Contour Turning of Aluminum Alloys with PCD Flat-faced and Diamond Coated Grooved Tools: A Study on Dry Machining Performance Evaluation

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ABSTRACT: This paper presents the results from an experimental and theoretical study of contour turning operations on aluminum alloys using PCD flat-faced and diamond coated grooved tools. The machining performance is assessed on the basis of cutting forces, chip flow, chip-form and surface roughness of the machined part. The constantly varying cutting conditions (especially effective depth of cut due to varying geometry of the contour surface) and effective tool geometry cause a wide fluctuation in cutting forces and the ensuing chip-flow. A comparative study on two grades of cutting tools, flat-faced PCD and grooved diamond coated tools was conducted on the basis of machining performance. Machinability issues specifically relevant to aluminum machining are also investigated and the major objective of this study is on attaining the best machining performance under dry conditions.

KEY WORDS: Contour turning, Aluminum alloys, Diamond-coated tool inserts.
1. Introduction

Machining of aluminum alloys has taken on significant importance in the sphere of manufacturing operations. The widespread material benefits afforded by aluminum alloys (such as low weight-strength ratio, lack of corrosion, etc.) provides a new impetus for detailed research on several new aspects related to machining performance. Correspondingly, the rapid development of diamond-based tool materials with focused impact on machining of non-ferrous alloys has thrown the limelight on performance issues in machining of aluminum alloys. An area of both fundamental and applied interest is the selection of appropriate cutting tools and cutting conditions in the contour turning of aluminum alloys. Another area of emphasis in this paper is the need for assessing the use of no coolants/lubricants during machining. This corresponds well with the recent developments advanced diamond-based cutting tools aimed at eliminating the need for coolants in machining, thereby leading to better environmentally conscious manufacturing practice.

Contour turning provides a unique problem due to continuously changing cutting conditions, and the resulting wide variations in chip flow and the consequent chip-form and surface finish issues due to geometric variations along the length of cut. This paper deals with all these issues along with tooling issues focusing on diamond-based cutting tools. This paper has been especially motivated by problems arising in the contour turning of aluminum alloy wheels for the automotive industry. The continuously changing effective geometry due to the contour shape results in severe chip control and surface roughness problems. Contrary to its practical importance, very little work has focused on machining issues in contour turning. More recently, there has been other contemporary work on using mechanistic methods to predict forces in contour turning [GAJ 98]. Before discussing the major issues it is important to define machining performance and its connotation especially when applied to the use of advanced cutting tool materials and coatings in current industrial operations.

1.1 Machining Performance and Its Measures

Traditional characterization of machining performance has been through the use of the term "machinability". Under this definition, only the work material was considered in the analysis, resulting in complete neglect of the tremendous advances in cutting tool and machine tool technology. Also, in order to consider the entire 'systems' effect it becomes necessary to identify the most major measures of machining performance [JAW 97]. In this regard, the following five measures are found to be fairly representative measures of machining performance: namely, cutting forces/power/torque, tool-wear/tool-life, chip-form/chip breakability, surface roughness/surface integrity, and part accuracy. In the current study, three major and associated performance measures will be evaluated: namely cutting forces, chip flow and surface roughness. In addition, the variation of chip-forms at different locations
associated with the effective chip flow along the contour will also be briefly discussed.

2. Prediction of Chip Side-Flow

There has been considerable work done on using the cutting forces to predict the chip flow direction. Early work on chip flow predictions remained largely geometrical in nature and did not account for the effect of the frictional force on the rakeface in evaluating the chip flow. In this regard, the pioneering work of Colwell [COL51] and Stabler [STA 51, STA 64], needs to be recognized in terms of their practical input towards assessing chip flow from an operations perspective. Later, significant work by Armarego and co-workers ([ARM67], [ARM 83], [ARM 96], [ARM 99]) served in emphasizing the need for incorporating forces into the chip-flow prediction problem. Recent predictive models typically extend to predictions of both cutting forces and chip flow in an iterative manner [ARM 99], [RED 99]. Other major work on prediction of chip side-flow has also been performed involving the use of cutting forces in the predictions ([LIN 82], [YOU 87], [ARS 95], [ARS 96]).

