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Experimental analysis of deburring process on inclined exit surface by new deburring tool

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ABSTRACT

The removal of macro-burrs formed after drilling has always been a difficult engineering problem, especially on inclined exit surfaces with intersecting holes. A new deburring tool is developed to remove burrs on inclined exit surfaces. The performance of the proposed deburring tool is analyzed according to changes in parameters including tool geometry, the deburring direction, and cutting conditions. Based on our analysis, proper tool geometry is suggested, and an efficient deburring method and deburring conditions are determined which satisfy the chamfered geometry and surface roughness of holes.

1. Introduction

A burr is formed as a result of plastic deformation at the end of the cutting process or blanking. It causes a reduction of product life, affects dimensional tolerances and the assembly process, and can cause injury to the operator. Additional deburring and edge finishing increases the cost of manufacturing. Gillespie stated that deburring and finishing can amount to as much as 30% of the cost of high precision parts [1].

Drilling is the most widely used machining process to produce holes quickly and at low cost. Intersecting drilled holes are common in industrial production. Burrs at cross-drilled intersections are found in the production of automotive engines, transmission components, and pressure components. Such burrs are difficult to approach and remove. There are many deburring methods for drilling burrs. However, most methods have difficulty controlling edge geometry and surface quality; these include thermal energy deburring, electrochemical deburring, ice blasting, and ultrasonic deburring. Moreover, these methods generally require specialized equipment [2–4].

In contrast, mechanized deburring by a cutting tool is a local method. The positions of application of the tools can be controlled. In addition, this method does not need specialized equipment for deburring, and a machining center can be used for mechanized deburring. Newly developed deburring tools can remove burrs at intersecting holes and on inclined exit surfaces. However, until now, no mechanized deburring tool could completely remove the burr on an inclined exit surface. A deburring tool developed by Beier can remove burrs at intersecting holes [5]. This tool enters through the main hole. It requires a special holder to supply air pressure and to satisfy the required accuracy, which makes it difficult to apply to general deburring at intersecting holes. Kim proposed a retractable cutter assembled into a circular bar that can remove burrs at intersecting holes [6]. This approach shows good deburring performance with an intersecting angle of 60°. For smaller intersecting angles (e.g., 45° and 30°), this deburring approach generally does not perform well. In this situation, there are differences between Kim's conclusions and our results. In addition, Kim's study does not consider the quality of the surface of the hole after deburring. To solve the burr problem on an inclined exit surface more completely, we designed a new deburring tool and conducted an experimental analysis of the deburring process.

2. Burr Formations on an inclined exit surface

Burr formations are affected by many factors such as the geometry of the drilling tool, the properties of the working material, cutting conditions, the exit surface angle, and the coolant. Min et al. [7] considered the influence of the exit surface angle on drilling burr formation. Burr formation can be classified into several types according to the material deformation behavior when the drilling tool leaves the workpiece at each step in the drilling process.

In our burr formation experiment [8], a sample (Fig. 1) was prepared with an inclined exit surface with inclination angle θ. The exit angle was defined as the angle formed between the machined surface in the feed direction and the exit surface in the normal direction at each point along the periphery on the exit surface, which is $90^\circ + \theta$ at point 1, 90° at points 3 and 7, and $90^\circ - \theta$ at point 5, as shown in Fig. 1(a). To observe burr formation on an inclined exit surface, Al6061 aluminum alloy was used to make specimens. A drill was rotated in the clockwise direction without coolant. Three inclination angles ($\theta = 15^\circ$, 30°, and 45°) were applied.

As shown in Fig. 1, we observed that small burrs formed along points 1-2-3-4-5, which is an entry part of rotating edge of drill. In contrast, points 5-6-7-8-1 had large burrs because this is an exit

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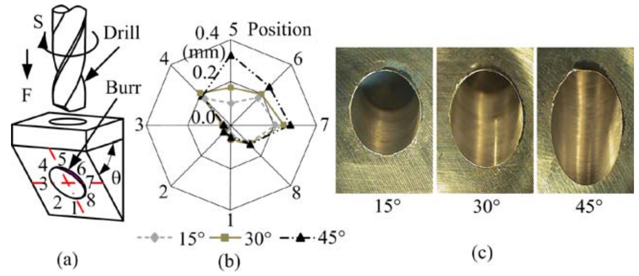

Fig. 1. Burr formation with different inclination angles with respect to the exit surface for aluminum (Al6061), a speed of 800 m/min, a feed rate of 100 mm/min, and dry conditions.

