State-of-the-art on Drilling Burrs: Mechanisms and Control

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Abstract: Presence of burrs at the component edgeshinders the assembly process, reduces the service life of the product as well as affects its performance. Therefore, designers demand burr free components after drilling operation. However, previous research has shown that burrs cannotbe totally avoided at the drilling stage. Thus, an additional burr removal operation (called deburring) has to be addedto the production processleading to requirement of skilled manpower, additional costand long process time. Hence, industries are interested in limiting the size of burr produced in the drilling stage, so as to facilitate automationof manufacturing process and lower deburring cost.This review paper presents state-of-the-art on various factors influencingburr formation and recently developed strategies for burr minimization and control. Influence of various process parameters, cutting environments, exit surface geometries, component and drill materials, wear and edge geometries of the drills on size of the burr has been critically examined and explained. In addition, burr formation mechanisms and detailed burr classifications are reviewed and discussed.

Keywords: Drilling burr, mechanism, burr control.

1. Introduction to concernsabout drilling burrs

Drilling is the one of the most important operations in the manufacturing industry, using which millions of circular holes are created on solid components every day. The drilled holes havea crucial role to play in assembly processes, product function as well as its overall performance. However, during the manufacturing of these holes, burrs are formedon the entrance and exit surface of the holes[1]. If these burrs are not removed from the components, they acts as (i) crack initiation points which reducethe fatigue life of the part, (ii) a source of misalignment and jamming in the assembly process and, (iii)a cause of dimensional error in the precision components.These burrs may also lead to injury to the fingersof assembly workers as the burrs are quite sharp.Further, if the loose burrs are present in the service condition, they may cause serious damage to moving parts and could contribute to electrical short circuits as well [1-12]. A well-known example of this is engine failure due to crankshaft burrs. Burrsare formed onthe crankshaft oil passageedges during drillingwhich move with cooling fluid in the various sections of the engine. They can become a potential cause of complete engine failure.Therefore, industries oftenspecify requirement of “burr-free edges” on the componentdrawings. This essentially requires addition of burr removal (deburring) operation to the production lines.

Deburring is a very labor intensive, complex and non-value added operation, which demandshigh skills, high cost and long processing time[2,4,12-17]. Automation of deburring isalso quite difficult due to highly varying shapes, dimensions and properties of the burrs[7, 8]. Therefore, minimizing burr formation at the drilling stage is the cheapest remedy[18]. This review paper, therefore, presents a state-of-the-art on various factors influencing burr formation and recently developed strategies for burr minimization and control. Influence of various process parameters, cutting environments, exit surface geometries, component and drill materials, wear and edge geometries of the drills on size of the burr has been critically examined and explained. Additionally, burr formation mechanisms and detailed burr classifications are reviewed and discussed.

2. Drilling Burr

Aurich et al. [2]defined burr as an unwanted projection of material formed at the edge of the machined surfaces. It isa result of plastic deformation and shearing at the end of the machined surfaces. ISO 13715 [19] defines that an overhang greater than zero at the workpiece edge is a burr. Specifically, in drilling, the extra portion formed around the perimeter of the holes at the entry and exit is a burr. However, entry burr is much smaller and easier to remove. Thus, the focus of recent research has been on exit burrs. Fig 1aschematically illustrates entry and exit drilling burrsandgivesburr nomenclature, burr thickness (t) and burr height (h).

Studies in this domain disclose drilling experiments on different materials with a wide range of feed rates and cutting speeds to reveal all the possible exit burr geometries. Further, these burr geometries have been classified based on size, such asburr thickness (t) and burr height (h),as thesecontrol the deburring cost.

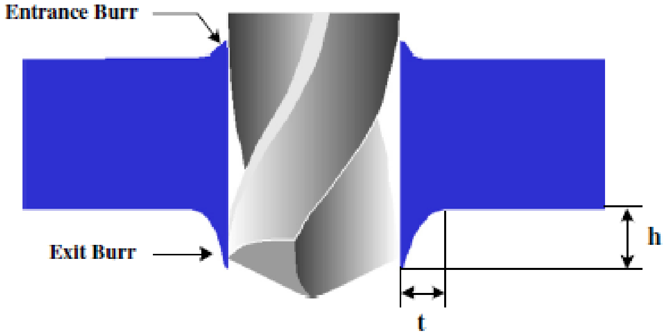
Table 1 shows classification and description of burrs defined by different research studies. Researchers observed uniform,transient, and crown or petal or bursttypes of exit burrs in low alloy steels[1][3, 6][5, 9] and copper[20, 21]. While, uniform and crown types of exit burrs were observed in stainless steel[1] and brass [22], and uniform and transient types of exit burrs were observed in aluminum (6061-T6) [23] and titanium (Ti-6Al-4V) [24, 25]. Researchers have further classified uniform burrs into two subgroups; small and uniform burrs without drill capand,large and uniform burrs with a drill cap.Dornfeld et al.[26]studied titanium drilling with or without cutting fluid and classified wet drilling exit burrs into the following three classes;

1. **Type A:** uniform burrs without attachment,
2. **Type B:** uniform burrs with ring formation and
3. **Type C:** uniform burrs with drill cap, refer Fig. 1b.

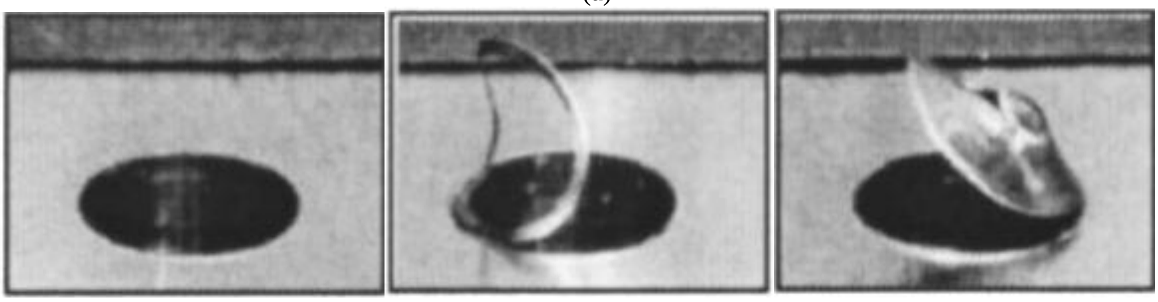
The dry drilling exit burrs have been classified into four classes,

1. **Type I:** uniform burr,
2. **Type II:**lean back burr,
3. **Type III:**rollback burr,
4. **Type IV:**rollback burr with widened exit, refer Fig 1c.

Recently, several authors[27], [28]observed various interlayer burrs in multi-layer materials, refer Fig 1d.Literature review reveals that no prior studies have examined and classified exit burrs in composite materials. The state of research reveals that the previous studies do not quantify the geometry of exit burrs (burr height and thickness) except for steel alloys. Hence, further detailed studies are required on exit burr quantification for the different grade of materials.



