Improvements of up to 17.78- 45.73 % are achieved.

Table 5(a) lists the experimental results for tool flank wear and its S/N ratios, while Table 5(b) and Figure 2 show the S/N response table and S/N response graph for tool flank wear. Figure 2 indicates using a cermet cutting tool NX2525 produces smaller flank wear, and flank wear decreases with the decreasing depth of cut.

Most materials generally soften with high temperature heating. However, at an appropriate temperature, Inconel 718 precipitates the hard secondary phase of γ'' (Ni_3Nb), increasing cutting difficulty. Working temperature level observation in Figure 2 reveals when a workpiece is heated for high-temperature (190℃) cutting, flank wear increases with temperature.

This investigation chooses two combinations of No.3 and No.17 in Table 5(a) for the experiment to inspect the ultrasonic-assisted cutting effect on flank wear. These two combinations represent the maximum and minimum flank wear combinations, respectively, from among eighteen combinations examined in the experiment. In Table 5(c), the experimental conditions of No.3 and No.17, No.3-1 and No.17-1 are cut with and without ultrasonic-assisted, and flank wear measurements are 28.15 mm^2 and 1.51 mm^2, 38.31 mm^2 and 2.81 mm^2, respectively. The experimental results show ultrasonic vibration application can markedly improve flank wear quality. Improvements of up to 26.52- 46.26 % are achieved.

Figures 3(a) and (c) show ultrasonic-assisted cutting obtaining low cutter flank wear. Moreover, BUE occurs at TN35 tungsten carbide, as shown in Figures 3(a) and (b), and is not found at NX2525 cermet, as illustrated in Figures 3(c) and (d), and the NX2525 cermet cutting tool obtains low flank wear (in Fig. 2).

B. Analysis of variance (ANOVA)

The purpose of ANOVA is to investigate the design parameters significantly affecting characteristic quality. The total sum of square SS_T from the S/N ratio η can be calculated as [14]:

$$SS_T = \sum_{i=1}^{n} (\eta_i - \eta_m)^2 \quad (3)$$

where n is the number of experiments in the orthogonal array and η_i is the mean S/N ratio for the i th experiment. The sum of squares from the tested parameter SS_P can be calculated as:

$$SS_P = \sum_{j=1}^{t} \frac{(S\eta_j)^2}{t} - \frac{1}{n}\left[\sum_{i=1}^{n} \eta_i\right]^2 \quad (4)$$

where p represents one of the tested parameters, j the level number of this parameter p, t the repetition of each parameter level p, $S\eta_j$ the sum of the S/N ratio involving this parameter p and level j.

The sum of squares from error parameters, SS_e is

$$SS_e = SS_T - SS_A - SS_B - SS_C \quad (5)$$

The total degrees of freedom are D_T = m-1, where the degrees of freedom of the tested parameter D_P = t-1. Parameter variance tested is $V_P = SS_P/D_P$. Then, the F-ratio for each design parameter is simply the ratio of the mean-of-squares deviations to the mean of the squared error ($F_P = V_P/V_e$). The corrected sum of squares S_P^* can be calculated as:

$$S_P^* = SS_P - D_P V_e \quad (6)$$

The percentage contribution σ can be calculated as follows

$$\sigma_P = \frac{S_P^*}{SS_T} \quad (7)$$

Table 6 shows ANOVA results for roundness and flank wear. Depth of cut (σ = 38.40 %) and feed rate (σ = 22.59 %) appear as the most significant cutting parameter affecting roundness. Cutting tool and cutting speed changes have an insignificant effect on machined workpiece roundness. The results of ANOVA for flank wear are shown in Table 6. Cutting parameter contribution order for flank wear is cutting tools (σ = 51.16 %) for different materials, followed by working temperature (σ=22.37 %), depth of cut (σ = 13.59 %) and ultrasonic power (σ = 5.79 %).