part of the rotating edge of the drill. The largest burrs formed at the part with a small exit angle in the feed direction and along the exit part of drill's rotating edges, along points 5-6-7 as shown in Fig. 1(b). The smallest burrs formed along points 1-2-3, where the exit angle is larger than 90° and which is an entry part of the cutting edge. At the same feed rate with an increased inclination angle, the burr height also increased as shown in Fig. 1(b) and (c). When the inclination angle increased, the exit angle along points 5-6-7 decreased, and the rigidity of remaining points 5-6-7 decreased. This allowed bending deformation at the remaining part to produce a large burr. In all materials, the burr height increases with increasing inclination angle θ. Burrs that form along the edge periphery are generally non-uniform, thin, and sharp. Therefore, it is difficult to measure burrs accurately. In this experiment, conoscopic holography, which uses a non-contact measurement method, was used. This method is widely used to determine burr parameters and can measure samples with inclination angles of less than 45° [9].

3. Development of new deburring tool

3.1. Requirement of new deburring tool for inclined exit surface

The requirements of the new deburring tool generally depend on the model used for burr formation. Ko and Lee [10] experimented with the Burr-Off® commercial deburring tool (Cogsdill Tool Products). Their experiment shows that the Burr-Off tool with only one rotational direction could not remove a burr on an inclined exit surface. Fig. 2 shows the results of their deburring experiment using the Burr-Off tool.

The burrs were pushed and increased in size instead of deburring. This is because the deburring rotational direction was the same as the direction of drilling. As a result, burrs formed along the exit during drilling were pushed back instead of being removed. Thus, the tip of the deburring tool must be designed for both deburring directions (clockwise and counter-clockwise) at the intersecting hole to cover the entire periphery of the hole for efficient deburring. The deburring tool is designed to maintain enough flexibility to pass the drilled hole as shown in Fig. 3, and can be manufactured easily at low cost.

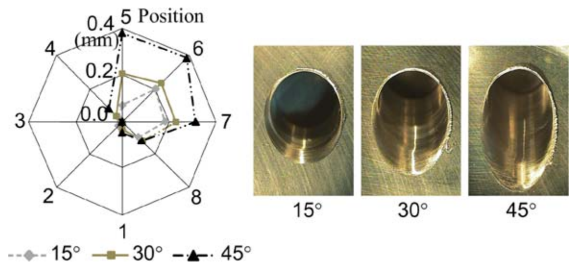

Fig. 2. Result of deburring experiment with Burr-Off tool with Al6061 under the following conditions: inclination angle of 15°, 30°, and 45°; spindle speed of 700 rpm; feed rate of 28 mm/min; diameter of 9 mm; with coolant.

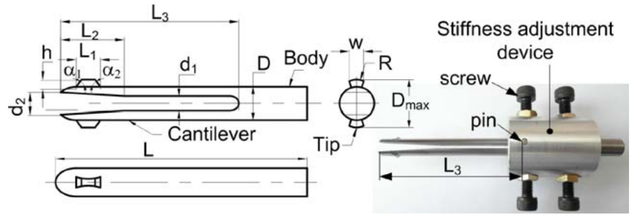

Fig. 3. Deburring tool geometry and stiffness adjustment device.

Table 1
Geometry of proposed deburring tools.

Tool	h (mm)	L_1 (mm)	w (mm)	R (mm)	$\alpha_{1,2}$ (°)	L_3 (mm)	D_{max} (mm)
1	0.85	2	1.5	2	55	80	10.5
2	0.85	2	1.8	4	70	80	10.5
3	0.85	2	1.8	4	85	80	10.5

3.2. Geometry of the deburring tool

The proposed deburring tool consists of a body and two cantilevers. Each cantilever has two cutting edges: one for the entrance burr and the other for the exit burr, with angles α_1 and α_2, as shown in Fig. 3. The shaft and cutting edges of the proposed deburring tool are composed of one body. The body was made of high speed steel to have spring properties in the two branches. The cantilever functions as a spring that can be pushed into the space inside when the deburring tool is forced through the drilled hole. The tip of the deburring tool was designed for both directions of rotation to remove all the burrs on the inclined exit surface. The outer surface of the tip was designed to keep round edges with radius R (as defined in Fig. 3) and smooth surfaces to avoid surface deterioration by sharp edges, and to improve surface roughness by the rubbing effect when the tips rotate inside a drilled hole. The tool passes through the drilled hole to reach the exit side. Deburring tools were designed and manufactured as described in Table 1. In order to perform the experiments more easily, a stiffness adjustment device was designed to change the length of the cantilever (L_3) by moving the location of pin, as shown in Fig. 3. In this way, the stiffness of the deburring tool was increased by decreasing the length of the cantilever (L_3).