(a)



Type A: Burr without attachment Type B: Burr with ring formation Type C: Burrs with drill cap

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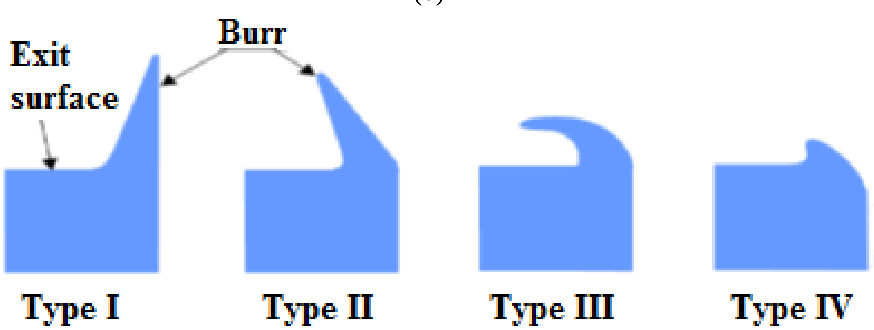

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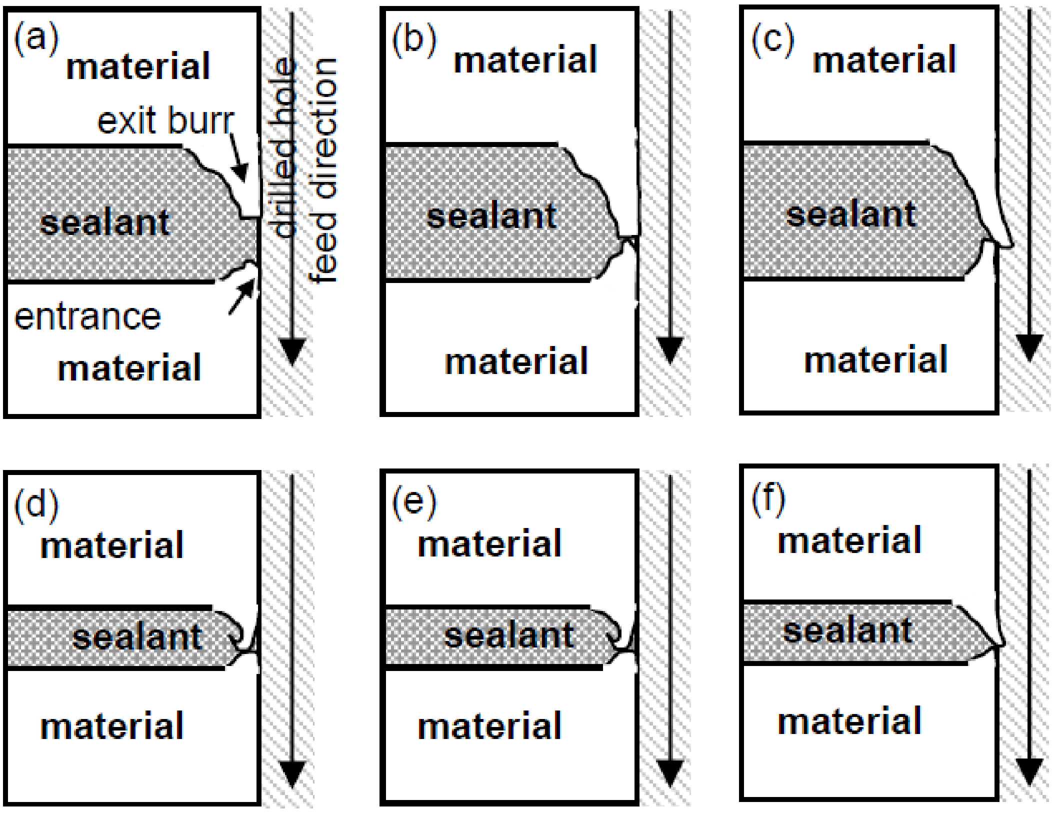
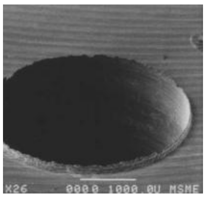
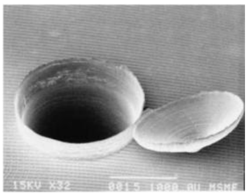
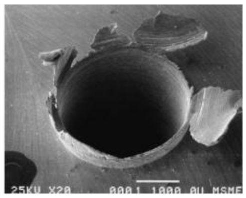
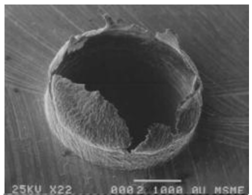
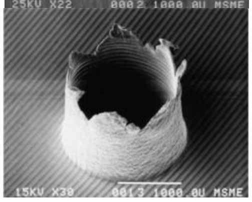
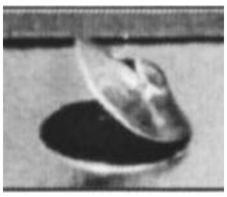


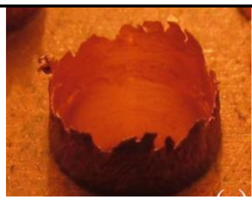
(d

(d)

Fig. 1) (a) Burr nomenclature[22], (b) Types of exit burrs in wet drilling of titanium alloy [29], (c) Types of exit burrs in dry drilling of titanium alloy [30], (d) examples of interlayer burrs in multilayer material [28]

Table 1: Classification of drilling burrs

Burr Types	Uniform burr		Transient burr	Crown or petal or burst burr
	Burrs without drill cap	Burrs with drill cap		
Examples	 AISI 4118 [9]	 AISI 304L [9]	 AISI 4118 [9]	  AISI 4118 [9], AISI 304L [9]
	 Copper [21]	 Ti-6Al-4V [31]	 Copper [21]	

				 Copper [21]
Burr height	~**0.18** AISI4118 [1, 9] ~**0.15** SS*[5, 6, 9, 32] **0.03** ~**0.15** SS* [33]	**0.18 – 1.0** AISI4118 [1, 9] **0.15 – 1.1** SS*[5, 6, 9, 33, 6]	**(1.1-1.5)d**/2** AISI4118[1, 9]	≅**(1.1~1.5)d**/2** AISI4118, SS* [1, 5, 6, 9, 32], ≅**(1.3)d**/2** SS* [33]
Burr Thickness	**0.8** ~**1.6** SS*[5] **0.04**~**0.1** SS*[33]	**1.5** ~**3.2** SS* [5] **0.8**~**0.3** SS*[33]		**3.8** ~**5.3** SS* [5], ≅**(0.3)d**/2** SS* [33]
Remarks	− Small uniform burr − least burr height and thickness − Easy to remove − Lowest deburring cost	− Small uniform burr with drill cap − Lower deburring cost	− No definite shape − Non-uniform burr height and thickness − Higher deburring cost	− Wavy burr profile − Highest burr height and thickness − Difficult to remove − Highest deburring cost

Burr height and thickness in mm, SS* indicates Stainless Steel, d** indicates drill diameter

3. Mechanisms of burr formation

The burr formation mechanism in drilling is controlled by the thrust force which is induced by the cutting parameters, drill geometries and tool/work orientations at drill exit[34]. These parameters dictate the amount of deformation and bending fracture location at the exit, which leads to formation of different types of burr[1, 4, 9, 35].Fig 2 illustrates typical conceptual models of burr formation mechanisms for ductile materials based on experimental [36-39] and simulation data[40-45]from literature. These models refer to the conditions of exit surfaces such as flat (a-e), inclined (f), and curved (g)surfaces. These mechanisms are divided into four stages;

(i) steady-state cutting stage,
(ii) initiation and/or development stage,
(iii) fracture and/or continuous cutting stage and,
(iv) burr formation stage.

