Study on optimal surface property of WC-Co cutting tool for aluminium alloy cutting

Mohd Nizar 1,2, Naoya Arimatsu 1, Hiroshi Kawamitsu 1, Kazuteru Takai 1 and Masahiro Fukumoto 1
1 Department of Mechanical Engineering, Toyohashi University of Technology, 1-1, Tempaku-cho, Toyohashi, Aichi, 447-8580, Japan
2 Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, 26600 Pekan, Malaysia

E-mail: m_nizar86@yahoo.com

Abstract. The light weight property as well as high corrosion resistance of aluminium alloy has increased their demand especially in automobile industries. Aluminium alloy as a matter of fact has a low melting point and high ductility that severely adhere to the cutting tool surface and cause deterioration of chip evacuation. This problem often resulting in tools breakage. In this paper, in order to impart functions of anti-adhesion, we propose a technique by controlling the grinding marks micro texture on the tool surface by using the blast polishing treatment without any coating technologies. The results show that the tool which underwent polishing treatment reduces the cutting force as well as the aluminium adherence during the initial cutting process, and become worst as the process cutting continues. These results indicate that grinding mark texture improves the anti-adhesion by reducing the contact area during cutting and provide storage for the lubricant. In addition, too much polishing on the tool surface may remove these textures and resultantly worsen the tool performance.

1. Introduction
In recent years, demand of aluminium alloy in automobile and aerospace industries has rapidly increased. This is due to its light weight property and high corrosion resistance. However, aluminium alloy has a low melting point and high ductility. Therefore in cutting process, aluminium chips severely adhere to the surface of the cutting tool and cause deterioration of chip evacuation that increases the cutting force, often leads to tool breakage. To address this problem cutting fluid is applied to provide lubrication and also to reduce the cutting temperature which can improve tool life to some extent. Despite these advantages, the cutting fluids have been questioned lately, due to the several negative effects they cause. For example, cutting fluids may damage soil and water resources, causing serious environmental degradation when inappropriately handled. In addition, the costs related to cutting fluids represent a large amount of the total machining costs. Therefore, the cutting fluid usage reduction is desirable. Dry machining process, without the use of cutting fluids satisfies the aforementioned circumstances, however the dry machining of aluminium alloy has proven difficult due to aluminium’s adhesion to the drill. The chips severely adhere to the drill, and create obstacles for chip evacuation through the drill flutes.

The challenge is to minimize the adhesion of aluminium to the drill. In order to impart functions of anti-adhesion to the cutting tool, researchers are focusing on the tool surface modification, such as the
development of the micro texture on the tool surface using laser technology [1-3]. These textures have been successful in improving the anti-adhesion by the reduction of real contact area and storage of the lubricant. However, these micro texture implantations are time consuming and also increase the production cost.

In this study, we propose the development of the micro texture by controlling the grinding mark, which already exist on the tool surface by using the blast polishing treatment without any coating technologies. In this experiment, untreated drill are prepared together with several drills which was treated with optimal polishing parameters of the blast polishing process as it was reveal in the studies conducted by Takai et al. [4, 5]. In his studies it has been revealed that by increasing the parameter of polishing media injection speed can result to a shorter time in achieving smooth flat surface [4]. In another study it has been reveal that the polishing rate is the highest in 30 seconds polishing time zone. In addition, injection angle of 45°shows the highest surface roughness reduction rate and surface removal rate where the surface profile flattening after 30 seconds of polishing. In contrary, no profile flattening can be observed for injection angle 90° where the initial bumpy shape still remain although had been polished for 30 seconds [5].

The cutting performance of untreated and treated drill are evaluates during the drilling of aluminium alloy, ADC12 in flooded condition using external coolant. The drilling performance was assessed by measuring the thrust force generated during drilling and by measuring the cumulative mass of the adhered aluminium after the drilling process.

2. Experimental Procedure

2.1. Properties of drills
The cutting tools used for the drilling were 10.00 mm diameter uncoated WC-Co drills manufactured by OSG Corporation (NF-GDN type). A schematic representation of the WC-Co drill and its geometry are shown in figure 1.

