11.12 Burr Formation in Machining Processes: A Review

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11.12.1 Introduction

The control and removal of burr have become one of the most important economic factors in machining processes and as a result have been the focus of research in machining operations in the last five decades (*1*). Burrs, which are small pieces of deformed material left on the edges of the workpiece, are found in most machining operations. It brings various challenges such as worsening the dimensional accuracy and surface finish, (*32*) reducing the cutting performance and life of the cutting tools, and potentially causing accidents to workers and consumers during usage. Burr formation is a complicated process, and its formation involves large plastic deformation of work material, while the type of burrs and their characteristics depend on the type of machining process, the process parameters, tool property, tool geometry, tool edge configuration, coolant, and workpiece material properties (*2*). The word 'burr' in machining process has been defined by many authorities. Schafer (*3*) described burr as the part of a workpiece that is produced through manufacturing processes on an edge or a surface and which lies outside the desired geometry. The ISO 13715 (*4*) defines the edges of a workpiece as burred if it has an overhang greater than zero, as shown in Figure 1. Ko and Dornfeld (*5*) defined burr as an "undesirable projection of material formed as the result of plastic flow from a cutting or shearing operation." One of the first researchers to study burr formation at an academic level was Gillespie (*6*), whose definition of burr is limited to cutting and shearing processes; hence, a burr produced by those operations includes "all the material extending past the theoretical intersection of two surfaces, which surround the burr." The reference in that case is the theoretical intersection of the two surfaces and not the desired surface and, in addition, Gillespie's definition includes burrs that lie inside the theoretical intersection as shown in Figure 2. Beier (*7*) gave a comprehensive definition of burr as a body created on a workpiece surface during the manufacturing of a workpiece

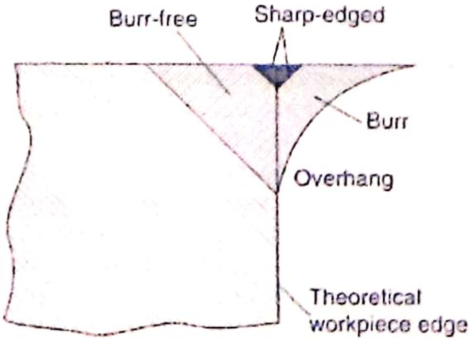


Figure 1 Definition of burrs according to ISO 13175. Reproduced from International Standard ISO 13715. Technical Drawings – Edges of Undefined Shape – Vocabulary and Indications, 2000.

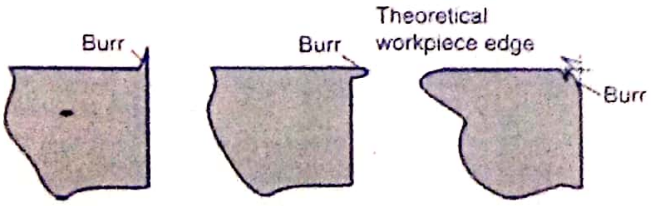


Figure 2 Examples of burr definition according to Gillespie. Reproduced from Gillespie, L. K. The Battle of the Burr: New Strategies and New Tricks. *Manuf. Eng.* **1996**, *116* (2), 69–78.

that extends over the intended and actual workpiece surface and has a slight volume in comparison with the workpiece, undesired, but to some extended, unavoidable.

The first researcher to investigate chip formation in cutting process and burr formation mechanism was Pekelharing (*8*), and his works described burrs formation in punching process, while the first fundamental work on burr formation mechanisms was published by Gillespie and Blotter (*9*). Gillespie (*10*) presented an analytical model that illustrated burr formation mechanisms and predicted burr properties. The results of this model were compared with experimental observations. The understanding of the mechanisms behind burr formation had helped researchers focus on deburring. Advanced technology for deburring becomes more important in order to improve productivity in machining of parts (*11*). Deburring has become a serious problem that needs urgent attention as the formation of burr edge fractures during machining means change of the geometry of products or parts. When the deburring of a precision part is not considered until the final stages of manufacturing, the potential loss due to any failure in the selection, planning, or execution of the edge-finishing process is great (*12*). The cost of deburring these components may contribute as much as 30% to the cost of finished parts (*13*). The selection of capable deburring and finishing processes for precision components is highly dependent on knowledge of burr properties. Burr size, shape, and location as well as the allowable surface finish are the primary factors in the selection of deburring process. Burr properties are influenced by part design and process planning decisions. To classify whether a particular burr property is influenced primarily by the design stage or the manufacturing stages requires burr formation data, burr formation models, and burr formation mechanism identification (*12*). Burr formation during machining process is therefore a phenomenon that is undesirable and at the same time unavoidable. However, there are many methods that have been suggested to either minimize burr formation or remove burrs.

Burr can be classified into rollover, Poisson, tear, and cutoff based on the mechanism of formation (*9*). It is sometimes classified as backward flow, sideway flow, forward flow, and leaned burr by the burrs formation direction (*14*) and also as entrance burr, side burr, and exit burr by the location of burr formation (*9,14*). However, two burr types have been identified to cause serious problems in practice, these are rollover burrs and Poisson burrs. Ko and Dornfeld (*5,11*) investigated the burr formation model for orthogonal cutting and their concern was the rollover burr mechanism, the forward flow, and exit burr. In another classification by Kishimoto (*15*), two types of burr, primary and secondary burrs, were identified. He claimed that through proper selection of cutting conditions and tool geometry, the rollover burr will be separated at its thinnest portion and only a small burr remained on the edge of the machined part. Hence, the former normal burr was named a primary burr and the later one a secondary burr, which is the material remaining after the breakage of the primary burr. Beier (*7*) described a secondary burr as material that remains on the edge of a part after a deburring process.

Some of the efforts in the past few decades have been devoted to study the mechanism of burr formation in machining processes without thoroughly exhausting all the factors that could affect burr formation as identified by Yu Long and Changsheng Guo (*2*). Kim et al. (*16*) studied formation in drilling process, and they found that shapes and sizes of drilling burrs depended on the process parameters. They equally observed that drilling burrs have uniform shape for most materials when the feed or cutting speed is low, and when material is ductile, the burrs are elongated, which results in a large burr height and burr volume. But if material is brittle in nature, catastrophic fracture makes irregular-shaped burrs when the feed and speed are increased (*17*). Pande and Relekar (*18*) described experimental investigations for reducing the burr formation while drilling through-holes in metals using uncoated standard twist drills. Stein and Dornfeld (*19*) presented a study on the burr height, thickness, and geometry observed in the drilling of 0.91-mm-diameter through-holes in stainless steel 304L. The mechanism of burr formation in face milling is similar to that in drilling (*20*). Milling burrs are created mainly when the milling cutter exists at the edge of workpiece (*21*). Efforts by Park and Dornfeld (*22*) and Min et al. (*17*) to study burr formation with FEM are yet to yield positive results due to the inability to simulate all four stages of burr formation as a result of material model limitation (*2*).

Available literature on burr formation in machining processes seems to be silent on the critical role played by different types of coolant applications, especially vegetable oil-based coolants, in determining the quality of surface finish of workpiece material. Most of the literature on burr formation focused on tool geometry, tool edge configuration, and workpiece material properties. In order to do justice to the causes of burr formation in machining process, it is necessary to take the temperature dependency of material properties into account when explaining burr formation phenomena (*23*). Again, it has been established that the chemical composition and mechanical properties of the work material, the tool, and the cutting fluid type are of vital importance in determining process performance and finished surface quality (*24*). Experimental results have confirmed that coolants based on vegetable oils show better performance than mineral oils during drilling of AISI 316L austenitic stainless steel using conventional high-speed steel (HSS) tools. Since the combinations of all the input parameters, including coolants, have effects on the surface integrity of the workpiece during machining process, the need to investigate the effect of different types of coolants on burr formation mechanism during machining processes is long overdue. The application of vegetable oil-based cutting fluids has shown that better results were obtained for the output parameters compared to when conventional or dry cutting were employed (*25–28*). This chapter therefore presents a review on burr formations in turning, drilling, and milling processes and highlights the need to study the effect of different coolants on burr formation mechanism.

