

DEVELOPMENT OF DRILL GEOMETRY FOR BURR MINIMIZATION IN DRILLING

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ABSTRACT

Drilling tests were carried out using drills with various drill shapes for burr minimization. Final objective of this study is to develop compatible drill shape for minimization of burr formation. For experiments, general carbide drills, round drills, chamfered drills and step drills are designed and manufactured. Burrs are formed by various cutting conditions and in 4 different work materials. Laser sensor is used to measure burr geometries. Cutting forces in drilling are also measured and compared in every drill. As a result of the experiments, step drills with specific step angle and step size are suggested for burr minimization.

1 INTRODUCTION

As one of the size error during drilling, projection of material, defined as “Burr” is formed. Burr is plastically deformed material, generated on the part edge during cutting or punching. This burr can be classified as entrance burr and exit burr. The entrance burr is formed around the drilled hole in the form of small wedge and the exit burr is formed on the other side, when the drill pierces workpiece by pushing out uncut volume. It must be noted that exit burr strongly affects product quality and assembly process. Due to this reason, additional deburring process is required. Usually this deburring process is done manually because of difficulties in automation. And it also may cause high cost in edge finishing of precision parts[1-2]. Basic mechanism of burr formation can be found in a large number of papers describing several ways to reduce effect of burr. Gillespie explained the burr formation process by three stages [3] and Pande and Relekar observed burr formation tendency especially to burr height and thickness by changing the cutting speed and the feed rate[4]. Takazawa K. has studied several elements forming burr during drilling[5]. And Stein observed the effect of the feed rate, cutting speed, pecking and tool’s material on burr height, thickness and shape using micro drill in stainless steel, and the influence of workpiece exit angle on burr formation in drilling intersecting holes[6].

Burr is formed by plastic deformation, and its size depends on cutting conditions like

cutting velocity and feed rate. The elements of drill shape, point angle, helix angle, length of chisel edge etc. influence cutting force, hole accuracy and burr formation as well[7].

In this paper, we achieved an experiment to observe burr formation in each material with modified drill with chamfer, round and step at the corner of the drill edge. Therefore, modified drill with optimal shape for minimization of burr has been verified through a cutting force measurement. According to the modified shape, the behavior of uncut volume in drill exit can be controlled to minimize burr size.

2 MECHANISM OF BURR MINIMIZATION BY MODIFIED DRILL

It was mentioned above that several researchers tried to reduce fundamental formation of burrs. Sofronas presented method to round the drill cutting edge, increase helix angle and harden the exit surface. But surface hardening makes a problem since this smaller burr causes more difficulty to be removed by exit surface hardening[8]. Another approach to reduce burr formation that involves a modification of the drilling process is the use of ultrasonic or low frequency vibratory techniques[9-10]. Lee has also used method of cutting condition changing, and controlled the thrust force by changing the feed rate during drilling[11].

During cutting process of drill, according to point angle, material's property and cutting condition, plastic deformation region is formed by the stress caused by cutting resistance in the slant section remained when drill exits hole as shown in Fig.1, and then burr is formed simultaneously with cutting. Therefore, as the volume for bending deformation in drilling is larger, larger exit burr is formed at the same time. According to this observation to minimize burr formation, step drill is designed and applied in this paper to reducing uncut volume and prolong cutting activity without bending deformation to the end of exit stage.

Fig.1 shows cutting process in step drilling. Unlike conventional drill, after the front cutting edge drills completely, the second cutting process starts at the step cutting edge. During second cutting process, cutting can be prolonged until plastic bending deformation occurs at the remained part. The position at which bending deformation starts is determined by the rigidity of the remained part shown in Fig.1. That's why, y_1 , R_1 in Fig.1 display critical point where 'cutting' is discontinued and 'bending' starts and the 'remains' is changed to burr. This critical position is decided by the shape of the remains. When the stiffness of the part which is bent by thrust force imposed in drill cutting edge is large enough, no bending occurs and cutting is continued. As a result, burr formation is delayed and small burr is formed. Therefore, to test burr minimization, we variously changed the drill geometry in step drill and measured its cutting force.