C.Confirmation experiments

Once the design parameter optimal level is selected, the final step predicts and verifies the quality characteristic improvements using optimal level design parameters. The estimated S/N ratio $Y_{predicted}$ using optimal level design parameters can be calculated as [15] :

$$Y_{predicted} = Y_m + \sum_{i=1}^{k} (Y_i - Y_m) \quad (8)$$

where Y_m is the total mean S/N ratio, Y_i is the mean S/N ratio at the optimal level, and k is the main design parameter number affecting the quality characteristic. The measuring data and actual S/N ratio of confirmation experiments are listed in Table 7. The largest S/N ratios in the L_{18} factor combinations of the two types of machining characteristics are -5.92 (Table 4(a)) and -3.61 (Table 5(a)), respectively. However, the S/N ratios of the confirmation experiments are -4.59 and -2.10, and are both larger than the above two. In addition, the S/N prediction, -5.04 and -1.70, are very close to the actual value. This finding indicates the experiments in this study possess excellent repetitiveness and great future reference potential

IV. NANO-MODIFIER FLUID

By taking advantage of low nano-particle friction with the contacting surface, the turning experiments use a cutting fluid mixed with nano-particles. This study uses a water-soluble nano-particle surface modifier, provided by Energy Release, USA. The particle sizes range between 5-20 nm. The dimension of the workpiece was Φ70 450 mm. The cutting parameters were as follows: the cutting tool was NX2525 cermet; cutting speed was 22 m/min; feed rate was 0.103 mm/rev for room-temperature cutting; ultrasonic power was 140 Watt. The Inconel 718 nickel-based alloy turning with traditional cutting fluid, and the nano-modified fluid were tested using various depths of cut.

Flank wear versus various depths of cut are shown in Figure 4 for comparison. The experimental results prove flank wear lessens with nano-modified fluid application. These results suggest nano-modified fluid action induces thin film formation on both the tool and workpiece. As a result of its high bonding force with contact surfaces, the real contact area between the cutter and workpiece reduces and, therefore, friction force decreases. The flank wear of various depths of cut could decrease for fluid mixed with nano-particles, as given in Figure 4.

V. CONCLUSION

This paper discusses the Taguchi method application for optimizing cutting parameters in turning Inconel 718 operations. This study discusses six machining parameters, including cutting tools for different materials, depth of cut, cutting speed, feed rate, working temperature, and ultrasonic power. The studied machining characteristics included roundness and flank wear. The following experimental results are obtained:

1. Formation of BUE when using a NX2525 cermet cutter is far less than a TN35 tungsten carbide cutter, and measured flank wear is lower than for a TN35 tungsten carbide cutter.
2. When the workpiece undergoes high temperature cutting (190℃), owing to the hard secondary phase of γ'' (Ni_3Nb) precipitation, cutting becomes increasingly difficult, and thus flank wear is higher than at room temperature.
3. The main contribution percentages of the depth of cut and feed rate for roundness are 38.40 % and 22.59 %, respectively.
4. The main contribution percentages of the cutting tools, working temperature, depth of cut and ultrasonic power for flank wear are 51.16 %, 22.37 %, 13.59 % and 5.79 %, respectively.
5. Cutting with ultrasonic-assisted improves roundness by 17.78 % to 45.73 %, as well as improving flank wear by 26.52 % to 46.26 7%. As a result, ultrasonic-assisted cutting enhances Inconel 718 cutting quality.

6. Nano-modifier fluid application decreases friction forces and flank wear, and improves tool life.

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Table 1 Machinability rates for metals (AISI Specification)

Workpiece material	Machinability rate (%)
Free machining steel (B1112)	100
Nickel-based alloy	6-15
Cast-iron	50
Pure iron	50
Stainless steel	40-65
Titanium	20-30
High-speed steel	30
Carbon steel	60-85

Table 2 Cutting tools

Type	Material	Comparison according to ISO	Insert specification
TN35	Carbide coating Al_2O_3	P20-P40	CCMT09T304
CT3000	Cermet	P05-P15, M05-M15, K05-K15	CCMT09T304 FG
NX2525	Cermet	P01-P20, K01-K20	CCMT09T304MW

Table 3 Setting of factors and levels in experiment

Symbol	Control factors	Level 1	Level 2	Level 3
A	Cutting tool	TN35	CT3000	NX2525
B	Depth of cut (mm)	0.1	0.2	0.3
C	Cutting speed (m/min)	22	43	73
D	Feed rate (mm/rev)	0.054	0.103	0.147
E	Working temperature	25	105	190
F	Ultrasonic power	140	160	180

