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Air–Oil Cooling Method for Turning of Hardened Material

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The hard turning process, defined as single-point turning of materials harder than H_R C 58, differs from conventional turning because of the hardness of the work materials and cutting tools needed in the process. In hard turning, tool life is very short, of the order of a few minutes, during which time the cutting tool is subjected to extreme stress and temperature. In this regard, it is well known that CBN tools are well suited for this process despite their high cost. In this research, we studied the feasibility of using lower-cost cutting tools such as TiN coated tools. To this end, a new cooling system was designed using an air–oil method, which is based on the principle of air vortex flow, for reducing tool temperature. In this system, the temperature of air at the outlet is lowered by more than 20°C using pressurised air of 5 kgf cm^{-2} at the inlet. The cooled air ejected at the tip of the cutting tool lowers tool temperature, and reduces the wear of a TiN coated tool to give 30% of CBN tool life with respect to the same cutting length.

Keywords: Air–Oil cooling; Hard turning; Taguchi's method; TiN coated tool

1. Introduction

The new manufacturing concept known as hard turning is booming owing to its capacity for lean production and agile manufacturing [1]. Hard turning is defined as finish machining of heat-treated materials harder than H_RC 58 [2]. In general, materials for machine elements need heat treatments for the improvement of strength and wear resistance. Some materials must be machined in the hardened state in order to maintain workpiece qualities such as surface finish, dimension accuracy, and shape. Conventional cutting tool materials, such as high-speed steel and tungsten carbide, are unsuitable for machining hardened materials because of reduced cutting tool life, and a grinding process is used for finish machining. As shown in Fig. 1, the new finishing process using hard turning requires fewer production steps than conventional processes, with the additional advantages of saving energy and machining time by the elimination of the second heat treatment and the grinding process.

With a change to hard turning, the elimination of subsequent grinding may increase productivity several times. Moreover, cutting tools in CNC lathes can be used for a wider variety of machining tasks and complex geometrical profiles, compared to a formed grinding wheel. Good surface integrity of machined parts is another consideration in favour of hard turning. Geometric accuracy is very high and surface roughness is less than 1.0 μm R_a. The residual stresses incurred by hard turning may be expected to lie within the compressive range, which is more favourable; for example, in automobile parts under fatigue load, wear resistance is increased owing to compressive stress [2,3].

However, in hard turning the cutting tool is subjected to extreme stress and temperature. Thus, tool life is shortened owing to high mechanical and thermal stresses as well as accelerated chemical reactions. Therefore, the requirements for

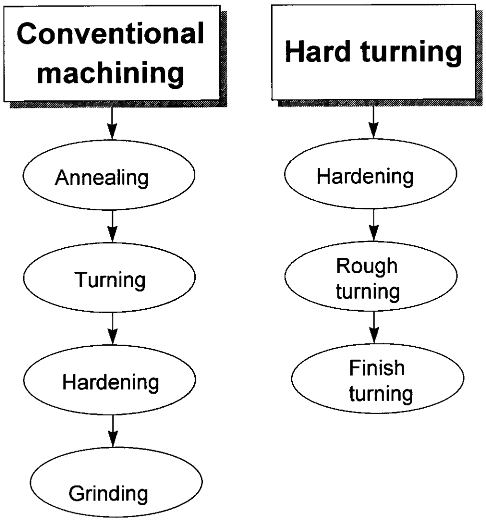

Fig. 1. Process comparison between conventional machining and hard turning.

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tool materials in hard turning include adequate hot hardness and thermal resistance. Also, the tool materials must be chemically stable, i.e. with resistance to oxidation and diffusion at elevated temperatures. CBN tool material is more suitable for these conditions than high-speed steel and tungsten carbide tools, since the latter either cannot machine hardened materials or are not cost-effective for machining. There are several CBN tool grades on the commercial market. BZN8100 (GE trade) is composed of 70% vol of CBN within titanium nitride (TiN) as the major binder, and is used for rough cutting. On the other hand, BZN6000 (90% vol TiN) is used for finish cutting owing to its high wear resistance and low surface roughness [4]. Besides the need for suitable tool materials, surface roughness corresponding to a ground surface cannot be obtained without high-precision machine tools [5,6]. Koenig has reported that there is no difference in surface integrity between a diamond turning lathe and a conventional lathe [3]. CBN tool material has therefore been seen as an absolute requirement for hard turning, regardless of its high cost.

