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COMPARATIVE PERFORMANCE OF COATED AND UNCOATED INSERTS DURING INTERMITTENT CUT MILLING OF AISI 4340 STEEL

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Abstract

Machining behaviour of TiN coated and uncoated cemented carbide tools were studied during intermittent milling operation of AISI 4340 steel. Series of orthogonal intermittent milling tests were performed subsequently to investigate the role of the selected tools and cutting parameters. Three cutting parameters namely cutting speed, feed and depth of cut with three different levels and two types of cutting tools (coated and uncoated) were considered for conducting the experimental trials. Intermittent face milling was employed to study the wear behaviour of the tools and the resulting surface roughness. The cyclic load induced during the entry and exit of the tool, leads to unstable temperature at cutting zone. This unstable temperature affects the tool life badly during intermittent milling. Tool wear increases considerably with an increase in frequency of the interruption. The experimental results indicated that the coated tool out performed uncoated tool in terms of tool life and surface finish. The other interesting observation was the uncoated tool performed better than coated tool at moderate cutting parameters. Results also indicated that the fracture and chipping were the dominant tool failure modes in uncoated tool. The chipping of uncoated tool causes the surface quality to deteriorate. TiN coating ensures the toughness of the cutting tool, which leads to good surface quality during the machining process. A detailed analysis of tool wear and surface roughness was done and the results are employed to create a linear regression model. This model established the relation between the cutting parameters and the response variables. ANOVA was used to identify the influential parameters which affect the tool wear and surface roughness.

Keywords: Intermittent cut, TiN Coated and uncoated inserts, Regression model, Flank wear, Surface roughness.

Nomenclatures

d	Depth of cut, mm
f	feed rate, mm/min
V_c	Cutting speed, m/min
Greek Symbols	
μ	Microns

1. Introduction

Xiaobin et al. [1], Asier et al. [2], Aslantas et al. [3], Kevin Chou [4], and Ezuguwu et al., [5] explain that knowledge of tool failure mechanisms in intermittent milling process is essential for proper application and material design of different cutting tools. Many research articles exist on tool failure mechanisms in intermittent cut. Even though vast research on tool wear mechanisms and failure modes of tools during intermittent turning exists, performance of the tools during intermittent milling is still not addressed. Tie bar bushes made of AISI 4340 steel used in injection moulding machine were subjected to the experimentation. Coated and uncoated SNMG 1205 milling inserts were used for the experiment.

Intermittent cut leads to major tool failures which reduce the tool life drastically. During intermittent cut, the alternate cyclic load on tool causes thermal instability and leads to catrostrophic tool failure. Intermittent cut machining produces severe pounding of tools at entry and exit of the tool induces high temperature fluctuation which leads to tool failure. The tool entry and exit angle was investigated during intermittent turning and found that lower exit angle is beneficial for reducing the degree of tool fracture [1]. High tool failure occurs during the exit of the tool rather entry of the tool. Chamfered tool edges can reduce this type of tool failure rate occurring during exit of the tool [6].

Maximum and mean cutting temperatures are lower for intermittent milling than for continuous milling due to the effect of the cooling intervals. Thus the amplitude of the temperature variation and this variation likely plays a role in tool failure due to thermal cycling/shock [7]. With an increase of cutting speed, the number of interruptions also gets increased which leads to rapid tool wear. Investigations were made on the frequency of interruption, and found that it is seriously affecting the tool wear. The predominant tool wear patterns were found to be adhesion and oxidation during intermittent cut [4, 8]. During intermittent milling of low alloy and carbon steels, at lower velocities tool failure is due to rake face pitting which is caused by the ‘adhered’ chip being thrown off the tool, [9]. Multi layered coatings presumably have a deteriorated thermal conductivity, thus not providing sufficient relieve to the cutting edge of cemented carbides in intermittent cut machining [10].

The influential cutting parameters affecting the tool life and surface roughness were cutting speed and feed rate during general milling. Cutting speed and feed rate are the influential factor of tool life during intermittent cut using TiN coated tools [5]. Surface roughness is determined by the variation of the relative position of the cutter and its growth is not closely related to the increase in the wear of the cutting edge [11]. The behaviour of surface roughness as cutting time elapses is very different in coated tool while comparing to the uncoated tool. Also surface roughness can be improved by controlling the feed rate during milling [12].