In steady-state cutting, material ahead of the drill tip is removed as chip and plastic zone appears under the drill tip. As the drilling progresses, this plastic zone also progresses along with the drill tip and finally reaches the drill exit surface. Once the plastic zone reaches the drill exit surface, it initiates deformation and bending under the chisel edge. Up to this point, material is removed by cutting edges of the drill. However, after this point, the bending of the deformed layer occurs. The process behavior after this point mainly depends on the thickness of the deformed layer, i.e.thematerial layer between the exit surface & drill cutting edge, marked by letter t in Fig.2.This deformed material layer is mainly controlled by thrust forces and cutting temperature. The deformed layer also defines the initial fracture location and the final burr shape in drilling. If the deformed layer is thin (t_1, t_2,and t_3), the final result is uniform burrs. On the other hand, if the deformed layer is thick, transient (t_4) or crown (t_5) burrs areformed ($t_1 < t_2 < t_3 < t_4 < t_5$) [1, 3, 4, 9, 36].

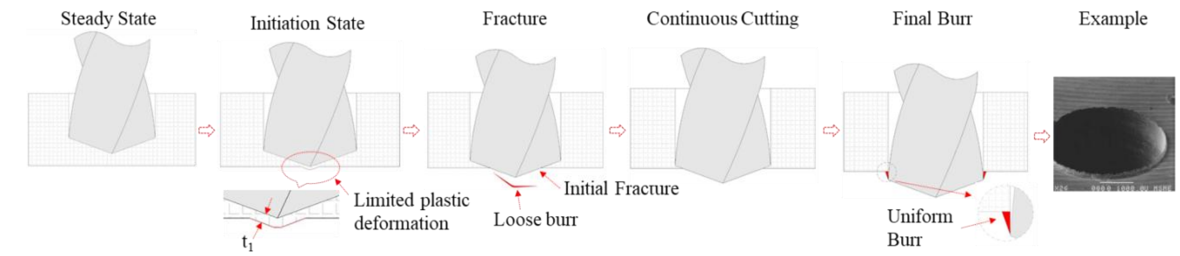
The thin material layer does not have enough support so as to be cut by the drill edges during the initiation /development stage. It results in a rapid transition from cutting to bending which leads to inefficient cutting. As the drill further advances, plastic deformation zone expands from the center to the outer edge of the drill. However, the material near the drill edge has sufficient stiffness to support the cutting forces. Therefore, material undergoes further cutting and bit of bending. As material near to the edge becomes thinner and thinner, it is unable to withstand the cutting forces. This leads to initiation of fracture near the cutting edge. After this, remaining material is bent and pushed out ahead of the drill to form a uniform burr with or without a cap[1, 4, 9], as shown in Fig. 2c.

The materials with limited plastic deformation show early fracture in the process near to the central region of the drill. After continuous cutting, uniform burr without drill cap is formed around the periphery of the hole, as shown in Fig. 2a.

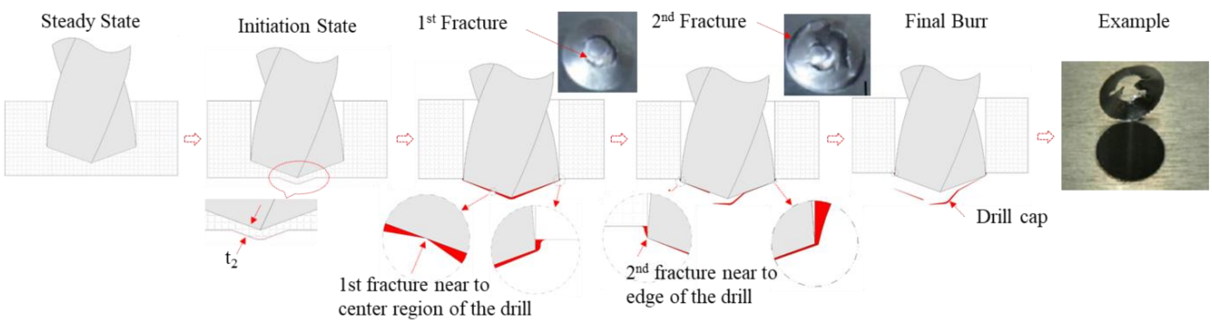
Sometimes, uniform burrs are formed with secondary drill caps remaining attached with main drill cap, as shown in Fig. 2b. The chisel edge playsa crucial role in developing the secondary drill cap. As the chisel edge is not involved in cutting, the material under the chisel edge undergoes only plastic deformation. As drill advances, the material around the chisel edge undergoes cutting and bending. This thins the material under the chisel edge. As the drill advances, initial fracture occurs near to chisel edge leading to secondary drill cap formation.

A thick material layer has sufficient stiffness so as tobe cut by the drill edges during the initiation / development stage. A slow transition from cutting to bending occurs, which ensures more material removal during the development stage. It also results in strain hardening due to application of maximum strain near to the center of the exit surface. The material in this region becomes brittle. Once the maximum strain exceeds the fracture strain of the material, initial fracture occur near the center of the drill and therefore, the material around of the drill is pushed out. It forms a crown burr, as shown in Fig. 2e[1, 4, 9]. During transient burr formation, multiple fractures occur simultaneously near the drill corner and at center of the drill. This results in uneven transient burrs, as shown in Fig. 2d.

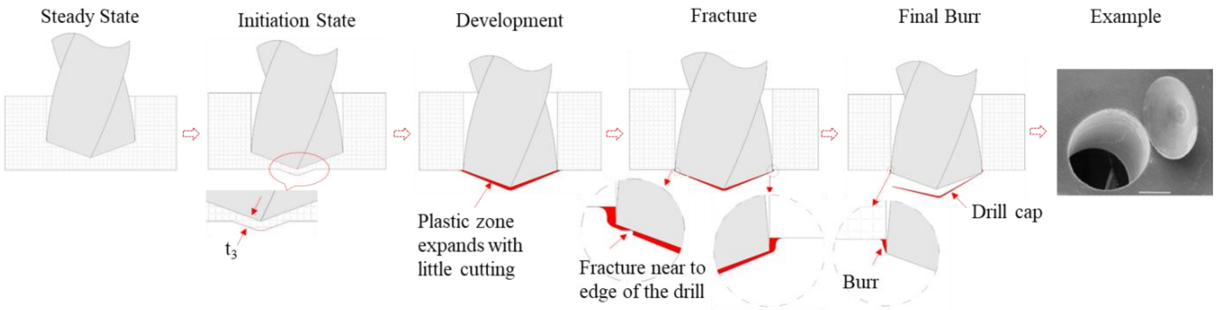
The exit surface geometry plays an important role in the burr formation mechanism.Oncethe drill tip reaches near the exit surface, deformed layer thickens under the drill is controlled by exit surface geometry, refer Fig. 2 f-g. At this stage, the region under the drill tip does not have sufficient strength to sustain the thrust force. This promotes a rapid transition from cutting to bending in the local area. In this region, the material is pushed ahead as drill advances and gets strain hardened. When the strain exceeds critical strain, initial fracture is formed near the drill tip giving rise to large burr formation. As the drill advances further, the material gets cut from the peripheral region, where it has sufficient stiffness. Thus, small burrs are formed along the perimeter of the holes [37, 46-48].