In this research, we study a machining system aimed at carrying out hard turning economically, using low-cost tool materials instead of CBN or ceramic cutting tools. Tool wear in hard turning mainly results from the decrease of hardness owing to the high temperature (600–1000°C) in the cutting region. Therefore, our approach is based on designing a suitable cooling system to decrease cutting temperature. In flood cooling, hardened chips can be wrapped between the cutting tool and workpiece, and this accelerates tool chipping. To avoid this, we studied air-jet and air–oil systems, both of which use an air-cooling method based on air vortex flow. To this end, first, no-chipping conditions are found using Taguchi's experimental method [7]. Then an optimal cooling system is designed, again using Taguchi's method. In the validation experiment, the cooled mist ejected at the tip of the cutting tool was found to lower tool temperature, which reduced the wear of a TiN coated tool to allow 30% of CBN tool life with respect to the same cutting length.

2. Cutting Temperature Analysis

In order to design a cooling system for machining hardened materials, the first step is to decide the ejection direction of the coolant. This can be done by a thermal analysis around the cutting tool, based on a finite difference method. The cutting process, in this research, is regarded as orthogonal cutting. There are four active regions in the process of orthogonal machining as shown in Fig. 2:

1. The primary plastic deformation zone.
2. The secondary plastic deformation zone.
3. The tool–chip interface zone.
4. The tool flank–workpiece interface.

Since 99% of the total energy consumed in the cutting process is dissipated as heat, these regions can be considered as the heat-generation sources in cutting. The energy Equation in this case is as follows [8]:

$$\rho c\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)-k\left(\frac{\partial^2 T}{\partial^2 x}+\frac{\partial^2 T}{\partial^2 y}\right)-q=0 \qquad (1)$$

where c is specific heat, ρ is density, u and v are velocities in directions x and y, respectively; k is the thermal conductivity of the tool material; and q is the heat flux. The chips are

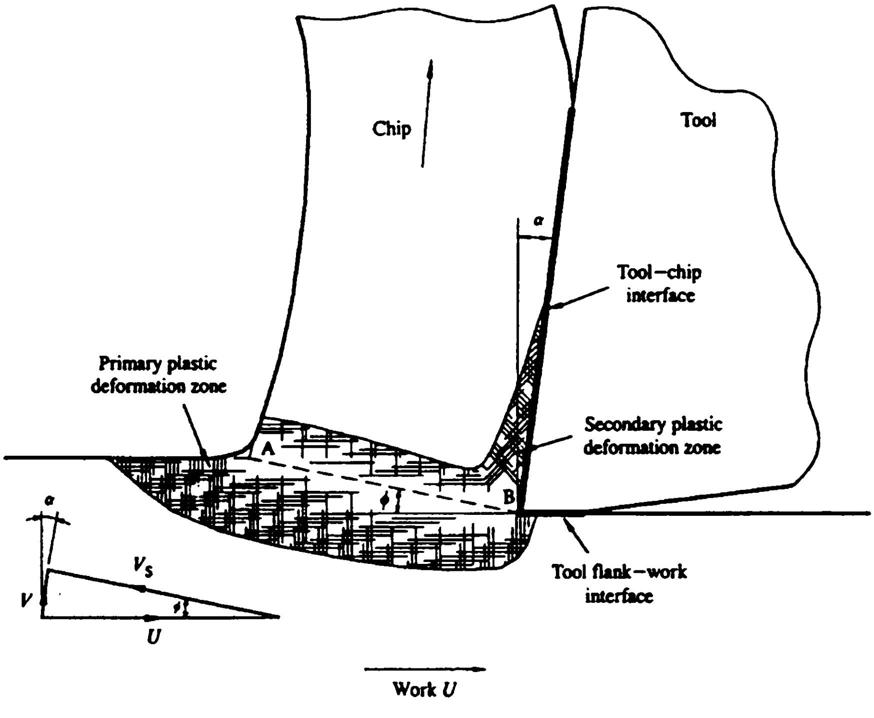

Fig. 2. Active regions of orthogonal cutting.