2. Experimental Procedure

2.1. Selection of work and tool material

AISI 4340 is one of the common steel materials used in automotive engineering, aerospace engineering and other general engineering applications. The chemical composition and mechanical properties of AISI 4340 is shown in Tables 1 and 2 respectively.

Tie bar bush as shown in Fig. 1 - a sub component of injection moulding assembly, made of AISI 4340 is being considered for the experimental trial. This component is so precise by its application and it is also a functional part in the assembly of injection moulding machine. Therefore the machinability of this component has to be studied in detail to optimize the machining process.

Table 1. Chemical Composition of AISI 4340 Steel.

Element	Content (%)
Iron, Fe	93.5
Nickel, Ni	1.75
Chromium, Cr	0.82
Manganese, Mn	0.73
Carbon, C	0.37
Molybdenum, Mo	0.24
Silicon, Si	0.19
Sulphur, S	0.04
Phosphorous, P	0.035

Table 2. Mechanical Properties of AISI 4340 Steel.

Density (x 1000 kg/m^3)	7.85
Poisson's Ratio	0.29
Elastic Modulus (GPa)	195
Tensile Strength (MPa)	740.5
Yield Strength (MPa)	469.3
Elongation (in %)	22
Reduction in Area (in %)	49.9
Hardness (HB)	217
Impact Strength (J) (IZOD)	51.1

In this direction, the machining experiments were conducted using a Vertical Machining Centre (Deckel Maho make) having rapid speed of 7500 rpm and the machine with fixture setup is shown in Fig. 2. Diameter 80 mm face mill cutter with an approach angles of 750 , negative radius rake angle of -100 and negative axial angle -40 has been used for the experimentation. The cutter was loaded symmetrically to the 80 mm diameter bore of the tie bar bush and the machining trials were conducted. The tool entry and exit around the bore was observed as intermittent cut during the experiment.

Experimental trials were conducted using SNMG 1205 (Taegutech make) of both coated (Titanium Nitride– TiN) and uncoated cemented carbide inserts. These inserts has rake angle of 110 and lead angle 110 respectively. These inserts were rigidly mounted on a SNMG face mill cutter and clamped mechanically. Coolant was not used during the experiment. After each experimental trial, the inserts were removed and its flank wear was measured using Optical Microscope (Carl Zeiss make) having magnification range of 500x. The average surface roughness on the work piece was measured using surface roughness tester (MAHR make).

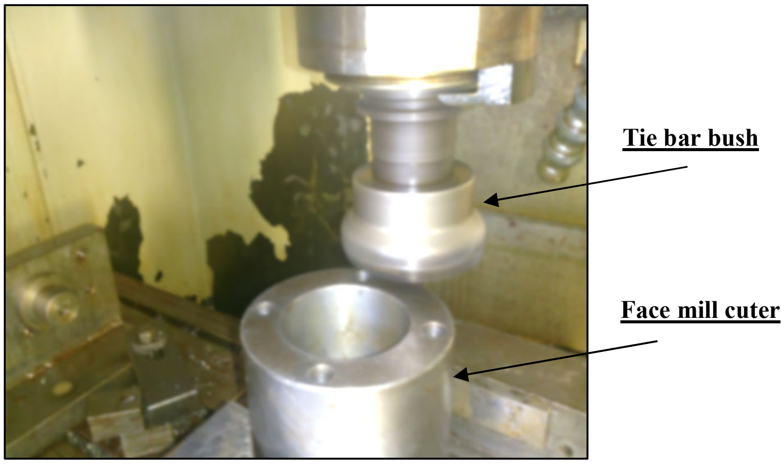

Fig. 1. Tie Bar Bush used for Experiment.

Fig. 2. Vertical Machining Centre used for Experiment.

2.2. Design of experiment

Taguchi's Design of Experiments (DOE) and orthogonal array was the base for the experiments. The inter relation between the factors which affects the process and the output of the process can be well established by using the Design of Experiments (DOE). DOE also reduces the number of trials to obtain the information of the process. Four input variables (cutting speed, feed, depth of cut and type of insert) were selected each at three levels. In order to accommodate all four factors, Taguchi's L18 array of mixed level design was chosen for the experimentation. The critical parameters and their levels selected were given in Table 3. The response obtained from the trials were recorded and further analysed as shown in Table 4.

Table 3. Critical Levels and Their Parameters.

