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The Effects of Machining Parameters on Cutting Forces, Surface Roughness, Built-Up Edge (BUE) and Built-Up Layer (BUL) During Machining AA2014 (T4) Alloy

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Tool wear, formed in cutting tool during machining processes, affects the surface roughness of the work piece, cutting forces and other output parameters. The effects of the machining parameters cutting speed (V_c) and the feed rate (f) on built-up edge (BUE), built-up layer (BUL), main cutting force (F_c), and surface roughness (R_a) is investigated in this study. The effects of the cutting parameters on cutting force and surface roughness has been examined by the use of Variance Analysis (ANOVA); and their optimum and critical cutting parameters were determined accordingly. AA2014 aluminum alloy was machined with uncoated carbide tools using Computer Numerical Control (CNC) turning machine under dry cutting conditions. Four different cutting speeds (200 m/min, 300 m/min, 400 m/min, and 500 m/min), five different feed rates (0.10 mm/rev, 0.15 mm/rev, 0.20 mm/rev, 0.25 mm/rev, and 0.30 mm/rev) and a constant depth of cut were selected as the machining parameters. BUE and BUL in the cutting tool were formed most at cutting speed 200 m/min and feed rate 0.30 mm/rev. The lowest cutting force was determined as 137 N at cutting speed 500 m/min and feed rate 0.10 mm/rev. The lowest average surface roughness, however, was determined as 0.93 µm at 500 m/min cutting speed and feed rate 0.10 mm/rev.

Keywords: AA2014 alloy, built-up edge (BUE), built-up layer (BUL), cutting force, surface roughness, machining

0 INTRODUCTION

Al-Cu alloys are one of the indispensable materials of the current industry because of their superior properties over other metal alloys. They can also undergo aging heat treatment which engenders them to be widely used in the industry [1] to [6].

Two different types of cutting methods (orthogonal-oblique) are implemented in the machining processes. Although most of the cutting processes are oblique, orthogonal cutting techniques are used in experiments to determine the effects of the parameters since mechanical behavior of the work piece is two-dimensional [7 to 9]. Tool rigidity, cutting speed, feed rate, depth of cut and tool geometry are also important factors for the determining of ideal machinability behaviors in addition to mechanical properties of a work piece [10] to [13].

AA2014 alloy, as an Al-Cu alloy, is generally shaped by using machining methods. BUE formation, occurring when aluminum alloys are machined at low cutting speeds, causes surface roughness (R_a) to increase [14] and [15]. Increasing the cutting speed during machining causes the cutting forces to decrease due to low frictional forces on the tool rake face at high cutting speeds [7], [8] and [11]; and consequently resulting an elimination of BUE formation improving surface roughness of the work piece [16]. BUE formation sometimes positively affects the surface roughness of the work piece since BUE formation increases tool nose radius [16].

In this study, AA2014 (T4) with uncoated carbide tools was implemented by using five feed rates and four different cutting speeds. AA2014 aluminum alloy was then machined with orthogonal cutting method with a constant depth of cut. The effects of cutting and feed rates on the main cutting force, average surface roughness, and BUE and BUL formations were researched in the study.

1 MATERIALS AND METHOD

1.1 Materials

The effects of machining parameters on the main cutting force, average surface roughness,

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and BUE-BUL formation were investigated and a correlation between these parameters was determined in this experimental study. Cutting speed and feed rate were used as machining parameters.

Test specimens, prepared by using the AA2014 aluminum alloy with 80 mm diameter and 500 mm length, were used for the experiments in this study. Chemical compositions of the test specimens can be seen in Table 1.

AA2014 (T4) alloy was measured to have 415 N/mm^2 tensile strength and 98 BHN ("Reicherter Brinell" Hardness) values. Hardness value measurements were implemented by using 10 mm depth test specimens in "Reicherter Brinell" hardness measuring device. 5 mm ball points and 125 kg weight were used for hardness measurement experiments. Average value of 10 trial measurements, from outside through the center, was used when material hardness values were determined.

1.2 Machining Parameters, Cutting Tool and Tool Holder

The tests were carried out at 20±1 ºC ambient temperature using changeable carbide inserts which have CCGT 120404FN-ALU geometry and K10 quality degree. CSRNR 2525 M12, the tool holder used for these tests, was appropriate to ISO 5608 and had a 90° approaching angle. Rake angle and clearance angles of the cutting tools were 7 and 5°, respectively. Cutting parameters used for the experiments and their levels can be seen in Table 2. Four different cutting speeds (200, 300, 400, and 500 m/min), five different feed rates advised by ISO 3685 (0.1, 0.15, 0.2, 0.25 and 0.30 mm/rev), and 1.5 mm constant depth of cut were selected for all cutting speeds. A total of 20 experiments were conducted according to cutting parameters and machining levels shown in Table 2.