Figure 1. Derivation of the chip flow angle and rakeface force components resulting from the forces $F_x$, $F_y$, and $F_z$. (a) within Plane $P_s$; (b) within Plane $P_n$; (c) on the rakeface [after RED 99].
In the current work, the chip side-flow angle is calculated by resolving the experimentally measured cutting forces into their rakeface frictional components (Eq. 1) and then using these friction force components to estimate the chip side-flow angle (Eq. 2 and 3). The procedure for resolving the forces on the rakeface and calculating the chip side-flow has been presented in detail in an earlier work [RED 99]. Figure 1 shows the basic orientation of the force components and the means of converting them into force components on the rakeface.

The rakeface force components can be calculated using:

\[
F_y' = (F_x \cos \kappa_{s1} + F_y \sin \kappa_{s1}) \cos \lambda_{s1} + F_z \sin \lambda_{s1} \\
F_x' = (F_x \sin \kappa_{s1} + F_y \cos \kappa_{s1}) \cos \gamma_{s1} + (F_z \cos \lambda_{s1} - (-F_z \cos \lambda_{s1} + F_y \sin \kappa_{s1} \sin \lambda_{s1}) \sin \gamma_{s1}
\]

The final equation for chip side-flow is given by:

\[
\eta_c = \tan^{-1} \left[ \tan \eta_c \cos \lambda_{s1} - \sin \gamma_{s1} \sin \lambda_{s1} / \cos \lambda_{s1} \right]
\]

where \( \eta_c \) is the chip side-flow angle on the rakeface which is given by:

\[
\eta_c = \tan^{-1} \left( F_{y'} / F_{x'} \right)
\]

where \( F_{y'} \) and \( F_{x'} \) are the rakeface force components.

3. Experimental Work

In order to comprehensively study the effects of contour geometry on machining performance in aluminum machining, a contour shape was specially designed to include a combination of features/regions. Figure 2 shows the part drawing illustrating these various regions of the contour surface to be studied in greater detail. The length of the contoured part (AB) is divided into four regions based on the varying nature of the contour. Region 1 comprises a convex positive contour slope which extends till a semi-sphere of radius 16.5 mm. Region 2 comprises the remainder of the sphere of radius 16.5 mm (this being a negative convex contour), and its intersection with the radius of 35.5 mm leading to a sudden shift in the contour shape to a negative concave surface at a distance of 23 mm from A. Region 3 begins once the contour profile assumes a positive concave shape. This positive concave shape suddenly changes over near the very end of Region 3 to a small positive convex profile (radius of 6 mm). At the point where this small positive convex profile ends, and a straight cylindrical surface begins, Region 4 is assigned. The entire length of the contoured part (AB) was fixed at 76 mm. It can be seen that in Regions 2 and 3 there are sudden changes from convex to concave and vice-versa geometries.
Figure 2. The specifications of the workpiece used in contour turning experiments.

The work materials used in the analysis were two grades of aluminum alloys: 2011-T3 and 6061B. Traditionally, from a machinability point of view, the 2011-T3 has excellent machinability characteristics whereas the 6061B alloy is more difficult to machine due to the rather ‘gummy’ material characteristics. The cutting tools selected were:

1. Polycrystalline diamond flat-faced tool insert (PCD) DCMW 11 T3 08F
2. Diamond-coated grooved tool insert (DCG) DCGX 11 T3 08-AL

The nose radius was maintained constant. A SDJCL-123B tool-holder was used for the machining of the aluminum alloys. The tool rake and inclination angles were 0 deg. each and the nominal cutting edge angle was 93 deg.

