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The Effects of Cutting Speed and Feed Rate on Bue-Bul Formation, Cutting Forces and Surface Roughness When Machining Aa6351 (T6) Alloy

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In this paper, the effects of machining parameters such as cutting speed and feed rate on BUE, BUL, main cutting force and surface roughness were experimentally investigated. Optimal and critical cutting parameters were determined. It was found that the cutting speed must be selected above 400-500 m/min in order to prevent BUE and BUL formation when machining of AA6351 (T6) alloy with uncoated carbide inserts. The results of this study show that the most important parameter affecting main cutting force and surface roughness is feed rate. As a result of this study, optimum cutting force and optimum feed rate were found in order to minimize surface roughness of the work piece.

Keywords: machining, built-up edge (BUE), built-up layer (BUL), cutting forces, surface roughness

0 INTRODUCTION

Turning operations constitute major portion of machining processes. Although most of the cutting processes are oblique cutting, two different cutting processes such as orthogonal and oblique cutting exist in metal cutting operations. However, since cutting mechanic behavior is two dimensional, generally orthogonal cutting method is used for the determination of the effects of machining parameters [1] to [3]. In addition to mechanical properties of work piece; other parameters such as tool rigidity, cutting speed, feed rate, depth of cut and tool geometry are also important factors for the determination of ideal machinability behaviors [4] to [6].

Aluminum alloys have been used for many years in the aviation industry. AA6351 alloy whose main alloy elements are Mg and Si, is one of the most important alloy among 6xxx series and has a natural aging capability. Strength and hardness of AA6351 alloy can be increased by heat treatment [4],[7] and [8].

Generally AA6351 (T6) alloy is machined by metal removing processes. When aluminum alloys are machined at low cutting speeds, BUE formation occurs on the rake face of the cutting tool, causing surface roughness (*Ra*) to increase [4],[9] and [10]. Due to low frictional forces on the tool rake face at high cutting speeds, increasing the cutting speed causes the cutting forces to decrease. This case results in a general elimination of BUE formation causing to improve surface roughness of the work piece [11]. Sometimes, BUE formation positively affects the surface roughness of the work piece, since BUE formation increases tool nose radius [12].

In this paper, the effects of machining parameters namely cutting speed (V_C) and feed rate (f) on BUE, BUL, main cutting force (F_C) and surface roughness (Ra) were investigated. Analysis of Variance (ANOVA) of these machining parameters was carried out; and optimal and critical cutting parameters were determined. AA6351 aluminium alloy having T6 heat treatment was machined with uncoated carbide tools using CNC turning machine under dry cutting conditions. Four different cutting speeds (200 m/min, 300 m/min, 400 m/min, 500 m/min), five different feed rates (0.10 mm/rev, 0.15 mm/rev, 0.20 mm/rev, 0.25 mm/rev, 0.30 mm/rev) and a constant depth of cut were selected.

1 MATERIALS AND METHOD

1.1. Material

In this experimental study, the effects of machining parameters on BUE-BUL formation, main cutting force and average surface roughness were investigated and a correlation between these parameters was determined. Cutting speed and feed rate were used as machining parameters.

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Test specimens used for the experiments were heat treated (T6) AA6351 aluminum alloy having 80 mm diameter and 500 mm length. Chemical composition and mechanical properties of the test specimens are shown in Table 1.

Brinell hardness number (BHN) of the work piece material used in the experiments was 102 BHN. The hardness values of the specimens were measured by means of a “Reicherter Brinell” hardness measuring device. Fine machined test specimens having 10 mm depth were prepared for the measurements. The test specimens were measured from outside through the center for 10 times and average measured value was used.