Table 4(a) Experimental results for roundness and S/N ratio

Experimental No.	Control factors A	B	C	D	E	F	Roundness (μm) Rd1	Rd2	Rd3	S/N ratio (dB)
1	1	1	1	1	1	1	3.6	2.8	2.2	-9.32
2	1	2	2	2	2	2	8.1	9.5	10.1	-19.34
3	1	3	3	3	3	3	3.8	4.1	4.0	-11.97
4	2	1	1	2	2	3	4.2	3.8	4.5	-12.42
5	2	2	2	3	3	1	2.4	5.6	3.9	-12.42
6	2	3	3	1	1	2	4.3	3.2	2.4	-10.61
7	3	1	2	1	3	2	2.7	2.0	2.3	-7.42
8	3	2	3	2	1	3	5.2	5.8	3.2	-13.74
9	3	3	1	3	2	1	5.1	3.1	2.8	-11.61
10	1	1	3	3	2	2	3.8	3.5	4.2	-11.70
11	1	2	1	1	3	3	2.9	2.7	2.8	-8.95
12	1	3	2	2	1	1	4.8	2.5	2.7	-10.86
13	2	1	2	3	1	3	3.0	3.2	2.4	-9.21
14	2	2	3	1	2	1	5.6	3.9	6.0	-14.40
15	2	3	1	2	3	2	1.5	4.0	3.2	-9.78
16	3	1	3	2	3	1	4.7	3.4	4.0	-12.19
17	3	2	1	3	1	2	11.8	10.2	8.1	-20.13
18	3	3	2	1	2	3	2.0	2.2	1.7	-5.92

Table 4(b) S/N response table for roundness

Level	Control factors A	B	C	D	E	F
1	-12.02	-10.38	-12.03	-9.44	-12.31	-11.80
2	-11.47	-14.83	-10.86	-13.05	-12.56	-13.16
3	-11.83	-10.12	-12.43	-12.84	-10.45	-10.37
Level effect	0.55	4.70	1.57	3.62	2.11	2.79

Table 4(c) Analysis of roundness with and without ultrasonic-assisted cutting

Experimental No.	Control factors A	B	C	D	E	F	Roundness (μm) Rd1	Rd2	Rd3	Mean value (μm)	Improvement rate (%)
17	3	2	1	3	1	2	11.8	10.2	8.1	10.03	17.78
17-1	3	2	1	3	1		13.1	11.6	11.9	12.20	
18	3	3	2	1	2	3	2.0	2.2	1.7	1.97	45.73
18-1	3	3	2	1	2		5.4	1.7	3.8	3.63	

Table 5(a) Experimental results for flank wear and S/N ratio

Experimental No.	Control factors A	B	C	D	E	F	Flank wear (mm^2) A1	A2	A3	S/N (dB)
1	1	1	1	1	1	1	1.61	2.12	4.20	-9.16
2	1	2	2	2	2	2	9.77	8.64	7.64	-18.82
3	1	3	3	3	3	3	45.26	15.33	23.85	-29.78
4	2	1	1	2	2	3	2.03	2.55	3.51	-8.84
5	2	2	2	3	3	1	3.33	5.36	5.44	-13.64
6	2	3	3	1	1	2	4.04	3.33	4.42	-11.94
7	3	1	2	1	3	2	3.07	3.52	3.33	-10.40
8	3	2	3	2	1	3	2.25	1.02	2.10	-5.45
9	3	3	1	3	2	1	1.77	2.04	3.71	-8.46
10	1	1	3	3	2	2	6.63	4.25	3.12	-13.79
11	1	2	1	1	3	3	18.66	15.47	17.23	-24.70
12	1	3	2	2	1	1	14.20	5.62	7.66	-19.88
13	2	1	2	3	1	3	1.05	3.12	3.98	-9.49
14	2	2	3	1	2	1	2.25	1.63	4.41	-9.57
15	2	3	1	2	3	2	6.26	3.06	4.45	-13.58
16	3	1	3	2	3	1	4.20	2.51	3.43	-10.76
17	3	2	1	3	1	2	1.42	1.36	1.74	-3.61
18	3	3	2	1	2	3	4.99	4.92	3.56	-13.14

Table 5(b) S/N response table for flank wear

Level	Control factors A	B	C	D	E	F
1	-19.35	-10.41	-11.39	-13.15	-9.92	-11.91
2	-11.18	-12.63	-14.23	-12.89	-12.10	-12.02
3	-8.64	-16.13	-13.55	-13.13	-17.14	-15.23
Level effect	10.72	5.73	2.84	0.27	7.22	3.32