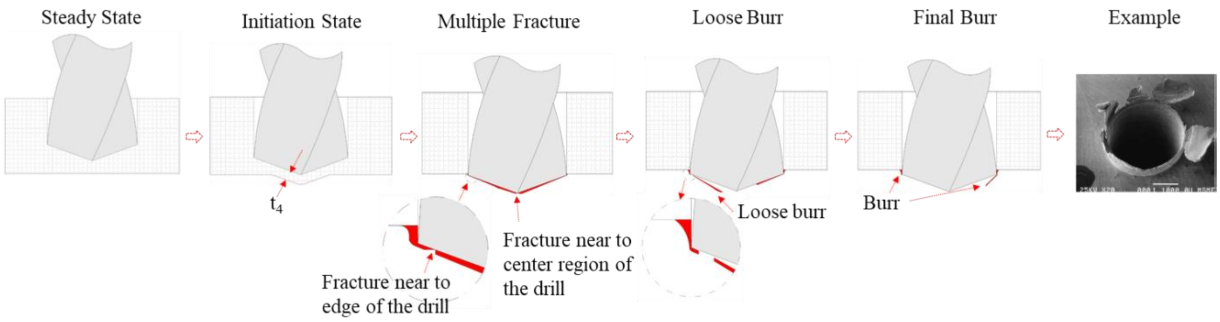
(a) Uniform burrs without drill cap redrawn based on[31, 27] (Example: AISI 4118 [9])



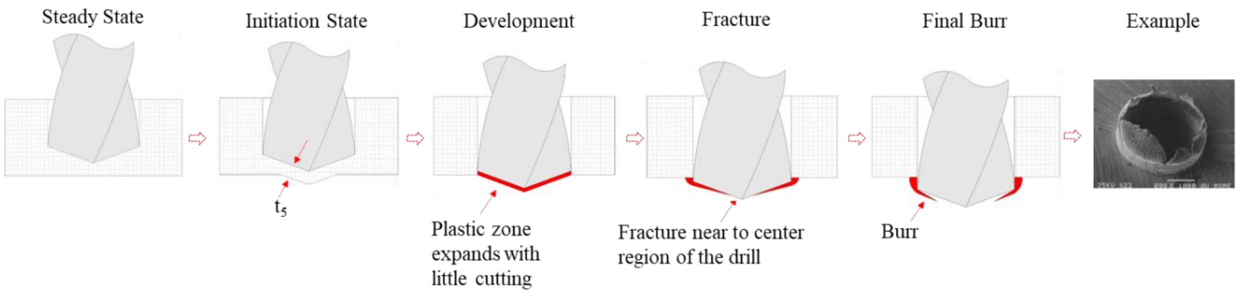
(b) Uniform burrs with drill cap redrawn based on[1, 24].(Example: Aluminum 2024 T354[49])



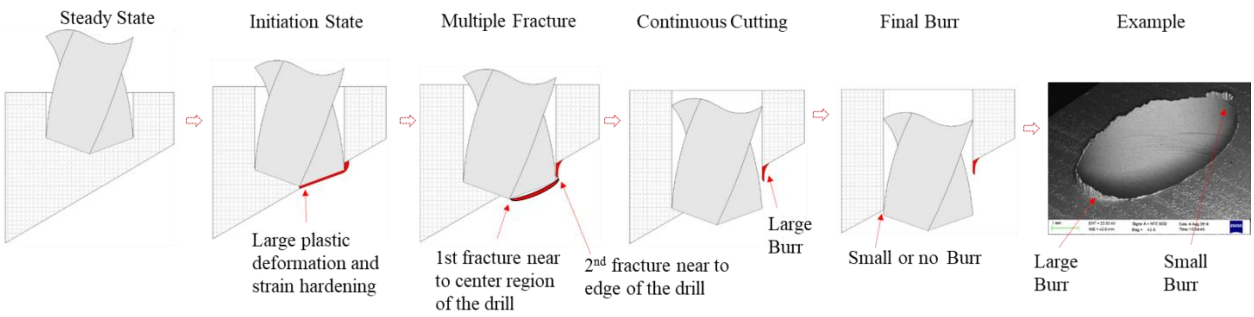
(c) Uniform burrs with or without drill cap redrawn based on[3, 31, 38, 40, 27](Example: Stainless steel [6])



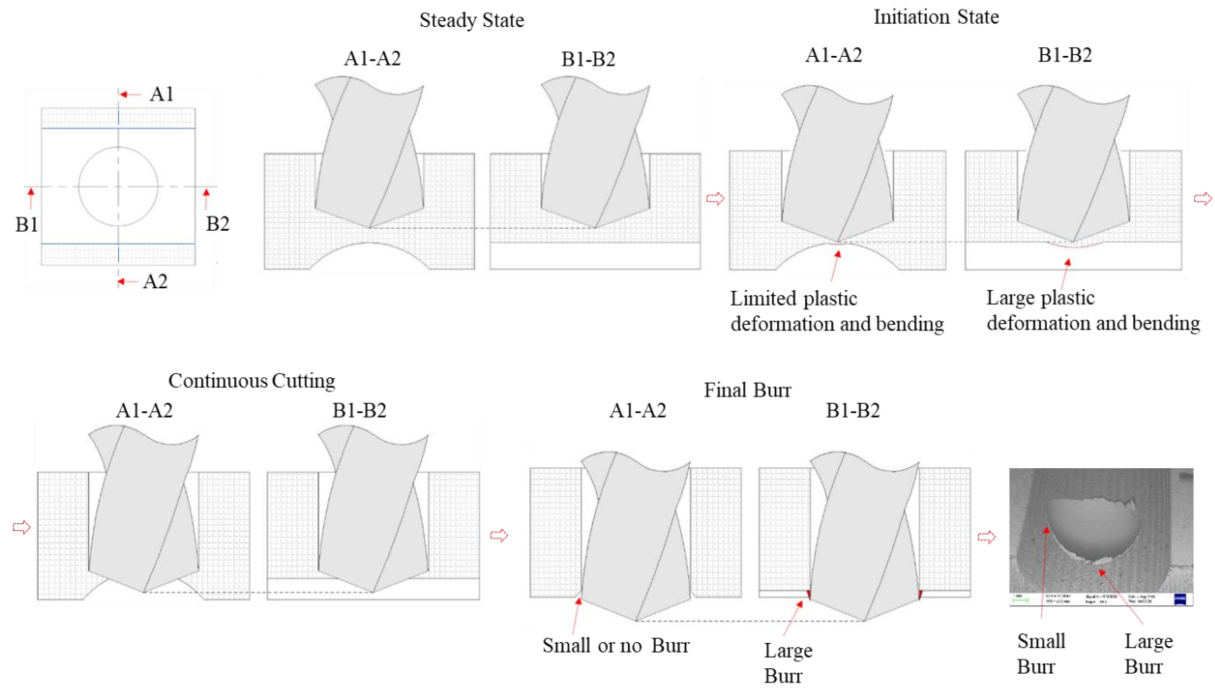
(d) Transient burr redrawn based on [1](Example:AISI 4118 [9])



(e) Crown burr redrawn based on [1, 4, 9, 31, 38, 40].(Example: AISI 4118 [9])