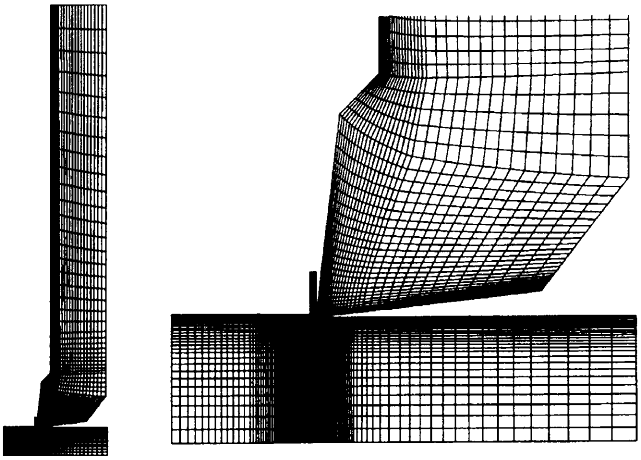

Fig. 3. Calculation grid for EDM.

Table 1. Cutting conditions and material properties.

Cutting tool (tungsten carbide: P20)	Rake angle	5°
	Density	13800.0 kg m^{-3}
	Specific heat	209 J kg^{-1}°C
	Heat transfer coefficient	74.05681 J sm^{-1}°C
Workpiece (carbon steel: 1010)	Density	7750 kg m^{-3}
	Specific heat	502 J kg^{-1}°C
	Heat transfer coefficient	41.84 J sm^{-1}°C
Analysis conditions	Undeformed chip thickness	0.2 mm
	Shear angle	22.5°
	Chip thickness	0.435 mm
	Cutting speed	170 m min^{-1}
	Chip–tool contact length	0.258 mm

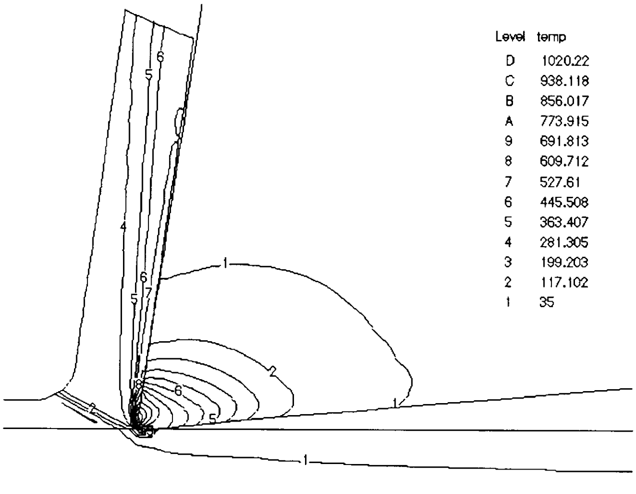

Fig. 4. Temperature distribution in orthogonal cutting.

produced by a shear process, and they flow with velocity V_c along the rake face according to the cutting speed of U. Figure 3 shows the grid for FDM analysis, where the grid intervals are small in the vicinity of the cutting region in order to increase analysis efficiency. Cutting conditions and material properties for analysis are listed in Table 1.

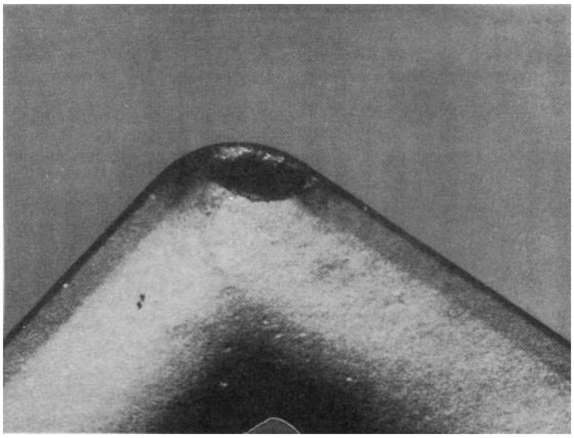

Fig. 5. Chipping which occurred in hard turning.