1.2. Machining Parameters, Cutting Tool and Tool Holder

Turning experiments were carried out at 20±1ºC ambient temperature using changeable carbide inserts having CCGT 120404FN-ALU geometry and K10 quality degree. Rake angle and clearance angles of the cutting tools were 7° and 5°, respectively. The tool holder used for the tests was CSRNR 2525 M12 having 90° approaching angle and agreeable to ISO 5608. Cutting parameters used for the experiments are shown in Table 2. Four different cutting speeds (200 m/min, 300 m/min, 400 m/min, 500 m/min), five different feed rates suggested by ISO 3685 (0.10 mm/rev, 0.15 mm/rev, 0.20 mm/rev, 0.25 mm/rev, 0.30 mm/rev) and 1.5 mm constant depth of cut were selected. A total of 20 experiments according to cutting parameters and machining levels shown in Table 2 were conducted. All turning tests were carried out under continuous dry cutting conditions.

1.3. Machine Tool and Measuring Equipment

All the tests were done with a “JOHNFORD T35” industrial type CNC turning machine having 10 KW power and revolving capability of 50-3500 rev/min. Kistler 9257B dynamometer was used to measure all cutting forces (F_C, F_f, F_p), where F_C, was the main cutting force, F_f, was the feed force and F_p, was the ploughing force.

MAHR-Perthometer M1 measuring equipment was used to measure surface roughness of the work piece material. All of the tests achieved were repeated three times in order to guarantee its precision. In order to measure surface roughness, cut-off length and sampling length were assumed to be 0.8 mm and 5.6 mm, respectively. Finally, after each turning test, the tools were further observed in a JEOL-JSM 6060 scanning electron microscope (SEM).

Table 1. *Chemical and mechanical properties of AA6351 alloy*

a) Chemical composition (% weight)

Si	Fe	Cu	Mn	Mg	Zn	Al
1,03	0,237	0,0723	0,584	0,665	0,003	Balance

b) Mechanical properties

Density (x1000 kg/m^3)	Elastic modulus GPa	Tensile Strength MPa	Elongation %	Hardness BHN
2.7	75	250	20	102

Table 2. *Cutting parameters used for the tests*

Level	Cutting speed V_C (m/min)	Feed rate f (mm/rev)	Depth of cut ap (mm)	Cutting Tool	Tool Holder
1	200	0.10	0.15	Uncoated Carbide CCGT 120404FN-ALU	CSRNR 2525 M125
2	300	0.15			
3	400	0.20			
4	500	0.25			
5		0.30			

The experimental results were analyzed with analysis of variance (ANOVA), which was used for identifying the factors significantly affecting the performance measures namely main cutting force and surface roughness.

2 RESULTS AND DISCUSSION

2.1 BUE and BUL Formation

Generally, tool life is determined by tool wear in machining processes. It can be observed from past studies that the wear mechanism which operates in the widest range of cutting temperatures is the adhesion mechanism [2]. Usually, adhesion wear occurs by the direct transfer of tool particles to the metallic chips. These particles adhered to the cutting tool face during machining process are mechanically unstable and, thus, they can be removed from the tool surface by the action of the high strength cutting forces that are produced. The work piece material adheres to the rake face of the tool in two different forms. The first and most known one involves the formation of a Built-up Edge (BUE) which is the adhesion of the work piece material to the cutting edge of the tool. In the second one, the material transferred is poured to wider areas on the rake face of the tool, giving rise to the so-called Built-up Layer (BUL) [2]. Generally, this BUL formation is seen during the machining of ductile materials. BUE and BUL regions can be clearly seen in Fig. 1.

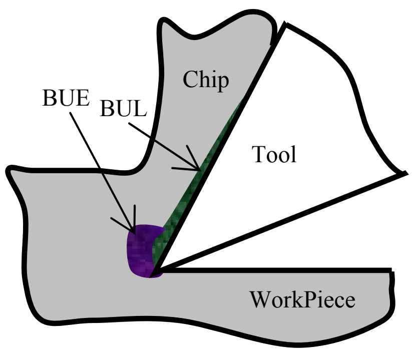


Fig. 1. *Schematic image of cutting tool with BUE and BUL*

The cutting tool is gradually worn since BUE formation is repeated periodically during metal cutting. It is known that a strong adhesion exists during machining of aluminum alloys [12]. Therefore, BUE and BUL formations must be taken into consideration when machining these aluminum alloys.