The major reasons for selecting advanced diamond-based tools was the need to maintain current trends in practical machining of aluminum alloys under dry cutting conditions. Traditionally PCD inserts have fared very well in the machining of aluminum alloys. However, recent advances in using a thin CVD diamond coating on a carbide substrate provide the superior wear characteristics of diamond allied with the ability to incorporate a suitable chip-groove to ensure effective chip control. The machining was performed for a roughing and a finishing operation, both under dry conditions. The cutting conditions associated with these operations are:
Roughing: $f = 0.35 \text{ mm/rev.}, \ a = 2.5 \text{ mm}, \ V = 394 \text{ m/min.}$
Finishing: $f = 0.15 \text{ mm/rev.}, \ a = 0.8 \text{ mm}, \ V = 640 \text{ m/min.}$

The cutting forces were measured using a KISTLER 9257B three component tool dynamometer allied with KISTLER charge amplifiers, Butterworth filters and a HT 600 data acquisition system. The forces were measured continuously for the entire length of the contour profile (AB). Simultaneously, using a common trigger mechanism, the machining process was filmed using a high speed motion analysis system (KODAK Ektapro 1100). Since the contour length was comparatively large, the chip formation process was filmed at 125 p.p.s and the then played back at a range of 1-5 p.p.s to measure the chip side-flow angle and to ascertain the continuous variation in chip-forms. A Taylor Hobson TALYSURF-50 surface measuring system was used to measure the surface roughness variations in the different regions of the contour profile.

In contour turning, there are two major geometrical variations encountered: namely the variation of the effective depth of cut and the effective cutting edge angle. Hence, although a nominal depth of cut of 2.5 mm and 0.8 mm in roughing and finishing operations respectively is maintained all along the contour, the effective depth of cut (in the radial Y direction) changes all along the contour. A schematic representation of the changing effective depth of cut due to the contour profile is shown in Figure 3. This calculated variation in the effective depth of cut is shown in Figure 4. It can be seen that at very beginning of the contour (A) the effective depth of cut is much larger than the nominal depth of cut and this variation is evidenced right along the contour profile. The sudden transition from a positive concave surface to the positive convex small radius in Region 3 is marked by a sudden peak in the effective depth of cut. A smaller, more gradual peak represents the transition from the negative convex surface to a negative concave surface in Region 2. Figure 4 shows the variation of the effective depth of cut from 3.9 mm to 2.5 mm in roughing and from 1.35 mm to 0.8 mm in finishing.

![Figure 3. Variation between effective depth of cut and prescribed nominal depth of cut due to variations in contour geometry.](image)

The effective side-cutting edge angle too changes all along the contour profile. The mapped variation in the effective side-cutting edge angle along the contour length...
AB is shown in Figure 5. A very wide range of variations from 120 deg. to 20 deg. is noted.

![Diagram of effective depth of cut along the axial length of the contour part for roughing and finishing operations.](image1)

**Figure 4.** Variation of effective depth of cut along the axial length of the contour part for roughing and finishing operations.

![Diagram of effective side-cutting edge angle along the axial length of the contour part.](image2)

**Figure 5.** Variation of effective side-cutting edge angle along the axial length of the contour part.
It is also to be noted that the effective feed rate along the contour profile changes, and these changes are included in the measurable cutting forces which are used for calculating the effective chip flow direction, as will be seen later.

4. Results and Discussion

The analysis of the results focus on the following parameters: the measured cutting forces, the predicted and experimental values of chip side-flow and the corresponding qualitative discussion on chip-forms, and the measured surface roughness values. It must be mentioned that for the cutting forces and the chip side-flow, only the roughing operation was considered, since the cutting force data remained very consistent for this particular operation. However, the surface roughness values were measured from the final finishing operation to estimate the machining performance with respect to the diamond-coated grooved tool (DCG) and the polycrystalline diamond flat-faced tool (PCD). The variations in these parameters due to the contour profile, different cutting tool inserts (PCD and DCG) and work materials (2011-T3 and 6061-B) are discussed in detail along with plots of the variations of these parameters.