11.12.2 Burr Formation in Turning Process

Burrs occurring in turning processes are Poisson burrs, which are formed when the cutting edge of a tool extends beyond the workpiece edge, as shown in Figure 3. A rollover burr can be formed if the cutting tool passes over a groove or cutting is interrupted due to other geometric features of the workpiece. Gillespie (*29*) observed that, in the turning process, most burrs are created as rollover burrs at the side of the workpiece when the tool exits from cutting.

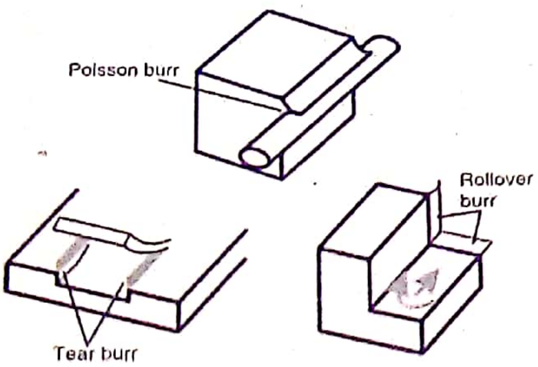


Figure 3 Schematic of Poisson, tear, and rollover burrs. Reproduced from Gillespie, L. K.; Blotter, P. T. The Formation and Properties of Machining Burrs. *Trans. ASME J. Eng. Ind.* **1976**, *98*, 66–74.

Pavel et al. (30) investigated the effect of tool wear on surface finish for a case of continuous and interrupted hard turning using two types of workpieces for continuous and interrupted cuts, respectively. The continuous surface was a camshaft 155 mm long with a 28.6 mm diameter. The material was AISI 1117 steel hardened to 62 ± 1 Rockwell hardness C scale (HRC), which is usually used where a combination of good machinability and more uniform response to heat treatment is needed. The second workpieces for longitudinal interruptions were shafts having 10 splines. The surface to be machined was 63.8 mm long and had a 34.9 mm diameter. The spline shafts were made of AISI 1137 steel having a medium hardness of 48 ± 1 HRC and widely used for parts where a large amount of machining is necessary or where threads, splines, or other operations offer special tooling problems. Amborite DBC50 and Amborite DBN45 tools specially designed for turning operations were used in this investigation. The following four types of tests were run and the surface finish was observed in parallel with tool wear. All the cutting parameters and setups were in accordance with regimes that are used in practice without cutting fluid.

1. Initial experiments – cutting regime: depth of cut ($a_p = 0.178$ mm), cutting speed ($v = 125$ m min^{-1}), and feed rate ($f = 0.15$ mm rev^{-1}).
2. Replica of initial experiments: first tests were replicated to verify and confirm the initial findings and avoided the possible outliers.
3. Higher speed experiments: depth of cut ($a_p = 0.178$ mm), cutting speed ($v = 175$ m min^{-1}), and feed rate ($f = 0.15$ mm rev^{-1}).
4. Production-run simulation: depth of cut ($a_p = 0.178$ mm), cutting speed ($v = 125$ m min^{-1}), and feed rate ($f = 0.102$ mm rev^{-1}).

One of the effects of tool wear on surface finish in interrupted cutting was an improvement on surface finish with tool wear, however, a negative effect was observed in terms of burr formation. It was noticed that the actual experiments provided significant burrs when tool wear reached relatively high levels ($VB_{max} > 0.15$ mm). Figure 4(a) and 4(b) shows a spline edge when hard turning was performed with a fresh tool and when flank wear had a value of approximately 0.17 mm at the same edge, respectively. One of the observations made in this study was that special care should be given to burr formation during interrupted cutting, to avoid damage to adjacent surfaces.

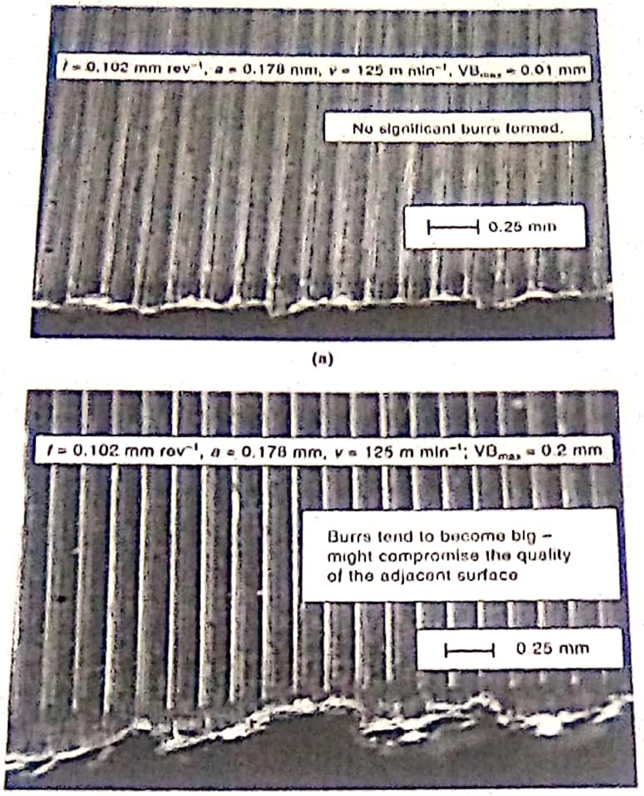
The results obtained for this experiment could give different results entirely if the application of coolant was considered. Different coolants have a way of affecting the performances of machining process, and it is believed that if coolant was applied, it will likely alter the results.

In another development, an experimental study of the burr formation mechanism in feed direction was conducted by Toropov et al. (31). Influence of tool angles and workpiece angles, as well as other cutting conditions, on burr dimension was considered. The experiments on burr formation were carried out on a computer numerical control (CNC) turning machine tool. The experimental setup, tool, and burr geometry are shown in Figure 5. While K10 grade of tungsten carbide–cobalt alloy was chosen as a cutting tool material in turning of aluminum alloy Al6061-T6. Tables 1 and 2 present tool geometry and cutting conditions used in the experiments, respectively.

The burr height (h) and burr thickness (b) were measured after every experiment using a laser measurement system (32). Table 3 presents cutting conditions used in a special experiment executed to allow observation of the burr formation process.

Figure 6 shows the influence of the lead angle (φ) on the burr dimensions for cutting conditions given in Table 3. For small lead angles, the burr formation is probably most related to sideward (or Poisson) burr.

Again, the influence of depth of cut on burr height shows that for a lead angle of 16°, the burr height is independent of depth of cut, whereas for a lead angle of 32° or 47°, the burr height increased proportionate to the depth of cut. They observed that clearance angle of the tool does not have any significant influence on burr dimensions, but increase in rake angle does cause considerable reduction of burr thickness and height. One of the conclusions reached by the authors is that the mechanism of burr formation in feed direction when cutting aluminum alloy Al6061-T6 using a sharp tool depends essentially on tool geometry, workpiece angle,



(a)

(b)

Figure 4 Burr formation in interrupted hard turning: (a) fresh tool, (b) worn tool. Reproduced from Pavel, R.; Marinescu, I.; Deis, M.; Pillar, J. Effect of Tool Wear on Surface Finish for a Case of Continuous and Interrupted Hard Turning. *J. Mater. Process. Technol.* 2005, *170*, 341–349.

and feed. The mechanism was determined mainly by the stress state in the chip formation zone, though stresses on the tool clearance face have a very slight influence on the burr formation. The increased tool rake angle led to a favorable change of the stress state in the chip formation zone, which resulted in a considerable reduction of burr dimensions.