Table 5(c) Flank wear analysis with and without ultrasonic-assisted cutting

Experimental No.	Control factors A	B	C	D	E	F	Flank wear (mm^2) R1	R2	R3	Mean value (mm^2)	Improvement rate (%)
3	1	3	3	3	3	3	45.26	15.33	23.85	28.15	26.52
3-1	1	3	3	3	3		23.91	60.59	30.43	38.31	
17	3	2	1	3	1	2	1.42	1.36	1.74	1.51	46.26
17-1	3	2	1	3	1		2.71	2.27	3.45	2.81	

Table 6 Results of ANOVA for roundness and flank wear

Roundness					
Control factors	Sum of square	Degree of freedom	Variance	F-ratio	Contribution percentage, σ (%)
A	0.95	2	0.47	0.06	0.43
B	84.02	2	42.01	5.66	38.40
C	7.99	2	3.99	0.54	3.65
D	49.42	2	24.71	3.33	22.59
E	15.92	2	7.96	1.07	7.27
F	23.44	2	11.72	1.58	10.71
Error	37.09	5	7.42		16.95
Total	218.83	17			100

Flank wear					
Control factors	Sum of square	Degree of freedom	Variance	F-ratio	Contribution percentage, σ (%)
A	376.37	2	188.18	36.74	51.16
B	99.97	2	49.98	9.76	13.59
C	26.34	2	13.17	2.57	3.58
D	0.26	2	0.13	0.03	0.04
E	164.55	2	82.28	16.06	22.37
F	42.63	2	21.31	4.16	5.79
Error	25.61	5	5.12		3.48
Total	735.73	17			100

Table 7 Confirmation experiment results for roundness and flank wear

Quality characteristic	Control factors A B C D E F	Prediction S/N ratio (dB)	Confirmation experiments: Measured data 1	2	3	Mean value	S/N ratio (dB)
Roundness	A_2 B_3 C_2 D_1 E_3 F_3	-5.04	1.75	1.90	1.40	1.68	-4.59
Flank wear	A_3 B_1 C_1 D_2 E_1 F_1	-1.70	1.24	1.08	1.47	1.26	-2.10