Figure 4 shows temperature distribution in orthogonal cutting. It can be seen that the temperature is higher around the rake and clearance faces than in other zones. The highest temperature region is located on the rake face away from the cutting edge, and exceeds 600°C in the case of a cutting speed of 170 m min^{-1} with a tungsten carbide tool. Hence, we conclude that cooling fluid should be ejected toward the rake and clearance faces, and experimental conditions for tool wear used the above directions of coolant flow.

3. Selection of Cutting Tool and Conditions Using the Taguchi Method

3.1 Cutting Experiment

Adequate tool material for hard turning is selected from among tool materials such as tungsten carbide (P25), coated tool (TiN) and cermet, which are cheap compared to CBN or ceramic tools. The geometry of the insert is CNMA120408, and a 50% vol CBN tool is used. The selection criterion is chipping occurrence. As shown in Fig. 5, chipping occurs owing to strength decrease while turning hardened materials, and it accelerates tool wear and affects the accuracy of machined workpieces. Experiments were performed with a conventional CNC lathe as shown in Fig. 6. Heat-treated bearing steel (SAE

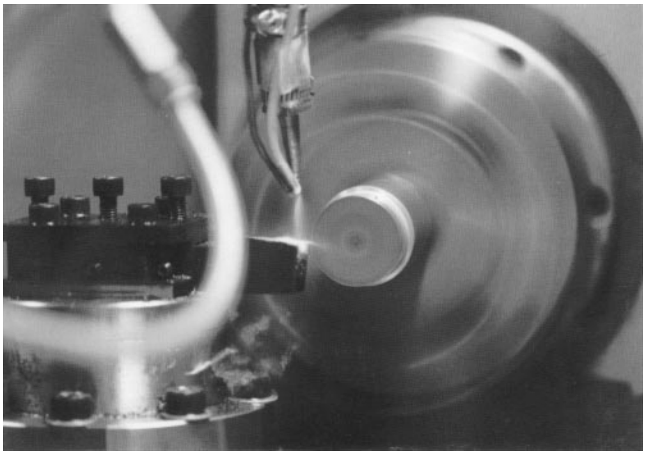

Fig. 6. Overview of experimental set-up.

52100) of H_RC 62–64 was machined by changing cutting conditions such as lead angle, coolant, cutting velocity, feedrate, depth of cut, and the nose radius of the cutting tool. Occurrence of chipping was checked both by eye and by tool microscope (Mitutoyo: TM301). Cutting force signals were measured by a tool dynamometer (Kistler: 9272) mounted on a gang-type table. Surface roughness was measured with a surface tester (Mitutoyo: Surftest 301) after each cut, in order to correlate cutting force, surface roughness and tool wear. From this experiment, optimal cutting conditions and tool material are selected and a cooling system is designed based on these conditions.

3.2 Application of the Taguchi Method

The number of cutting experiments considering three kinds of tool materials and six cutting condition factors, as summarised in Table 2, is too high to be practical. For the sake of efficiency, particularly to reduce the number of experiments, Taguchi's method is introduced as a means of choosing no-chipping conditions.

Following Taguchi's method, each design parameter to be optimised is identified as a factor, and in Table 2 the experimental parameter values are assigned factor levels. Based on the factor level, an orthogonal array is constructed with respect to each tool material, as shown in Table 3.

From the assumption of the independence of each factor, we can measure not only the effect of a factor under study on the average result, but also determine the deviation from the average result. Thus, it allows the relationship among factors to be investigated. In order to do this, each level has an equal number of occurrences within each column. Therefore, each factor level is equilibrated, and the effect of a factor is evaluated by separating it from other factors. In the table, each row corresponds to a factor, and each column is the order of experiment. The value of a factor represents a factor level, e.g. if factor A (leading angle) is 2 in the tenth experiment, the leading angle is 15°. Columns *e*1 and *e*2 represent dummy columns, which are required to make up an orthogonal array of 8 columns. A large variation of level value in a dummy column means a large error in the experiment.

Optimisation of cutting tools is a minimisation problem (smaller-the-better in Taguchi's method), since chipping should be avoided during cutting. Table 4 shows an S/N (signal to noise ratio) response table of TiN coated tool according to Eq. (2).

Table 3. Orthogonal array of TiN coated tool.

