Review of Burr Minimization Approaches

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Abstract

This paper aims to review researches in milling burr formation as classified by the 4 levels of integration of design and manufacturing proposed by Stein (1996). It summarizes approaches taken by a number of researchers to study burr formation as well as relevant matters. Detailed studies on deburring process, however, are not included due to space limitations. Lastly, future directions on burr research are provided.

1. Introduction

In manufacturing environment, machining processes often introduce edge imperfections on to the part produced. Such edge defects may be in the form of protruding, ragged material along part's edges, known as burrs. The study of burr formation and deburring first received much attention from researchers in the early 1970s. Since then, many researchers and companies have developed a vast amount of deburring techniques tailored to different workpiece setups. The Society of Manufacturing Engineers (SME) and a number of researchers have attempted to develop the general guidelines for deburring process selection. Researchers at academic institutions paid close attentions to burr formation mechanisms as well as deburring process improvement.

Due to many reasons that lead to difficulties in deburring operation, much of research efforts have been spent on deburring process improvement. A far less number of researchers focused on the understanding of burr formation mechanisms. By studying the key parameters governing burr formation, researchers can gain useful insights in selecting part design and machining process parameters in order to minimize burr formation. Therefore, further necessary edge finishing operation is minimized. Clearly, the edge finishing problem should be addressed as early as in the part designing and process planning stages.

This paper aims to review researches in milling burr formation as classified by the 4 levels of integration of design and manufacturing proposed by Stein (1996). First, however, the focus will be on researches in characterizing burrs and the use of burr prediction scheme to evaluate different process plans. When this background is laid out, researches on how part design (level I) and machining process parameters (levels II and III) might affect burr formation will be addressed.

While precision deburring, specifically chamfering, had received much attention from researchers in robotics community, it will not be discussed here. Deburring process mechanics will be addressed minimally with the emphasis on material removal mechanism in the interest of evaluating deburring cost more effectively. The issue of deburring planning with the objective to minimize the deburring cost will be of the main focus at this level IV of the integration.

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2. Burr Characterization and Prediction

The fundamental burr formation mechanism is found to consist of 4 stages (Park, 1996): initiation, initial development, pivoting point, and final development stages. The initial stage represents the point where the plastically deformed region appears on the edge of the workpiece. In the initial development stage, significant deflection of the workpiece edge occurs. The mechanism involved in this stage is similar to bending deformation. The pivoting point stage represents the point where material instability occurs at the workpiece edge. From this stage on, catastrophic bending at the workpiece edge occurs. In the final development stage, a burr is further developed with the influence of the negative deformation zone formed by a shearing process. Hence, plastic bending and shearing are the dominant mechanisms in this stage. Depending on the cutting conditions and material properties, edge breakout can occur through the negative deformation zone. Many researchers believe burr characteristics may be useful indication of the burr formation mechanism.

2.1 Burr Characterization

Burrs are normally characterized by their height and thickness. The usual definition of burr height and thickness is shown in Figure 1(a) below. Burr thickness is long considered the key measure of difficulty in deburring. Implicitly, it also represents a lower bound on chamfer depth achievable on the part's edge. The deburring process selected must be capable of creating at least that minimum chamfer depth in order to assure complete burr removal. Burr height, on the other hand, is used to determine the time required for the part to spend in a deburring cell.

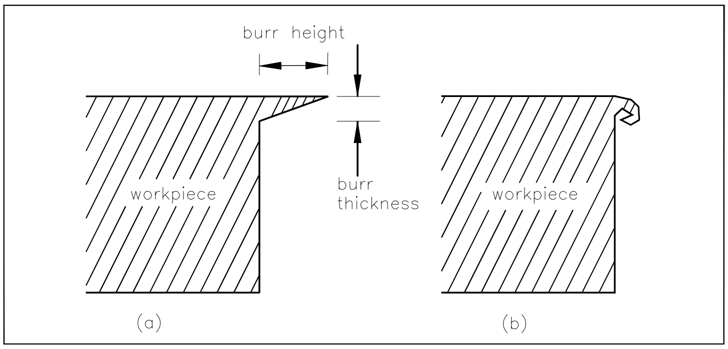

Figure 1. (a) Burr size measurement, and (b) its difficulty

Needless to say, burr size measurement received special attention from researchers. It is the most fundamental form to quantify burr characteristics. Yet burr size measurement is found to be a tedious task and, sometimes, left to engineering judgement. An example of burr that is difficult to measure is shown in Figure 1(b). Schafer (1975a) proposed to describe these types of burr through 4 quadrants defined by the two intersecting surfaces. Konig (1993) defined "burr value" in terms of burr height, thickness, and its root radius.

