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Review Article

RECENT RESEARCH WORKS ON BURR MINIMIZATION IN MILLING

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Abstract: A burr is an undesirable projection of material formed in machined parts that makes handling as well as assembly of mechanical components difficult, and hence, it needs be subsequently removed, or its formation needs be suppressed to allow the parts to meet desired tolerances, thus, need of deburring will either not be required, or needed to a less extent. A brief overview of techniques to minimize formation of milling burrs is made in this paper.

Keywords: Milling, Burr, In-plane exit angle, Edge beveling, Control of burr.

1. Introduction

Burrs usually form at the edge of a workpiece during machining, and other manufacturing processes. Burrs are not desired, as they cause difficulty in handling manufactured parts, and subsequent assembly operations. Deep notch wear also occurs due to burr. Increased notch, in turn, results in increase in the rate of growth of burr as observed by Nakayama and Arai [1].

Generally burrs are removed by deburring processes. However, it was found by Gillespie [2,3] that for manufacture of precision components, deburring cost could be about 30% of the total manufacturing cost of components.

A number of experimental studies was made by researchers [4,5] to understand the cause and mechanism of burr formation, and to reduce the same to minimize the cost of deburring. Olvera and Barrow [6] carried out experiments to find out the effect of machining parameters on burr formation in square shoulder face milling, while Shefelbine [7] experimented on face milling of aluminium-silicon alloys and cast iron, and observed that size of burr reduced considerably with new tools rather than a worn-out tool using appropriate coolant. In cast iron, naturally, burr size is negligible. Approximate tool geometry and tool path were designed by Chu and Dornfeld [8] to avoid the tool exit, such that minimum burr formation occurs.

Although a number of deburring processes are available, they involve additional processing time and cost. Hence, focus is made on reduction or elimination of burr formation during machining itself. An algorithm was developed by Narayanaswami and Dornfeld [9] for minimization of burr formation, while Chu and Dornfeld [10] proposed a geometric algorithm to increase the edge quality and to reduce burr formation, and Ko and Dornfeld [11] proposed a model related to fracture of burr considering shearing and bending deformation. They found significant influence of cutting speed and feed on burr formation. Hasimura et al. [12], on the other hand, observed the change in burr dimensions with different feeds and tool edge radii, and proposed a burr formation model.

Saha and Das [13, 14] employed experiments, as well as FEM-based analysis to find a significant influence of exit edge bevel angle on burr formation during orthogonal machining operation. The research group led by Das [15-18] performed experiments on different steels and aluminium alloy, and observed that beveling exit edge of the workpiece and selection of an appropriate in-plane exit angle reduces burr formation substantially. Through ANOVA and stress analysis, they found that at 15^0 exit edge bevel angle, burr formation is substantially reduced, if not completely eliminated.

Luo et al. [19] performed experiments on aluminium alloy in slot milling, and found out that during orthogonal milling, with the increase in exit angle, exit burr size increases. The largest exit burr was produced at a 90^0 in-plane exit angle. They found out further that exit burr size in up-milling increased with the increase in oblique cutting angle. In milling operation, exit burrs of primary and secondary types are produced; size of primary burr is large and it is reported [20] to be difficult to remove. An algorithm by optimizing feed direction was developed to reduce the size of primary burr. Avila and Dornfeld [21] also reported a detailed analysis after experimental investigation on burr formation in face milling regarding in-plane exit angle and its effect on burr minimization.

2. Burr and its Effects

In recent times, lot of research interests have been focused on problems associated with burrs formed in machining and other manufacturing processes, as presence of burr on the workpiece might lead to various problems such as:

1. Increase in the cost and time of production for employing deburring operation.
2. Decrease in the fit and hence, causes difficulty in assembly of parts.
3. Causing dimensional in accuracy and poor surface.
4. Reducing cutting performance and tool life.
5. Chance of injury to workers and consumers.
6. Problem of electrical short circuit.
7. Poor machinability.
8. Poor aesthetics of the component.

3. Mechanism of Milling Burr Formation

Gillespie and Blotter [22] identified three basic mechanisms involved in the formation of burrs, namely i) lateral deformation of material, ii) bending of the chip, and iii) tearing of the chip. The classification and definition of burr are based on these mechanisms: Lateral deformation of material is responsible for Poisson burr, whereas roll-over burr is an outcome of bending of the chip and tearing of the chip results in formation of tear burr.