1.3 Machine Tool and Measuring Equipment

All the machining processes were done with a "JOHNFORD T35" industrial type Computer Numerical Control (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). F_c represented the main cutting force during tests whereas F_f was the feed force and F_p was the ploughing force. MAHR-Perthometer M1 measuring device was used to measure surface roughness of the work piece material. These measurements were repeated three times for its precision. Cut-off length and sampling length assumed in order to measure surface roughness were 0.8 and 5.6 mm, respectively. Finally, JEOL-JSM 6060 scanning electron microscope (SEM) was used for the analysis of BUE and BUL formed on the cutting tool.

1.4 Statistical Analysis

A multiple analysis of variance (ANOVA) was used for identifying the factors significantly affecting the performance measures of main cutting force and surface roughness during machining AA2014 (T4) alloy. Duncan test was further applied to the findings with changes to find the significance level of the changes.

Table 1. *Chemical compositions of the test specimens (% weight)*

Si	Fe	Cu	Mn	Mg	Zn	Al
0.672	0.512	4.33	0.564	0.401	0.168	Balance

Table 2. *Cutting parameters used for the tests*

Level	Cutting speed V_C [m/min]	Feed rate *f* [mm/rev]	Depth of cut [mm]	Cutting Tool, Grade, Form	Tool Holder
1	200	0.10, 0.15, 0.20, 0.25, 0.30	1.5	Uncoated Carbide K10 CCGT 120404FN-ALU	CSRNR 2525 M12
2	300				
3	400				
4	500				

2 RESULTS AND DISCUSSION

2.1 Formation of BUE and BUL

Tool life is generally determined by tool wear in machining processes. Adhesion wear occurs by the detachment of tool particles from the cutting tools with the help of metallic chips. The formation of BUE and BUL on the cutting tool is caused by tool-tool chip interface temperature and extreme pressure. The work piece material adheres/emanates to the rake face of the cutting tool in two different forms. The first method involves the formation known as Built-Up Edge (BUE); which is the emanation of the work piece material to the cutting edge of the tool. In the second method, known as the formation of Built-Up Layer (BUL), the material is adhered by pouring to wider areas on the rake face of the tool. This second type formation is frequently observed in machining ductile materials. BUE and BUL regions can be seen clearly in Fig. 1.