In this part of the study, four different cutting speeds were used in order to obtain the effects of cutting speed on BUE and BUL formation, then, SEM images of BUE-BUL formations were evaluated. Since the highest BUE and BUL formation was observed to SEM Image of BUE and BUL formed on uncoated insert surface at 200 m/min and 0.30 mm/rev is shown in Fig. 2. occur at the feed rate of 0.3 mm/rev, this rate was assumed to be the constant feed rate.

It is observed from this figure that, a metal accumulation on the tool surface is associated with the BUL formation and on tool edge with the BUE. It can also be seen from Fig.2 that the major part of BUE formation occurs at the tool main cutting edge and at the region that chip contacts with the air from tool nose through tool holder. This case is connected with the temperature at the second deformation region which is called tool-chip interface. Temperature of tool-chip interface decreases as moving away from tool nose through tool holder [13]. Test results showed that lesser amount of BUE was formed close to tool nose. This case can be attributed to less temperature at this region then that of max BUE region. Past studies claimed that BUE formation caused tool rake angle to increase [14] to [16]. The experimental results of this study also agree with the results of past studies.

BUE and BUL formation regions on tool surface at various cutting speeds (300 m/min, 400 m/min and 500 m/min) are depicted in Figs. 3 to 5, respectively.

From the Figs. 2 to 3, BUE formation can bee seen at tool nose region and main cutting edge. Moreover, comparison of Fig. 2. with Fig. 3. shows that larger cutting speeds have a favorable effect on reduction of BUE-BUL formation. Increasing the cutting speed from 300 to 400 m/min, BUE-BUL reduction can be seen more clearly.