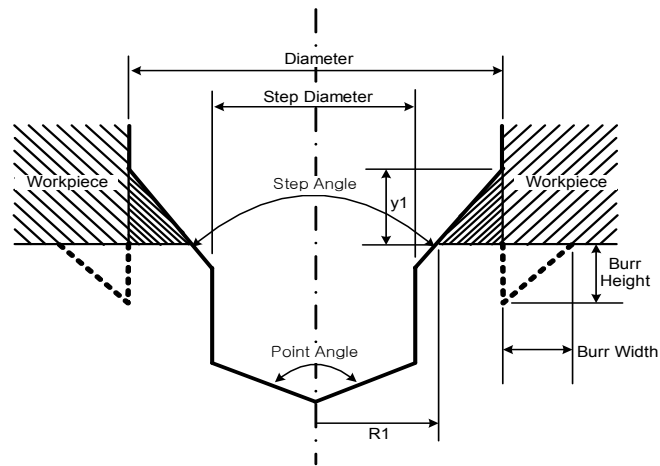


Fig. 1 Process of step drilling burr formation

Drill	Drill geometry	Picture of Drill Point
HSS Drill		
Carbide Drill		
Chamfer Drill		
Round Drill		
Step Drill		

Fig. 2 Configuration of Drills

3 BURR FORMATION EXPERIMENT AND OBSERVATION BY MODIFIED DRILL

3.1 The geometry of drill

To find out effects by various geometrical factors, 5 kinds of drills are designed and manufactured. Usual High Speed Steel(HSS) drill and carbide drill are used, which are commercialized. Chamfer drill is designed to have chamfer at the corner of edge, which is specified as chamfer length, L , and chamfer angle, θ_2 , as in Fig.2. Round drill with radius, R , at corner and step drill with step angle, θ_2 , and step diameter, D_2 , are produced as specified in Table 1.

3.2 Burr formation experiment in SM45C

The drilling is carried out in CNC Machining center (Hyundai SPT18S). SM45C is used as workpiece. Cutting condition is described in Table 2. Cutting speed is fixed and feed rate which has serious effect on burr formation is changed in 5 steps. Coolant is not used to observe the generation of cap when the burr is formed.

To measure burr geometry, burr measurement system is developed[12]. Burr geometry is defined by burr height and burr thickness as shown in Fig.1. Burrs are formed using various drills proposed in Table 1. In Fig.3, the measured burr heights are listed in each drill

3.2.1 Observation of burr formation in chamfered drill

Chamfer drills with 60° and 40° chamfer angle at the corner of cutting edge are designed for burr formation. In Fig.3(a), the burrs formed in drilling by conventional High Speed Steel drill and carbide drill are measured and compared with the burr by chamfer drill. The burr height from conventional drills is larger than that from chamfered drill. The chamfered drill with 60° chamfer angle produces larger burr than in drill with 40° chamfer angle. Fig.4 shows the drilling process at the moment after cutting by main cutting edge with 140° point angle. The chamfered edge starts cutting and burr is formed by bending deformation. Considering the same normal stress on the chamfered edge, it can be predicted intuitively that the stiffness of the remained part which is represented as hatched area in Fig.4 is larger in the case with 40° chamfer angle than in the case with 60° chamfer angle. The remained part will be cut if this part keeps enough stiffness not to be bended into burrs. This is the key concept for the drills for burr minimization.

3.2.4 Observation of burr formation in round drill

In round drill, the drills with corner radii $R_{1.5}$ and $R_{2.5}$ at drill cutting edge have been used. It is observed from Fig.3(b) that larger burrs are formed in drill with $R_{2.5}$ corner radius which is larger than $R_{1.5}$. The uncut volume in $R_{1.5}$ drill is much smaller than in $R_{2.5}$ drill as the hatched area in Fig.5 represents the stiffness roughly, which means that the stiffness of the remained part in $R_{1.5}$ drill is much larger than in $R_{2.5}$

drill when drill exits. More bending deformation in R2.5 drill produces larger burr. Therefore it can be insisted that the larger cutting resistance in drill with larger corner radius at the moment of drill exit will induce larger burr.