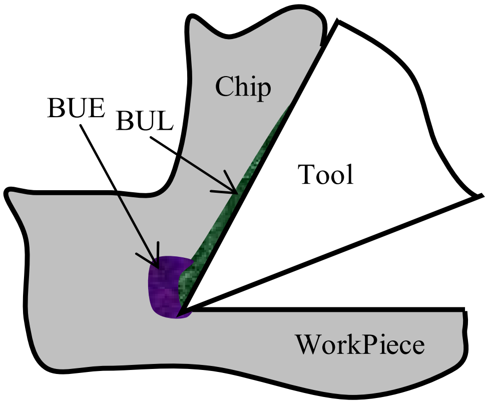


Fig. 1. *Schematic image of cutting tool with BUE and BUL [18]*

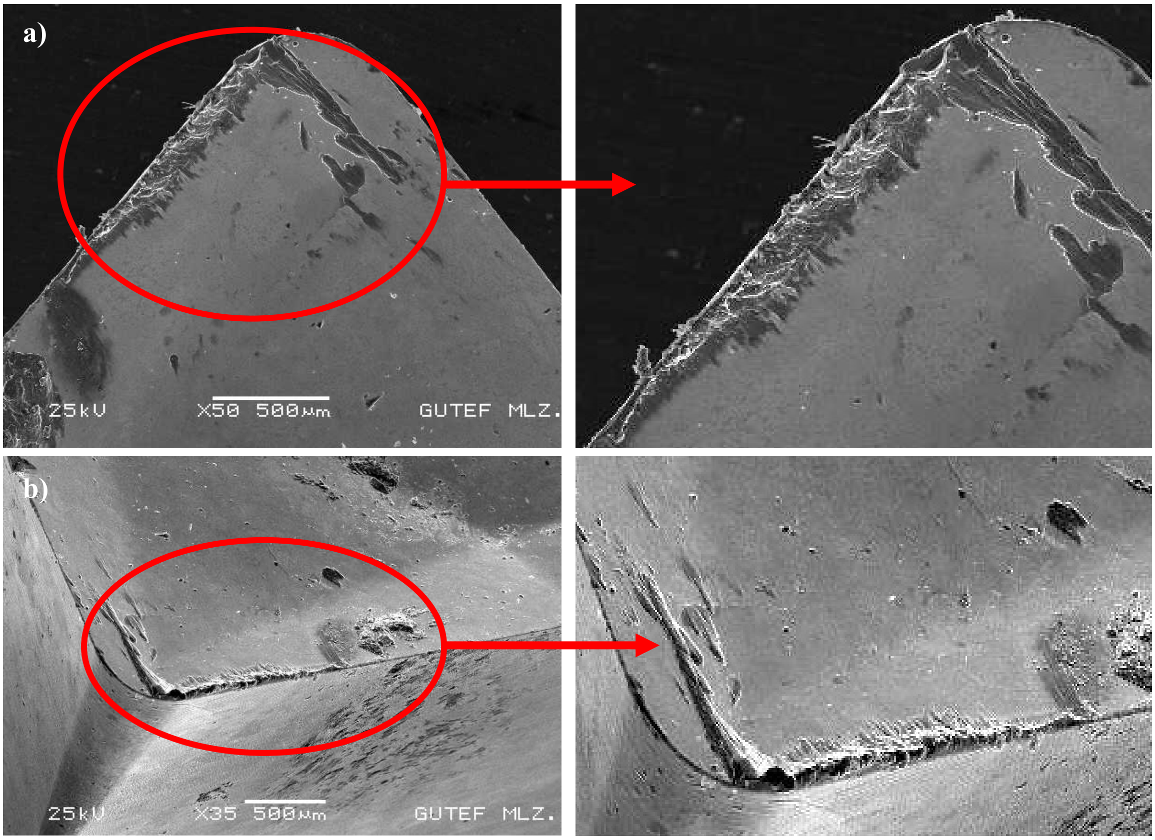


Fig. 2. *SEM image of AA2014 (T4) alloy's BUE and BUL formation on uncoated sementite carbide surface at 200 m/min and 0.30 mm/rev: a) SEM image of the tool rake face, b) 3D SEM image of the cutting tool*

A piece from the cutting tool also detaches from the tool with the detachment of the gradually hardened BUE formed in the cutting tool and therefore breaks occur via adhesion wear mechanisms. Cutting edge gradually wears since the formation of BUE occurs periodically during machining. A strong conjunction between the work piece material and cutting tool is known to occur during the machining aluminum alloys [17]. Accordingly, BUE and BUL formation should certainly be considered during the machining of such materials.

Four different cutting speeds and five different feed rates were used to determine the effects of cutting speed on BUE and BUL formation in this part of the study. SEM images of BUE and BUL formations at 0.30 mm/rev feed rate was evaluated, since the highest BUE and BUL formation was observed to be occurring at this rate.

SEM photograph depicting BUE and BUL formation of AA2014 aluminum alloy on uncoated sementite carbide cutting tool at 200 m/min and 0.30 mm/rev can be seen in Fig. 2. BUL formation was observed to be accumulated on the tool surface whereas BUE was formed on main and collateral cutting edges of the tool by accumulating on the tool rake face.

The major part of BUE formation was observed at the tool main cutting edge and where the chip makes contact with the air from the tool nose through the tool holder in Fig. 2. The cutting tool nose radius also increased due to BUE formation. A formation of BUE in lesser amounts near tool nose radius can be attributed to a lower temperature around the tool nose radius.