Research in burr measurement has been driven by the need for deburring automation. Careful burr measurement through optical microscope is only acceptable in research laboratory. The need to perform deburring planning in real time had been addressed by Stein, et al. (1993). Computer vision system is, by far, the most popular. The technique calls for placing laser beam across the part's edge. Disruption in the laser beam as observed by camera can be calibrated for burr size calculation. Work material's reflectivity, its orientation, lighting condition, and camera resolution present great challenges in using this technique to automate burr measurement.

Gillespie (1973) was among the first researchers to study burr formation. He identified basic mechanisms of burr formation as lateral deformation of material, bending and tearing of the chip. Nakayama (1987) proposed the burr formation scheme based on the cutting edge involved and burr location. His scheme is applicable across different machining processes. His burr nomenclature for milling is shown in Figure 2.

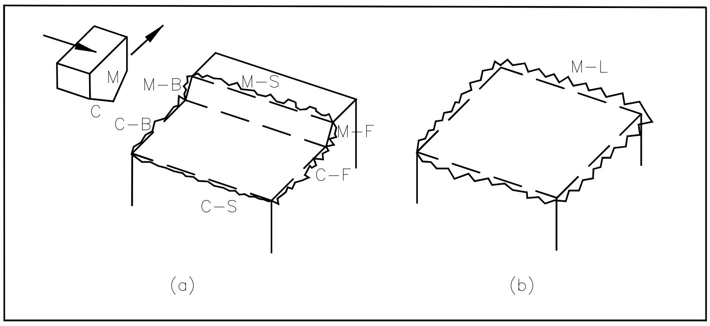

Figure 2. Schematics of milling burr classification

Table 1. Two systems of machining burrs classification (Nakayama (1987))

		Symbol
(1)	Cutting edge directly concerned	
	Major cutting edge	M
	Minor cutting edge	C
(2)	Mode and direction of formation	
	Backward flow (entrance burr)	B
	Sideward flow (sideward burr)	S
	Forward flow (exit burr)	F
	Leaning to feed direction (Leaned burr)	L

The notation used to describe burrs is shown in the Table 1. The cutting edges involved are classified into major (M) and minor (C) cutting edges. Burr formation mechanism is described in terms of direction of formation, i.e. forward or sideward. The information about burr shape is not addressed.

Chern (1993) has observed exit burrs in different shapes during his experimental study on Aluminum. He found burr shapes produced to be among knife-type, curl-type, wave-type, edge breakout, and secondary burrs as shown in Figure 3 below. The transition from one burr shape to another was found depending upon in-plane exit angle. Here, his burr shape scheme is limited to merely exit burrs found in Aluminum alloy.

Gillespie attempted developing the standard for burr nomenclature and edge finishing requirement for the part. His proposed standard (1995) included edge quality requirement for the parts, burr appearance, and its formation mechanism. Edge quality and standard specified for deburring purpose is of practical value. The relationship between burr appearance and its formation mechanism, however, is unclear.

2.2 Burr Prediction

When a process planner designs a process plan to minimize burr formation, the need to predict burr size accurately before hand becomes apparent. The ability to predict burr size and its location provides infrastructure for process plan optimization. Different process plans can be compared in terms of burr sizes, locations, shapes, and profile. The burr profile information can then be used further in deburring planning. Burr size and its location lead to deburring process selection, while burr size variation can warn deburring planners of problematic areas where drastic change in burr cross-sectional area will take place. Figure 4 shows an example of a "watch-out" point where there is a transition between primary and secondary burrs. Certainly, significant change in burr size can occur within primary burr region itself and therefore, complete burr size profile is necessary.