![Figure 1. Geometry of WC-Co drill of 10.00 mm in diameter. The drill consists of two flutes surface with helix angle of 20° and point angle of 130°. The length of flute is 65 mm and the shank length is 44mm.](image1.png)

![Figure 2. Grinding mark on the untreated drill flute surface shown in white.](image2.png)

2.2. Polishing treatment condition
Figure 2 shows the grinding mark that existed on the flute surface. This mark was left by the grinding machine during the production of the drill. In order to investigate the optimum surface condition to add the anti-adhesion properties to the drill, the untreated drill and the drill treated using the blast polishing method are prepared. It is believed that the grinding mark height as well as concave and convex shape can be controlled by manipulating the parameters of this blast polishing machine. The schematic of the blast polishing treatment are shown in figure 3 and the polishing conditions are shown in table 1. Figure 3 shows the position relation of nozzle and drill under injection angle 45 °. The injection angle is changed by inclining the drill during polishing process. The injection distance is fixed to 20 mm in each injection angle of 45 ° and 90 ° condition. The drill was polished for 1 minute/flute and 3 minutes/flute
in each injection angle condition. Therefore, a total of four treated drills with different treatment condition were prepared.

![Diagram of blast polishing treatment to the drill flute surface](image)

**Figure 3.** Schematic of blast polishing treatment to the drill flute surface.

| Polishing condition | Injection speed (m/s) | Polishing time/flute (min) | Injection volume (g/s) | Injection angle (deg.) | Injection distance (mm) | Nozzle width (mm) |
|---------------------|-----------------------|----------------------------|------------------------|------------------------|-------------------------|------------------|
|                     | 59.5                  | 1                          | 36                     | 45                     | 20                      | 8                |

Table 1. Polishing treatment conditions.

The polishing media used was developed by Yamashita Works Co., Ltd [6]. This polishing media is composed of two main materials. One is the core material, Multi-Cone (made from gelatine consisting of particle size around 0.5-2.0mm which has the viscoelasticity characteristics by absorbing water and the abrasive grain. Another is Multi-Powder (consist of diamond and SiC with the particle size of 5μm, which has the role of cutting edge for the polishing media). The viscoelasticity of the Multi-Cone can be controlled by changing the water quantity to it absorbed [7]. In this study, the water content was fixed to 30% which is the recommended value by the developer. The machine used for the polishing treatment was SMAP-II type developed by Toyo Abrasive Industry Co., Ltd. As refer to the Table 1, injection speed 59.5 m/s is the highest speed that can be achieve by this blast polishing machine.

2.3. Surface topography and surface roughness measurement

Surface topography and surface profile measurement was conducted using atomic force microscope (AFM), SPM-9500J3 developed by Shimadzu Corporation. The flute surface roughness measurement was conducted using laser microscope, LEXT OLS3100 developed by Olympus Corporation Co., Ltd. Figure 4 shows the observation area and the measurement direction on the drill flute surface. The measurement direction was perpendicular to the direction of the grinding mark.
2.4. Drilling tests and thrust force measurement

The experimental setup of the drilling test is shown in figure 5. The drilling test were performed using a computer numerically controlled (CNC) machine, MB-5000HA manufactured by Okuma Corporation. The test was conducted in horizontal direction under flooded condition, as shown in figure 5. The work piece used in this experiment is aluminium alloy, ADC12. The drilling station was equipped with an external coolant system. Details of the experimental condition and lubricant are shown in Table 2. The cutting experiment was repeated two times for each drill condition to ensure that the experimental results were repeatable. The most repetitive experimental data were selected for presentation in this paper.

Table 2. Condition of drilling experiment.

| Cutting conditions | Cooling/lubricant system |
|--------------------|--------------------------|
| Cutting speed (m/min) | No. of revolution (min⁻¹) | Feed length (mm) | Feed rate (mm/rev) | Hole depth (mm) | Cutting condition | Coolant type | Product name/Manufacturer |
| 100 | 3200 | 480 | 0.15 | 28 (Blind hole) | External, Flooded | Emulsion | FGE360/Yushiro Chemical Industry Corp. |

The drilling was conducted until 100 holes and the thrust force was measured at the initial drilling test, 2nd hole and at the end of test, 100th hole. Thrust force measurement was conducted by using dynamometer sensor, Type 9272 developed by Kistler Instrument Corporation which was mounted between the jig and the work piece. Each drilling cycle requires approximately 5 s duration between the initial contact and the complete retraction of the drill bit. The average thrust force was calculated from the difference in thrust between the onsets of chip clogging to the retraction of the drill, as depicted in figure 6. The cumulative mass of the adhered aluminium was calculated after drilling 100th hole by measuring the weight of the drill before and after the drilling experiments, using an electronic balance of sensitivity ± 10⁻⁴ mg. This measurement was repeated 5 times and the average weight was then calculated.
Figure 5. Experimental setup of the drilling test.