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

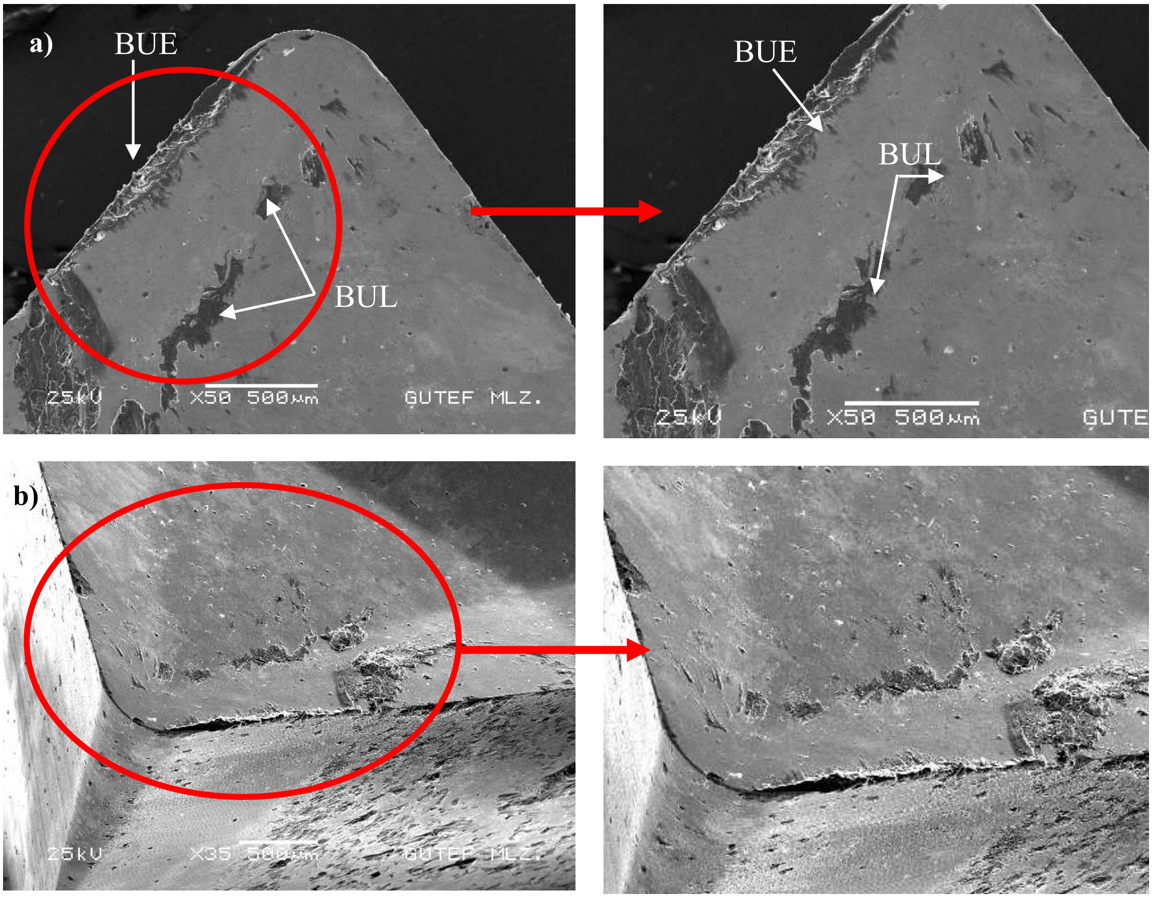


Fig. 3. *BUE and BUL image of machining AA2014 (T4) alloys at 300 m/min cutting speed and 0.30 mm/rev feed rate: a) SEM image of tool rake face, b) 3D SEM image of the cutting tool*