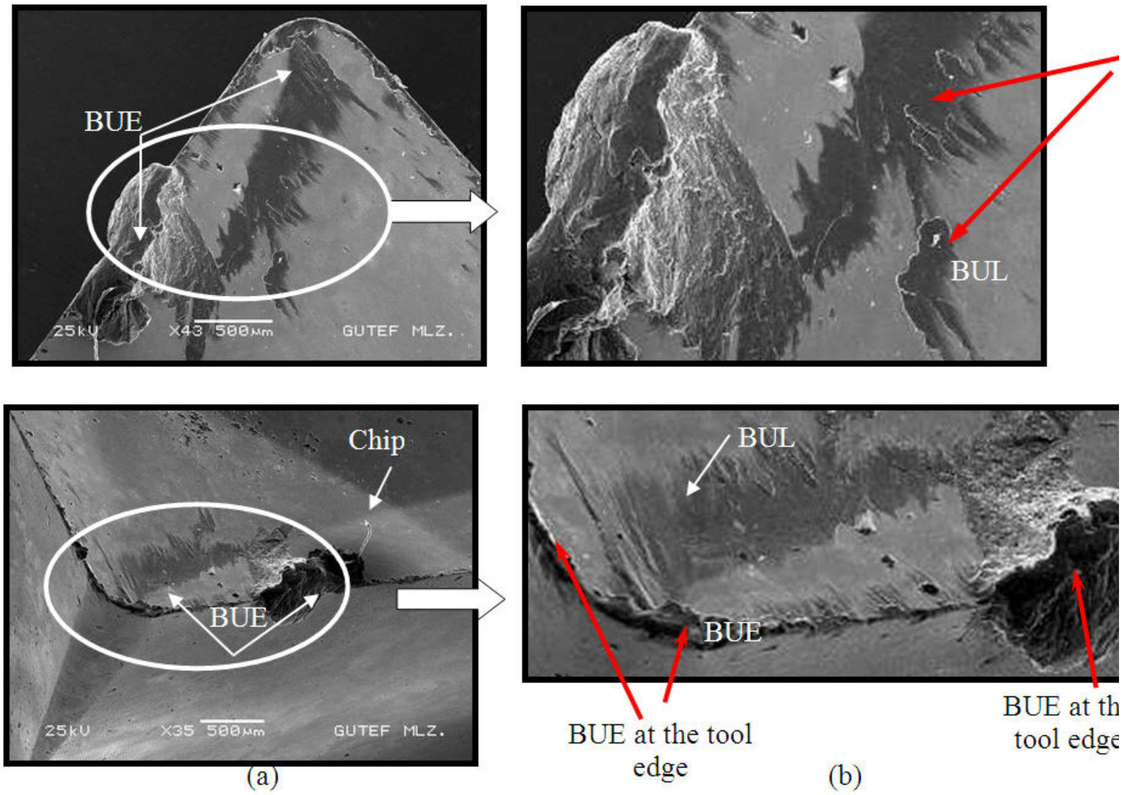


Fig. 2. *SEM Image of BUE and BUL formed on uncoated insert surface at 200 m/min and 0.30 mm/rev. a) SEM image of tool rake face b) 3D SEM image*

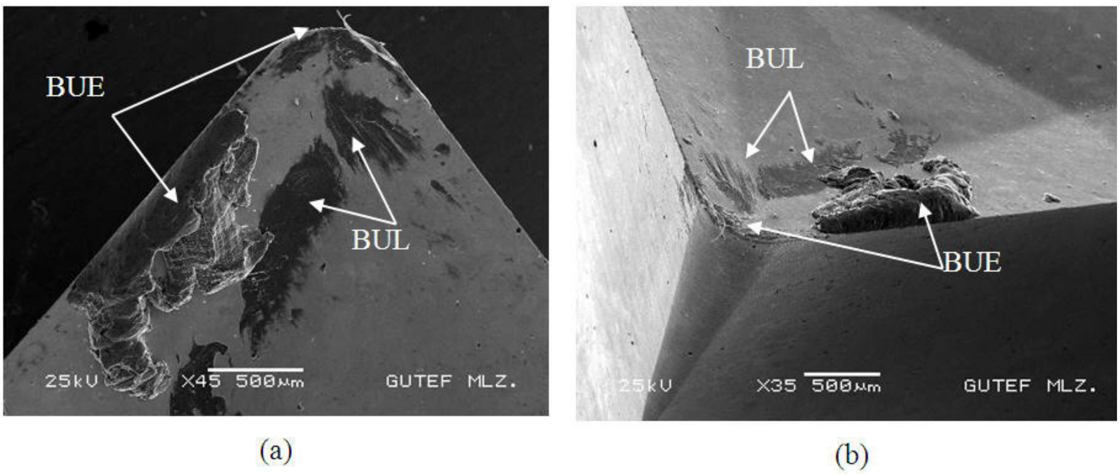


Fig. 3. *SEM Image of BUE and BUL formed on uncoated insert surface at 300 m/min and 0.30 mm/rev. a) Tool rake face x45 magnification b) 3D SEM image*