4.1 Cutting Forces

Due to the continuously changing geometry of the contour profile and the resultant changes in the effective depth of cut (see Figure 4) and the effective side-cutting edge angle (see Figure 5), there is a consistent variation of all three force components along the length of the contour AB. Figure 6(a) and (b) show the variation of the three force components along the axial length of the workpiece denoted by AB. The demarcation of the forces across the different regions is also shown. Figure 6(a) illustrates the force variation for 2011-T3 and Figure 6(b) shows these variations for 6061-B when machining with the polycrystalline diamond flat-faced tool (PCD). It can be seen in Region 1 that initially the X and Z (axial and tangential) components of the force are very high due to very high values of effective depth of cut and a low effective side-cutting edge angle. Gradually the forces drop as the effective depth of cut decreases and the effective side-cutting edge angle increases. In Region 2, the forces begin to increase once again as the effective depth of cut rises due to the negative slope of the convex contour profile. Once the transition point to the negative concave surface is reached, the forces peak and then begin to drop once again until the end of Region 2. In the major portion of Region 3 we see an increase in the cutting forces once again as the effective depth of cut increases and the effective side-cutting edge angle decreases. However, at the sharp transition into a positive convex surface towards the end of Region 3, the forces peak suddenly and then drop off as the tool moves in towards the straight horizontal surface (Region 4). The force patterns exhibit very similar behavior for the diamond-coated grooved tool (DCG) for both work materials (see Figure 7(a) and (b)). It was observed that the force trends in each of the regions of the contour...
appear very consistent with the changes in tool geometry with very little deviations from the contour profile. Moreover, the magnitude of forces when machining with the diamond-coated grooved tool are much higher than when machining with the PCD flat-faced tool. This can be attributed to the better frictional properties of PCD, as well as the fact that the diamond coating is relatively thin and rests on a traditional carbide substrate. Additionally, the edge radius or hone values for CVD diamond-coated tools are much higher than PCD tools, resulting in increased ‘edge’ forces.

Another point of discussion from the force data for the DCG tool is the relative increase in radial force component ($F_r$) compared with flat-faced tools. This is due to the traditional role of the chip-groove in obstructing the chip-flow in a radial direction thereby contributing to increased radial forces.

4.2 Chip Side-flow

Although, in the traditional definition of machining performance measures [JAW 97], chip-form and chip breakability are considered as the measures to be focused upon, there is the flexibility of adjusting the performance measures to suit the specific materials being machined and the operation needs and specifications. In typical machining of non-ferrous materials, control of chip flow is of as much or even more importance than chip-form of chip breakability. This is especially true in contour turning, since, no universal chip-groove is available to handle the myriad variations in effective geometry along a contour profile. However, if the direction of chip-flow can be controlled effectively, the machining performance desired is attainable in many cases. Hence in this current study, chip flow is assigned the status of a machining performance measure. Figure 8 shows a schematic of chip side-flow measurement convention adopted in the present study.

In this study, the chip side-flow in machining only with flat-faced (PCD) tools was measured and predicted. This limitation was due to the fact that in machining with a grooved tool, there is a pronounced chip back-flow effect [JAW 90, JAW 91] leading to actual 3-D chip-flow. The theories used in this study for prediction of chip flow are restricted only to the chip side-flow for flat-faced tools. Also, the chip side-flow is easier to measure when machining with flat-faced tools, since the absence of chip back-flow provides reliable data for chip flow values. Recently, a cutting force and chip flow prediction model was developed which is capable of predicting both cutting forces and chip flow from limited orthogonal cutting data [RED 99]. However, in the current study, we do not predict the forces; rather, the chip side-flow is predicted using the experimentally measured forces for the PCD tools [GHO 94].
Figure 6. Variation of cutting forces along the axial length of the contour part in the roughing operation for (a) 2011-T3 and (b) 6061-B aluminum alloys when machining with PCD flat-faced tools.