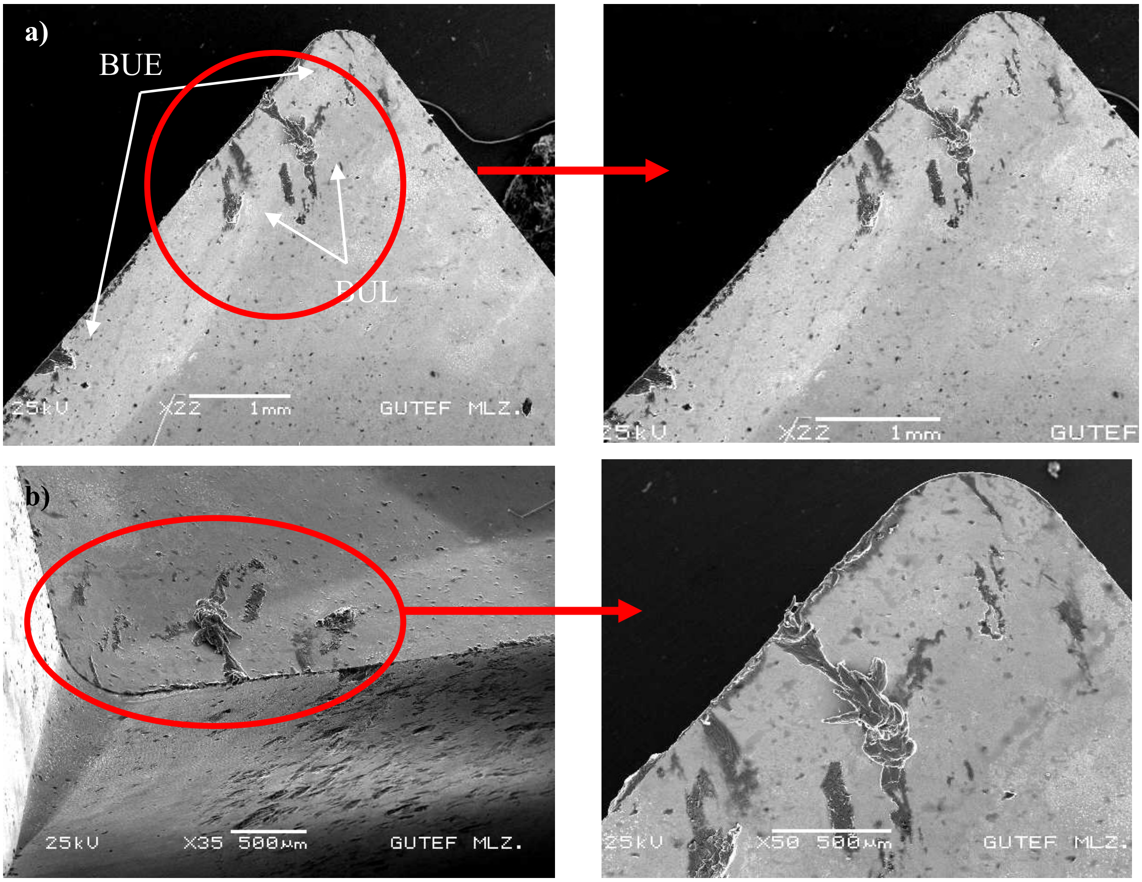


Fig. 4. *BUE and BUL image of machining AA2014 (T4) alloys at 400 m/min cutting speed and 0.30 mm/rev feed rate a) SEM image of tool rake face, b) 3D SEM image of the cutting tool*

BUE formation can be clearly observed at the tool nose radius and the main cutting edge when Figs. 2 and 3 are analyzed. Furthermore, BUE and BUL formation at 300 m/min cutting speed was observed to be smaller than the BUE and BUL formation at 200 m/min when the two figures are compared. Likewise BUE and BUL formation was observed to be decreasing when the cutting speed was increased to 400 m/min (Fig. 4). This situation can be connected to the temperature increase in the second deformation region [12] and [19]. A decrease in the formation of BUE and BUL, compared to the formation at 400 m/min cutting speed, was also observed at 500 m/min cutting speed (Fig. 5). According to the conducted tests, lower cutting speeds (200 and 300 m/min) were observed to cause formation of BUE and BUL in higher amounts during the machining of AA2014 alloy. In conclusion, 500 m/min or higher cutting speeds were determined to prevent BUE and BUL formation for the machining of AA2014 alloy.

2.2 Changes in Cutting Forces and Surface Roughness

2.2.1 Change in Cutting Forces

The main cutting force (F_c) and surface roughness (R_a) values determined from the experiments depending on cutting speed and feed rate cutting parameters, can be seen in Table 3.

The effects of cutting speed and feed rate on the main cutting force were evaluated by applying analyses of multiple variances on the determined data. Significant changes with a confidence level of 95% were determined between all the factors according to the results of the analysis of variance. The analysis of variance implemented to determine the effects of cutting speed and feed rate can be seen in Table 4.