Researchers have developed analytical tools for burr prediction. Sokolowski et al. (1994) attempted using neural networks and fuzzy logic for burr prediction in face milling. Their models were based on an experimental study by Girase (1992). Both methods perform comparably well. Park (1996) used finite element model to study burr formation mechanism in orthogonal machining. He primarily studied the effect of edge angle and the tool's rake angle. The results of his models correspond well with experimental results by other researchers such as Guicheng (1994). He also developed burr control chart that combines experimental data and probability model to predict burr type. This analytical model incorporates feed per tooth, depth of cut, in-plane exit angle, and its gradient into the prediction of burr type.

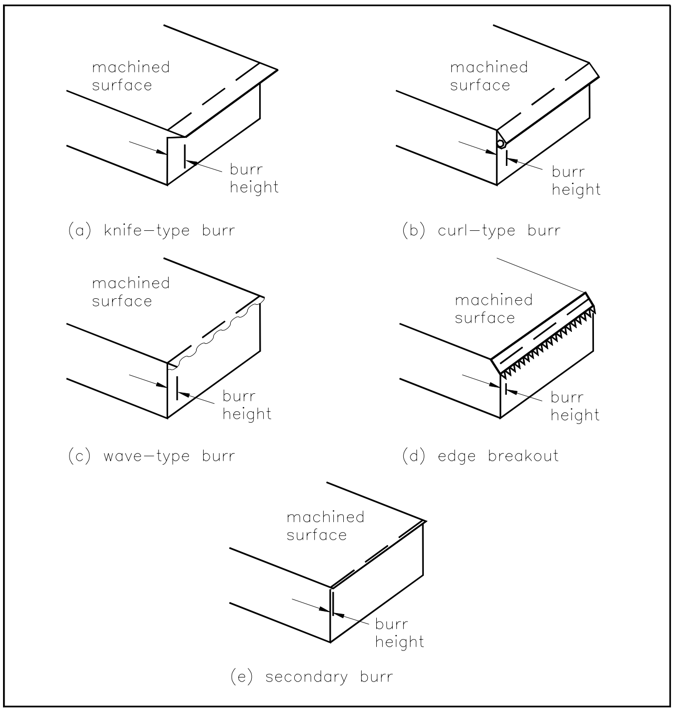

Figure 3. Exit burr shapes observed by Chern

Burr size can also be predicted using pre-existing burr database. With the data-driven model, the appropriate interpolation scheme between data points can provide reasonable estimates on burr size. This scheme was used in Narayanaswami (1995) and Abeyta (1995) as they developed software tools for milling tool path planning.

It should be noted that model-based prediction is useful in terms of its ability to interpolate and extrapolate non-linearity, but it requires much more time and effort in analysis than the database approach. Burr prediction using database can be useful when the process planning must be done quickly.

3. Integration of Design and Manufacturing

As discussed previously, edge finishing quality of the parts should be taken into account early in part design and process planning. stages. Stein (1997) has proposed 4 levels of integration in the design to fabrication cycle. The integration distinguishes design environments with freedom for adjustments in part design, manufacturing, and finishing. Table 2 illustrates the integration scheme at different levels. Level I refers to part design stage where the freedom in designing a part and developing its process plan is high. Levels II and III represent process planning stages for the part. The difference between both levels is that level II focuses on the overall process planning scheme, while level III focuses on fine-tuning machining parameters for optimal process plan. Level IV then addresses the secondary operations such as deburring and surface finishing.

The rest of this paper will review previous studies on the effects of part design (level I), the effects of machining parameters (levels II and III) on edge quality of the parts. Then, given that burr formation took place, research efforts to assist deburring planning will be addressed (level IV). It should be recognized that these 4 levels of integration also imply different objectives in the optimization scheme. At level IV, process planners only aim to minimize deburring cost. In levels II and III, machining cost must be included in evaluating a process plan. And in level I, tradeoffs between part's performance and manufacturing cost is to be incorporated.