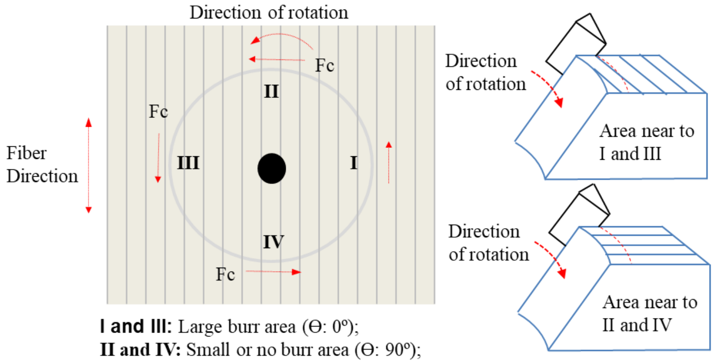
(f) Burr formation in intersecting hole redrawn based on[6][47][50](Example: Steel[50])



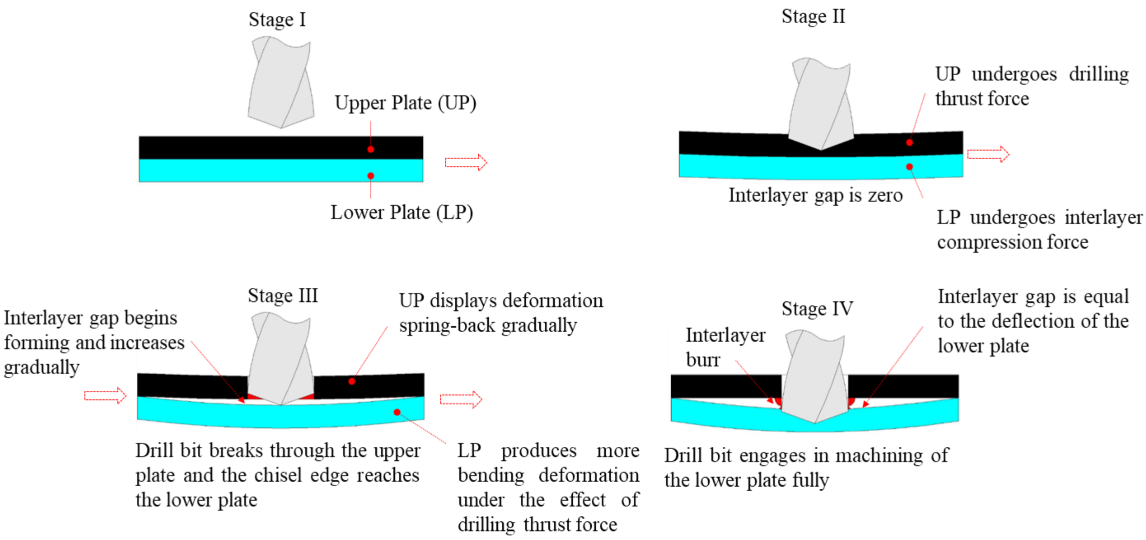
(g) Burr formation with curved exit surface redrawn based on [50][51](Example: Steel [50])

Fig. 2 Schematic of burr formation mechanisms; (a-e) flat exit surface; (f) inclined exit surface; (g) curved exit surface

Burr formation studies in CFRP composite materials suggest that the angle (ϴ)between the direction of cutting force (F_C) and fiber orientation plays a crucial role in defining the burr size. It is evident that the maximum burr occurs at 0º angle, where fiber cutting is inefficient, see areas near locations I and III in Fig. 3a. The burr is minimum at 90º,where fibers cut effectively, see areas near locations II and IV in Fig. 3a[52, 53].Recent studies have shown that debonding is more dominant in the regions I and III, Fig 3a. Thedebonded fibers suffer large deflection, which leads to delamination or the fiber pull-outs at the end of drilling[54].In the case of burr formation in multilayer sandwich materials, the size of interlayer burrs are mainly governed by the gap formed at the interfaces due to drilling thrust[55, 27]. Fig. 3b describes the interlayer burr formation inmultilayer sandwich materials.



(a)



(b)

Fig. 3 (a) Burr formation in CFRP composite redrawn based on[52]; (b) Burr formation in multilayer sandwich materials redrawn based on [27]

4. Factors influencing burr formation

In drilling, burr formation phenomena is influenced by large number of factors; see Table 2.Whilethe drilling burr formation cannot be completely prevented, the size and shape of burrs can be reducesignificantlyby choosing appropriate drilling conditions. In the following sections, various factors influencing the burr formation are discussed.

Table 2: Factors affecting the burr formation[1, 2, 30, 56, 57]

Category	**Factors**
Work and Drill Material.	Material Properties (Ductility, Strength, Strain-Hardening characteristics and Hardness)and Drill Coatings
Cutting Environment	Dry, Wet, Mist or MQL, Cryogenic, etc.,
Work Geometry	Exit Surface Geometries
Process Parameters	Feed, Spindle Speed, Drill Size and Length to Diameter Ratio
Drill Parameters	Point Angle, Lip Clearance Angle, Helix Angle, Chisel Edge, Point Shape and Sharpness (Wear)
Other	Machine Tool Vibration and Deflections

4.1 Work material

The material properties like ductility, hardness, thermal conductivity, composition, etc., has significant effect on the drilling burr formation process [58-61]. Studies have found that ductile materials like copper, aluminum, stainless steel, etc., produce larger exit burrs. The reason is the large plastic deformation facilitated by ductility in drilling. On the other hand, brittle materials, which cannot sustain even small amount of plastic deformation, produce very small exit burrs[58, 62]. The Link [63]shows the influence of ductility on burr size in the form of a burr tendency equation. In the proposed equation the author has accommodated material properties like tensile strength, yield strength, percent elongation at fracture and percent reduction of the area which essentially measure ductility of the material. The material hardness also plays a crucial role in defining burr size. Higher workpiece hardness requires larger thrust during drilling operation, which yields larger burrs. Pande et al. [58] found that workpiecematerials having a hardness in the range of 130 to 140 BHN produce least burrs. The author also observed that the optimum hardness is driven by the length to diameter ratio. Burr formation studies on thermal conductivity of the work material found that the materials with lower thermal conductivity produces thick burrs[64]. The reason is the thermal expansion facilitated by the limited heat dissipation. Studies oncomposite materials have found that adding graphite particles in the composite facilitates reducing the burr size during drilling [65-69].

4.2 Drill material

Drill material considerably affects the final size of the exit burrs [70][71]. Table 3 shows the drill materials and/or coatings recommended by researchers for least burr formation. Ramula et al. [70] found that carbide drills produce smallest burrs with different levels of feed and speed over the HSS and HSS-Co drills. The reason of larger burrs could be the rapid tool wears, more heat and larger thrust associated with the HSS drills. The coatings on drill also helps to reduce the burr size [72-74]. The reason could be the reduced friction at different interfaces, which further resist the drill wears [75] and reduce the thrust requirement[76]. Feldshtein[72] usednanolayerTiAlNcoating in his study and found a significant improvement in the shape of the burrs on steel. Sivarao et al. [73]studied the different levels of cutting speed and feed with TiN and TiAlN coatings, and found that TiAlN coatings have better results over TiN coating. Recently, Orazio et al. [77] found the least burr with DLC (diamond-like carbon) coating over the TiAlNcoating. While Luis et al. [74] found TiAlN-WC/C multilayer coating have better results over DLC coating. Controversial results were recently noted by Kumar et al.[78]in their research. The authors found that the TiAlN coated solid carbide drill is not suitable to reduce burr size, specifically in titanium alloy. The state of research ensures that coatings have potential to reduce drilling burrs size, while all coating materials are not tested on a single platform. Thus, further detailed studies have to be carried out in which performance of different coating materials are studied on a single platform.