The authors considered the influence of tool angles and workpiece angles to study burr formation in turning aluminum alloy. In spite of significant success in studying burr formation in feed direction, it is still unclear about the mechanism behind it. The information available on the cutting conditions shows that the experiment was conducted in dry cutting mode. Since one of the

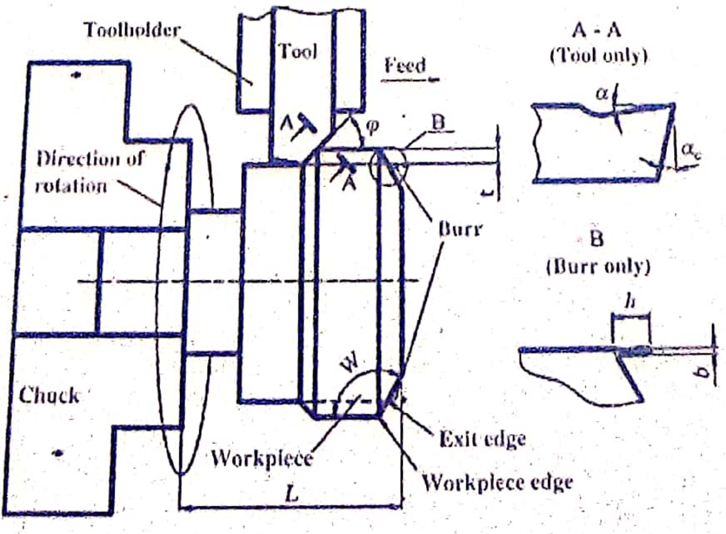


Figure 5 Experimental setup, tool geometry, and final burr dimensions. Reproduced from Toropov, A.; Ko, S.-L.; Kim, B.-K. Experimental Study of Burrs Formed in Feed Direction when Turning Aluminum Alloy Al6061-T6. *J. Mach. Tools Manuf.* 2005, *45*, 1015–1022.

Table 1 Tool geometry used in experiments

Rake angle α (°)	Clearance angle α_c (°)	Lead angle φ (°)	Inclination of major cutting edge (°)	End cutting edge angle (°)	End relief angle (°)
−5, 0, +5, +10, +20	5, 10, 15, 20	16, 32, 47, 66, 81	0	5	5

Reproduced from Toropov, A.; Ko, S.-L.; Kim, B.-K. Experimental Study of Burrs Formed in Feed Direction when Turning Aluminum Alloy Al6061-T6. *J. Mach. Tools Manuf.* **2005**, *45*, 1015–1022.

Table 2 Cutting conditions used in experiments

Cutting speed v (m min^{-1})	Feed rate f (mm rev^{-1})	Depth of cut t (mm)	Workpiece angle W (°)
800	0.05, 0.1, 0.15, 0.2	0.5, 1.0, 1.5, 2.0	90, 109, 118, 133, 147

Reproduced from Toropov, A.; Ko, S.-L.; Kim, B.-K. Experimental Study of Burrs Formed in Feed Direction when Turning Aluminum Alloy Al6061-T6. *J. Mach. Tools Manuf.* **2005**, *45*, 1015–1022.

Table 3 Constant cutting conditions used in experiments

Cutting speed v (m min^{-1})	Feed rate f (mm rev^{-1})	Depth of cut (mm)	Workpiece angle W (°)	Rake angle α (°)	Clearance angle α_c (°)	Inclination of major cutting edge (°)	End cutting edge angle (°)	End relief angle (°)
800	0.1	1	90	0	10	5	5	5

Reproduced from Toropov, A.; Ko, S.-L.; Kim, B.-K. Experimental Study of Burrs Formed in Feed Direction when Turning Aluminum Alloy Al6061-T6. *J. Mach. Tools Manuf.* **2005**, *45*, 1015–1022.

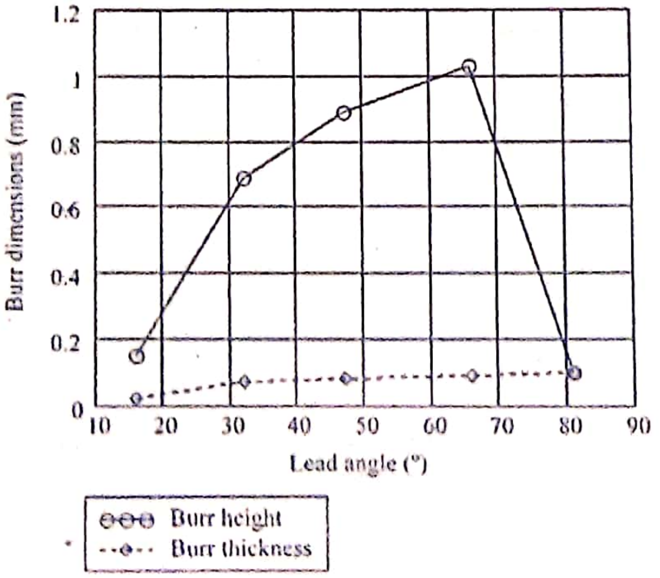


Figure 6 Burr dimensions vs tool lead angle (cutting conditions as in Table 3). Reproduced from Toropov, A.; Ko, S.-L.; Kim, B.-K. Experimental Study of Burrs Formed in Feed Direction when Turning Aluminum Alloy Al6061-T6. *J. Mach. Tools Manuf.* **2005**, *45*, 1015–1022.

functions of coolant is to cool at high temperature, it is possible that if coolant was employed in this research, a different response would have been obtained on the burr formation parameters.

Ma et al. (33) examined the suppression of burrs in turning with ultrasonic elliptical vibration cutting using theoretical models of the stresses of deformation zone on the workpiece edge in burr formation in ultrasonic elliptical vibration cutting based on three-dimensional cutting model. The theoretical model was clarified experimentally and observed that friction between the tool rake face and the chip is reduced or reversed by the elliptical vibration (34–36). The cutting conditions for the experiment are shown in Table 4.

The heights of the feed direction burrs measured in three cutting methods are shown in Figure 7. It can be understood that the heights of burrs generated in both conventional vibration cutting and elliptical vibration cutting were reduced and became smaller and smaller with the increase of maximum vibration speed to cutting speed ratio. Based on theoretical analysis, the authors believed that the pushing stress and bending stress of deformation zone on the workpiece edge in burr formation for two vibration-cutting methods are reduced due to the separating characteristics between the rake face of the tool and the chip, which resulted in decreased heights of the burrs. The authors observed that both the theoretical analysis and experimental results proved that burrs can be effectively suppressed by ultrasonic elliptical vibration cutting.

Table 4 Cutting conditions

Work material	
Size	Aluminum (52S)
Tool insert and its geometry	30 mm × 200 mm
	Carbide (rake angle: −5°)
	Clearance angle: 12°
	Approach angle: 65°
Cutting conditions	Nose radius: 0.1 mm
	Speed: 3.94–18.3 m min^{-1}
	Feed rate: 0.025 mm rev^{-1}
Vibration conditions	Depth of cut: 0.05 mm
	Locus: circle (radius: 3.5 μm)
	Linear (amplitude: 3.5 μm)
	Resonant frequency: 18.66 kHz

Reproduced from Ma, C.; Shamoto, E.; Moriwaki, T.; Zhang, Y.; Wang, L. Suppression of Burrs in Turning with Ultrasonic Elliptical Vibration Cutting. *Int. J. Mach. Tools Manuf.* 2005, *45*, 1295–1300.