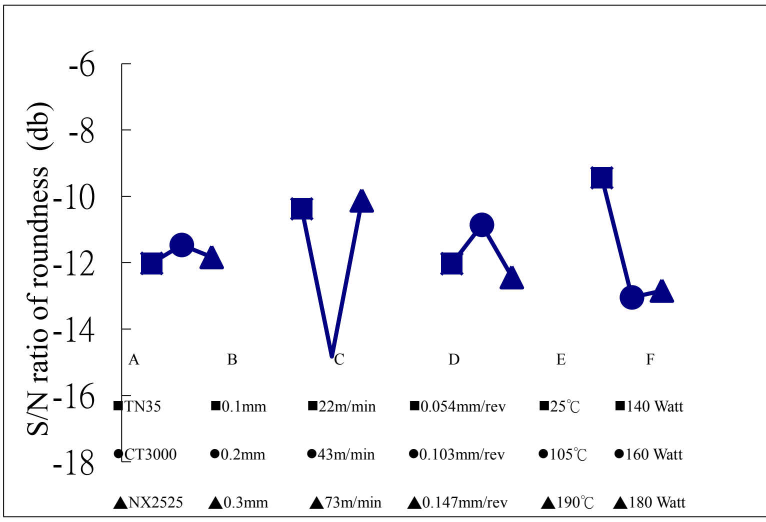


Figure 1 S/N graph for roundness

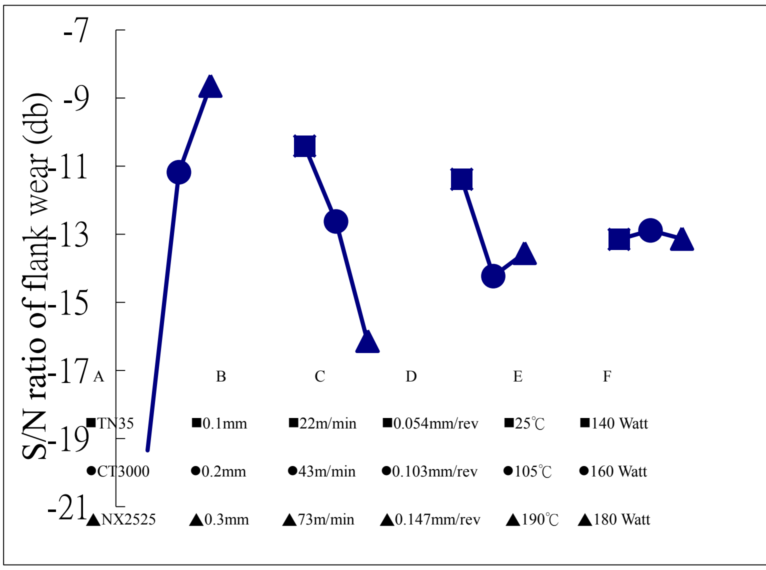
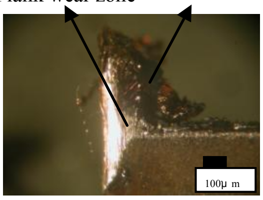
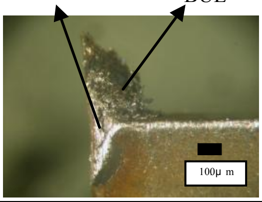


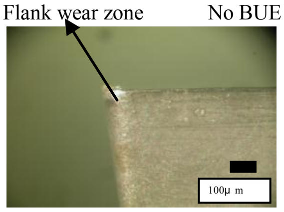
Figure 2 S/N graph for flank wear



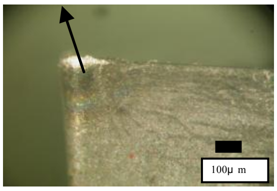
(a). Cutting with ultrasonic-assisted
Cutting tool: TN35, Depth of cut: 0.3 mm
Cutting speed: 73m/min, Feed: 0.147 mm/rev
Working temperature: 190℃
Ultra. Power: 180 Watt, Frequency: 20 kHz
Flank wear area: 15.33 mm^2



(b). Cutting without ultrasonic-assisted
Cutting tool:TN35, Depth of cut: 0.3 mm
Cutting speed: 73m/min, Feed: 0.147 mm/rev
Working temperature: 190℃
Ultra. Power: 0, Frequency: 0
Flank wear area: 23.91 mm^2



(c). Cutting with ultrasonic-assisted
Cutting tool: NX2525, Depth of cut: 0.2 mm
Cutting speed: 22m/min, Feed: 0.147 mm/rev
Working temperature: 25℃
Ultra. Power: 160 Watt, Frequency: 20KHz
Flank wear area: 1.36 mm^2



(d). Cutting without ultrasonic-assisted
Cutting tool: NX2525, Depth of cut: 0.2 mm
Cutting speed: 22m/min, Feed: 0.147 mm/rev
Working temperature: 25℃
Ultra. Power: 0, Frequency: 0
Flank wear area: 3.45 mm^2

Figure 3 Comparisons of flank wear with and without ultrasonic-assisted cutting

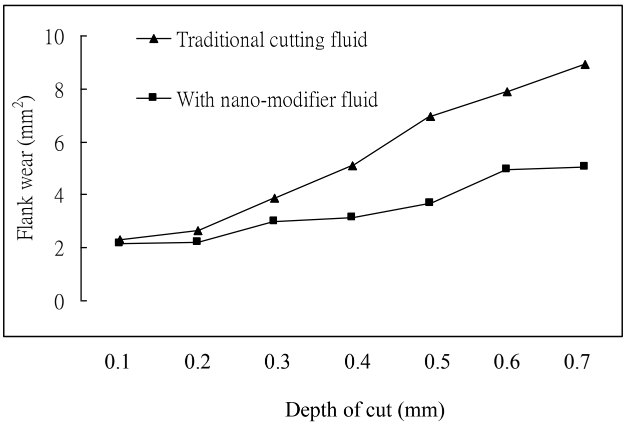


Figure 4 Comparisons of turning performance with different cutting fluids (NX2525 cermet, cutting speed = 22 m/min, feed rate = 0.103 mm/rev, room temperature cutting and ultrasonic power = 140 Watt.)