(V = 394 m/min., f = 0.35 mm/rev., nominal depth of cut = 2.5 mm)
Figure 7. Variation of cutting forces along the axial length of the contour part in the roughing operation for (a) 2011-T3 and (b) 6061-B aluminum alloys when machining with diamond coated grooved (DCG) tools. 

\(V = 394 \text{ m/min.}, \ f = 0.35 \text{ mm/rev.}, \ \text{nominal depth of cut} = 2.5 \text{ mm}\)
Figure 8. Schematic diagram showing measurement convention for chip side-flow in contour turning.

It must be mentioned that the chip side-flow predictions and measurements are referenced with respect to the horizontal X-axis. Figures 9 and 10 show the predicted chip side-flow angles from experimental data on measured forces for machining with 2011-T3 and 6061-B aluminum alloys respectively. It was observed that in Region 1, the chip side-flow angle kept increasing drastically from a large negative value to a more stable (and traditional) positive value. This is due to the innate transition from a pure facing operation at the very beginning of Region 1 (at A) to pure horizontal turning, and again into combined turning and facing, at the end of Region 1, corresponding to the rapid decrease in the effective depth of cut followed by a slight increase as shown in Figure 4. In Region 2 the chip side-flow angle decreases until the transition point to the negative concave surface and then once again begins to increase. In Region 3, there is a sharp decrease in the chip side-flow leading to negative values as the effective side-cutting edge angle decreases drastically. The chip side-flow can have negative values due to the inherent slope of the contour profile in this region, allowing for a more unobstructed canopy for the chip to flow into. However, the chip side-flow once again increases drastically due to the transition to the small positive convex shape at the end of Region 3. Finally, in Region 4, the chip side-flow stabilizes to that found in traditional turning operations. It can be seen that there are comparatively larger variations between the predicted and measured values of chip side-flow in Region 3. This is due to the great difficulty in actually locating the chip flow direction due to a mass of snarled, unbroken chips that obscured the view during the high-speed filming process. This also is the reason for only limited experimental measurements as compared to predicted values all along the contour profile.
Figure 9. Variation of predicted and experimentally measured chip side-flow angle along the contour profile during roughing of 2011-T3 aluminum alloy with PCD flat-faced tools
($V = 394$ m/min., $f = 0.3$ mm/rev., nominal depth of cut = 2.5 mm)

Figure 10. Variation of predicted and experimentally measured chip side-flow angle along the contour profile during roughing of 6061-B aluminum alloy with PCD flat-faced tools
($V = 394$ m/min., $f = 0.3$ mm/rev., nominal depth of cut = 2.5 mm)
4.3 Chip-forms

This paper does not deal with the detailed classification of chip-forms. The traditional definitions of up-curl or side-curl dominated chips as well as the use of parameters such as a twist angle [NAK 78; GHO 96] apply only for well broken chips. Recent work has aimed at relating the tool geometry and cutting parameters to the chip flow and curling patterns [BAL 99]. It was observed that when machining with the flat-faced PCD tool, in Region 1, predominantly up-curl ed chips were initially formed due to the large depth of cut and low effective side-cutting edge angle. In the remainder of the regions, the chip-form classification was very difficult since the chip flow was continuous with no chip breaking. This resulted in continuous build-up of a huge mass of snarled chips that defied traditional classification into up-curl ed or side-curl ed chips. On the other hand, the chip-groove in the DCG tool promoted formation of mixed mode chips by imparting more up-curl to the conventional side-curl ed chips. The degree of chip control effected by the DCG tool was very significant; the PCD tool rarely exhibited chip breaking even during the roughing operation. A more detailed analysis of the morphology of the chip-form and the effect of tool-chip interfacial friction is the subject of current ongoing work. Figure 11 shows the improved chip control obtained by using a DCG insert as compared to a PCD insert.