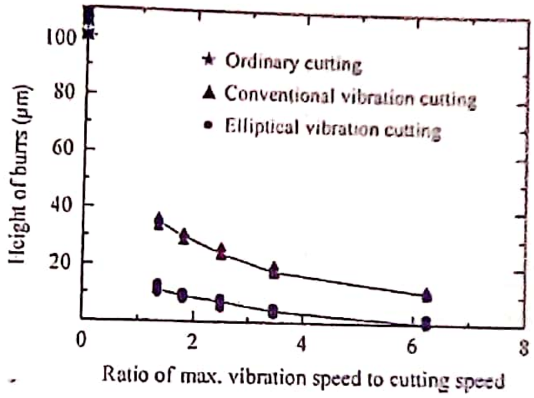


Figure 7 Height of burrs in three cutting methods. Reproduced from Ma, C.; Shamoto, E.; Moriwaki, T.; Zhang, Y.; Wang, L. Suppression of Burrs in Turning with Ultrasonic Elliptical Vibration Cutting. *Int. J. Mach. Tools Manuf.* 2005, *45*, 1295–1300.

It has been understood experimentally and theoretically that the friction between the tool rake and chip is reduced or reversed by the elliptical vibration. It is therefore suggested that an alternative or control experiment with the use of vegetable oil-based coolant, which has the ability to improve friction between tool rake and chip, be used to study the burr formation under these conditions.

11.12.3 Burr Formation in Drilling Process

Drilling is the most popular in machining, and burrs are formed in every machining process as a result of plastic deformation of the work material. Burrs are formed when a drill enters and exits the hole (37). In drilling, the burr that forms at the entrance of the hole can be as a result of tearing: a bending action followed by clean shearing or lateral extrusion. The burr that is formed when a sharp drill exits the workpiece is a Poisson burr resulting from rubbing at the margins of the drill, and when a normal or worn-out drill exits the uncut chip rolls, it results in a rollover burr (29). Serious problems in deburring occur on the exit stage when burrs formed are much larger or when the exit burr is formed inside a cavity or inside a crossing hole, because there are no tools available for deburring (37, 38) and sometimes, deburring is not possible.

Ko et al. (39) examined the effect of drill's geometry on burr formation. In their study, the need to use a drill with varying geometry, i.e., step angle and point angle, was emphasized. Two types of drills with a cutting speed of 35 m min^{-1} and five feed rates at 50, 100, 150, 200, and 250 mm min^{-1} were used for SM45C alloy steel. The two types of drills were conventional carbide drill

Table 5 Specification of drills for burr formation experiment

Drill	*Point angle, Θ_1 (°)*	*Diameter, D_1 (mm)*	*Step angle, Θ_2 (°)*	*Step diameter, D_2 (mm)*	*Step length, L (mm)*
Conventional drill	140	10	0	0	0
Step drill	140	10	130	8	2
	140	10	75	8	2
	140	10	60	8	2
	140	10	40	8	2

Reproduced from Ko, S.-L.; Chang, J.-E.; Yang, G.-E. Burr Minimizing Scheme in Drilling. *J. Mater. Process. Technol.* 2003, *140*, 237–242.

with a 140° angle and a step drill designed to contain two different cutting edges. Each cutting edge of the step drill had a specific angle and diameters of Θ_1 and Θ_2 and D_1 and D_2, respectively, and a step distance between edges was L. Table 5 presents the geometrical specification of the conventional drill with a 140° point angle and the step drills to compare burr formations.

The front cutting edge with 8.0 mm diameter and 140° angle performed the drilling. The step edge with a 75° step angle and 10.0 mm diameter removed the remaining part that resulted in a 10.0 mm hole. This experiment was conducted without using any coolant.

Figures 8 and 9 show the burr formation classification in drilling process and the burrs formed using two kinds of drill in this study, respectively. It was observed that the burr formed by the conventional drill had uniform shape (type B burr in Figure 8). The type B burr was formed using a step drill that first cut through the front edge, which was similar to conventional drilling. The second drill that cut through the step edges removed the burr formed during the first cutting and produced very small burrs, as shown in Figure 9. The cap remained with a 250 mm min^{-1} feed rate. This cap produced during the first drilling was attached to the burr formed in the second drilling. It was equally observed that, in the step drilling, only very tiny burrs that can be easily removed were formed. A laser sensor was used to measure burr geometry. The average burr heights were represented and compared in Figure 10. The burr height in conventional drills started at 0.14–0.33 mm and increased with the feed rate, which was larger than those ranging from 0.07 to 0.23 mm in step drills. It was noted that it was possible to effectively use the step drill in minimizing burr formation in this study.

This experiment was carried out without the use of coolant because the authors wanted to have a clear view of the burr formation process. The use of coolant could still be adopted as there are many types of coolant applications in machining processes. The application of coolant in this type of experiment could help to understand burr minimization in drilling better.

Dornfeld et al. (41) investigated the effects of tool geometry as well as process conditions on the drill burr formation using titanium alloy (Ti–6Al–4V) material. Drilling was done with solid carbide tools with and without coolant and high-speed cobalt drills without coolants. For the dry cutting, two different types of carbide drills were used with the following geometries: (a) two-flute drill 6.35 mm diameter and 118° point angle and (b) three-flute drill of 6.35 mm diameter, 150° point angle, both with 25° helix angle. The cutting conditions involved were cutting speed, 36.6 and 42.7 m min^{-1}, and three levels of feed rate, 0.0254,

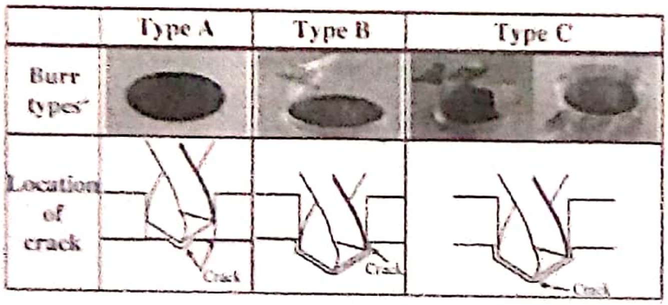


Figure 8 Classification of burr formation in drilling. Reproduced from Ko, S.-L.; Chang, J.-E.; Yang, G.-E. Burr Minimizing Scheme in Drilling. *J. Mater. Process. Technol.* 2003, *140*, 237–242.

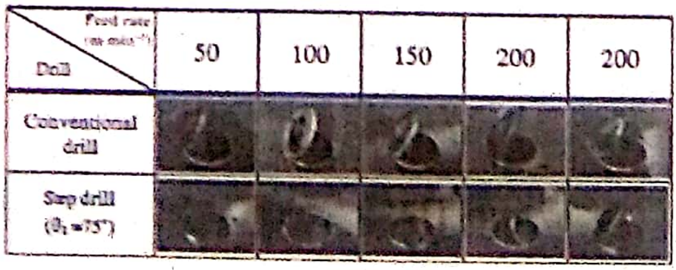


Figure 9 Burr formation in each drilling operation for SM45C. Reproduced from Ko, S.-L.; Chang, J.-E.; Yang, G.-E. Burr Minimizing Scheme in Drilling. *J. Mater. Process. Technol.* 2003, *140*, 237–242.

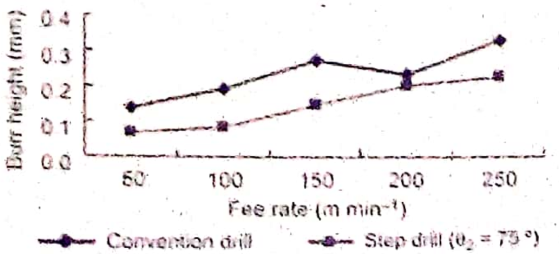


Figure 10 Burr height in each drilling operation for SM45C. Reproduced from Ko, S.-L.; Chang, J.-E.; Yang, G.-E. Burr Minimizing Scheme in Drilling. *J. Mater. Process. Technol.* 2003, *140*, 237–242.