Figure 6. Thrust force curve. The average thrust force was calculated by the data taken from onset to the retraction of the drill.

Figure 7. Topographies and profiles of drill flute surfaces obtained by AFM. (a) Untreated drill. (b) Polishing treatment under injection angle 45° for 1 minute, (c) for 3 minutes. (d) Polishing treatment under injection angle 90° for 1 minute, (e) for 3 minutes.
3. Result and discussion

3.1. Surface condition before and after polishing treatment

Results of the observation by AFM are summarized in figure 7. Surface topographies are shown as 3 dimensional views and the surface profile measurement results are shown below them.

The untreated flute surface as shown in figure 7 (a) revealed that the grinding mark wave is constant in terms of its width and height. In addition it is clear that the wave has a wide convex shape and narrow concave shape. After the polishing treatment, in the condition of polishing time 1 minutes under injection angle 45 °, the wave shape are still observable with the reduction in its height and the concave shape became wider, refer figure 7 (b). After further polishing treatment until 3 minutes, no more wavy shape are observable where the surface profile flatten with small concave and convex shape on the surface which is left by the abrasive grain during the polishing treatment, refer figure 7 (c).

On the other hand, in case of polishing treatment under injection angle 90 ° condition, the wavy shape remain in both polishing time 1 minute and 3 minutes, refer figure 7 (d) and (e). Moreover in case of 1 minute polishing time condition, the concave shape remain narrow but shallower than the untreated condition as the height decrease, figure 7 (d). Then as the polishing treatment increase for 3 minutes, the height decrease further and the concave shape became wider, figure 7 (e). The polishing characteristics of this polishing media was the main reason for the aforementioned appearance where under injection angle 90 °, the polishing media polish the surface without flattening the surface. This is due to lack of horizontal component force under this injection angle which was essential in flattening the surface [5].

![Figure 8](image_url)

Figure 8. Surface roughness measurement result by laser microscope. (a) Surface roughness, $R_a$. $R_a$ is the arithmetic mean roughness value from the amounts of all profile values. (b) Surface roughness, $R_{sm}$ and $R_z$. $R_{sm}$ is the arithmetic mean value of the width of the roughness and $R_z$ is the maximum height of profile.

The results of the measurement by laser microscope are shown in figure 8. From figure 8 (a), it is clear that the surface roughness, $R_a$ decreases after the polishing and continue to decline as the polishing time increase for both injection angle. However, the declining rate for the surface roughness treated under injection angle 90 ° was observed to be slower than the injection angle 45 °. Next, the grinding mark width, refer as surface roughness, $R_{sm}$ in figure 8 (b) shows that the width are almost unchanged and are constant in the range between 6 μm and 8 μm for both the untreated and treated drill condition. Therefore from this result we can consider that the width of the grinding mark cannot be control by this polishing treatment. However, the average height of the grinding mark, refer as surface roughness, $R_z$ in figure 8 (b) are found to decline as the polishing time increase in same reduction rate for both injection...
angle. After 1 minute of polishing treatment, the grinding mark height had been reduced to about 30% from its initial height. Further polishing until 3 minutes reveals that the grinding mark height further reduces to almost 50%. The height reduction rate for both injection angle are same as it was reduces to equally after each polishing time while the concave and convex appearance were not equal as revealed in figure 7.

Therefore from these results, it is confirmed that blast polishing treatment on the drill flute surface are able to control the concave and convex shape of grinding mark property without damaging nor destroying it. This make possible by manipulating the polishing parameters as it becomes clear by Takai et al [4, 5]. However the width of the grinding mark cannot be controlled by this treatment and the width can be controlled only by manipulating the grinding machine parameters during the production of the drill.

3.2. Thrust force and cumulative weight of adhered aluminium

The results of thrust force measurement are shown in figure 9. At the 2nd hole, refer figure 9 (a), almost no significant different was observable for the average thrust force neither in the untreated drill nor in the treated drill condition. However, maximum thrust force value for injection angle 45 ° was found to be lower compare to other condition. Moreover, this maximum thrust force was found to be lowest at 3 minutes polishing condition.