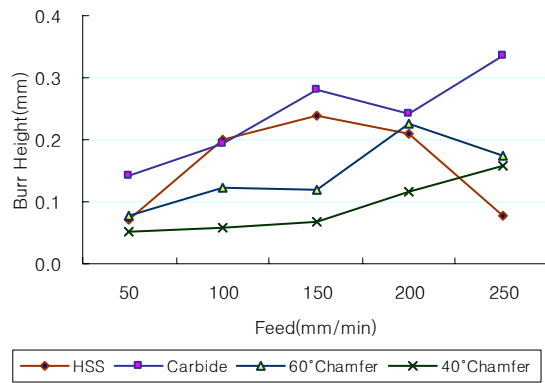
The round drill can be treated as chamfered drill approximately if the line connected from start point of corner to the end point of corner radius. Burr formation mechanism will be similar to that of chamfered drill. The remained part of drill with R2.5 is much larger than that of the drill with R1.5 corner radius, which results in producing larger burr in drill with larger corner radius.

Table 1 Specifications of Drill Geometry

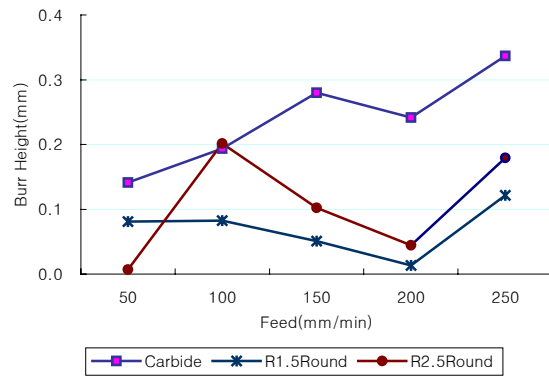
Drill Geom.	HSS		Carbide Drill											
	Drill		Chamfer		Round		Step							
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14
θ_1 (Pt.Ang.)	118°	140°	140°	140°	140°	140°	140°	140°	140°	140°	140°	140°	140°	140°
θ_2 (Chamfer/ Step Ang.)	.	.	60°	40°	.	.	130°	100°	75°	60°	40°	75°	60°	40°
D ₁ (mm)	10	10	10	10	10	10	10	10	10	10	10	10	10	10
D ₂ (mm)	.	.	.	.	.	.	8	8	8	8	8	9	9	9
R(mm)	.	.	.	.	1.5	2.5	.	.	.	.	.	.	.	.
L(mm)	.	.	2	2	.	.	2	2	2	2	2	2	2	2

Table 2 Cutting Conditions for Burr Formations in Drilling

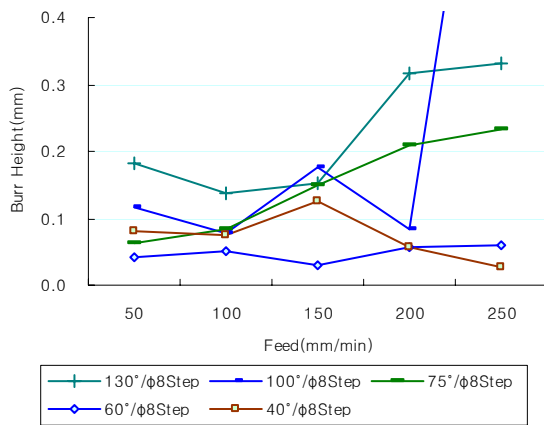
Drill	Material (Hardness)	Speed (m/min)	Feed (mm/min)	Coolant
HSS Drill			50	
Carbide Drill			100	
Chamfer Drill	SM45C (HRC14)	35	150	Dry
Round Drill			200	
Step Drill			250	



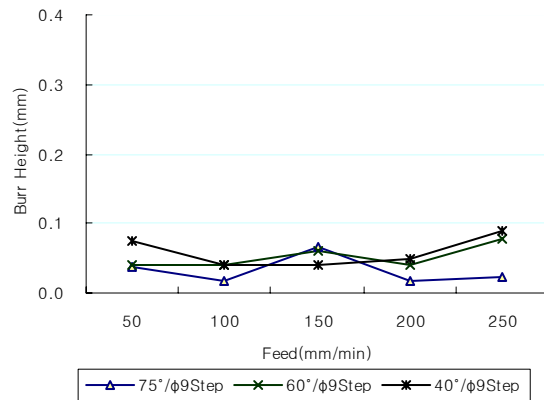
(a) Chamfer Drill



(b) Round Drill



(c) Step Drill (Ø8 step)