Table 6 Tool geometry for wet cutting

Group	*Point style*	*Point angle (°)*	*Helix angle (°)*	*Lip relief angle (°)*
1	Split point	135	35	12
2	Split point	130	35	12
3	Split point	118	35	12
4	Split point	135	35	10
5	Split point	135	35	14
6	Split point	135	30	12
7	Helical point	135	30	12

Reproduced from Dornfeld, D. A.; Kim, J. S.; Dechow, H.; Hewson, J.; Chen, L. J. Drilling Burr Formation in Titanium Alloy, Ti-6Al-4V. CIRP Ann. 1999, 48 (1), 73–76.

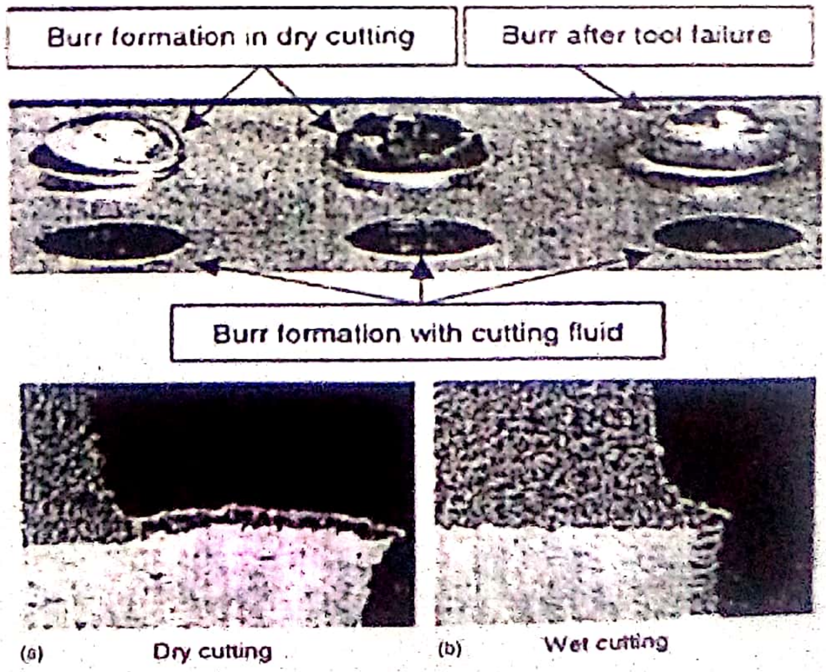
0.0508, and 0.0762 mm rev^{-1} were selected for each types of drill, hence a total of 12 cutting conditions (42). For the wet cutting conditions, two sets of drilling experiments were conducted with coolant. The first experiment was to determine the infiuence of the tool geometry on the burr formation, and the second experiment was designed to determine the influence of the cutting conditions such as feed rate and cutting speed on burr formation. Cobalt high speed steel drills with diameter 10 mm and various tool geometries as shown in Table 6 were used.

All the experiments were conducted on Ti-6Al-4V plates of 125 mm × 100 mm × 6 mm using a CNC-milling machine. The following observations were made by the authors:

1. Four types of burr formations, uniform burr, lean back burr, roll back burr, and roll back burr with widened exit, were seen in dry cutting of Ti–6Al–4V.
2. Roll back burr due to thermal effects was observed in dry cutting with relatively high feed rates and cutting speeds. This was confirmed by comparison with burrs in wet cutting with reduced thermal effects.
3. Ring formation burr was observed in wet cutting and is an intermediate type between plain uniform burr without attachment and a burr with a drill cap formation.
4. Geometry of the drill greatly affects burr formation; helical point drill produced smaller burrs than split point drill, larger helix angle and increasing point angle both reduced burr height and thickness.

In this study, an attempt was made to compare the effects of coolant on burr formation during drilling of Ti–6Al–4V alloy. It is clearly depicted in Figure 11 that the use of coolant can improve the burr formation during any machining processes (43). It confirmed that the need to take the temperature dependency of material properties into account when explaining burr formation phenomena is very significant.

Lin and Shyu (44) described an experimental investigation of improvement of tool life and exit burr using variable feeds when drilling stainless steel with coated drills. The experiment was conducted on a CNC machine using an austenitic stainless steel plates



(a) Dry cutting (b) Wet cutting

Figure 11 Burrs observed in drilling Ti–6Al–4V. Reproduced from Dechow, H. Influence of the Tool on Hole Quality when Drilling Ti-6Al-4V Including the Aspects of Reaming. Diploma-Thesis Study, LMA, University of California, Berkeley.

SUS 304 of 150 mm × 100 mm × 15 mm with four types of twist drills (TiN, TiCN, CrN, and TiALN) coating standard HSS drills. The diameter of the drill and the cutting speed employed was 8 mm and 25.2 m min^{-1}, respectively. The thickness of all the coatings on the drills was 3 μm. A chuck was used to hold the drills and a water-soluble coolant was supplied at a rate of 5.01 L min^{-1}. The authors observed that the burr formation was severe in the exit zone when drilling stainless steel; they suggested that it may be due to the high toughness of the stainless steel. Figure 12 indicates the exit burr height for the holes for constant and variable feed machining with a TiN-coated drill. It can be seen that the maximum burr height occurred with constant feed machining.

The amplitude of variation $a = 0.8$ represents a lower feed at the exit zone and a higher feed at the middle zone. However, it does not produce the lower burr height, as seen from this figure. This is due to the increased outer corner wear of the drill at the higher feed machining in the middle zone. The burr height is smallest when the amplitude of the variation $a = 0.6$. Figure 13 shows the burr height versus holes for the four different coated drills. The TiN-coated drill showed the smallest burr height while the

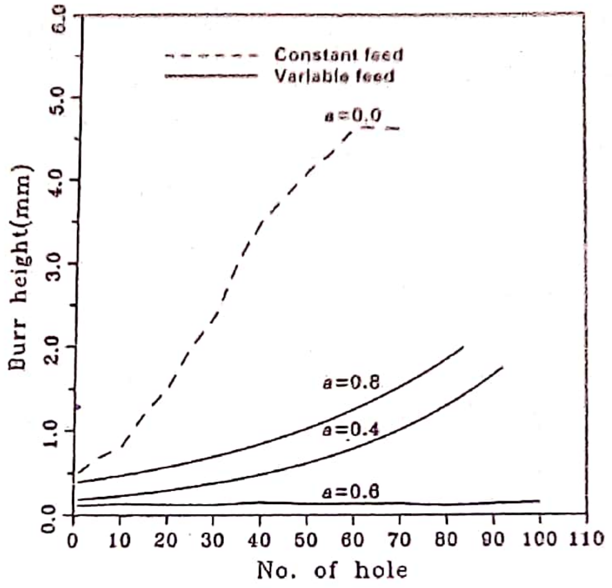


Figure 12 Burr height vs holes for constant and variable feed machining Ti-coated drill. Reproduced from Lin, T.-R.; Shyu, R.-F. Improvement of Tool Life and Exit Burr Using Variable Feeds when Drilling Stainless Steel with Coated Drills. *Int. J. Adv. Manuf. Technol.* 2000, *16*, 308–313.