Table 3: Researchers recommended drill materials or coatings for least burr

Reference	Work Material	Tasted drill materials or coatings				Recommended drill materials or coatings for least burr
		HSS	Coated HSS	Carbide	Coated carbide	
Ramula et al. [70]	Gr/Bi-Ti stack	✓ HSS, HHS-Co	-	✓	_	Solid carbide
Arun et al. [79]	Stainless steel	-	✓ TiAlN	✓	✓ TiAlN	TiAlN coated HSS drill
Feldshtein[72]	Stainless steel	✓	✓ TiAlN	-	-	TiAlN coated HSS drill
Sivarao et al. [73]	Stainless steel	-	✓ TiN, TiAlN	-	✓ TiN, TiAlN	TiAlN coated drill
Lin et al. [80]	Stainless steel	-	✓ TiN, TiCN, CrN, TiAlN	-	-	TiN HSS drill TiCN HSS drill
Caydas et al. [81]	Stainless steel	✓	✓ TiN	✓	-	TiN-coated HSS drill
Feldshtein[72]	Titanium alloy	✓	✓ TiAlN	-	-	Negligible effect within the experimental domain
Borba et al. [82]	Aluminum A306	-	-	✓	✓ TiN	Negligible effect within the experimental domain
Luis et al. [74]	Aluminum 7075	-	-	✓	✓ TiAlN-WC/C, DLC	TiAlN-WC/C multilayer coated drill
Li et al. [83]	Aluminum 2219	✓ HHS-Co	-	✓	✓	HHS-Co drill
Xavier et al. [84]	Al6063 matrix alloy	✓	✓ Cobalt	-	✓ Black oxide	Black oxide coated carbide drill
Ravindranath et al. [69]	Al2219 matrix alloy	✓ M42	✓ TiN	✓	-	Carbide drill
Melkote et al. [85]	Aluminum stack	✓	✓ TiN, Black oxide	-	-	Black oxide coated HHS drill

Bakkal et al. [71]	Bulk metallic glass	✓	✓	-	✓ WC–Co	WC–Co drill
Orazio et al. [77]	CFRP/AA7075 stacks	-	-	-	✓ DLC, TiAlN	DLC coated tungsten carbide
Rubio et al. [21]	Sandwich composite	✓	✓ TiO2	-	-	TiO2 coated HSS drill
Swain et al. [86]	Nimonic 80A	-	-	✓	✓ TiAlN	TiAlNcoated carbide drill
HSS- High speed steel, DLC- Diamond-like Carbon						

4.3 Cutting environment (Cutting fluid)

Cutting fluids are used in drilling operation to cool and lubricate the drill as well as the workpiece. Both these actions influence the burr forming mechanism and subsequently the final size of the burrs. As a coolant, cutting fluids convey heat away from the cutting zone and as a lubricant, it reduces the frictional forces among the various contacts. This results in lower temperature and thrust during drilling. These drilling conditions are favorable for reducing the size of burrs at the perimeter of the drilled hole[92].

The introduction of cutting fluids during drilling operation by methods like wet, mist / MQL, cryogenic, etc., is beneficial to reduce burr size in comparison to dry drilling. In Table 4recommendations given by various researchers as regards to optimum drilling environment for least burr formation has been compiled. The studies employed on the various cutting fluid application methods found that the smallest burr is produced in the cryogenic environment. However, the cryogenic burrs are not much smaller or differ from other methods like wet and MQL. Zedan et al. [87] found that the burr size reduced by 75% with mist cooling and 70% with wet cooling over dry drilling. Similar findings have been observed by Mathew et al.[88]in their study. Kandu et al. [89]conducted the experiments with water and soluble oil and found that water as cutting fluid has better performance in reducing the burr size as compared to soluble oil. Similar findings have been noted by Mondal et al. [90]. Biermann et al. [91]experimented withCO_2 as cutting fluid to reduce burr size. The authors used CO_2 to cool the exit side of the workpiecewhich causes the exit surface to become brittle. This results in lower burr heights. The studies also observed that higher cutting speeds lowers the effectiveness of cutting fluids in reduction of burr size[87, 92].

The state of research assures that the MQL lubrication method has the potential to produce similar burrs like wet or cryogenic drilling with lower lubrication cost. While only a few researchers have addressed MQL in their studies. Thus, further detailed studies have to be carried out on MQL with reference to mass flow rate, different lubricant compositions and air pressure.

Table 4: Researchers recommended drilling environment for least burr

Reference	**Work Material**	**Drilling environment**					**Recommended environment for least burr**
		Dry	**Cryogenic**	**Wet lubrication**	**MQL or Mist lubrication**		
Murthy et al. [93]	Al 6063 T6	✓	_	✓ Water soluble oil	Flow rate Pressure Lubricant	50 ml/ min, 5 bar UNIST coolube 2210	MQL
Mathew et al. [130]	Titanium aluminide	✓	_	✓ Soluble oil diluted with water	Flow rate Pressure	200 ml/h 6 bar	Wet and MQL
Zedan et al. [23, 87]	Aluminum alloy (T6-6061)	✓	_	✓ Water-miscible mineral oil 5000 ml/h	Flow rate Pressure Lubricant	50 ml/h, 6 bar, Vegetable oil	Wet and Mist
Senthilkumar et al. [94]	CFRP/Ti6 Al4V stacks	_	_	_	Flow rate Pressure Lubricant	25, 50, 75 ml/h 5 bar, LRT30.	50 ml/hr flow rate.
Lotfi et al. [95]	AISI 1045 steel	✓	_	_	Flow rate Pressure	100 ml/h 4 bar	Insignificant within the

					Lubricant	Accu-lube FG-2000	experimental domain.
Shyha et al.[96]		–	–	✓	✓		Wet cooling (high pressure~70 bar)
Biermann et al. [91]	Steel Aluminum	✓	✓ CO_2	✓	–		Cryogenic cooling,
Percin et al. [25]	Ti–6Al–4V alloy	✓	✓ Liquid Nitrogen	✓	✓		Cryogenic cooling.
Ucak et al. [97]	Inconel 718	✓	✓ Liquid Nitrogen	✓ Synthetic oil-water	–		Cryogenic cooling
Kundu et al. [98][89]	Aluminum alloy	✓	–	✓ Water, Soluble oil	–		Soluble oil.
Kamboj et al.[99]	Composite (Al6063/15%/SiC)	✓	–	✓ Water-soluble oil, Synthetic oil	–		Water soluble oil.
Mondal et al. [90]		✓	–	✓ Water	–		Insignificant within the experimental domain.
Shefelbine et al.[100]	AlSi9MgWa	✓	–	✓ Flood coolant.			Flood coolant.
Bagchi et al. [101]	Stainless Steel	✓	–	✓ Water, Coolant	–		Dry drilling.
MQL: Minimum quantity lubrication							

4.4 Exit surface geometry

The exit surface of drilled holes is not always flat in industrial applications. It may be curved or angled as per the demands of assembly or application. The most common example of a curved or angled exit surface is the intersecting holes, typically used to lubricate a rotating component. The exit surface geometries have potential to vary the burr sizes[51]. Min et al. [47] studied burr formation associated with different types of exit surfaces and defined exit surfaces using two angles namely, (i) exit surface angle i.e. the angle between the tangential line to the exit surface and normal line to the drill path, and (ii) interaction angle i.e. the angle between the cutting edge and the exit surface. Their observations are,

(i) a higher value of exit surface angle yields smaller burr and
(ii) an are a where burr is likely to form is controlled by the interaction angle.