Kishimoto et al. [23], Chern [24] and Trimmer [25] observed that cumulative roll-over process of the chip upon exit is responsible for the formation of knife burrs. Hashimura et al. [12] observed that uniform burrs are formed due to cumulative leaning of the transition material that is pushed by the tool flank during each successive pass. They found out that exit burr forms due to leaning of plastically deformed transition material towards the machined surface, as opposed to roll-over of the chip. They proposed that the ability of the backup material to support cutting forces controls formation of the burr and chip. Various geometrical and kinematical parameters on which burr formation depends are discussed in the following paragraphs as reported by Lin [26], Avila and Dornfeld [21], Tripathi and Dornfeld [27], Chern et al. [28], Saha et al. [15], Saha and Das [29], Das et al. [30] and Das et al., [31] and Saha and Das [18].

3.1. Tool exit theory

Tool exit theory states that burrs are formed when tool cutter exits the workpiece edge. Here, exit has been referred specifically to the tool cutting edges moving out of the workpiece at an edge while removing material. On the other hand, tool edge enters the workpiece while removing material. Functionality of the component has not been affected by entrance burrs so much because of their small size, and are generally neglected as opined be Chu [32], Rangarajan and Chu [33].

3.2. In-plane exit angle theory

In-plane exit/entrance angle, Ψ, is defined as the angle between the cutting velocity vector, Vr, at the point where the tool coincides with the edge of the workpiece, and the vector, that contains the theoretical edge, pointing from tool entrance to tool exit region, as shown in Fig. 1, according to Avila and Dornfeld [21] and Das et al. [17]. Vr is composed of the tangential velocity V_t and feed velocity V_f. In face milling process, Vr can be approximated to the tangential velocity V_t, as the feed component, V_f is usually very small compared to V_t. Under this condition, tool exit occurs when $0° < \Psi < 180°$.

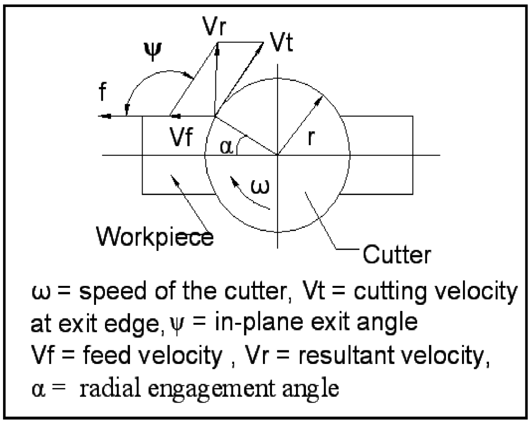

Fig.1. Schematic presentation of in-plane exit angle

3.3. Exit order sequence

In a milling operation, the direction of chip flow is closely related to burr formation. Based on this observation, Exit Order Sequence Theory (EOS) has been proposed by Hashimura et al. [12], to predict burr size on the exit surface. EOS considers the three-dimensional chip-flow characteristics of the work material, associated with the order in which the major and minor cutting tool edges exit the workpiece, tool geometry, feed rate, and depth of cut governing the exit order of cutting edges. When the tool exits the workpiece, a separation point between the chip and the workpiece exists along the workpiece edge.

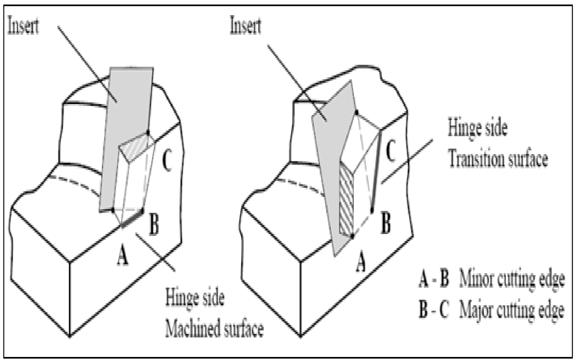

Fig.2. Schematic view of exit order sequence (Left figure: tool sequence C-B-A, figure on the Right: Tool sequence A-B-C)

In Fig. 2, B is the tool tip, and A and C are the intersections of the minor and major cutting edges respectively, with a border of geometric contact area between the tool and workpiece. Under the assumption that the tool tip radius is smaller than the uncut chip thickness, if the minor cutting edge A-B exits the workpiece sooner than the major cutting edge B-C, the chip hinges on the machined surface, forming large exit burrs expectedly (Fig. 2 (a)). Exit order of the tool edges is C-B-A. On the contrary, if A-B exits the workpiece later than B-C, the chip hinges on the transition surface and a small side burr is formed. Exit order of the tool sequence is A-B-C (Fig.2(b)).

3.4. Exit edge bevel angle

Gillespie [5] observed way back in 1976, that beveling of the edge of a workpiece may reduce burr formation. With this concept, Saha et al. [35] carried out extensive experiments and found that exit edge bevel angle of workpiece is highly responsible for burr formation. Minimum burr is observed at 15° exit edge bevel. It may be due to availability of required back up support at the beveled exit edge of the workpiece due to gradual reduction in depth of cut requiring decreasing cutting forces. In that situation, positive shear plane on the whole, does not tend to switch over to the negative shear plane, as a result of which negligible burr is formed at 15° exit edge bevel. Fig.3 shows exit edge beveling.