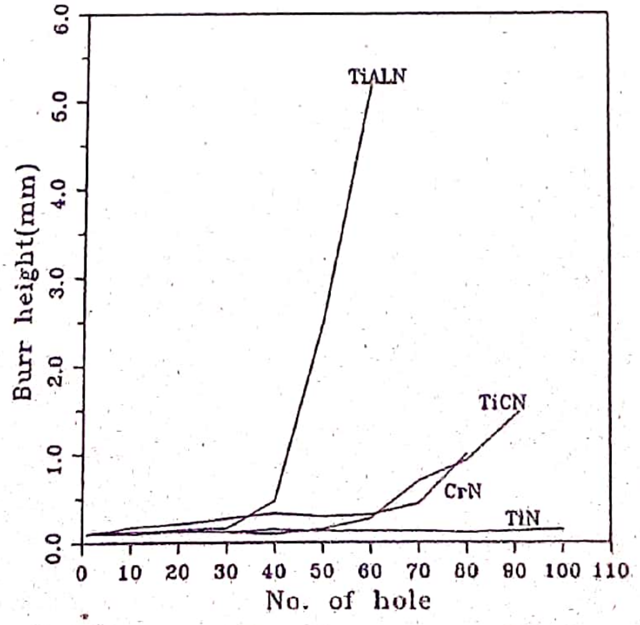


Figure 13 Burr height vs holes for variable feed machining when the amplitude of variation $a = 0.6$. Reproduced from Lin, T.-R.; Shyu, R.-F. Improvement of Tool Life and Exit Burr Using Variable Feeds when Drilling Stainless Steel with Coated Drills. *Int. J. Adv. Manuf. Technol.* 2000, *16*, 308–313.

TiAlN-coated drill exhibited the largest burr height. It was also found that the burr height increases suddenly during the drilling of the last holes for most of the coated drills.

It was observed that the variable feed machining was superior to constant feed machining with respect to tool life or burr height and the amplitude of variation of feed $a = 0.5$ is optimum for maximum tool life or minimum burr height.

The authors employed a water-soluble coolant supplied at a rate of 5.0 l L min^{-1}, this is the only information about the application of coolant in this experiment, it was never considered during the analysis of results because a control experiment was not set up. To determine the effect of coolant in this type of experimental setup, a conuol experiment is necessary. This will help to understand the role played by the application of coolant in the setup.

11.12.4 Burr Formation in Milling Process

The type of burr in milling has been described by Chern (21) as highly dependent on the in-plane exit angle. He observed five types of burrs in milling process: (1) knife-type burr, (2) wave type burr, (3) curl type burr, (4) edge breakout burr, and (5) secondary burr. Olvera and Barrow (45) studied the influence of cutting parameters on the formation of burrs in square shoulder face milling. Exit burr in the cutting direction, exit burr in the feed direction, and burr formed at the top edge were discussed through their extensive experimental research. Another study of burr formation was done by Lin (46). He conducted a series of single-tooth face milling tests on stainless steel to study burr formation and tool chipping. He found that the burr formation is closely related to the chipping depth of tool edge. Chern (47) observed burr formation and edge breakout on the workpiece exit edge in orthogonal cutting and in face milling of aluminum alloys. Kishimoto et al. (48) conducted face milling experiments in normalized carbon steel S45C to investigate the burr formation in connection with cutting conditions and tool geometry. In their tests, two types of burrs were found and named (1) primary burr and (2) secondary burr. The primary burr is the rollover burr produced on the tool exit edge. The burr thickness was found to vary from minimum burr thickness to maximum burr thickness along the length of the burr.

Chern (21) experimentally examined burr formation mechanism in face milling of aluminum alloys. The experiment involved the use of three types of aluminum alloys (Al1100, Al2024-T4, and Al6061-T6) with a fly milling cutter (tool bit) made of high-speed steel. The cutting speed, which had been found to have insignificant influence on burr formation (47,49), was fixed for all the tests. Tables 7 and 8 show the cutting conditions and tool geometry.

The following were observed: (1) in-plane exit angle strongly influences the geometry of the burrs in face milling and the five types of burrs were created in the experiments on aluminum alloys; (2) wave-type burr was created when in-plane exit angle approximates 90°, wave-type burr will increase the difficulty of deburring due to its complexity of geometric shape and larger thickness and thus should be avoided, and (3) formation of the secondary burr was dominated by the depth of cut, with some influence of increase in the feed rate. The value of the critical depth of cut for the secondary burr increased with in-plane exit angle and fracture strain of the workpiece.

This study involved the burr formation in the face milling process by investigating the influence of cutting conditions on burr formation in face milling of aluminum alloys. The cutting conditions show that the experiment was conducted without the use of coolant. It is likely that the application of coolant in this study will alter the results of the experiment, since the temperature of the material will definitely change under coolant condition.

Heisel et al. (50) examined burr formation in milling with minimum quantity lubrication (MQL). The tests were conducted on an EX-CELL-O XHC241 machine center using a single channel unit of Lubrix as the MQL system. Ecocut Mikro plus 82 developed

Table 7 Cutting conditions

Cutting speed	2.48 m s^{-1} (fixed)
Depth of cut	0.25–2.00 mm
Feed rate	0.03–0.46 mm per tooth
In-plane exit angle	30–165°
Cutting fluid	Air

Reproduced from Olvera, O.; Barrow, G. An Experimental Study of Burr Formation in Square Shoulder Face Milling. *Int. J. Mach. Tools Manuf.* 1996, *36* (9), 1005–1020.

Table 8 Tool geometry

Geometry	*Unit*
Corner angle	30°
Axial relief angle	15°
End cutting edge angle	10°
Axial rake angle	15°
Radial rake angle	0°
Nose radius	1 mm

Reproduced from Olvera, O.; Barrow, G. An Experimental Study of Burr Formation in Square Shoulder Face Milling. *Int. J. Mach. Tools Manuf.* 1996, *36* (9), 1005–1020.

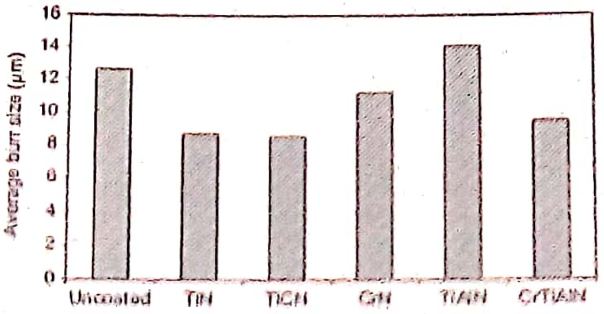


Figure 14 Burr formation. Reproduced from Aramcharoen, A., Mativenga, P. T., Yang, S., Cooke, K. E., Teer, D. G. Evaluation and Selection of Hard Coatings for Micro-milling of Hardened Tool Steel. *Int. J. Mach. Tools Manuf.* 2008, *48*, 1578–1584.

especially for MQL machining and based on special fatty alcohols was used as lubricant. A face milling cutter and an angle milling cutter were used as test tools. The CVD coated indexable inserts have a layer structure of TiCN + Al_2O_3 (+ TiN) and a cutting edge length of $b = 1.2$ mm. The tool cutting edge angle is $k = 90°$ for both milling cutters. The heat-treatable steel C45E was used as reference material. The face milling cutter has a diameter of $d = 50$ mm, a helix angle of $\delta = 12°$, and six indexable inserts. It can be used for a cutting speed of up to $v_c = 250$ m min^{-1} and a depth of cut of $a_p = 11$ mm. The angle milling cutter has a diameter (d) of 25 mm, a helix angle of $\delta = 8°$, and three indexable inserts. It can be used for the same parameters as the face milling cutter. The indexable inserts used were identical for both tools and merely differed in corner radius, which was $r_\varepsilon = 0.4$, 0.8, and 1.2 mm for the tests. The cutting speed was $v_c = 225$ m min^{-1} for the comparative tests, and the feed per tooth (fz) was 0.11 mm rev^{-1}. For further tests, the cutting speed was varied in the range from $v_c = 150$ to 225 m min^{-1}, and the feed per tooth was varied in the range between $fz = 0.05$ and 0.11 mm. The tests were performed at a constant depth of cut of $a_p = 3$ mm. In addition to that, the width of cut a_e was varied. Concerning the face milling cutter, the milling was conducted in the middle of the workpiece with a width of cut of $a_e = 12.5$, 25, and 37.5 mm. Regarding the angle milling cutter, widths of cut of $a_e = 6.25$, 12.5, 18.75, and 23.5 mm were investigated.