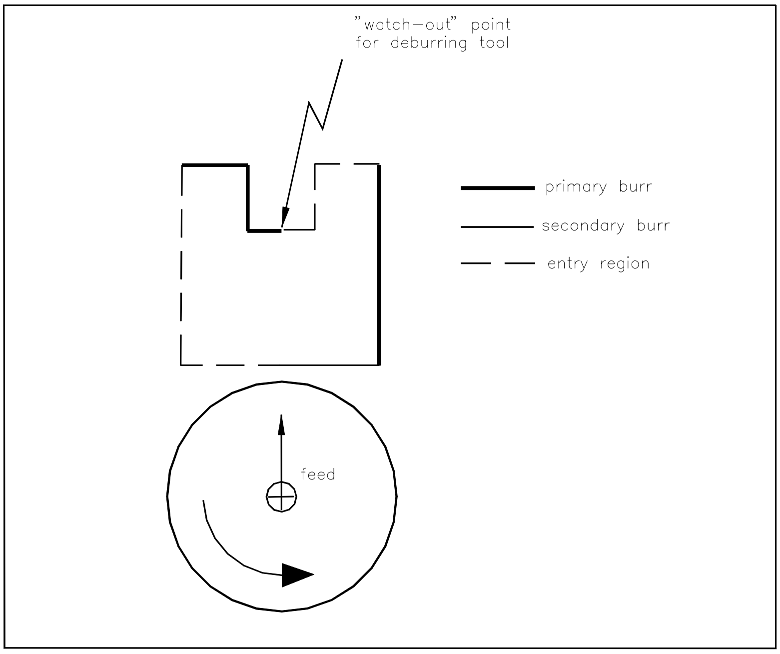

Figure 4. Burr profile information help identify problematic area with expected sudden change in deburring force

Table 2. Four levels of integration in the design to fabrication cycle

Level	Process planning software expert and agent task	Freedom for adjustment
1	Feature prediction, control, and optimization in an iterative design and process planning environment	Design : High Manufacturing : High Finishing : High
2	Feature prediction, control, and optimization through the selection of a manufacturing plan in an "over-the-wall" design to manufacturing environment	Design : None Manufacturing : High Finishing :High-> Low
3	Feature prediction and control through limited adjustments to a pre-established manufacturing process	Design : None Manufacturing : Low Finishing :High-> Low
4	Feature prediction for finishing process planning, finishing tool trajectories and sensor-feedback strategies	Design : None Manufacturing : Low Finishing: High

4. Level I: Part Design

In designing a part, designers need to pay attention to burr formation potential on part's edges. Burr at certain location on the edges can affect part's performance drastically. Exit burr from an intersecting hole in a valve, for example, can change fluid flow characteristics. To the minimum, designer should be aware of the impact of edge finish on the part's performance. The critical edge where burr formation is not allowed must be clearly specified.

Schafer (1975b) had studied the effects of part's edge angle on burr formation. His result is shown in Figure 5 below. It is clear that whenever possible, the part's edge angle should be greater than 90^o, especially when burr formation is critical. This same idea leads to the notion of pre-chamfering part's edge to avoid burr formation in milling, and bushing to avoid burr formation in drilling.

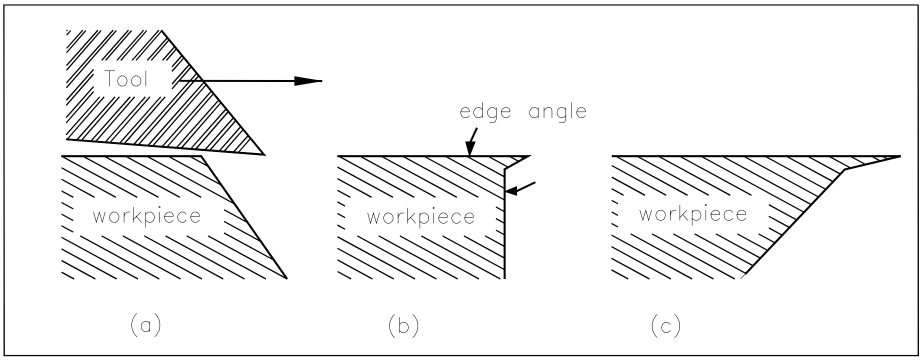

Figure 5. Effects of part's edge angle on burr formation: (a) large edge angle, smaller burr, (b&c) small edge angle, larger burr

In other example, the concept of screw machine product design to avoid burr formation at critical locations had been well-established (see American Machinist,1964). The effects of certain part's features on burr formation, however, are still unclear.

5. Level II and III: Process Planning

Process planning covers a variety of considerations. According to Stein, at level II, process planners have complete freedom to develop an entire process plan. At level III, on the other hand, the machines have been set. If the adjustment is necessary, only machining parameters, i.e. cutting speed, feed, are allowed to change. In this section, the distinctions between levels II and III will be neglected. The effects of process parameters will be discussed from the approach researchers have taken, ranging from geometric models to experimental studies.