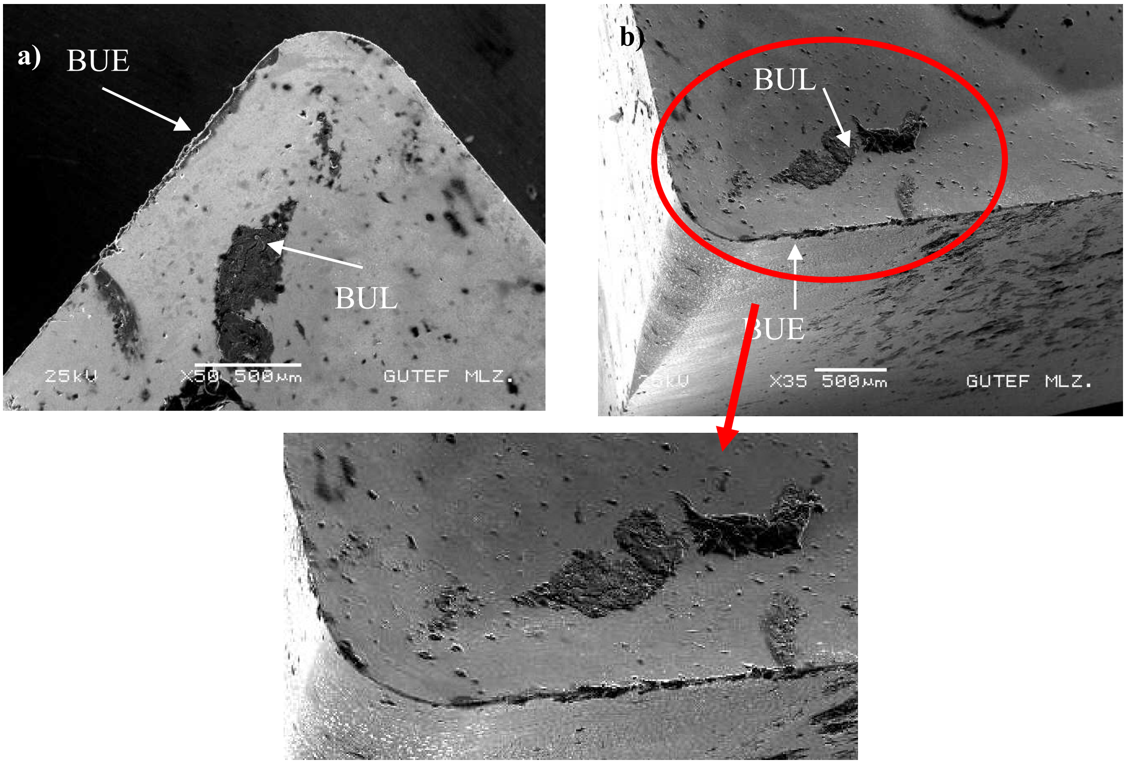
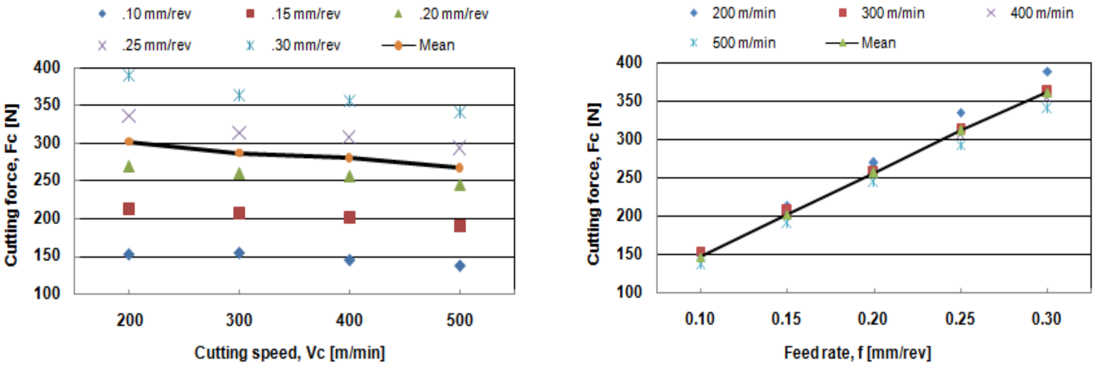


Fig. 5. *BUE and BUL image of machining AA2014 (T4) alloys at 500 m/min cutting and 0.30 mm/rev feed rate a) SEM image of tool rake face, b) 3D SEM image of the cutting tool*



a) b)

Fig. 6. *Main cutting force values for AA2014 (T4) alloy determined during machining with uncoated carbide cutting tool: a) depending on cutting speed, b) depending on feed rate*

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 [20]. The minimum main cutting force value according to the feed rate was determined at 0.10 mm/rev; and the minimum value for the cutting force regarding the cutting speed was determined at 500 m/min. A detailed graphic of the main cutting force values, obtained from the experiments, depending on cutting speed and feed rate is depicted in Fig. 6.