Process parameters	Parameters designation	Levels		
		1	2	3
Insert Type	**A**	**Coated**	**Uncoated**	
Cutting speed (V_c) m/min	**B**	300	350	500
Feed (f) mm/min	**C**	297	372	446
Depth of cut (d) mm	**D**	0.5	0.7	0.9

Table 4. L18 Taguchi Array of Experiment and Observations.

Insert Type	V_c	F	D	R_a	V_b
A	300	297	0.5	1.03	36
A	300	372	0.7	1.07	33
A	300	446	0.9	1.10	35
A	350	297	0.5	0.97	41
A	350	372	0.7	0.92	39
A	350	446	0.9	1.00	40
A	500	297	0.7	0.93	47
A	500	372	0.9	0.91	55
A	500	446	0.5	0.96	62
B	300	297	0.9	1.09	42
B	300	372	0.5	1.13	46
B	300	446	0.7	1.16	43
B	350	297	0.7	1.02	47
B	350	372	0.9	0.99	42
B	350	446	0.5	1.00	40
B	500	297	0.9	0.97	59
B	500	372	0.5	0.93	57
B	500	446	0.7	0.99	65

3. Statistical Analysis and Mathematical Modelling

3.1. Statistical analysis of variance

ANOVA was used to determine the significant parameters influencing the tool wear and surface roughness during intermittent milling. The observed values of tool flank wear (Vb, mm) and surface roughness (Ra, mm) were used for determining the influential factors during the machining process. This analysis was carried out for significance level with confidence level of 90%. The sources with lesser P-value were considered to have a statistically significant contribution to the performance measures. The statistical ANOVA tables for all variances are shown in Tables 5-8. From the table values, it is being inferred that the cutting speed is the most dominant factor which affects the tool wear and surface roughness. Feed rate is the next most dominant factor which affects the surface roughness.

Table 5. ANOVA for Tool wear: V_b versus V_c (For Coated Inserts).

Source	DF	SS	MS	F	P
V_c	2	1195.11	597.556	22.84	0.003
F	2	18.78	9.389	0.36	0.708
Interaction	4	117.56	29.389	1.12	0.404
Error	9	235.50	26.167		
Total	17	1566.94			
S=5.115	R-Sq=84.97%	R-Sq=(adj)= 71.61%			

Table 6. ANOVA for Surface Roughness: R_a versus *f*, V_c (Coated inserts).

Source	DF	SS	MS	F	P
f	2	0.061778	0.0030889	2.64	0.002
V_c	2	0.0721444	0.0360722	30.77	0.127
Interaction	4	0.0042222	0.0010556	0.90	0.503
Error	9	0.0105500	0.0011722	0.90	0.503
Total	17	0.0930944			
S=0.03424	R-Sq=88.67%	R-Sq(adj)=78.59%			

Table 7. ANOVA for Tool wear: V_b versus V_c (Uncoated Inserts).

Source	DF	SS	MS	F	P
Vc	2	1195.11	597.556	22.84	0.014
F	2	18.78	9.389	0.36	0.708
Interaction	4	117.56	29.389	1.12	0.404
Error	9	235.50	26.167		
Total	17	1566.94			
S=5.115	R-Sq=84.97%	R-Sq(adj)=71.61%			

Table 8. ANOVA for Surface Roughness: *Ra* versus *f*, V_c (Uncoated Inserts).

Source	DF	SS	MS	F	P
F	2	0.0061778	0.0030889	2.64	0.126
V_c	2	0.0721444	0.0360722	30.77	0.012
Interaction	4	0.0042222	0.0010556	0.90	0.503
Error	9	0.0105500	0.0011722		
Total	17	0.0930944			
S=0.03424	R-Sq=88.67%	R-Sq(adj)=78.59%			

3.2. Mathematical modelling

Multiple linear regression models were developed for tool wear and surface roughness using Minitab-15 software for the recorded values. The response variable is the tool wear and the surface roughness, whereas the input variables are cutting speed, feed rate, depth of cut and tool type. Accordingly, the equations of the fitted model for tool wear and surface roughness is given below.

$$R_a = 1.15 - 0.000624\ V_b + 0.000223 f + 0.0167\ d \quad (1)$$

$$V_b = 6.8 + 0.0951\ V_c + 0.0145\ f - 3.75\ d \quad (2)$$

where V_b is the tool wear in mm, V_c is the cutting speed in m/min, *d* is the depth of cut in mm, *f* is feed rate in mm/rev, *Ra* is the surface roughness in μm.