5.1 Geometric Models

While burr formation process involves work material's properties, geometric considerations of the cutting tool and workpiece can provide a reliable indicator of burr formation. Hashimura and Hassamontr (1998) used geometric concept of chip flow direction to explain the effect of milling tool geometries such as axial and radial rake angles on burr formation mechanism on transition and machined surfaces. Figure 6 illustrates their findings.

Narayanaswami (1995) considered face milling, single tool path planning where he included primary and secondary burr lengths in the objective function. Abeyta (1996) developed software tool allowing user's interaction on multi-tool path planning. Resulting exit burr size and location is then used to evaluate different tool path plan. Hassamontr (1998) modified window framing tool path planning scheme for end milling in order to avoid exit burr formation. The schematic of his tool path plan is shown in Figure 7. With the outside tool paths removing the work material around the edges, then the remaining material (shaded area) can be removed without burr formation concern.

5.2 Connections between Tool Wear and Burr Formation Studies

Burr formation always takes place at the workpiece edge, as the tool enters or exits the part. Researchers studying tool wear have long identified the tool's entrance angle (sometimes called angle of engagement) and exit angle as critical parameters governing tool wear. Some of their work showed elegant parallelism with burr formation study. Kronenberg (1964) studied the tool entry order of contact points with respect to tool wear. His work corresponds well with the exit order study by Hassamontr (1995). The same tool geometries such as axial rake, radial rake, and lead angles were considered. However, one considered the tool entry, and the other considered the tool exit.

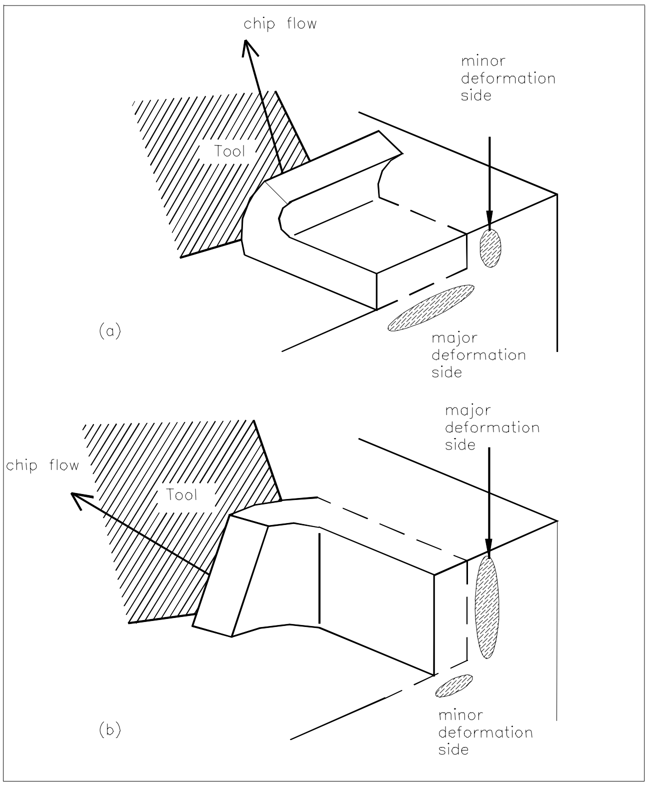

Figure 6. Direction of chip flow at the tool's exit point (Hashimura (1998))

The tool exit angle also turned out to be a critical parameter in tool wear as confirmed by Pekelharing (1978) and Ramaraj (1988). Pekelharing determined the range of exit angles that are unsafe for the tool life through his experimental study. His work led to a series of research work in tool path planning that incorporated favorable tool entry and exit conditions, such as Raman and Lakkaraju (1993) for zig-zag tool path planning, and Ma (1995) for window framing tool path planning. The geometric models developed in these tool wear studies can be used by researchers studying burr formation in designing more realistic process plan to address both problems simultaneously.

5.3 Finite Element Models

Park (1996) developed finite element models for orthogonal machining to study the effects of tool rake angles and part's edge angle on burr formation. His model showed the pivoting point as the cutting tool approaches the workpiece's edge. Negative shear stress was discovered as burr formation took place in front of the cutting tool. The phenomena are similar to ploughing. The experimental results from various researchers had corresponded well with his models.