![Figure 9. Thrust force measurement result. (a) Measurement during drilling the 2nd hole. (b) Measurement during drilling the 100th hole](image)

Thrust force measurement at the 100th hole reveals that the thrust force for the untreated drill condition is the lowest which is about 15% lower than the average thrust force if those treated with injection angle 45 ° and about 10% lower of those treated with injection angle 90 °. In addition, the thrust force for drill treated under injection angle 90 ° condition is higher compare to the untreated, but slightly lower than the injection angle 45 ° condition, in both average thrust force and maximum thrust force results.

The average cumulative mass of adhered aluminium after drilling 100th hole are shown in figure 10. From this figure, it is observable that there exist a correlation between the thrust force in figure 9 (b) and the adhered aluminium in figure 10. The untreated drill condition for both measurement shows the
lowest value compare to those treated drill condition. Moreover the drill treated under injection angle 90 ° condition is lower than the injection angle 45 ° condition for both in the adhered aluminium weight as well as thrust force value.

![Cumulative mass of the adhered aluminium](image)

**Figure 10.** Cumulative mass of the adhered aluminium after 100th hole of drilling.

![Illustration of the grinding mark transformation and the relation of concave and convex shape before and after the polishing treatment](image)

**Figure 11.** Illustration of the grinding mark transformation and the relation of concave and convex shape before and after the polishing treatment
3.3. Anti-adhesive effect of grinding mark properties

In the case of drill treated under 1 minute treatment, the concave of the \( w_{45(1)} \) is wider than \( w_{90(1)} \) and also \( w_{0(0)} \), but both \( w_{45(1)} \) and \( w_{90(1)} \) depth are shallower than \( w_{0(0)} \) because of the decrease in height, refer to figure 11. Therefore during the drilling process, in the case of \( w_{45(1)} \), wider concave area compared to \( w_{90(1)} \) makes aluminium chips easy to enter the concave area and produces chip adhesion inside it, defined as genesis phase. The genesis phase is the initial formation of chip adhesion. In the genesis phase, the lubricant film on the cutting tool surface are removed by severe sliding contact between tool and chip, the tool surface comes into direct contact with the chip surface and having high chemical activation. Then a thin adhesion layer is formed on the tool surface. The next phase of the chip adhesion formation is the growing phase. In the growing phase, the chip material becomes deposited on the thin previously formed adhesion layer, which makes the chip adhesion on the tool rake face grow more easier and larger [8, 9].

Back to the case of 1 minutes polishing treatment, with narrower concave area in the case of \( w_{0(0)} \) and \( w_{90(1)} \), it is sufficient as lubricant pocket for the lubricant to retain in the grooves and prevent chip from adhering inside it. In addition, \( w_{0(0)} \) provides better lubricant pocket than \( w_{90(1)} \) due to its deeper concave area. At this state, due to chip formation difficulty to enter the concave area, the formation of chip adhesion are believed to be happened only on the top of the convex area, resultantly forming a thin adhesion layer called as Built-Up Edge (BUE) with only at the genesis phase formation. Therefore these BUE region are believed to be unsteady and are easily ripped off during drilling without further entering the growing phase and then replace with new unsteady BUE.

In the case of 3 minute of polishing treatment, for injection angle 90 ° the concave becomes wider, \( w_{90(3)} > w_{90(1)} \), and its height further decrease, refer to figure 11. In this case, the lubricant pocket still exists because the grinding mark groove are still observable, however it is believed that this pocket is not sufficient for the lubricant to retain inside it during drilling. In contrary, for injection angle 45 °, it was found that at the 2nd hole, the maximum thrust force value was the lowest compare to other conditions. The reason of this is because of its flat surface. The friction at the interface between the tool and chip is lower which result into lower thrust force value. However, at this state, the adhesion formation already happens and at the genesis phase, forming a thin adhesion layer of BUE. When the drilling continues, severe sliding contact at the interface surface between the tool and the chip occurs. Because of no lubricant pocket for the lubricant to retain on surface to prevent adhesion and with large contact area at the interface, the chip adhesion may enter into the growing phase. Finally the surface completely buries and replaces with thicker and steady BUE layer with high adhesion strength.

4. Conclusions

In this study, the flute surface of WC-Co cutting tools were treated by blast polishing with several selected parameters in order to investigate the optimal surface property to impart anti-adhesive function in cutting of aluminium alloy. The results are summarized as followings:

1. Blast polishing treatment, reduces the grinding mark heights proportionally with the time of treatment. However, a different appearance in grinding mark concave and convex shape after polishing under injection angle 45 ° and 90 °. In case of injection angle 45 °, the grinding mark concave becomes wider and as the treatment time continues, the surface flattens. In contrary, treatment under injection angle 90 ° flattens the upper convex shape and at the same time keeps the concave shape narrow.