It was observed that lower cutting speed values decreased as the values of cutting speeds were increased from a lower cutting speed (200 m/min) to a higher cutting speed (500 m/min) as can be analyzed in the graphic in Fig. 6. Increasing the cutting speed to obtain smaller values of cutting forces is the most frequent method used in the literature [7] and [8]. High temperature at the flow zone and decreasing surface area are considered to be the reasons of this inverse proportion. The reduction amount in cutting forces can depend on work piece material, working conditions, and cutting speed ranges. A decrease in average main force values was observed depending on the increase on the tested values of cutting speeds in this study. An increase of 150% in cutting speed caused 11.67% decrease (266.75 N) while working on the lower speeds (200 m/min). Maximum cutting force value (390 N) was determined at 200 m/min cutting speed and 0.30 mm/rev feed rate when machining AA2014 alloy in this study. The minimum cutting force (137 N), on the other hand, was determined at 500 m/min cutting speed and 0.10 mm/rev feed rate.

Higher feed rates were observed to be causing higher cutting forces when the results of the experiments conducted with five different feed rates are analyzed. A direct relation between the tested feed rates and the main cutting force was determined.

Therefore, feed rate values should be decreased in order to decrease the main cutting force; as the increase in the main cutting force depending on the feed rate is an expected result [21] and [22]. An increase of 200% at 0.1 mm/rev feed rate caused 146.25% increase (362 N) in the main cutting force. The maximum cutting force value (362 N) depending on the feed rate was determined at 0.30 mm/rev. The minimum cutting force (147 N), on the other hand, was determined at 0.10 mm/rev feed rate.

2.2.2 Change in Surface Roughness

The surface roughness (R_a) values determined from experiments when machining AA2014 alloy with uncoated carbide cutting tool can be seen in Table 3. The effects of cutting speed and feed rate on surface roughness were evaluated by applying analyses of multiple variances on the determined data. The analysis of variance implemented to determine the effects of cutting speed and feed rate can be seen in Table 5. The minimum average value of surface roughness depending on the cutting speed was determined at 500 m/min whereas the minimum average value depending on the feed rate was determined at 0.10 mm/rev.

Maximum average surface roughness value (5.34 µm) was determined at 300 m/min cutting speed and 0.30 mm/rev feed rate in this experimental study. Minimum average surface roughness value (0.93 µm), on the other hand, was determined at 500 m/min cutting speed and 0.10 mm/rev feed rate (Table 3). A detailed graphic of average surface roughness values, obtained from the experiments, depending on the cutting speed and feed rate is depicted in Fig. 7.

Table 3. *Main cutting force (F_c) and average surface roughness (R_a) values depending on cutting speed (V_c) and feed rate (f)*

Test No	V_c [m/min]	f [mm/rev]	F_c [N]	R_a [µm]
1	200	0.10	152	1.15
2	200	0.15	212	1.68
3	200	0.20	270	1.81
4	200	0.25	336	3.72
5	200	0.30	390	5.19
6	300	0.10	154	1.29
7	300	0.15	207	2.31
8	300	0.20	260	2.93
9	300	0.25	313	4.10
10	300	0.30	363	5.34
11	400	0.10	145	1.10
12	400	0.15	201	1.58
13	400	0.20	255	2.37
14	400	0.25	307	3.65
15	400	0.30	355	5.14
16	500	0.10	137	.93
17	500	0.15	190	1.44
18	500	0.20	244	2.04
19	500	0.25	293	3.17
20	500	0.30	340	4.44

Table 4. *Variance analysis (ANOVA) regarding main cutting force (F_c)*

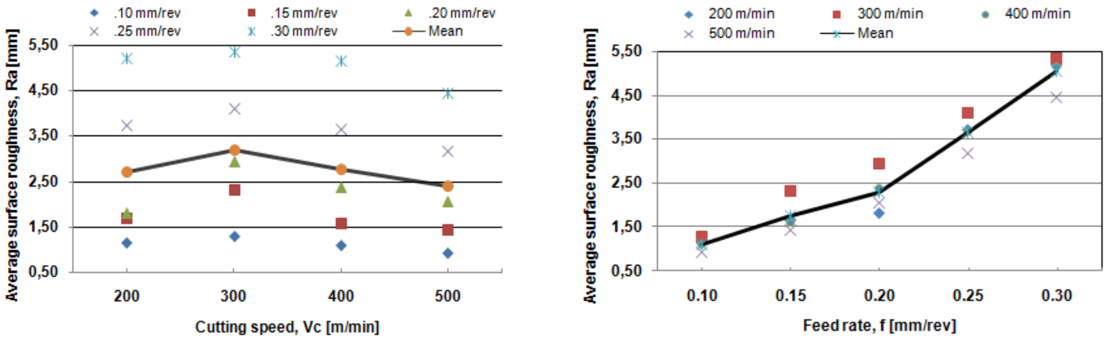
Source of Variance	Sum of Squares	Degree of Freedom	Variance	*F* Value	*P* Value
Factor A	1153620.000	4	288405.000	430204.125	.000
Factor B	25240.809	3	8413.603	12550.291	.00
A*B	5239.625	12	436.635	651.314	.00
Error	120.000	179	.670		
Total	14208780.000	199			
Adjusted Total	1189634.271	198			