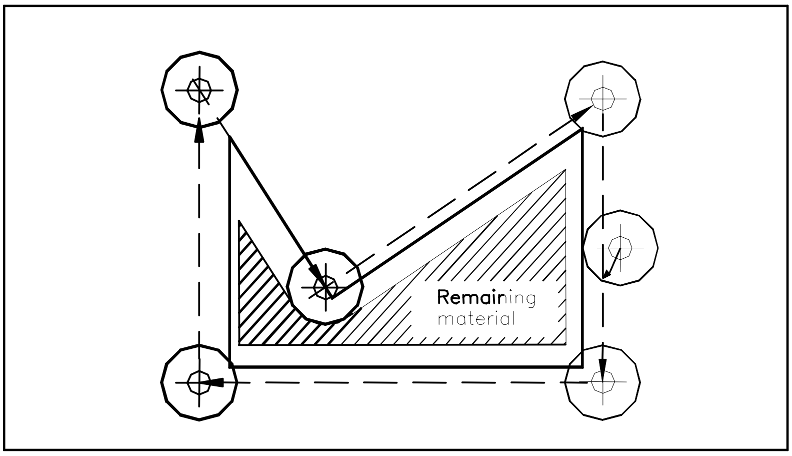

Figure 7. Schematic of tool path generation to avoid exit burrs

5.4 Experimental Studies

There have been several experimental studies investigating the effects of process parameters on burr formation. Some are driven by geometric models, others by the design of experiments. Table 3 aims to summarize the studies conducted up until present. Hopefully, it can provide manufacturing engineers resources to look up if they run into similar machining situations and are in need of fine-tuning machining process parameters.

The studies were classified into work material, milling tool, workpiece, and machining process parameters. The research works are denoted by the first three characters of the first author's last name and the year that their data was published. For example, [KIS-81] denotes the research work by Kishimoto et al. in 1981. The full citation can be found in the reference. The bullets in the table represent the inclusion of the effects of certain parameters in the study. It would be best to identify the parameter ranges for all these bullets. Certain parameters such as cutting fluid have not been investigated rigorously, even though a few researchers have conjectured that cutting fluid should discourage burr formation. The key parameters governing burr formation are found to be in-plane exit angle and depth of cut. The exit angle gradient was found recently to be another critical parameter governing burr formation by Chang (1997).

6. Level IV: Deburring Planning

Currently, there are more than 57 (Gillespie, 1996) distinct deburring processes available. Each process has special advantage over others in certain capabilities. Some processes work well for certain work material and deburring configuration. It is important that the information regarding deburring process capabilities and limitations are gathered. Selecting the most effective process can be an overwhelming task. In a way, deburring process planning required selections of deburring process, deburring tool, deburring tool path, and process parameters. This level IV in itself can be viewed as the repetition of levels II and III for edge finishing.

6.1 Deburring Process Selection

Gillespie (1978) developed deburring process selection scheme. He also considered the interaction between part design and deburring tool's accessibility. In 1981, Ioi et al. had developed computer program to assist process planner in selecting deburring process. Their program output the ranking of deburring methods with cost information for each deburring setup. The deburring process parameters were also provided. Since then, specialized software tools for deburring had received special attention by various researchers. Stouffer et al. (1993) developed Advanced Deburring And Chamfering Systems (ADACS) for robotic chamfering planning through CAD interface. Ioi and Kanda (1989) laid out expert system for process planning in deburring, then went on to develop an expert system for barrel finishing (1995). Sickle and Flores (1997) elaborated the scheme for brush deburring setup.

Table 3. Summary of experimental studies of burr formation in milling

Work Material	Milling tool			Workpiece				Machining parameters		
	Face/End	geometries	tool stage	edge angle	exit angle	exit angle gradient	special treatment	cutting speed	feed	depth of cut
C steel S45C										
[KIS-81]	F	•			•					•
[KIT-90]	F				•				•	•
[GUI-94]	F			•	•					•
C Steel 1018										
[GIR-92]	F				•			•		•
[TRO-97]	F	•			•			•	•	•
C Steel 1020										
[BLO-80]	F,E		•					•	•	
C Steel 1040										
[OLV-96]	F	•			•			•	•	•
Stainless 304L										
[HAS-95]	F	•			•					
[CHA-98]	E					•		•	•	•
Al 1100										
[GIR-92]	F				•			•	•	•
[CHE-93]	F				•					
Al 2024										
[CHE-93]	F				•				•	•
[HAR-96]	F	•			•			•	•	•
Al 6061										
[GIR-92]	F				•			•	•	•
[CHE-93]	F				•				•	•
Al 319										
[CHO-97]	F				•			•	•	•
Al 356										
[JON-97]	F		•		•		•	•	•	
ABS Plastic										
[CHA-95]	E		•		•				•	•