2. A correlation exists between the thrust force during the drilling and the adhered aluminium after drilling 100th hole. The untreated drill for both measurement shows the lowest value compare to those treated drill condition. Additionally, the drill treated under injection angle 90 ° condition is higher compare to the untreated, but slightly lower than the injection angle 45 ° condition, both in the thrust force and adhered aluminium.

3. Too much polishing treatment, especially under injection angle 45 °, will destroy the grinding mark on the flute surface. With no pocket for lubricant to retain on the surface, the lubricant layer on the cutting tool are removed by a severe sliding contact at the interface and result into the formation of
4. It is clear from this study that the untreated drill shows better anti-adhesive property. The reason for the occurrence are considered to be the factors of lubricant pocket. Deep and narrow concave provides better lubricant pocket. With lubricant retained inside the pocket making the chip difficult to enter which prevents adhesion inside it. Therefore the formation of chip adhesion is believed to be happened only on the top of the convex area.

5. The grinding mark plays role as the lubricant pocket which preventing the adhesion layer from entering the growing phase. With only formation at the genesis phase, these BUE regions are unsteady and easily ripped off and replaces with new unsteady BUE repeatedly during drilling. As conclusion, these results indicate that grinding mark micro texture improves the anti-adhesion by reducing the contact area during cutting and provide storage for the lubricant. In addition, too much polishing on the tool surface may remove these textures and resultantly worsen the tool performance.

Acknowledgement
The authors gratefully acknowledge OSG Corporation for providing the experimental equipment and financial support in this work. The authors would also like to thank the OSG corporation staffs for their invaluable assistance, advice and technical support.

References
[1] Noritaka Kawasegi, Hiroshi Sugimori, Hideki Morimoto, Noboru Morita, Isao Hori: Development of cutting tools with microscale and nanoscale textures to improve frictional behavior, Precision Engineering. Volume 33, Issue 3, July 2009, Pages 248-254. http://dx.doi.org/10.1016/j.precisioneng.2008.07.005
[2] Tatsuya Sugihara, Toshiyuki Enomoto: Development of a cutting tool with a nano/micro-textured surface – Improvement of anti-adhesive effect by considering the texture patterns, Precision Engineering Volume 33, Issue 4, October 2009, Pages 425–429. http://dx.doi.org/10.1016/j.precisioneng.2008.11.004
[3] Tatsuya Sugihara, Toshiyuki Enomoto: Improving anti-adhesion in aluminum alloy cutting by micro stripe texture, Precision Engineering Volume 36, Issue 2, April 2012, Pages 229–237. http://dx.doi.org/10.1016/j.precisioneng.2011.10.002
[4] Kazuteru TAKAI, Mohd NIZAR, Masao UEMURA and Masahiro FUKUMOTO: Polishing mechanism of cemented carbide using blast polishing process, 1th report: Effects of injection speed and polishing time on surface roughness, Journal of the Japan Society for Abrasive Technology Vol. 57 (2013) No. 4 p. 253-258. http://doi.org/10.11420/jsat.57.253
[5] Kazuteru TAKAI, Mohd NIZAR, Masao UEMURA and Masahiro FUKUMOTO: Study on polishing mechanism of cemented carbide using blast polishing process, 2nd report: Effect of kinetic energy and injection angle on surface condition of cemented carbide, Journal of the Japan Society for Abrasive Technology Vol. 58 (2014) No. 6 p. 386-391. http://doi.org/10.11420/jsat.58.386
[6] Kenji Yamashita: polishing method using a water-containing polishing media "Aero Lap method", Machine Technology, 54,10 (2006) 34-36
[7] Fuji Tetsuya, Kitajima Koichi, Kenta Kano, Kenji Yamashita: A Study on the blast polishing method using animal protein complex polishing media, Japan Society for Precision Engineering 2005 Fall Meeting academic lecture Conference Paper Library, (2005) 1115-1116
[8] Andrew William Batchelor, Gwidon W. Stachowiak: Tribology in materials processing. Journal of Materials Processing Technology. Volume 48, Issue 1-4, 15 January 1995, Pages 503-515. doi:10.1016/0924-0136(94)01689-X
[9] Hidehiko TAKEYAMA, Tomohiko ONO: Basic research on built-up edge. Trans JSME, 32 (242) (1966), pp. 1563–1570. http://doi.org/10.1299/kikai1938.32.1563