(d) Step Drill (Ø9 step)

Fig.3 Burr Height by modified Drill in SM45C

3.2.5 Observation of burr formation in step drill

In step drill, the drills with various step angle and step diameter have been used. 5 drills with different step angles, 130°, 100°, 75°, 60° and 40°, are manufactured with same step diameter, 9mm. In Fig.3(c), the burr height in drills with 130° and 100° step angle is almost same as that in conventional drill as shown in Fig.3(a). When the step angle reduced to 60° and 40°, the burr height reduced to less than 0.1mm. The mechanism of burr formation in step drill can be explained by Fig.6. The remained part just before step edge exits hole keeps very thin shape, which keeps very small stiffness to bending deformation. Then it can be easily predicted that the thin part will be bent to large burr. During this process, step edge does not machine the part, instead it pushes the remained part into burr. From Fig.6, the cap which produced in first cutting by front cutting edge with 140° point angle and attached to the burr by bending deformation is a clear evidence of this mechanism. The cap formed at the first cutting is pushed out along with burr at the second cutting by step drill with 100° and 130° step angle because

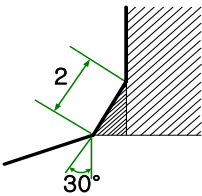

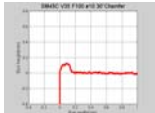
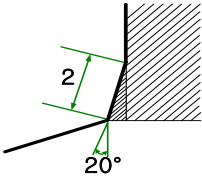
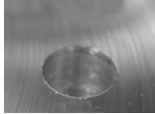
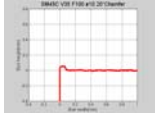
Chamfer Drill	Burr Formation	Exit Side Picture Laser Measurement
60°		 
40°		 

Fig.4 Schematic Illustration of Drilling Process when drill exits with chamfered drill.

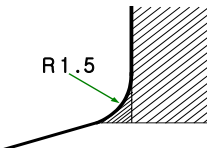
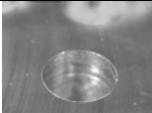
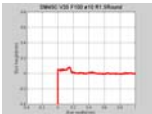
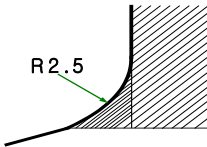
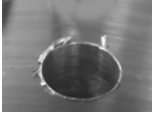
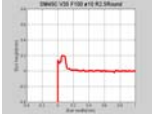
Round Drill	Burr Formation	Exit Side Picture Laser Measurement
R 1.5		 
R 2.5		 

Fig.5 Schematic Illustration of Drilling Process when drill exits with rounded drill.

stiffness is not enough to support thrust force in uncut volume. Therefore, the burst type burr is largely formed according to the size of difference between drill diameter and step diameter. Burr can be reduced when step cutting edge has small step angle less than 75° , in which case the remained part keeps larger stiffness and small burr will be produced as a result of less deformation. In Fig.3(d), the effect of step diameter on burr formation can be observed. By reducing the step size from 1mm to 0.5mm, the burr height decreases drastically and more stable size according to the change of feed rate. For all step drills with 0.5 mm step size and step angle less than 75° , the burr height is less than 0.1mm. When the step size reduced with smaller step angle, the uncut volume which is remained when drill exits becomes very small as shown in Fig.6, which guarantees small and stable burr formation. However too small step size will induce burnishing effect rather than cutting operation in step edges. Therefore it will be necessary to determine optimal step size for minimization of burr formation.