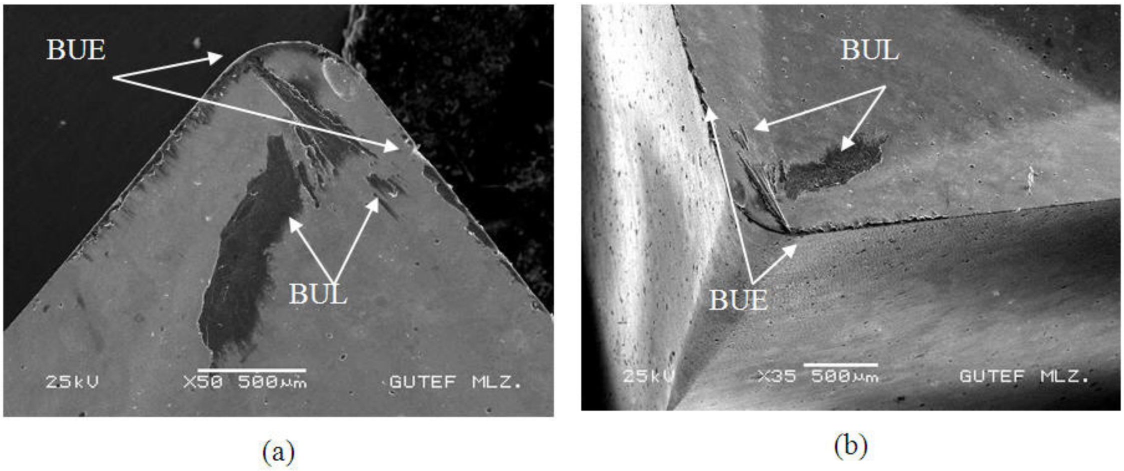


Fig. 4. *SEM Image of BUE and BUL formed on uncoated insert surface at 400 m/min and 0.30 mm/rev. a) Tool rake face x50 magnification b) 3D SEM image*

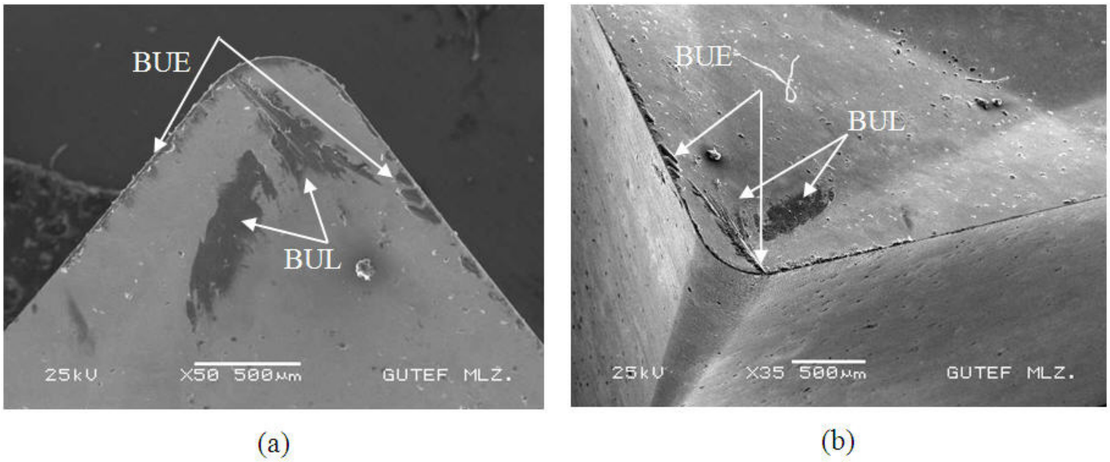


Fig. 5. *SEM Image of BUE and BUL formed on uncoated insert surface at 500 m/min and 0.30 mm/rev. a) Tool rake face x50 magnification b) 3D SEM image*

This is caused by temperature increase at second deformation zone since temperature at the second deformation zone increases with cutting speed [8]. Fig. 5 shows the BUE-BUL formation at 500 m/min. Comparison of this figure with Fig. 4 shows a weak increase in BUE-BUL. Test results show that lower cutting speeds (200m/min and 300 m/min) cause greater BUE-BUL formation on tool surface when machining AA6351 alloys. It can be concluded from these results that 400 -500 m/min or higher cutting speeds must be selected in order to prevent BUE-BUL formation.

2.2 Cutting Forces and Surface Roughness

2.2.1 Cutting Forces

The effects of cutting parameters on main cutting force were evaluated in this part of the study. Main cutting force and surface roughness values determined from the experiments depending on cutting parameters namely cutting speed (V_C) and surface roughness (Ra) are shown in Table 3.

The experimental results were analyzed with analysis of variance (ANOVA), which is used for identifying the factors significantly affecting the performance measures.