4. Experiment and discussion

A deburring experiment was developed using a full factorial experiment design, and was performed as shown in Table 2. The goal of the experiment was to assess the effect of process input factors on deburring efficiency, surface quality, and chamfer size. The efficiency (E) of the deburring process was calculated using Eq. (1):

$$E = \frac{\sum_{1}^{8} h_i - \sum_{1}^{8} h_j}{\sum_{1}^{8} h_i} \times 100 \quad (1)$$

where h_i and h_j are the burr heights at points along the periphery on the exit surface before and after deburring, respectively (Fig. 1(a)). A

Table 2
Control factor of full factorial experiment design.

θ (°)	R (mm)	$\alpha_{1,2}$ (°)	Speed (rpm)	Feed rate (mm/tooth)	L_3 (mm)
15	2	55	700	0.02	70
30	4	70	1060	0.04	80
45		85			

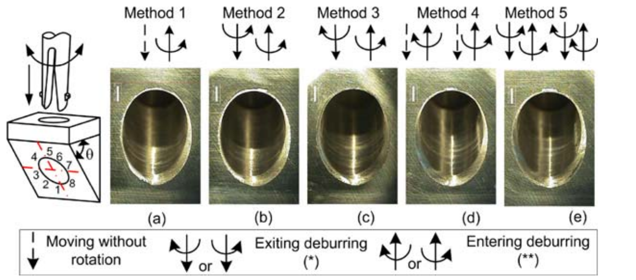

Fig. 4. Deburring experiment results using different methods. (a) Method 1, (b) Method 2, (c) Method 3, (d) Method 4, and (e) Method 5.

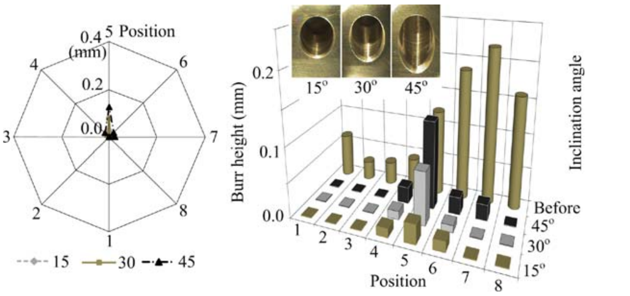

Fig. 6. Result of the deburring experiment using tool 2 with inclination angles of 15°, 30°, and 45°; a speed of 700 rpm; a feed rate of 28 mm/min; a diameter of 9 mm; and using Method 4.

Hyundai SPT18S machining center was used for the drilling and deburring operations. The specimens used in the experiment were made from Al6061. The drilled holes were deburred using the proposed tool and flood coolant. After deburring, the burr height was measured at 8 points using a burr measurement system [9].

4.1. Effect of deburring method

To consider the effect of the process parameters including rotational directions, feed directions, and the number of deburring process, our experiments were carried out in five different ways. The deburring process was defined according to two parameters: the deburring direction (entering deburring and exiting deburring), and the deburring rotation (clockwise and counter-clockwise). As shown in Fig. 4, (*) indicates an exiting deburring process with a clockwise or counter-clockwise rotation. In addition, (**) indicates an entering deburring method with a clockwise or counter-clockwise rotation. Exiting and entering are named with respect to the exit surface. After deburring, the chamfer size of the drill hole is not the same for both sizes using Methods 1 and 2, as shown in Fig. 4(a) and (b), respectively. Large chamfers were produced on half of the drill hole. Methods 1 and 2 show that an inclined exit surface requires bidirectional rotation for deburring. Method 3 (Fig. 4(c)) shows that the entering deburring process is more dominant than the exiting deburring process. Methods 4 and 5 show the same chamfer along the edge periphery as shown in Fig. 4(d) and (e). However, Method 4 produced a smaller chamfer than Method 5, which means that exiting deburring contributed to chamfering. The remaining burr at 5 is inevitable using the new deburring tool, which is a problem that must be solved in a future study.