Similar findings have been noted for exit surface angle and interaction angle by Dornfeld et al. [4, 102] and Heisel et al. [103] in their respective studies. Jason et al. [104] found smaller burrs for a curved exit surface as compared to a flat surface. The author noted average burr size of 104.7 micron for a flat exit surface, whereas, the same is 44.7 microns for a curved concave exit surface under the same cutting environment. The reason could be the extra support from curved exit surface which delays the cutting to bending transformations.

The state of research shows that the exit surface geometry has considerably influence on drilling burr size and real-life applications exit surface became curved and/or inclined. While, limited studies have considered exit surface geometry along with the wide range of materials, cutting parameters, drill geometries and drilling environments. Thus, most of the researcher's recommendations are not directly useful to industrial applications. Hence, more detailed studies need to be carried out on the effect of drilling exit surface geometries on the shape and size of burrs which replicates real-life application.

4.5 Process parameters

The process parameters that influences exit burr formation in drillinginclude cutting speed, feed, drill size and length to diameter ratio (L/D ratio). Table 5compiles the behavior of different materials with various cutting speeds and feedsas observed in the literature. Generally, feed is the most significant factor that defines burr size and shape followed by cutting speed and drill size.

Table 5 shows that, lower feed rates and lower cutting speeds are appropriatefor drilling of steel alloys to reduce exit burrs. Similar findings were observed in drilling of copper and brass as well. Whereas, for aluminum, titanium and composites different combinations of parameters are recommended to reduce the exit burrs.

Table 6 shows the specific recommendations on speed and feed rate for various material grades and size of drill used. Fig. 4 shows the best combinations of feed-speed observed by different research groups for different materials yielding the least exit burrs. It indicates that feed rates below 0.2 mm/rev help to generate smaller exit burrs irrespective of material. For steel and titanium alloys, cutting speed below 20 mm/min and 40 mm/min helps to get smaller exit burrs. However, the testing ranges of cutting speed used for these materials is also limited (3.5-39 mm/min for steel and 10-63 mm/min for titanium). On the other hand, aluminum and composites are tested for a wide range of cutting speed, 4-300 mm/min and 2-170 mm/min,respectively.

The minimum burr at a lower speed and feed are explained using the following hypotheses, (i) at higher feed rate and cutting speed conditions in drilling higher thrust forces and enormous heat is generated. This induces early plastic deformation and easy flow of material during drilling[105]. As result of this, a heavy crown type burr is formed at the perimeter of holes. Thus, to avoid heavy crown type burr, moderation in feed-speed conditions in drilling is recommended [106].

While, controversial results, smaller burr at higher speed and feed are explained using the following hypotheses, (i)higher feed ratereducesthe local efficiency of the rising heat during the cutting[107]as well as reduce the number of revolutions per unit length [108], which results in less drill wear, and (ii)higher cutting speedreducesthe friction between chips and drill[99]. This increases the shear angle andsubsequently reduces the chip thickness. Its result is reduction in plastic strain associated with chip formation. This reduction might be reducing the burr size[87]. Palanikumar et al.[109] also observed the higher cutting speed conditions reduces thrust force generation and it further helps to reduce the drilling burr size and shape.

In a drilling operation, feed rate contributes towards the thrust force, while the cutting speed contributes toward the heat generation at cutting edge [110, 111].The higher values of feed rates increase the thrust force in drilling[112],which has the direct role in increasing burr size as mentioned in section 3, but it also reduces the total cutting duration, so the material doesn’t have enough time to soften before cutting, which is beneficial to reduce the thickness of plastic deformation zone and further contributes towards the reducing of exit burr size[108]. On the other hand, higher cutting speed generate higher temperature at cutting zone. This rise in the temperature mostly facilitates rapid wear at drill cutting edge[62]. It results in an inefficient cutting which further contributes towards the higher exit burrs. On the other hand, the rise in temperature helps in reducing the magnitude of cutting force to some extent by reducing shear strength of the material. It results in lesser thrust force and eventually helpsin reducingexit burr size [21, 113]. In drilling, a major part of the cutting zone heat is transferred through the chip which is further accelerated by using higher cutting speed. It could help in reducing the plastic deformation zone which might further contribute towards the reduction of exit burr size. From this it can be understood that the final exit burr size is mostly controlled by the heat input provided by the speed-feed combinations, and different combinations of speed-feed might help in generating optimum heat at the cutting zone. It might be the reason why different studies found different combinations of speed-feed to reduce the burr morphology. From the productivity point of view, lower speed-feed recommendation is undesirable. Hence, more research is required to be done on different combinations of speed-feed, which contribute towards higher productivity along with optimum thermal input (which produce minimum exit burrs).

In 2000, Lin et al [80, 114] studied drilling operation with variable feed-speed wherein maximum feed was maintained at the center of the drill depth, while least feed was maintained at the entry and exit. Using this methodology, up to 40% reduction in exit burr size was found along with improved tool life and productivity for stainless steel. This innovative concept has not been further explored by any other researchers. Hence, further studies have to be carried out in the field of variable feed-speed for different materials.

Burr height increases with drill size [66, 109, 115-122].Smaller is the diameter of the drill, smaller is the contact length between work material and tool cutting edge which results in less cutting thrust and torque [123]. Lower thrust and torque requires less support material at the exit surface. These conditions produce smaller burrs at the perimeter of the holes. Pande et al. [58] statedthat thedesign parameters of a standard drill, like the ratio of chisel edge length to drill diameter and helix angle, varies with the drillsizewhich might be affecting the burr size. Gaitonde et al. [124-126] and Kadivar et al. [127]observed that the optimum values of feed and point angle is controlled by drill size. While, Gaitonde et al.[124]tested drill size between 12-28 mm range and found burr size increased up to 15 mm drill size, after which it decreased in the drill size range of15-26 mm, and again increased beyond 26 mm.

The L/D ratio is the least considered parameter in drilling burr studies. Only Pande et al [58]has considered L/D ratio in their study and recommended 0.45-0.75 range for least exit burrs. The drilling with very small L/D ratio makes the entry and exit deformation zones very close to each other. There is always a chance of overlapping of these deformation zones with each otherwhichmight give a larger burr size when small L/D ratio is used in drilling. However, large L/D ratio generates enormous heat at cutting zone as drill advances towards the exit surface. This enormous heat produces localized softening and early plastic deformation in the processes which results in heavy burrs on the perimeter of the drilling holes. The range of L/D ratio tested and recommended by Pande et al [58] is too short as compared to actual industrial applications. Most of the industrial products demand higher L/D ratio in drilling to fulfill the application needs. This gap hasreducedthe usefulness of the researcher's feed-speed recommendations. Hence, more studies need to be carried out on different L/D ratios along with different combinations of feed-speed.