4.4 Surface Roughness

The surface roughness was measured as the average of three measurements at six different locations along the contour profile (see Figure 12). The measured $R_a$ values are plotted in Figure 13. The observations show that 6061-B aluminum alloy shows remarkably better surface roughness values when machining with the flat-faced PCD tool rather than the diamond-coated grooved tool. Conversely, the diamond-coated grooved tool performs much better in terms of surface roughness than the PCD flat-faced tool when machining 2011-T3 aluminum alloy. This contrasting trend for the surface roughness shows the intrinsic importance of considering a work material — cutting tool pair. The traditional poor machinability of 6061-B alloy seems to be overcome only by the polycrystalline diamond tool material. It is apparent that the better chip control afforded by the diamond-coated grooved tool is negated by the inherent mismatch of the work material – tool material pair. The larger side-spreading tendency and the resulting burrs due to the chip curl imparted by the DCG insert when machining 6061-B alloy also contribute to scratching of the machined surface and poor surface roughness. It is also observed, that the surfaces where the local orientation of the part was straight cylindrical as per nominal effective depth of cut and side-cutting edge angle (at distances of 16.5, 38 and 74 mm from A) exhibited the poorest surface roughness. The negative and positive concave features at 27 and 52 mm points displayed the best comparative surface roughness. This is due to the combined favorable effect of the end-cutting edge angle and the chip side-flow angle, as well as the gradual slope of the contour profile. This change in the effective geometry and chip flow patterns ensures that the surface roughness is comparatively better on the concave surfaces.
Figure 11. High-speed filming photographs of comparative chip flow and chip formation at different locations along the contour profile when machining 2011-T3 alloy (Left column: PCD flat-faced tool insert, Right Column: Diamond-coated grooved tool insert)

5. Summary and Concluding Remarks

This paper has thrown new light on machining performance issues during dry contour turning of aluminum alloys using advanced cutting tools. The major conclusions from this paper can be summarized as follows:

- Contour turning provides a serious challenge to modelers and cutting tool designers due to the wide variations in the effective geometry all along the contour profile. Especially, the large variations in the effective depth of cut and the effective side-cutting edge angle provide large variations in parameters such as cutting forces and chip side-flow.
- The three force components vary widely depending upon the location along the contour profile and the corresponding effective depth of cut and side-cutting edge angle. It was observed that the PCD tool insert exhibited much lower forces than the diamond-coated grooved insert. The forces showed a greater deal of variation when machining 6061-B alloy due to the inherent poor machinability, even with PCD tools.
Figure 12. Schematic diagram showing locations for surface roughness measurements.

Figure 13. Average surface roughness values at selected locations along the axial length of the contour part in machining a combination of two work materials and two cutting tool inserts.
• The chip side-flow predictions and measured values showed similar trends. However, it was observed that the predictions varied with the measured values. A major reason for this variation is the unbroken, snarled nature of the chip when machining with flat-faced PCD inserts which deflects the chip from its original chip flow direction and the poor visibility of the actual chip side-flow due to the unbroken mass of snarled chips. The continuously increasing dynamic weight of the chip is capable of shifting the original chip side-flow orientation.

• The shape of the different regions on the contour part profile and the corresponding chip flow characteristics with different work materials affects the surface roughness. Additionally it was observed that as far as surface roughness was concerned, the flat-faced PCD insert performed better with 6061-B alloy whereas the DCG insert gave better $R_a$ values with 2011-T3 alloy. It was also observed that in the positive and negative concave surfaces in Regions 2 and 3, the surface roughness was comparatively much better due to favorable combination of end-cutting edge effects and the chip side-flow, and the gradual slope of the concave surface. These results also show the importance of considering a work material – cutting tool pair for better understanding of the process mechanics in contour turning.

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7. References