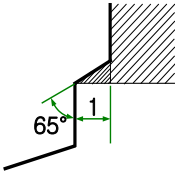
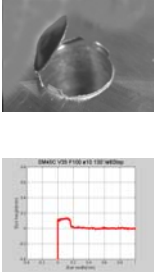
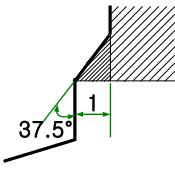
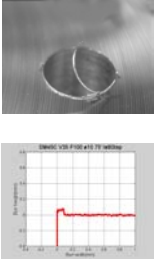
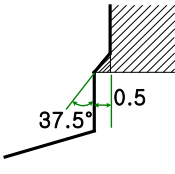
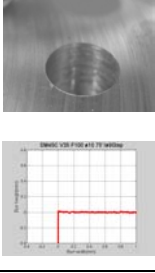
Step Drill	Burr Formation	Exit Side Picture Laser Measurement
130° Ø8		
75° Ø8		
75° Ø9		

Fig.6 Schematic Illustration of Drilling Process when drill exits with step drill.

3.3 Burr formation according to the change of work material

3.3.1 Cutting condition in experiment

Drilling tests are conducted in several work material whose material properties are listed in Table 3 to observe the influence of the material properties on burr formations. Al2024-T4 shows brittleness comparing other materials. All drill samples listed in Table 1 are used using the fixed cutting condition as in Table 4.

3.3.2 Experimental results

Fig.7 shows burr heights measured at exit surface, which are obtained in drilling by all drills in 4 different workpieces. In A6061 and SS400 which keep low yield strength and high elongation rate, relatively large burrs are formed, which is called as burst type burr. The burst type burr is formed as result of fracture at point edge and has very large and irregular shape. This kind of data is excluded in graph because of difficulty of measurement. Therefore the absent data can be understood as burst type burr which is very large and irregular in shape. In A2024 and SM45C which keep relatively high yield strength, the regular type burr with cap is usually formed, whose size is small as can be seen in Fig.7.

Table 3 Mechanical properties of workpiece

Property Workpiece	Yield Strength (kg/mm ²)	Tensile Strength (kg/mm ²)	Elongation (%)	Fracture Strain
SM45C	40.1	68.1	23.4	0.62
SS400	31.5	45.6	35.9	1.05
Al6061-T6	28.1	25.7	17.6	0.65
Al2024-T4	40.2	55	10.3	0.14

Table 4 Experiment Conditions with developed Drill in each material.

Drill	Material	Speed (m/min)	Feed (mm/min)	Coolant
HSS Drill	SM45C	35	150	Dry
Carbide Drill	SS400			
Chamfer Drill	A6061			
Round Drill	A2024			
Step Drill				

3.3.3 Characteristic of burr formation in each workpiece.

In SM45C, the characteristics according to the change of drill geometry and material properties are well represented as shown in Fig.3 and Fig.7. The burr formed in chamfered and round drill (#3,4,5,6 drill) is smaller than conventional drill but larger than step drill with small step angle (from #9 to #14). The step drill with 130° and 100° step angle produces larger burr than any other drills. The influence of step angle is shown clearly in drill #7 to #11. As it increases, larger burr is formed. The influence of the step size can also be observed. The drill with 1mm step size(#9, 10, 11) produces larger burr than that in drill with 0.5mm step size(#12, 13, 14). Step drill #14 produces least size of burr formation among samples.

In SS200, the behavior of burr formation is very similar to that in SM45C. But the burr size increases much more than in SM45C due to the ductility which can be explained by yield strength and elongation. The influence of step angle is represented much more clearly in drills #7 - #11 as shown in Fig.8. Also the burrs in drill with larger step size are larger than with smaller step size. Drill #14 which is step drill with 40° step and 0.5mm step size produces minimum size of burr.

In A6061 which has less elongation and less yield strength than SS200, the burst type burrs are formed often, which is impossible to be measured by laser measurement system. The burst type burrs are formed in chamfered drill and the step drill with 130° step angle. However in step drills, similar influence is observed by change of step angle and step size. Even though the difference of the burr height in #2, #6 and #14 drills is not large, #14 step drill produces smallest burr.

In A2024, burrs are formed with less than 0.1mm burr height due to the brittleness of material. In this case, the bending deformation of material at the exit stage is not allowed. The fracture before bending deformation forms negative burr, which is classified A type burr in previous work[7].