Factor A; Feed rate (0.1, 0.15, 0.20, 0.25, 0.30 mm/rev)
Factor B; Cutting speed (200, 300, 400, 500 m/min)

Table 5. *Variance analysis (ANOVA) regarding the surface roughness (R_a)*

Source of Variance	Sum of Squares	Degree of Freedom	Variance	*F* Value	*P* Value
Factor A	395.491	4	98.873	1483090.500	.000
Factor B	15.867	3	5.289	79333.000	.00
A*B	5.512	12	.459	6890.500	.00
Error	1.200E-02	180	6.667E-05		
Total	1950.354	200			
Adjusted Total	416.882	199			

Factor A; Feed rate (0.1, 0.15, 0.20, 0.25, 0.30 mm/rev)
Factor B; Cutting speed (200, 300, 400, 500 m/min)



a) *b)*

Fig. 7. *Average surface roughness (R_a) values for AA2014 (T4) alloy determined during machining with uncoated carbide cutting tool: a) depending on cutting speed, b) depending on feed rate*

Minimum average surface roughness values were determined at 500 m/min cutting speed as can be seen in Fig. 7a. Average surface roughness was increased when the cutting speed was increased from 200 to 300 m/min. This was because BUE formations at 200 m/min cutting speed increased the tool nose radius causing an increase in surface roughness (Fig. 2). These results show similarity with the literature. BUE formation sometimes improves the surface roughness since it increases the tool nose radius [12] and [23]. An improvement was also observed at 400 and 500 m/min cutting speeds depending on the increase in cutting speeds. This improvement can be attributed to a simpler deformation process, easier deformation of the working piece around the cutting edge and tool nose radius, formation of flow zone (F_z) due to a higher temperature, and the prevention of BUE formation [10] and [22].

Minimum average surface roughness (1.12 µm) depending on feed rate was determined at 0.10 mm/rev feed rate. Maximum average surface roughness (5.03 µm), on the other hand, was determined at 0.30 mm/rev. A detailed graphic of average surface roughness values, obtained from the experiments, depending on feed rate is depicted in Fig. 7b.

It was observed that average surface roughness was increasing as the feed rate was increased when average surface roughness values at 0.10, 0.15, 0.20, 0.25 and 0.30 mm/rev feed rates were analyzed. An increase of 200% at 0.1 mm/rev feed rate caused 349.3% increase (5.03 µm) in the average surface roughness. A direct relation was determined between the tested feed rates and average surface roughness. Therefore, feed rate values should be decreased in order to decrease the average surface roughness as the increase in the main cutting force depending on the feed rate is an expected result [22].

3 CONCLUSION

Conclusions drawn from the results, within the testing limits defined in the aim of the study, are given below.

BUE formation on the cutting tool caused an increase in the tool nose radius on the cutting tool surface. This BUE formation at lower cutting speeds (200 m/min) positively affected the surface roughness.

BUE and BUL formed at greater amounts on the surface of the cutting tool at 200 and 300 m/min cutting speeds, whereas BUE and BUL formation was observed at lesser amounts at 400 m/min and 500 m/min cutting speeds. Maximum BUE and BUL formation occurred during the machining process at 200 m/min cutting speed.

500 m/min and higher cutting speeds were determined for the selection of cutting speed to prevent BUE and BUL formation when machining AA2014 (T4) alloy with an uncoated sementite carbide cutting tool.

The minimum cutting force depending on the cutting speed and feed rate (137 N) was determined at 500 m/min cutting speed and 0.10 mm/rev in this study. The maximum cutting force value (390 N), on the other hand, was determined at 200 m/min cutting speed and 0.30 mm/rev feed rate.

The minimum average surface roughness value (0.93 µm) was determined at 500 m/min cutting speed and 0.10 mm/rev feed rate in this experimental study. The maximum average surface roughness value (5.34 µm), on the other hand, was determined at 300 m/min cutting speed and 0.30 mm/rev feed rate.

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