Based on our experiment on the effect of the deburring method, we note that entering with rotation (**) is efficient for deburring on an inclined exit surface. Therefore, to remove all burrs on an inclined exit surface, entering deburring with both directions of rotation is necessary. Exiting deburring (*) is less efficient than entering deburring (**), but is helpful because it decreases the chamfer size. Measured burr sizes from Methods 1 and 4 are shown in Fig. 5. Method 1 does not eliminate burrs along points 3-4-5, whereas Method 4 removes all the burrs except at point 5. Deburring was performed under the conditions shown in Fig. 2 and using Method 4. Compared to the results shown in Fig. 2. Fig. 6 shows that most burrs were removed except the burr at point 5.

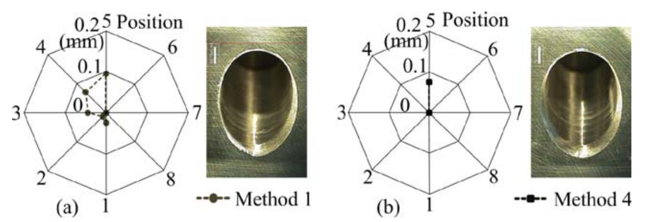

Fig. 5. Burr size after deburring with tool 2 at a spindle speed of 700 rpm, a feed rate of 28 mm/min, an inclination angle of 30°, and with coolant using (a) deburring Method 1 and (b) deburring Method 4.

4.2. Effect of tool geometry

The cutting forces in deburring processes are determined by the inclined angle of the tool tip (α_1 and α_2 in Fig. 3), the stiffness of the deburring tool, and the amount of deflection of the tool when it passes through the drilling hole, which is determined by the difference between D_{max} and the diameter of the drilled hole. The amount of deflection, which determines the length of the working edges, is very important because it affects deburring performance. If the length of the working edge is inadequate, deburring will not work properly. The cutting edge must cover at least the root thickness of the largest burr along the edge of the hole. From the viewpoint of deburring force, a tool with greater stiffness and a larger inclined angle (α_1, α_2) can induce a larger deburring force, and produce a larger chamfer along the edges.

When inclination angle θ increased, the remaining burr at point 5 increased, as shown in Fig. 6. During drilling, large burrs were formed along points 5, 6, 7, and 8, as shown in Fig. 1, which is the exit burr location with a small exit angle. Most burrs were removed by the bidirectional deburring process except the burrs at point 5. Burrs at point 5 were very difficult to remove because the tip could not approach the burr effectively.

Significant features of the deburring processes of the new deburring tool are described in Fig. 7. First, the deburring efficiency decreased with increased feed rate and spindle speed; second, the increase in stiffness of the deburring tool at L_3 = 70 mm reduced deburring efficiency; and third, the best deburring performance occurred at an inclined tool tip angle of α_2 = 70°.

4.3. Surface quality in the deburring process

The factors affecting surface quality are represented as the output of the experimental design, as shown in Fig. 8. R_a is the most commonly specified roughness measure, and is well suited for monitoring the consistency of a machining process. Roughness values R_a were measured using a surface roughness tester (SJ-400, Mitutoyo).

The roughness of the inner surface of the drilled hole was affected by the outer geometry of the tool tip, which contacted the inner surface of the drilled hole. Only the deburring area was considered. Fig. 8 shows that the surface roughness was improved after deburring. The outer radius of the tool tip, R in Fig. 3, must be less than the radius of the drilled hole. However, if the outer radius of the tool tip is too small, the diameter of the drilled hole is

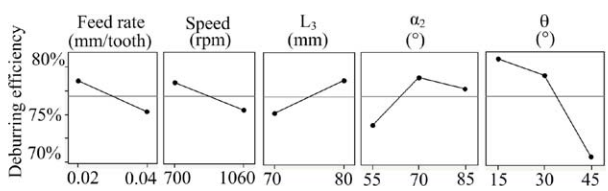

Fig. 7. Change of deburring efficiency according to the change of parameters.

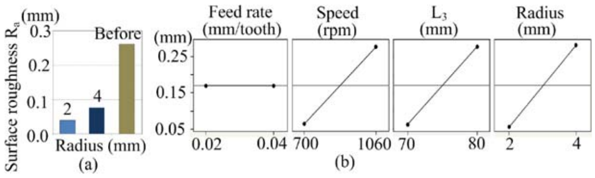

Fig. 8. Change of surface roughness according to the change of (a) radius of tool tip, (b) some parameters.