Level	Factor							
	A	B	*e*1 (dummy)	*e*2 (dummy)	C	D	E	F
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	2	1	2	1	3	2	3
8	1	2	2	3	2	1	3	1
9	1	2	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	2	1	3	2	3	1	2
17	2	2	2	1	3	1	2	3
18	2	2	3	2	1	2	3	1

Table 4. S/N response table of TiN coated tool (unit: dB).

Level	Factor					
	A	B	C	D	E	F
1	–51.1	–48.5	–40.1	–53.9	–51.5	–45.8
2	–46.1	–48.8	–49.4	–46.9	–47.8	–52.8
3	–	–	–56.3	–45.0	–46.6	–47.3

$$\eta = \text{S/N ratio, i.e. } \eta = -\log \sigma^2,\ \sigma^2 = \frac{1}{n}\left(y_1^2 + y_2^2 + \ldots + y_n^2\right) \tag{2}$$

where n is the repeated number of experiments and y_n is the repeated experimental data. Response tables of cermet and tungsten carbide are also obtained in a similar manner to Table 4. A graphical representation of response to level changes is shown in Fig. 7.

Table 2. Factor levels for the selection of cutting conditions.

Level	Factor					
	A lead angle	B coolant	C cutting speed (m min^{-1})	D feedrate (mm min^{-1})	E depth of cut (mm)	F nose radius (mm)
1	–5°	Off	30	10	0.05	0.4
2	15°	On	80	25	0.15	0.8
3	–	–	150	40	0.3	1.2

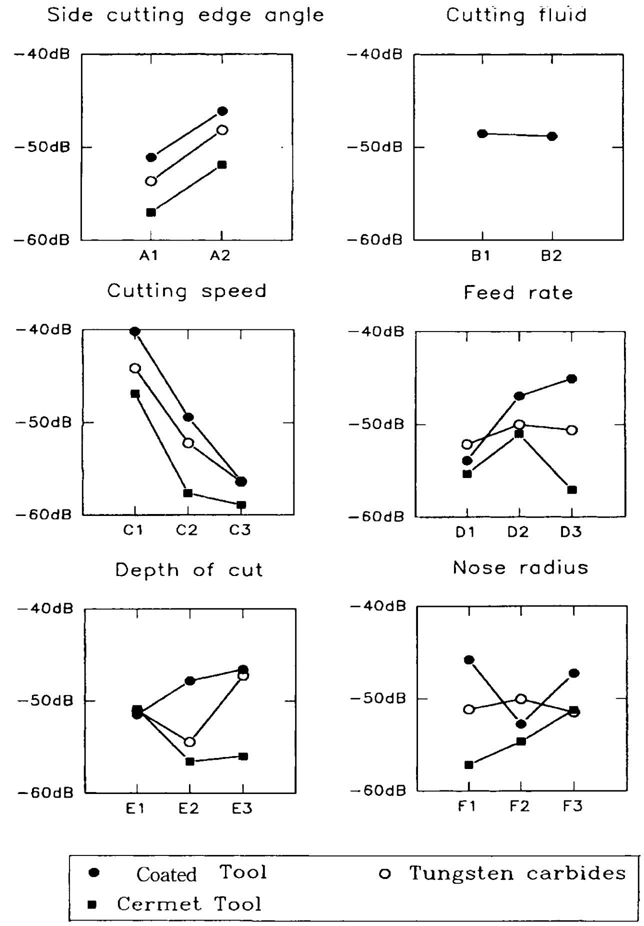

Fig. 7. Response graph with respect to each factor.