From the results presented in Fig.7, it can be observed that the #14 step drill with 40° step angle and 0.5mm step size produces minimum size of burr. To compare the burr formations between conventional drill with 140° point angle and step drill #14, burrs formed in each drill are illustrated in Fig.9. Except in A2024, burrs with cap are produced in every work material when drilled with conventional drill. However step drill #14 produces very small burr without cap formation. Minimum burrs are produced by reducing the uncut volume when step edge exits. The uncut volume can be reduced by reducing step angle and step size. However the minimum size of step must be decided considering burnishing effect which happens in machining with small depth

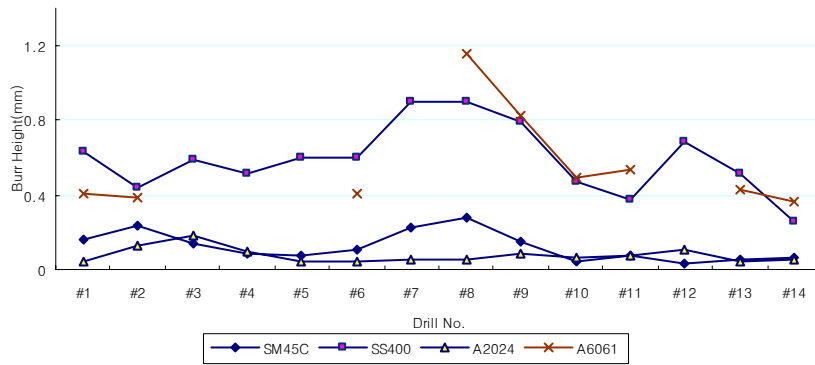


Fig.7 Burr Height by Developed Drill in each material

Drill No.	#8 (100° Step)	#9 (75° Step)	#10 (60° Step)	#11 (40° Step)
Burr Shape				

Fig.8 Burr Formation by step drill with various step angles in SS400

Drill No.	SM45C	SS400	A2024	A6061
#2 Conventional Carbide Drill				
#14 40°/ Ø9 Step Drill				

Fig.9 Burr Formation of Step drill compared with general carbide drill in each material

3.4 Cutting force test in modified drill

3.4.1 Cutting condition in test

Cutting forces are measured to observe the behavior of burr formation and the influence of the change of drill geometry to the drilling stability when drill exits. Experiment set up is shown in Fig.10. The same machining center is used. Kistler 9257B is used for measuring cutting forces. The data are processed through data acquisition system and stored. In two materials, A6061 and SM45C, drilling is performed by the cutting conditions listed in Table 5.

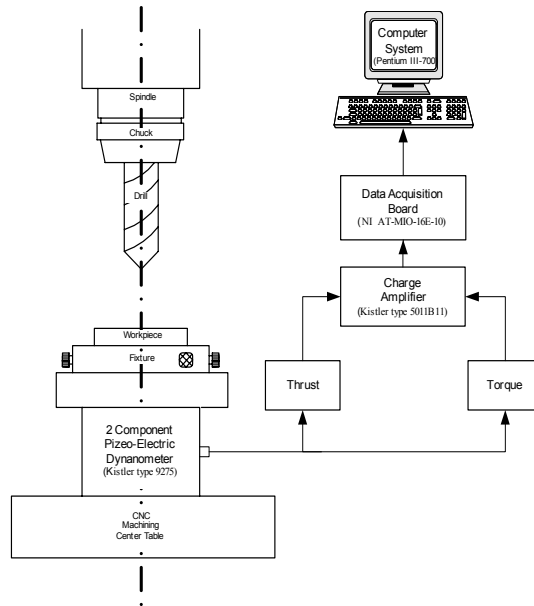


Fig.10 Schematic Illustration of Experimental setup and Data acquisition system.

Table 5 Experiment Conditions of Cutting force with developed Drill

Drill	Material	Speed (m/min)	Feed (mm/min)	Sampling rate
HSS Drill				
Carbide Drill	SM45C	35	150	300
Chamfer Drill				
Round Drill	A6061			
Step Drill				