6.2 Deburring Cost Estimation

Gillespie (1978,1981) laid out deburring cost estimates for different deburring processes. However, estimates for deburring time per part are assumed known advance. This required that material removal rate for the deburring process be calculated. Blotter and Huang (1980) recognized this and assumed loose abrasive deburring process into his cost function as they considered machining cost and deburring cost altogether. They found the optimal machining speed when deburring cost is included is higher than when deburring cost is neglected. The result of their findings is depicted in Figure 8.

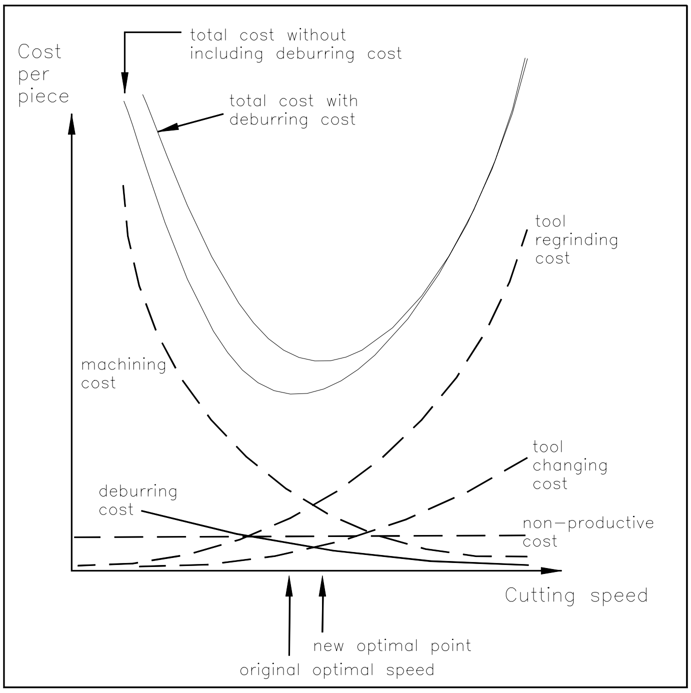

Figure 8. Effects of including deburring cost into part cost

6.3 Deburring Process Mechanisms

Many deburring processes are not well-understood. Without deburring process mechanics, it is difficult to develop process parameter selection scheme and obtain the estimate for deburring time. Many researchers have developed the deburring process models through their experimental studies. For chamfering, several deburring process exist. Examples include the studies from Gillespie (1987) and Stouffer et.al. (1993) in his ADACS system.

Chen, Cariapa, and Stango (1991) developed material removal model for circular, non-filamentary brushes. Alwerfalli used design of experiment to develop the material removal model for abrasive jet deburring process. Loose abrasive deburring process, i.e. vibratory finisher, was found by various researchers (Blotter and Huang, 1980) to have linear relationship between deburring time and burr thickness. Material removal models for many other deburring processes are still not available.

7. Conclusion

In this paper, past researchers on burr formation and deburring have been discussed and classified from the ground rule set by Stein's 4 levels of integration of design to fabrication cycle. The majority of works have concentrated on investigating the effects of machining process parameters on burr formation. Despite much attention from various researchers focusing on part design and feature interaction, the research work classified as Level I contribution is little.

Whenever burr formation can be minimized, if not completely avoided, the deburring cost will decrease drastically. This cost savings is often overlooked by engineers as they are resigned to the misconception that burr formation cannot be avoided. The research works classified in levels II and III should be consulted as a quick tool to avoid burr formation.

Even when burr formation takes place, works classified in level IV can come in handy. Deburring planning is mostly considered simplest using hand deburring. However, as parts get more sophisticated, hand deburring will no longer be sufficient. Commercially available deburring processes must be considered. The most effective one, in terms of cost and technical capability, must be selected, and the operating parameters optimized.

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