3.3 Selection of Cutting Tool and Cutting Conditions

According to Fig. 7, the TiN coated tool is superior to the other tools in terms of response value. That is, response value is small with respect to all factors, or in other words, the chipping rate is low. From this result, first of all, the coated tool is selected for hard turning. Furthermore, we see that cutting speed and lead angle have a large effect on chipping of all three kinds of tool material. Cutting conditions affecting chipping are considered in more detail using the analysis of variance based on response values [7,9]: factors with large variance ratio have the greatest effects on chipping. Table 5 identifies four factors strongly affecting chipping, in the order: cutting speed, feedrate, lead angle, nose radius. In this case, the optimal levels and corresponding values are as follows: A2 (lead angle: 15°), C1 (cutting speed: 30 m min^{-1}), D3 (feedrate: 40 mm min^{-1}), F1 (nose radius : 0.4 mm)

Therefore, the least chipping can be expected under the above cutting conditions. Expected chipping size is calculated from the following equation:

$$\eta = m + (A2 - m) + (C1 - m) + (D3 - m) + (F1 - m) \tag{3}$$

where m is the average value of the response ratio, and $A2$, $C1$, $D3$, $F1$ are response ratios of each level, respectively. From the above equation, expected chipping value is −31.25 dB, and the translated value is 36.52 μm. No chipping occurred in three repetitions of the validation experiment.

4. Cooling System Design Using Air–Oil

4.1 Application of Air-Cooling Using a Vortex Tube [10]

An air-cooling system was designed for the selected no-chipping conditions of cutting tool and factor values. The objective is to reduce the tool wear induced by the high cutting temperature while hard turning. As shown in Fig. 8, the system uses air-vortex flow. Compressed air is supplied at pressure P_a and temperature T_a in a tangential direction to produce a vortex within the tube. Part of the gas escapes through the larger exit tube at a rate controlled by a valve located 30 or more diameters downstream. The remaining air, at a lower pressure, escapes through a concentric orifice into a tube leading in the opposite direction. The fraction of gases (x) escaping through the orifice is at a temperature T_b that is lower than T_a, while the fraction $(1 - x)$ is at a temperature T_c that is higher than T_a. The temperature differences produced depend on the pressure ratio P_a/P_b, and on the fraction x, which is controlled by the valve. If air pressurised to 5 kg cm^{-2} is used, the temperature difference between inlet and outlet is theoretically predicted to be 30°C. In the experiment, temperature is decreased about 20°C in the same conditions. Therefore, air initially at room temperature is ejected towards the cutting region at 0°C. Figure 6 shows the overall experimental set-up, where the air-cooler is mounted on the tool post of the machine.

An optimal cooling system was designed experimentally by applying the Taguchi's method again. Design parameters are ejection direction, flow rate, and ejection distance. However, in order to avoid thermal cracking due to abrupt cooling of the cutting region, data for the nose radius of the cutting tool and chip breaker are also included. Table 6 shows factor levels for this analysis. The ejection direction is selected from overhead, oblique and flank directions by considering thermal analysis results, as shown in Fig. 9. Table 7 represents the orthogonal array. Effects with respect to each factor level are investigated by cutting experiments, as shown in Fig. 10, Table 8 is the response table. Tool wear is small at a large nose radius and with no chip breaker, owing to the reduced concentration of thermal stress. From the analysis of variance, as shown in Table 9, the following factors were shown to minimise tool wear: A1 (overhead cooling), C2 (nose radius : 0.8 mm), D1 (no-chip breaker).

4.2 Application of Air–Oil Cooling

From hard turning experiments with the above cooling system, we know that tool wear is reduced compared to dry cutting. However, the performance is not superior to that of flood cooling in terms of tool wear. The reason is that air cooling alone cannot provide a lubrication effect, so that increased

Table 5. Variance analysis of TiN coated tool.

Factor	Item			
	Degrees of freedom	Sums of squares (dB)	Mean squares (dB)	F (variance ratio)
A	**1**	**111.15**	**111.15**	**11.79**
B	1	0.27	0.27	–
C	**2**	**786.34**	**393.17**	**41.71**
D	**2**	**244.7**	**122.35**	**12.98**
E	2	77.88	38.94	–
F	**2**	**162.16**	**81.08**	**8.06**
Residual	7	16.12	2.3	–
Total	17	1398.62	–	–
(Pooled residual)	(10)	(94.27)	(9.427)	–

Bold = strong factor
F (variance ratio) = mean squares/mean squares of pooled residual