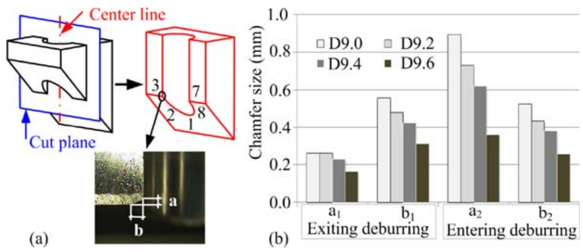

Fig. 9. (a) Definition of cutting plane and chamfer size. (b) Chamfer size of drilled hole after deburring with exiting deburring (a_1, b_1), entering deburring (a_2, b_2), tool 2, a spindle speed of 700 rpm, a feed rate of 28 mm/min, and an inclination angle of 15°.

affected. The mechanism of the improvement of surface roughness involves initiating rubbing instead of cutting by reducing the outer radius of the tool tip. Surface quality increases with decreasing spindle speed, thereby increasing the stiffness of the deburring tool. For a feed rate from 0.02 to 0.04 mm/tooth, no change in the surface roughness occurred.

4.4. Chamfer size after deburring

To measure the chamfer sizes, the specimens after deburring were cut in half. The cutting plane passed through point 3, point 7, and the center of the drilled hole, as shown in Fig. 9(a). The chamfer sizes were observed and measured at point 3 with an optical microscope at 100×. The chamfer size at point 7 was not considered because it was not produced by one-directional deburring (clockwise rotation). Dimension "*a*" in Fig. 9(a) was projected on the plane normal to the exit surface because the cutting plane was not perpendicular to the exit surface. In this experiment, deburring methods and tool stiffness were considered for controlling chamfer size by changing the drilled hole diameters from 9.0 mm to 9.6 mm, and by using two methods such as entering and exiting deburring. By increasing the diameter of the drilled hole, the deflection of the deburring tool decreased and the deburring forces decreased.

Fig. 9(b) shows chamfer size a_1, which was produced by exiting deburring and was less than chamfer size a_2 from entering deburring. Thus, there is an effect of feed direction on size *a*. Chamfer size b_1 is nearly equal to chamfer size b_2 with the same drilled hole, which means that width *b* was not dependent on the deburring method (entering or exiting). However, size *b* was affected by the length of the cutting edge and by the tool stiffness. Thus, the chamfer sizes can be controlled by changing the length of the cutting edges, the stiffness of the deburring tool, and the deburring methods. Fig. 9(a) clearly shows that "*a*" is determined by cutting forces and "*b*" is the size of the root of the chamfer, which can be calculated geometrically. Thus, the amount of deformation must be larger than the size of the root of the burr. In this sense, the chamfer size can be simulated from the deburring force model, and a cutting force model for exiting and entering deburring must be developed separately.

Considering that deburring Method 4 (Fig. 4) is the most suitable, the geometry of the chamfer must be symmetric. This means that the chamfer geometry at point 7 is the same as the geometry at point 3. The maximum size of the chamfer was to be formed at location 1, and the minimum size was to be formed at location 5 with micro-burrs. Similarly, using a cutting plane that includes points 1 and 5, the chamfer geometry can be identified. If the geometry of the chamfer can be identified and controlled by changing the conditions, it is possible to determine the deburring conditions for a specified chamfer geometry.

5. Conclusion

The proposed deburring tool was designed using the initial requirements. On an inclined exit surface, the tool removed burrs effectively using the bidirectional deburring process. For successful deburring, proper stiffness and the inclined tip angle must be designed according to the burr properties. The length of the cutting edge must also be correctly determined.

In our tests, almost all burrs were removed using the proposed deburring tool on an exit surface with an inclination angle of less than 30°. For an inclination angle of greater than 30°, a burr at location 5 could not be removed on the exit surface, which is a problem to be solved in future research. The best deburring tool performance occurred for an inclined angle of $\alpha_2 = 70°$ and $L_3 = 80$ mm. The surface quality of the drilled hole was improved by the tip of the deburring tool, which was made in a round shape with a radius less than that of the drilled hole.

Chamfer size "*b*" was not dependent on the method of deburring (entering or exiting). However, chamfer size "*a*" was affected by the method of deburring. Chamfer size "*a*" was produced by entering deburring and was larger than the chamfer size "*a*" from exiting deburring. A deburring tool with greater stiffness resulted in a greater chamfer size.

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