4. Results and Discussion

4.1. Tool wear

It is found that rapid tool wear occurs both in coated and uncoated during intermittent cut. Coated tool performs better comparing to uncoated insert, as TiN coating resists the adhesion of work material to tool edge. ANOVA shows that the cutting speed is the most significant factor for the tool wear and feed rate is next to that.

From the main effects plots as shown in Fig. 3, it is evident that an increase in cutting speed causes rapid increase in the tool wear. The amplitude of the tool/chip interface temperature fluctuation increases with an increase in cutting speed (S.M Bhatia et al., 1978). In coated insert, during initial stages a few layer of coating was taken away from the tool due to abrasion between the tool and the work piece. This was due to the high instability of temperature at cutting zone which is due to intermittent cut. As the inserts come in contact with workpiece in alternative cycle (i.e., for every revolution, the tool has an entry and exit for the workpiece) high instability of temperature was observed which lead to major tool failure. Uncoated tools have higher wear as compared to coated tools, the least wear is observed in TiN coating as shown in Fig. 3. The tool wear rate is low at higher cutting speeds, but a very smaller difference is observed at different feed rates, as seen in Fig. 4. Similarly, feed rate establishes a linear effect on the wear. With increase in feed rate, the tool wear also gets increased since feed rate increases with increase in force on cutting edge of tool.

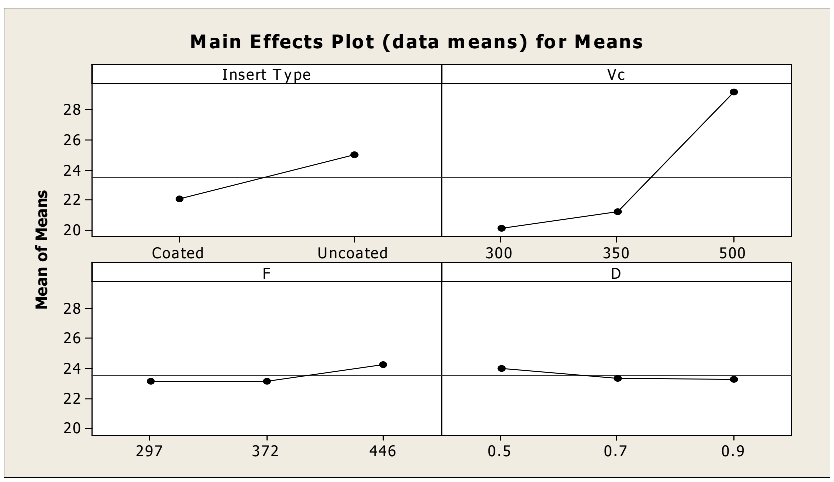

Fig. 3. Main Effects Plot for Means.

Uncoated tools exhibiting higher flank wear than coated tools. It is also observed that flank wear is high for higher cutting speeds. For higher cutting speeds, the frequencies of interruptions are high due to which inserts lose hot hardness. All the tools exhibit higher flank wear at higher feeds. To a limited extent, the trend of flank wear is linear but after that it is very rapid. The initial wear was observed at the tool tip which was found at lower cutting parameters.

Flank wear was the initial tool wear pattern observed at the nose of both coated and uncoated tools. Flank wear was also increasing rapidly, which is accompanied by severe abrasive marks during cutting in both tools. At the cutting speed of 350 m/min, uncoated inserts performed well with minimum tool wear and good surface finish. At the cutting speed of 500 m/min, the coated tool resulted with maximum tool wear and minimum surface roughness. In particular, at cutting speed 500m/min the higher tool wear has been recorded.

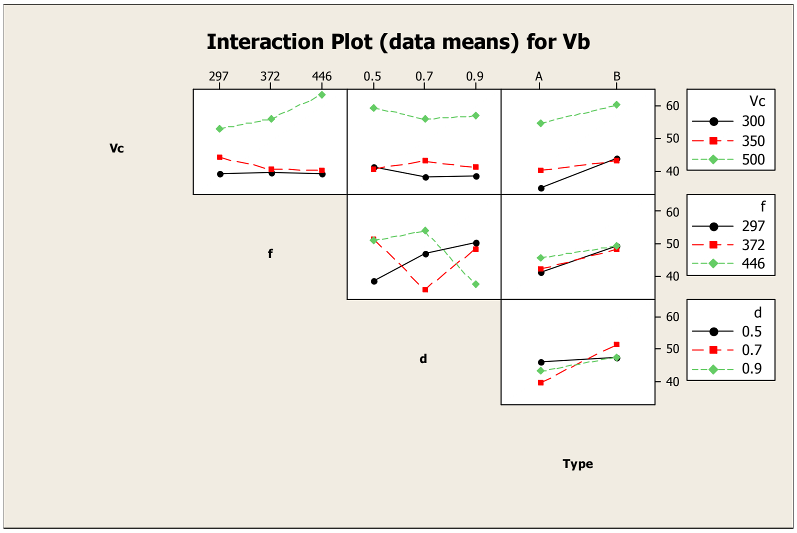

Fig. 4. Interaction Plot for Means (V_b).