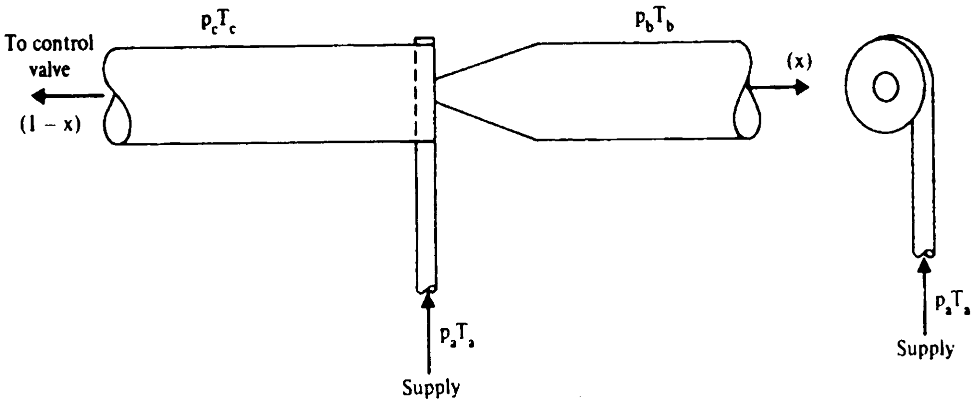

Fig. 8. The principle of the air vortex tube.

Table 6. Factor levels for the selection of cooling conditions

Level	Factor			
	A ejection direction	B $(L \times D)$ (mm^{-2})	C nose radius (mm)	D chip breaker
1	Overhead	31.5	0.4	Without
2	Oblique	55	0.8	With
3	Flank	70	–	–

D = nozzle radius (1.4 mm) L = ejection distance

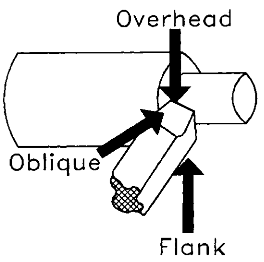

Fig. 9. Ejection direction of the coolant.

Table 7. Orthogonal array of air-jet experiment.

Level	Factor			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	2	1
4	2	1	2	1
5	2	2	2	1
6	2	3	1	2
7	3	1	2	2
8	3	2	1	1
9	3	3	2	1

temperature due to friction increases tool wear. As a further improvement, an air–oil cooling system is designed where an oil coolant is supplied at the cooling nozzle. Thus, mist coolant can be supplied to the cutting area at a temperature of 0°C, providing cooling and lubrication effects concurrently. This system is similar to a conventional mist coolant system except that it uses cooled air. In this study, a water-soluble coolant was used in order to avoid fire.

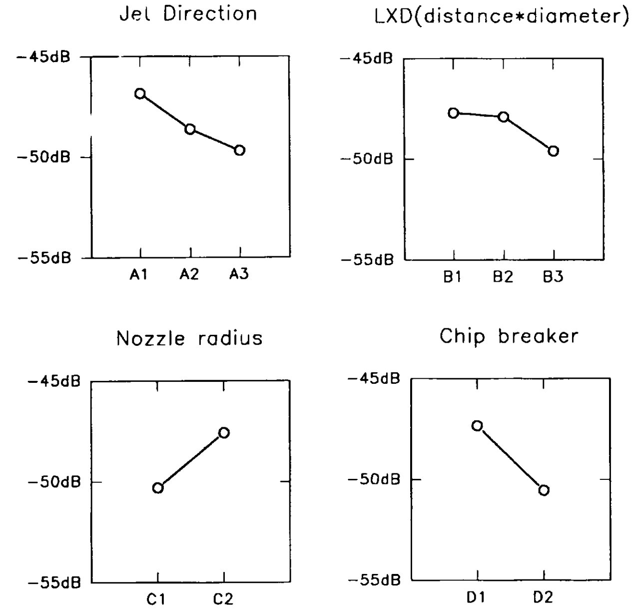

Fig. 10. Response graph with respect to each factor.

Table 8. S/N response table of air–jet cooling (unit : dB).