The results obtained show that the burr value increases in the machining with minimum quantity lubrication compared to dry machining, but does not change when varying the minimum quantity. A variation in cutting speed at constant feed showed no considerable influence on burr formation. However, when varying the feed per tooth, the exit burr curve of the lateral face shifts toward higher values in dry machining compared with minimum quantity lubrication. Regarding angle milling cutters, investigations into the influence of corner radius revealed that the burr value increases with growing corner radius. In face milling, it can be detected that the burr value decreases with increasing corner radius. The supply of the fluid to the cutting region is another parameter that was varied within the framework of these investigations. In this connection, the supply of the fluid through an external nozzle proved to be disadvantageous. The burr values of the exit burrs were higher than those of the internal supply and dry machining.

The results of this experiment show that it is not only the application of coolant that can have an effect on the machining output, but also the method of applications such as conventional method (flooding), high-pressure coolant, and MQL will in one way or the other affect the burr formation mechanism in any machining processes.

Aramcharoen et al. (*51*) evaluated some selected hard coatings for micromilling of hardened tool steels. The experiment involved the use of hardened H13 tool steel (45HRC) as workpiece material and a cutting tool made from ultrafine tungsten carbide grain structure with a two-flute flat microend mill. The tools were coated using (CFUBMSIP) technology (*52*) in TiN, CrN, TiCN, TiAlN, and CrTiAlN coatings (*34*) and the evaluation of coating performance carried out at cutting conditions. Cutting parameters were a spindle speed of 30 000 rpm, depth of cut of 20 mm, maximum undeformed chip thickness of 5 mm, and feed rate of 300 mm min^{-1}. After machining, tool wear condition was evaluated using the SEM.

One of the observations made by the authors, which is relevant to this chapter is that, in general, most coatings led to reduced burr size compared to the uncoated tools, as shown in Figure 14.

Thus both a sharp cutting edge (as reported in the literature) and thin, high-performance tool coatings are essential in reducing burr size. The use of a coating (with good adhesion) provides some protection from chipping for the cutting edge and also slows down along cutting edge radius. Otherwise, increased edge radius results in more negative rake angles, which promote a plowing mechanism for material removal and burr formation. This experiment was conducted without the use of coolant; these results could be improved with the application of coolants.

11.12.5 Conclusion and Future Research Direction

Types of machining process, the process parameters, tool property, tool geometry, tool edge configuration, coolant, and workpiece material properties are reported to be responsible for burr formations in machining processes. The influence of the tool lead angle (Θ) on the burr dimension has been established. It was observed that the smaller the lead angle (Θ), the increased probability that sideward or Poisson burr would be formed during turning of aluminum alloy Al6061-T6 with a K10 grade tungsten carbide–cobalt alloy tool. The use of an ultrasonic elliptical vibration system during machining of aluminum 52S with a carbide tool was found to be capable of suppressing burr formation during turning.

The type of drills used in drilling process was found to have an effect on the burr height. For instance, the burr height in a conventional drill started at 0.14–0.31 mm and increased with feed rate, which was found to be larger than those in the range of 0.07–0.21 mm in step drills while drilling SM45C alloy material. It was equally observed that geometry of the drill greatly affects burr formation; a helical point drill produced smaller burrs than a split point drill, and larger helix angle and increasing point angle both reduced burr height and thickness during drilling of Ti–6Al–4V material with cobalt high-speed drills. Burr formation in face milling process by investigating the influence of cutting conditions on burr formation in face milling of aluminum alloys shows that the value of the critical depth of cut for the secondary burr increased with in-plane exit angle and fracture strain of the workpiece.

The role of different coolants and method of application on burr formation has not been thoroughly investigated. Since burr formation is a complicated process and its formation involves large plastic deformation of work material, any factor that affects the temperature behavior of the material must be investigated. For instance, ring formation burr was observed in wet cutting and was an intermediate type between plain uniform burr without attachment and a burr with a drill cap formation during drilling of Ti–6Al–4V material with cobalt high-speed drills. This affirmed the need for research work to be focused on the effect of coolant on burr formation mechanism.