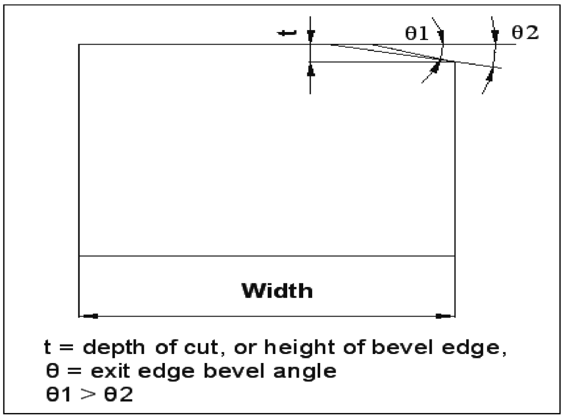

Fig.3. Schematic diagram of workpiece which indicates exit edge bevel

3.5. Uncut chip thickness

It has been observed that an increase in feed per tooth within the range used in finishing operations (0.05 – 0.2 mm/tooth) has a slight effect on the primary to secondary burr transition. Trimmer [25] observed that the critical depth of cut on low carbon steel increases from 0.75 mm to 1 mm when feed per tooth is increased from 0.05 to 0.2 mm. Avila [21] found that during machining of Al-Si alloy using a tool path normal to the edge under a constant feed rate, primary burrs may appear at an in-plane exit angle close to 90°, because uncut chip thickness becomes very small in these areas, and plastic deformation is favoured.

Many studies have found that primary to secondary burr transition is sensitive to in-plane exit angle and depth of cut (Kishimoto et al. [23]; Chern [24]; Olvera and Barrow [6], Trimmer [25], Avila [21]). Trimmer [25] performed milling tests on low carbon steel, and recorded a critical depth of cut of primary to secondary burr transition at different in-plane exit angles. He found that critical depth of cut has increased monotonically with in-plane exit angle. This is explained by the fact that at higher depth of cut, the transition material is less likely to lean towards the machined surface to form primary burrs. Similar behaviour has been observed in Al alloys (Chern [24], Avila [21]). Primary burr formation at high radial tool engagement is reduced by increasing the depth of cut. However, surface finish worsens when depth of cut is increased. The maximum depth of cut that can be used will be limited by the surface roughness requirement of the application.

3.6. Rake angle

Positive rake angle reduces cutting forces, and consequently the degree of plastic deformation of the transition material ahead of the tool. Park and Dornfeld [35] found that the rate of plastic work with low rake angle would be greater than high rake angle. Thinner burr would be obtained with high rake angle, but, as rake angle increases, the tool tip becomes more vulnerable to fracture.

4. Concluding Discussion

From the discussion made in the above section of this paper, following conclusions may be made:

1. Cumulative roll-over process of the chip upon exit is responsible for the formation of knife burrs.
2. Tool exit theory states that burrs are formed when tool cutter exits the workpiece edge. Here, exit has been referred specifically to the tool cutting edges moving out of the workpiece at an edge while removing material.
3. Exit Order Sequence Theory (EOS), considers the three-dimensional chip-flow characteristics of the work material, associated with the order in which the major and minor cutting tool edges exit the workpiece, tool geometry, feed rate, and depth of cut governing the exit order of cutting edges. When the tool exits the workpiece, a separation point between the chip and the workpiece exists along the workpiece edge.
4. Appropriate exit edge bevel angle of workpiece with suitable in-plane exit angle, Ψ may be provided for reducing burr formation. Minimum burr is observed at 15° exit edge bevel. It may be due to requirement of quite less back up support at the beveled exit edge of the workpiece due to gradual reduction in depth of cut requiring decreasing cutting forces. In that situation, positive shear plane on the whole, does not tend to switch over to the negative shear plane, as a result of which negligible burr is formed at 15° exit edge bevel. Low in-plane exit angle also reduces burr due to less tool engagement.
5. It has been observed that an increase in feed within the range used in finishing operations (0.05 – 0.2 mm/tooth) has a slight effect on the primary to secondary burr transition.
6. At higher depth of cut, the transition material is less likely to lean towards the machined surface to form primary burrs. Correspondingly, there can be a critical depth of cut that increases monotonically with in-plane exit angle.
7. The rate of plastic work with low rake angle would be greater than high rake angle. Thinner burr would be obtained with high rake angle than the lower one.
8. Although a number of investigations has been carried out in the past, appropriate strategy for complete elimination of burr during the material processing, or removal, stage still remains to explore.

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