4.2. Surface roughness

The pounding of tools due to intermittent cut gets heavier when the feed rate is high, which also leads to high temperature at tool chip interface. The contact time between tool and the work piece get increase due to feed rate increase. This leads to chipping off of tool cutting edges. Poor surface finish is achieved with chipped off tools. The geometrical damage on the cutting edge due to wear process for uncoated tools was faster than for the coated tools, which results in high surface roughness. With an increase of feed rate, the surface roughness also got increased for both coated and uncoated tools.

From Fig. 5 it is inferred that feed rate is most dominant parameter in controlling surface roughness. It is also evident that next to feed rate, cutting speed plays a significant role on surface roughness. It is also evident from Fig. 5 that at higher cutting speeds, the surface finish is high [10]. It was found that feed rate is most dominant factor in controlling surface roughness [7]. Ra values are almost in same range for lower values of depth of cut and cutting speed for both coated and uncoated inserts. Figure 6 shows that higher cutting speeds and with lower feed rates, the surface finish is high. Depth of cut has very less influence on surface roughness, but when depth of cut increases considerable increase in surface roughness was observed. Lastly, the type of tool has also dominant influence in controlling surface roughness.

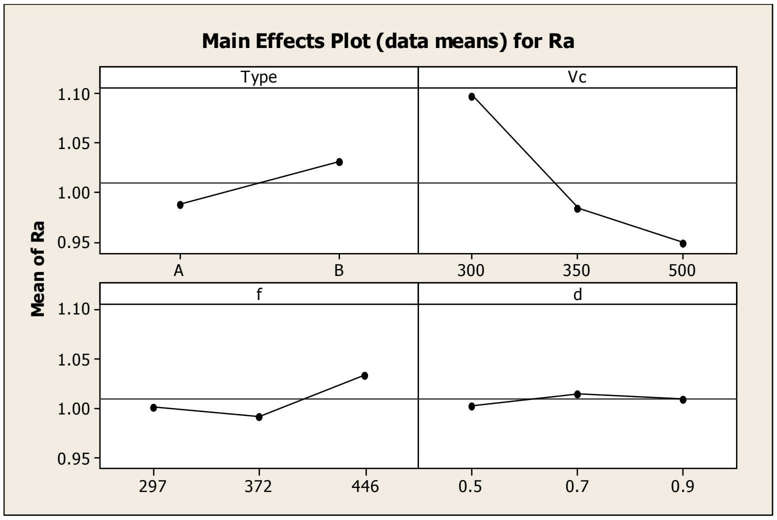

Fig. 5. Main Effects Plot for Means (R_a).

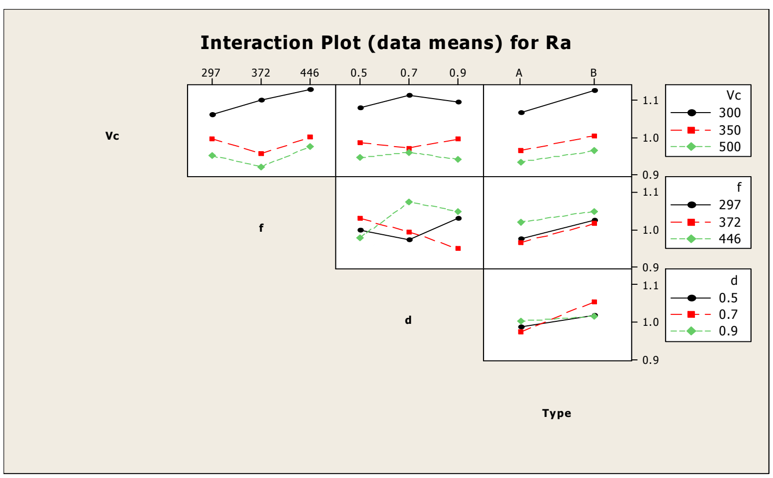

Fig. 6. Interaction Plot for Means (R_a).