References

1. Auchi, J. C.; Dornfeld, D.; Arrazola, P. J.; Franke, V.; Leitz, L.; Min, S. Burrs-Analysis, Control and Removal. *CIRP Ann. Manuf. Technol.* **2009,** *58*, 519–542.
2. Long, Yu; Guo, Changsheng. Finite Element Modeling of Burr Formation in Orthogonal Cutting. *Mach. Sci. Technol. Int. J.* **2012,** *16* (3), 321–336.
3. Schäfer, F. *Deburring*; Krausskopfverlag: Mainz, 1975 (in German).
4. International Standard ISO 13715. Technical Drawings – Edges of Undefined Shape – Vocabulary and Indications, 2000.
5. Ko, S. L.; Dornfeld, D. A. A Study on Burr Formation Mechanism. *Trans. ASME J. Eng. Mater. Technol.* **1991,** *113* (1), 75–87.
6. Gillespie, L. K. The Battle of the Burr: New Strategies and New Tricks. *Manuf. Eng.* **1996,** *116* (2), 69–78.
7. Beier, H. M. *Handbuch Entgrattechnik: Wegweiser zur Gratminimierung und Gratbeseitigung für Konstruktion und Fertigung*; Hanser Verlag, 1999.
8. Pekelharing, A. J. Why and How Does the Chip Curl and Break. *CIRP Ann.* **1964,** *12* (3), 144–147.
9. Gillespie, L. K.; Blotter, P. T. The Formation and Properties of Machining Burrs. *Trans. ASME J. Eng. Ind.* **1976,** *98*, 66–74.
10. Gillespie, L. K. *Quantitative Approach to vibratory deburring effectiveness*. SME Technical paper MRR75-11, 1975.
11. Ko, S. L.; Dornfeld, D. A. Analysis and Modeling of Burr Formation and Breakout in Metal. In *Mechanics and Deburring and Surface Finishing Process*; Stango, R. J., Fitzpatrick, P. R., Eds.; American Society for Mechanical Engineering: New York, 1989; pp 79–91.
12. Leopold, J.; Schmidt, G.; Hoyer, K.; Freitag, A. Modeling and Simulation of Burr Formation – State of the Art and Future Trends. In *Proceedings of the 8th International Workshop on Modeling of Machining Operations*, Chemnitz, Germany, 2005; pp 73–83.
13. Gillespie, L. K. Deburring Precision Miniature Parts. *Precis. Eng.* **1979,** *1* (4), 189–198.
14. Nakayama, K.; Arai, M. Burr Formation in Metal Cutting. *CIRP Ann.* **1987,** *36* (1), 33–36.
15. Kishimoto, W.; Miyake, T.; Yamamoto, A.; Yamanaka, K.; Takano, K. Study of Burr Formation in Face Milling. *Bull. Jpn. Soc. Precis. Eng.* **1981,** *15* (1), 51–53.
16. Kim, J.; Min, S.; Dornfeld, D. A. Optimization and Control of Drilling Burr Formation of AISI 304 L and AISI 4118 Based on Drilling Burr Control Charts. *Int. J. Mach. Tools Manuf.* **2001,** *41*, 923–936.
17. Min, S.; Dornfeld, D. A.; Kim, J.; Shyu, B. *Finite Element Modeling of Burr Formation in Metal Cutting*; Consortium on Deburring and Edge Finishing, Laboratory for Manufacturing and Sustainability, UC Berkeley, 2007.
18. Pande, S. S.; Relekar, H. P. Investigations on Reducing Burr Formation in Drilling. *Int. J. Mach. Tools Des. Res.* **1986,** *26* (3), 339–348.
19. Stein, J. M.; Dornfeld, D. A. Burr Formation in Drilling Miniature Holes. *CIRP Ann.* **1997,** *46* (1), 63–66.
20. Min, S.; Dornfeld, D. A. *Technology Assessment on Current Advanced Research Projects in Burr Formation and Deburring*. Report; The Association for Manufacturing Technology, 2004.
21. Chern, G. L. Experimental Observation and Analysis of Burr Formation Mechanism in Face Milling of Aluminum Alloys. *Int. J. Mach. Tools Manuf.* **2006,** *46*, 1517–1525.
22. Park, I. W.; Dornfeld, D. A. A Study on Burr Formation Processes Using the Finite Element Method: Part I. Transaction of ASME. *J. Eng. Mater. Technol.* **2000,** *122*, 221–228.
23. Link, R. Gradtbildung und strategien zur gratreduzierung bei der zerspanung mit geometrisch bestimmter schneide. Ph.D. dissertation, RWTH Aachen, Germany, 1992.
24. Kajdas, C. Additives for Metalworking Lubricants - a Review. *Lubr. Sci.* **1989,** *1* (4), 385–409.
25. Belluco, W.; De Chiffre, L. Surface Integrity and Part Accuracy in Reaming and Tapping Stainless Steel with New Vegetable Based Cutting Oils. *Tribol. Int.* **2002,** *35*, 865–870.
26. Belluco, W.; De Chiffre, L. Testing of Vegetable Based Cutting Fluids by Hole Making Operations. *Lubr. Eng.* **2001,** *57* (1), 12–16.
27. Belluco, W.; De Chiffre, L. Performance Evaluation of Vegetable – Based Oils in Drilling Austenitic Stainless Steel. *J. Mater. Process. Technol.* **2004,** *148*, 171–176.
28. Huseyin, M. Cetin; Ozcelik, Babur; Kuram, Emel; Demirbas, Erhan Evaluation of Vegetable Based Cutting Fluids with Extreme Pressure and Cutting Parameters in Turning of AISI 304L by Taguchi Method. *J. Cleaner Prod.* **2011,** *19*, 2049–2056.
29. Gillespie, L. K. *Deburring and Edge Finishing Handbook*; Society of Manufacturing Engineers: New York, 1999.
30. Pavel, Radu; Marinescu, Ioan; Deis, Mick; Pillar, Jim Effect of Tool Wear on Surface Finish for a Case of Continuous and Interrupted Hard Turning. *J. Mater. Process. Technol.* **2005,** *170*, 341–349.
31. Toropov, Andrey; Ko, Sung-Lim; Kim, Byung-Kwon Experimental Study of Burrs Formed in Feed Direction when Turning Aluminum Alloy Al6061-T6. *J. Mach. Tools Manuf.* **2005,** *45*, 1015–1022.
32. Ko, S. L.; Lee, J. K. Development of Burr Measurement System Using Laser and Its Application. In *Proceedings of the Sixth International Conference Precision Surface Finishing and Deburring Technology*, St. Petersburg, 21–23 Sept 2000; pp 109–123.
33. Ma, Chunxiang; Shamoto, E.; Moriwaki, T.; Zhang, Yonghong; Wang, Lijiang Suppression of Burrs in Turning with Ultrasonic Elliptical Vibration Cutting. *Int. J. Mach. Tools Manuf.* **2005,** *45*, 1295–1300.
34. Shamoto, E.; Moriwaki, T. Elliptical Vibration Cutting. *CIRP Ann.* **1994,** *43*, 35–38.
35. Shamoto, E.; Morimoto, Y.; Moriwaki, T. Elliptical Vibration Cutting (The Second Report). *J. Jpn. Soc. Precis. Eng.* **1999,** *65*, 411–417.
36. Ma, C.; Shamoto, E.; Moriwaki, T.; Wang, L. Study of Machine Accuracy in Ultrasonic Elliptical Vibration Cutting. *Int. J. Mach. Tools Manuf.* **2004,** *44*, 1305–1310.
37. Stein, J. M. Burr Formation in Precision Drilling of Stainless Steel. Ph.D. Dissertation, University of California, Berkeley, 1995.
38. Stein, J. M. Influence of Workpiece Exit Angle on Burr Formation in Drilling Intersecting Holes. *Trans. NAMRI/SME* **1998,** [illegible]

39. Ko, Sung-Lim; Chang, Jae-Eun; Yang, Gyun-Eui Burr Minimizing Scheme in Drilling. *J. Mater. Process. Technol.* **2003,** *140,* 237–242.
40. Ko, S. L.; Lee, J.-K. Analysis on Burr Formation in Drilling with New Concept Drill. *J. Mater. Process. Technol.* **2001,** *113,* 392–398.
41. Dornfeld, D. A.; Kim, J. S.; Dechow, H.; Hewson, J.; Chen, L. J. Drilling Burr Formation in Titanium Alloy, Ti-6Al-4V. *CIRP Ann.* **1999,** *48* (1), 73–76.
42. Communication with Chen, L. J.; El-Wardany, T. of United Technology Research Centre.
43. Dechow, H. Influence of the Tool on Hole Quality when Drilling Ti-6Al-4V Including the Aspects of Reaming. Diploma-Thesis Study, LMA, University of California, Berkeley.
44. Lin, T.-R.; Shyu, R.-F. Improvement of Tool Life and Exit Burr Using Variable Feeds when Drilling Stainless Steel with Coated Drills. *Int. J. Adv. Manuf. Technol.* **2000,** *16,* 308–313.
45. Olvera, O.; Barrow, G. An Experimental Study of Burr Formation in Square Shoulder Face Milling. *Int. J. Mach. Tools Manuf.* **1996,** *36* (9), 1005–1020.
46. Lin, T. S. Experimental Study of Burr Formation and Tool Chipping in the Face Milling of Stainless Steel. *J. Mater. Process. Technol.* **2000,** *108* (1), 12–20.
47. Chern, G. L. Analysis of Burr Formation and Breakout in Metal Cutting, Ph.D. Thesis, University of California, Berkeley, CA, 1993.
48. Kishimoto, W.; Miyake, T.; Yamamoto, A.; Yamanaka, K.; Takano, K. Study of Burr Formation in Face Milling. *Bull. JSPE* **1981,** *15* (1), 51–52.
49. Chern, G. L., Dornfeld, D. A. Burr/Breakout Models Development and Experimental Verification. *J. Eng. Mater. Technol.* **1996,** *118,* 201–206.
50. Heisel, U.; Schaal, M.; Wolf, G. Burr Formation in Milling with Minimum Quantity Lubrication. *J. Prod. Eng. Res. Dev.* **2009,** *3,* 23–30.
51. Aramcharoen, A.; Mativenga, P. T.; Yang, S.; Cooke, K. E.; Teer, D. G. Evaluation and Selection of Hard Coatings for Micro-milling of Hardened Tool Steel. *Int. J. Mach. Tools Manuf.* **2008,** *48,* 1578–1584.
52. Teer, D. G. Magnetron Sputter Ion Plating. U.S. Patent No. 5556519, 17 September, 1996.