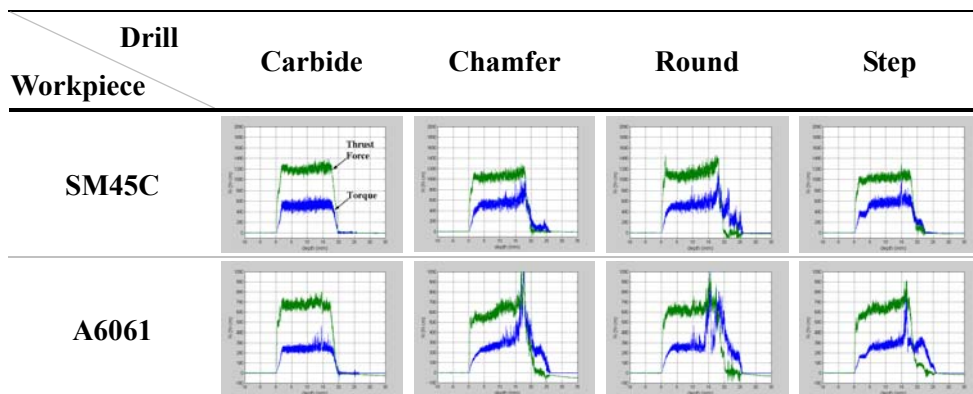


Fig.11 Cutting force by developed drill in SM45C and A6061

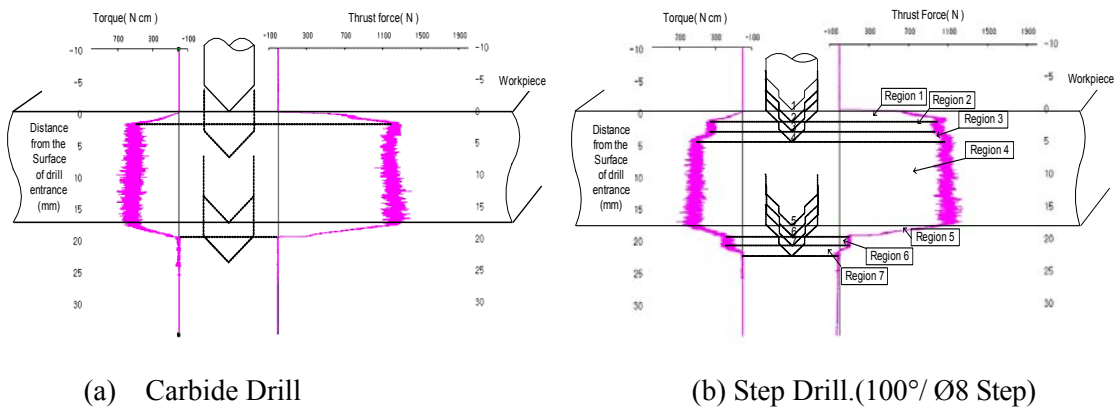
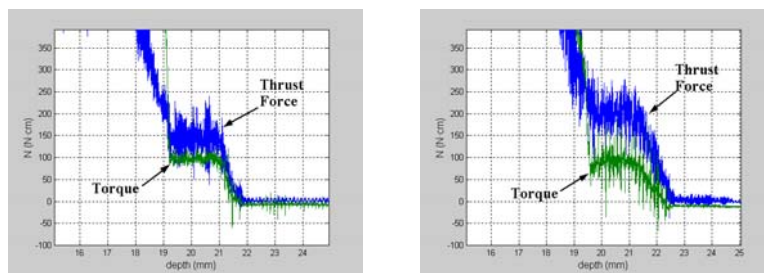


Fig.12 Cutting Thrust and Torque according as distance from the surface of entrance in drilling process.

Region	1	2	3	4
Entry Process				
Region	5	6	7	8
Exit Process				

Fig.13 Drilling Process in each region.(100°/Ø8 Step drill)



(a) 130° / Ø8 step drill (#7)

(b) 75° / Ø8 step drill (#9)

Fig.14 Cutting force during cutting uncut volume in step cutting edge in SM45C.

3.4.2 Test results

Fig.11 shows the results of cutting force test by each drill in SM45C and A6061. Thrust force and torque are measured. The cutting forces are about two times higher in SM45C than in A6061 because of larger yield strength. In conventional carbide drill, cutting forces are stable during whole process because the flute of drill is well designed for good chip formation. However unstable signals appears in drilling by modified drill with chamfered and round corner and step. Comparing the signals in chamfered and round drill, the force in step drill is more stable. The chip formation in chamfer and round drill is not stable due to the chip from the corner edge. In the case of step drill, due to the step length which separates the front cutting edge and step edge produces conducts better chip formation. This observation is more clear in drilling A6061. Because A6061 is more ductile, chips are not formed smoothly as in SM45C. The more unstable behavior of the chip formation in chamfered and round drill can be observed compared to that in step drill.