Table 3. *Main cutting force (F_C) and average surface roughness (Ra) values depending on cutting speed (V_C) and surface roughness (Ra)*

Test No	Factors		Performance measures	
	V_C m/min	f mm/rev	F_c N	Ra µm
1	200	0.10	113	0.80
2	200	0.15	163	1.19
3	200	0.20	203	1.45
4	200	0.25	303	2.13
5	200	0.30	326	4.97
6	300	0.10	132	1.19
7	300	0.15	182	1.85
8	300	0.20	264	3.25
9	300	0.25	290	4.42
10	300	0.30	343	5.47
11	400	0.10	130	1.54
12	400	0.15	177	2.43
13	400	0.20	226	3.43
14	400	0.25	276	4.71
15	400	0.30	326	5.98
16	500	0.10	118	0.70
17	500	0.15	165	1.08
18	500	0.20	214	2.07
19	500	0.25	265	3.42
20	500	0.30	316	5.32

The results of the ANOVA with the cutting force are shown in Table 4. This statistical analysis was performed for a confidence level of 95%. *P*-values shown in Table 4 are the realized significance levels, associated with the *F*-tests for each source of variation. The sources with a *P*-value less than 0.10 are considered to have a statistically significant contribution to the performance measures [17]. Moreover, the last columns of the Table 4 shows the percent contribution of each source to the total variation indicating the degree of influence on the result. Table 4 shows that the only significant factor for the cutting force F_C is feed rate *f*, which explains 96.6% of the total variation. It can be concluded from Table 4 that cutting speed V_C having 1.73% significance level does not have a significant contribution to total variation. According to test results, minimum cutting force considering feed rate and cutting speed was determined at 0.10 mm/rev and 500 m/min, respectively.

Main cutting forces depending on cutting speed and feed rate determined from experiments are depicted in Fig. 6. Earlier studies have shown that as cutting speed is made larger, the cutting forces become smaller [1], [5] and [13]. However, the results of this figure indicate that lower cutting speeds (200 m/min) give lower cutting forces up to a certain cutting speed (300 m/min). It is considered that high temperature at the flow zone and decreasing surface area are the reasons of this case. Reduction amount in cutting forces depends on work piece material, working conditions and cutting speed ranges. Fig. 6 indicates that the relationship between cutting forces and cutting speed is inversely proportional after 300 m/min. BUE and BUL formations cause the tool rake angle to increase and thus, the results of past studies indicate that increasing the tool rake angle improve the cutting stability and decreases cutting forces [4], [5] and [15]. Experimental results agree with these results. Therefore, BUE and BUL formations are considered to be responsible for this inverse relationship between cutting speed and cutting force, Figs. 2. to 4. Increasing cutting speed for 66.6% caused cutting force to decrease for 11.15% according to the test results. Maximum cutting force value (343 N) was determined at 300 m/min cutting speed and 0.30 mm/rev when machining AA6351 alloy while minimum cutting force was determined at 200 m/min and 0.10 mm/rev. According to feed rate, minimum and maximum main cutting forces were observed at 0.30 mm/rev and 0.10 mm/rev, respectively.

The results of the experiments conducted with five different feed rates indicated that higher feed rates caused higher cutting forces. For example, according to the test results, increasing the feed rate for 200% resulted in a 165.8% increase in cutting forces. It is suggested that the feed rate must be decreased in order to decrease cutting forces [13].

Table 4. *Analysis of variance (ANOVA) for main cutting force*

Source of Variance	SS	df	Variance	F- Value	P- Value	C (%)
A (VC, m/min)	1947.6	3	649.2	4.16	0.031	1.73
B (f, m/min)	108634.8	4	27158.7	173.87	0	96.60
A · B	1874.4	12	156.2			1.67
Error	0	0	0			
Total	112456.0	19				100