5. Conclusions

Experimental trials on AISI 4340 work material using cemented carbide tool inserts (coated and uncoated) were conducted. To get the valid and objective conclusions, L18-orthogonal array has been adopted and a regression model has been proposed using the experimental data. An analysis of variance (ANOVA) was performed and it was found that feed rate has greater impact on surface roughness and cutting speed has greater impact on tool wear. Using Regression Analysis method an equation has been derived for tool wear and surface roughness. Based on the observation recorded, the other major conclusions drawn are:

- Coated carbide tools perform better than uncoated carbide tools during intermittent cut milling. It is observed that the effect of cutting speed is predominant factor while comparing to the feed and the depth of cut in determining the surface roughness for both coated and uncoated inserts.
- Coated tools produces better surface finish at higher cutting speeds, but the tool wear rate is very rapid after a certain limit. Dominant tool wear is at flank face and the abrasion is the wear type.
- With an increase in cutting speed the frequency of interruptions also gets increased. This leads to high tool wear rate and poor surface finish.
- The entry and exit of the tool, and the time between the entry and exit of the tool are critical factors to decide the tool/chip interface.
- Uncoated inserts performs better at moderate cutting speeds comparing to coated inserts, but at higher cutting speeds the tool experienced maximum flank wear. At lower cutting speeds, the surface roughness is high.
- The minimum wear rate was observed at lower feed rates and moderate cutting speeds. Ra values on work piece surface subjected to machining by uncoated and coated tools were in range of 1.10 to 0.91 microns and 1.16 to 0.93 microns respectively.
- The optimum surface roughness value while machining with coated tool was observed at 350 m/min and feed rate 372 mm/min.

References

1. Xiaobin, C.; Jun, Z.; Yonghui, Z.; and Guangming, Z. (2013). Damage mechanics analysis of failure mechanisms for ceramic cutting tools in intermittent turning. *European Journal of Mechanics A/Solids*, 37, 139-149.
2. Asier, U.; Rachid, M.S.; Ainhara, G.; and Arrazola, P.J. (2012). Machining behaviour of Ti-64 Al-4-V and Ti-5533 alloys in interrupted cutting with PVD coated cemented carbide. *Conference on High Performance Cutting,* 202-207
3. Aslantas, K.; Ucun, I.; and Cicek, A. (2012). Tool life and wear mechanism of coated and uncoated Al_2O_3/TiCN mixed ceramic tools in turning hardened alloy steel. *Wear*, 274-275, 442-451.
4. Kevin Chou, Y. (2003). Hard turning of M50 steel with different microstructures in continuous and intermittent cutting. *Wear*, 255(7-12), 1388-1394.
5. Ezugwu, E.O.; and Okeke, C.I. (2001). Tool life and wear mechanisms of TiN coated tools in an intermittent cutting operation. *Journal of Materials Processing Technology*, 116(1), 10-15.
6. Pekelharing, A.J. (1980). Cutting tool damage in interrupted cutting. *Wear*, 62(1), 37-48.

7. Armendia, M.; Garay, A.; Iriarte, L.M.; and Arrazola, P.J. (2010). Comparison of the machinabilities of Ti6Al4V and Ti metal 54M using uncoated WC–Co tools. *Journal of Materials Processing Technology*, 210, 197-203.
8. Ercan, S.; Kubilay, A.; and Adem, C. (2009). Tool wear mechanism in interrupted cutting conditions. *Materials and Manufacturing Processes*, 24(4), 476-483
9. Ghani, A.K.; and Barrow, G. (1985). Tool failure at exit by interrupted cutting. *CIRP Annals - Manufacturing Technology,* 34(1), 71-74.
10. Knotek, O.; Loffler, F.; and Kramer, G. (1996). Cutting performance of multicomponent and multilayer coatings on cemented carbides. *International Journal of Refractory Metals Hard Matter*, 14(1-3), 195-202.
11. Anselmo, E.D.; and Jose, C.F. (1999). Influence of the relative positions of tool and workpiece on tool life, tool wear and surface finish in the face milling process. *Wear*, 232(1), 67-75
12. Bonifacio, M.E.R.; and Diniz, A.E. (1994). Correlating tool wear, too life, surface roughness and tool vibration in finish turning with coated carbide tools. *Wear*, 173(1-2), 137-144.