3.4.3 The variation of cutting force in step drill

In Fig.12, the thrust force and torque generated in drilling process are simultaneously represented as drill advances from entry surface to exit surface. Conventional drill and step drill are used to measure cutting forces. The sectional views in each cutting region are shown in Fig.13.

Fig.12(a) shows thrust force and torque in drilling SM45C with conventional drill with 140° point angle. When drill enters from point, the forces increase to the stable force which is generated in stable cutting. During the stable cutting the forces are very stable due to the smooth chip formation. Most commercial drills are carefully designed for successful chip flow. As drill exits, the force decreases rapidly as it enters.

In Fig.12(b), detail behavior of drilling process by step drill can be observed. Each drilling process by step drill can be classified into 7 regions. Each drilled state in workpiece is illustrated in Fig.13, which is provided by cutting cross section by wire EDM after drilling to each state. The region 1 and 2 is the cutting process by only front cutting edge which is same process as the conventional drilling as in Fig.12(a) with smaller diameter. In region 3, the forces increase by the additional cutting by step edge. Region 4 represents the steady state cutting by front cutting edge and step edge. The slight increase of cutting force shows the interference in chip formation and evacuation of chips. In this region, two kinds of chips are produced, one from front cutting edge and another from step edge. The chips from front cutting edge are well formed into small size to be delivered to outside due to the design of drill flute. However the long chips are formed from step edge. As the depth increases, interference by the long chips will increase the resistance. In region 5, front cutting edge is going out the workpiece and the force decrease. During this process, burr is formed as a result of 1st cutting by front cutting edge. The cap is produces as shown in Fig.13. In region 6, the steady cutting by only step edge is performed. The duration for this process is determined by the step length in Fig.2. The existence of step length help separation of chip formation by two cutting edges, which makes more stable cutting than in chamfered drill and round drill as shown in Fig.11. During region 7, the final burrs are formed by step edge

when it exits. According to the geometry of step angle and step size, the burr formed by front cutting edge may be removed into small burr, or remained with the burr formed by step edge. In Fig.13, larger burr can be observed due to large step angle, 100° , and large step size, 1mm, as discussed before.

Detail behavior of the region 7 can be seen in Fig.14, which shows cutting forces in two step drills with step angles, 130° and 75° , and step edge, 1mm. In the step drill with 130° step angle, bending deformation occurs earlier than in the drill with 75° step angle and the cutting process is stopped earlier. The torque in Fig.14(b) decrease more slowly than that in Fig.14(a), which means the continuous cutting due to small step angle, 75° .

CONCLUSION

Drill geometry are modified for minimization of burr formation. Conventional drill with 140° point angle is modified at the corner of edge. Chamfered drill, round drill and step drill is designed and manufactured.

1. Modified 3 drills produced less burr than the conventional drill. Step drill with step angle less than 75° and 0.5mm step size produces least burr. As a mechanism of minimization of burr formation, the remained part just before drill exits workpiece must keep larger stiffness and less volume to continue the cutting process to the end of drilling and to reduce the volume for deformation.

2. 4 materials which have different properties are used for burr formation with modified drills. Ductile materials like SS200 and Al6061 produce larger burr with some burst type burr. Al2024 and SM45C produce uniform and small burr with cap. In all materials, the influence of step angle and step size are investigated. Except A2024 in which most burrs are small and uniform regardless drill geometry, step drill with less step angle and less step size produce smaller burr.

3. Cutting forces are measured to observe the detail behavior of drilling in each modified drill. Chamfered drill and round drill show unstable forces due to the chip formations from front cutting edge and from edge corner. In step drilling more stable forces are observed due to the chip separation by step length. It can be observed that also the slow decrease of torque when step drill exits because of continuous cutting by step edge to the end of drilling.

for observation characteristic of burr formation in each material with different

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