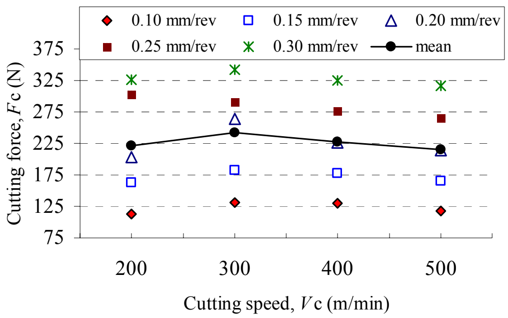
SS: sum of squeres , df: degree of freedom , C: percent contribution

2.2.2. Surface roughness

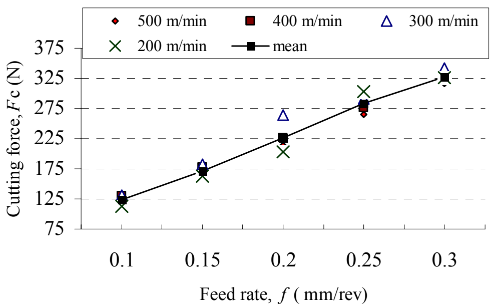
The surface roughness values determined from experiments when machining AA6351 alloy are shown in Table 3. The effects of cutting speed and feed rate on surface roughness were investigated in this part. The experimental results were analyzed with ANOVA and these results with the surface roughness are shown in Tables 5.

Table 5 shows that the only significant factor for surface roughness Ra is feed rate f, which explains 84.4% of the total variation. It can be concluded from Table 5 that cutting speed V_C having 12.2% significance level has less contribution to total variation then that of feed rate. According to test results, minimum surface roughness considering cutting speed and feed rate was determined at 200 m/min and 0.10 mm/rev, respectively. The test results show that maximum surface roughness (5.98 µm) was obtained at 400 m/min cutting speed and 0.30 mm/rev feed rate while minimum surface roughness (0.70 µm) was obtained at 500 m/min cutting speed and 0.10 mm/rev feed rate, Table 2. Detailed average surface roughness values versus cutting speed and feed rate are depicted in Fig. 7.

Producing a better surface finish at higher cutting speed is not something unusual in metal cutting, but the conventional explanations are usually related to BUE [17]. That is, the formation of a built-up-edge is favored in a certain range of cutting speed. By increasing cutting speed beyond this region, BUE will be eliminated and as a result the surface finish will improve [17]. The experimental results show that this cutting speed is above 500 m/min.



(a)



(b)

Fig. 6. *Cutting forces using uncoated carbide tools*
a) Cutting forces vs cutting speed
b) Cutting forces vs feed rate.

Table 5. *Analysis of variance (ANOVA) for surface roughness (Ra)*

Source of Variance	SS	df	Variance	F- Value	P- Value	C (%)
A (VC, m/min)	6.990	3	2.330	14.34	0.0003	12.2
B (f, m/min)	48.503	4	12.126	74.64	0	84.4
A · B	1.949	12	0.162			3.4
Error	0	0	0			0
Total	57.443	19				100

SS: sum of squeres , df: degree of freedom , C: percent contribution.

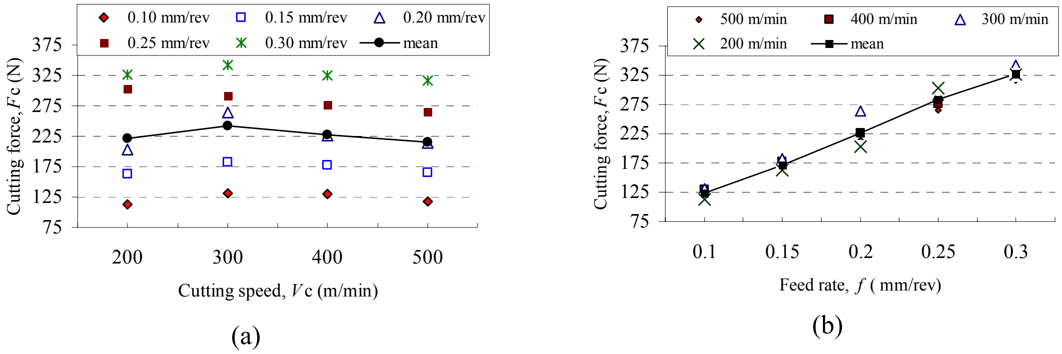


Fig. 7. *Surface roughness values using uncoated carbide tools*
a) Surface roughness vs cutting speed
b) Surface roughness vs feed rate