Level	Factor			
	A	B	C	D
1	–46.83	–47.68	–50.03	–47.32
2	–48.63	–47.89	–47.57	–50.53
3	–49.7	–49.6	–	–

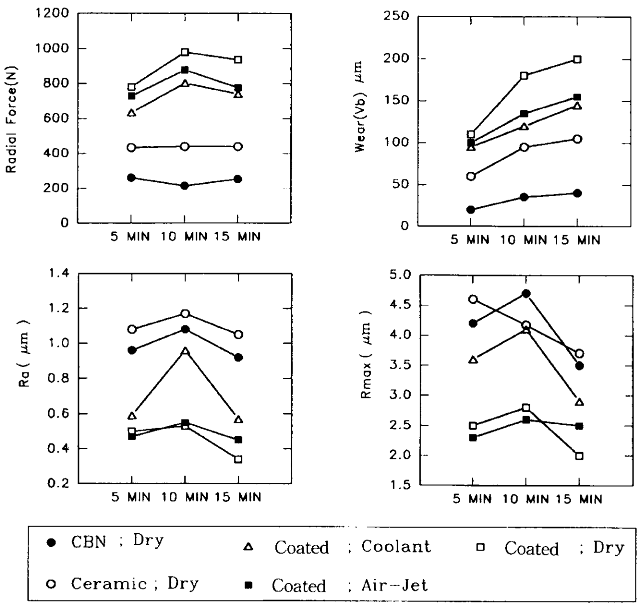

Fig. 11. Cutting tool performance in hard turning.

5. Results

In order to compare the performance of low-cost TiN coated tools using the air–oil cooling system, cutting experiments were carried out under different conditions: CBN and cermet cutting tools with dry cutting, and TiN coated tools with dry cutting, flood coolant, air-jet cooling, and air–oil cooling. Figure 11 shows cutting forces in the radial direction, tool wear, and maximum and average surface roughness. The radial force signal is measured, since it is sensitive to the tool wear. Surface roughness of the machined workpiece with a worn tool is better than with a mildly worn tool since the tool nose radius is increased with tool wear.

The coated tool suffered severe wear while hard turning, and also showed the highest cutting force among the different cutting tools. In this case, cutting force is reduced after some cutting length, since the real depth of cut is smaller than the ideal owing to tool wear. However, the tool wear of cermet or CBN with dry cutting is small compared to that for a tungsten carbide tool. Also, as we know, cermet tool wear is relatively high. In the case of a coated tool with flood coolant, tool wear is less than with air-jet cooling. However, as mentioned before, tool chipping was observed along the cutting edge. By changing to air–oil cooling, tool chipping was eliminated and tool wear was reduced by over 13% relative to air-jet cooling. This performance is also better than flood cooling, and similar to the cermet. This improved performance is attributed to the simultaneous reduction of temperature and friction by the mist coolant. If an index of tool wear is 100 for a coated tool, indices of the cermet and CBN tool are 78 and 30, respectively. CBN cutting tools are best for hard turning. Although cermet tools are not superior to CBN, cermet tools are better than coated tools by 22%. However, if we also consider tool cost and tool change-time simultaneously, TiN coated tools with air–oil coolant are economical in hard turning.

6. Conclusions

This research was a feasibility study for using low-cost TiN coated tools instead of expensive CBN tools in hard turning. For this purpose, a new cooling system was designed for reducing the temperature of the cutting tool. The cooling system relies on a vortex tube for cooling ejected air, and liquid coolant misted by the air. Taguchi's method was used to obtain cutting conditions for reduced chipping of the cutting tool. In these experiments, cutting speed, feedrate, nose radius and lead angle were found to affect tool chipping, and optimised values were obtained. Then, the Taguchi method was again used to design an optimal air–oil cooling system to reduce tool wear. In experiments with this cooling system, the life of a coated tool is 30% that of the CBN cutting tool. We conclude that it is possible to machine hard materials at a lower cost using TiN coated tools instead of expensive CBN tools.

Table 9. Variance analysis of air–oil experiment.

Factor	Item			
	Degrees of freedom	Sums of squares (dB)	Mean squares (dB)	*F* (variance ratio)
A	**2**	**12.62**	**6.31**	**3.69**
B	2	6.65	2.22	–
C	**1**	**12.1**	**12.1**	**7.08**
D	**1**	**20.6**	**20.6**	**12.1**
Residual	2	0.193	2.3	–
Total	8	51.97	–	–
(Pooled residual)	(4)	(6.84)	(1.71)	–

Bold = strong factor

F (variance ratio) = mean squares/mean squares of pooled residual

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