It can be concluded from Fig. 7 that depending on the cutting speed, minimum surface roughness was obtained at 200 m/min. Interestingly, when the cutting speed was increased to 300 m/min, surface roughness also increased. It is considered that larger BUE formations existing on the cutting tool at lower cutting speeds (200 m/min) caused the tool geometry to change as seen in Fig. 2. Therefore, cutting tool geometry was effected by cutting speed depending on BUE and BUL formation. It was observed from experiment results that BUE formations increased the tool nose radius causing to improve surface roughness. These results agree with some earlier studies [12]. Since less BUE formation exists at the cutting speed of 400 m/min, maximum surface roughness was determined at this cutting speed. This case can be attributed to a small mount of BUE formation on tool surface (Fig. 3, initial BUE formation). Previous studies claimed that surface roughness shows a decrease at higher cutting speeds [5], [10] and [18] to [20]. In agreement with the earlier studies [5], [10], [13] and [18], in the present study, surface roughness gradually decreases after 400 m/min as the cutting speed increases as shown in Fig. 7. The possible reasons of this case can be explained as high temperature, BUE elimination and high deformation velocity [4] and [16].

Test results show that the surface roughness increases as feed rate increases (Fig. 7). Depending on the feed rate, minimum surface roughness (1.06 µm) was obtained at 0.10 mm/rev while maximum roughness (5.43 µm) was obtained at 0.30 mm/rev. Surface roughness showed 412.2% increase when increasing feed rate about 200%. It can be concluded that feed rate must be reduced in order to improve surface quality. Although roughness is affected by feed rate, the trend is less significant for the tools with large nose radius. A recommendation can therefore be made to the tool users that if the inserts of 1 mm nose radii are used, feed rates as large as 0.3 mm/rev may be used in order to promote productivity when finishing without significant deterioration in surface roughness [18].

3 CONCLUSIONS

The effects of machining parameters namely cutting speed and feed rate on BUE, BUL, main cutting force and surface roughness were both experimentally and statistically investigated.

BUE and BUL formations caused the tool nose radius and effective rake angle of cutting tool to increase. BUE was formed at especially low and middle cutting speeds. BUE-BUL formations positively affected the cutting forces and surface roughness at lower cutting speeds. Higher cutting speeds caused BUE formation to reduce improving machined surface quality.

It was observed from test results that the most important parameter affecting main cutting force FC and surface roughness was the feed rate. Significance level of these effects was 96.6% for main cutting force and 84.4% for surface roughness. Contribution of cutting speed V_C to total variation was found be more important for surface roughness.

BUE-BUL formations on tool surface at the cutting speeds of 200 and 300 m/min were found to be larger than those of 400 and 500 m/min. Maximum BUE-BUL formation was observed at 200 m/min cutting speed. It was concluded that cutting speed must be selected above 400 - 500 m/min cutting speed in order to prevent BUE and BUL formation.

According to feed rate and cutting speed, maximum cutting force value (343 N) was determined at 300 m/min cutting speed and 0.30 mm/rev when machining AA6351 alloy while minimum cutting force was determined at 200 m/min and 0.10 mm/rev.

In order to minimize surface roughness, optimum cutting speed and feed rate were found to be 500 m/min and 0.10 mm/rev, respectively. The test results showed that maximum surface roughness (5.98 µm) was obtained at 400 m/min cutting speed and 0.30 mm/rev feed rate while minimum surface roughness (0.70 µm) was obtained at 500 m/min cutting speed and 0.10 mm/rev feed rate.

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