Table 5: Effect of cutting speed and feed on burr formation

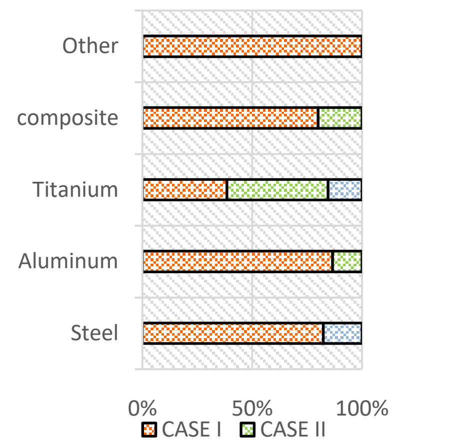
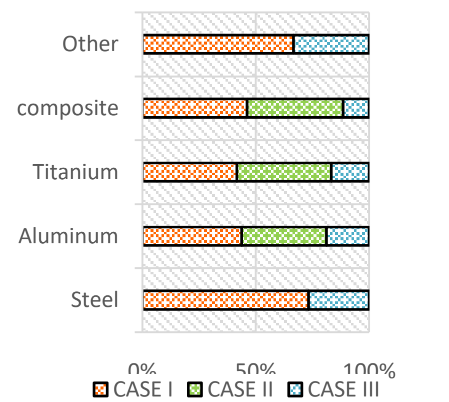
Reference					**Analysis**
Steel	**Aluminum**	**Titanium**	**Composite**	**Other**	
CASE I: BF formation reduced by Lowering feed					
[1, 115, 116, 128, 129, 130, 60, 104, 124, 106][126, 131, 79, 132]	[8, 56, 60, 133, 89, 134, 10, 135, 131, 98]` [136, 137, 138]	[139, 140, 112, 112, 25]	[141, 142, 110, 109, 143, 144, 145, 146, 21, 147][99, 112, 65, 148, 66, 149, 84, 69, 150, 105][85]	Brass [22, 151] Copper [22, 20]	
CASE II: BF formation reduced by increasing feed					
	[87, 23]	[70, 152, 153, 24, 154, 155]	[107, 70, 156, 71, 157]		
CASE III: BF formation doesn't get much affected by feed or not cleared					
[158, 159, 111]		[26, 72]			
CASE I: BF formation reduced by Lowering speed					
[158, 115, 116, 128, 130, 104, 125, 106, 131, 79] [132]	[8, 60, 135, 98, 160, 136, 138]	[139, 70, 140, 24, 112]	[141, 142, 107, 70, 144, 112, 65, 161, 157, 150] [105, 119]	Copper [20] Brass [151]	
CASE II: BF formation reduced by increasing speed					
	[87, 162, 133, 134, 23, 137]	[162, 152, 112, 153, 154, 25]	[109, 146, 21, 99, 163, 164, 66, 113, 149, 84] [69]		
CASE III: BF formation doesn't get much affected by speed or not cleared					
[1, 129, 60, 159]	[56, 60, 131]	[26, 72]	[110, 145, 156]	Copper[22] Brass[22]	

Table 6: Recommendations from different researchers on feed rate and cutting speed.

Reference	Work Material	Drill Diameter (mm)	Factor range tested	Recommendation
Gaitonde et al. [158, 128, 130, 132]	AISI 316L stainless steel	28 [158] 10, 16, 22, 28 [128] 16 [130] 4, 10, 20, 28 [132]	F: 0.04, 0.08 , 0.12	0.08 [158, 128, 130] 0.04 to 0.08 [132]
			S: 8, 16, 24	8
Gaitonde et al. [115, 116]	AISI 316L stainless steel	10, 16, 22 [115] 4, 10, 16, 22, 28 [116]	F: 0.04, 0.06, 0.08 ,0.1,0.12	0.04 to 0.07
			S: 8, 12, 16, 20, 24	8 to 12
Gaitonde et al. [125]	AISI 316L stainless steel	4, 10, 16, 22, 28	F: 0.04, 0.06, 0.08 ,0.1,0.12	0.08
			S: 8, 12, 16, 20, 24	8
Karnik et al. [129]	AISI 316L stainless steel	10, 16, 22	F: 0.04, 0.08 , 0.12	0.08
			S: 8, 16, 24	Negligible effect
Arun et al. [79]	AISI 316 austenitic stainless steel	10	F: 0.04, 0.08 , 0.12	0.04
			S: 12, 14, 16	12
Gaitonde et al. [124, 126]	AISI 316L stainless steel	12, 20, 28[124] 8, 18, 28[126]	F: 0.04, 0.08 , 0.12 S: 12 (constant)	0.04 to 0.07 [124] 0.04 to 0.09[126]
Alrabii[165]	AISI 316L stainless steel	12.5	F: 0.08 – 0.32 S: 4.9 – 13.9	0.16 4.9
	ST37 low carbon steel	12.5	F: 0.11 – 0.45 S: 3.5 – 27.9	0.11 3.5
Gaitonde et al. [106]	AISI 1018 steel	6	F: 0.04, 0.06, 0.08 ,0.1,0.12	0.04
			S: 8, 12, 16, 20, 24	8
Gaitonde et al. [111]	AISI 304 stainless steel	10	F: 0.04, 0.12, 0.20	0.12
			S: 8, 12, 16	12
Bagchi et al. [101]	AISI 304 stainless steel	5	F: 0.02, 0.04, 0.1	0.04
			S*: 18, 32, 39	18
Varatharajulu et al. [166]	Duplex 2304	6	F: 0.038, 0.076, 0.203	0.038
			S*: 5, 7, 10	10
Varatharajulu et al. [167]	Duplex 2205	6	F: 0.038, 0.076, 0.203	0.203
			S*: 5, 7, 10	9
Gaitonde et al. [168]	Mild steel	4, 6, 8, 10, 12	F: 0.04, 0.08, 0.12 ,0.16, 0.2	0.04
			S: 8, 12, 16, 20, 24	21
Mondal et al. [90]	Low alloy steel	14	F: 0.032 to 0.08	0.08
			S: 20 to 31	20
Koklu[8]	Al-2024, Al-7075 and Al-7050	8,10,12	F: 0.05, 0.1, 0.15	0.05
			S: 20, 30, 40	20
Zedan et al. [87]	Al 6061-T6	9.525	F: 0.15, 0.25, 0.35	0.35
			S: 60, 150, 240	240
Lauderbaugh[56]	Al 2024-T351, Al 7075-T6	3.1750, 4.7625	F: 0.101 to 0.254	0.101
			S*: 9 to 22	Negligible effect
Abdelhafeez et al. [162]	AA7010, AA2024	6.35	F: 0.08, 0.16, 0.24	0.16
			S: 50, 100, 150	150
Pilny et al. [133]	Aluminum alloy	1.6 , 2	F: 0.035, 0.064, 0.093, 0.121, 0.15	0.035
			S: 80, 115, 150, 186, 220	220
Kandu et al. [89]	Aluminum alloy	9	F: 0.032, 0.08, 0.125	0.032
			S: 12.5, 20, 32	20
Sreenivasulu et al. [169]	Al 2014, Al 6061, Al 5035 Al 7075	8,10,12	F: 0.3,0.5,0.6	Al 2014,Al6061,Al7075: 0.5 Al5035: 0.3
			S: 15.08, 25.13, 37.7	Al 2014: 25.13, Al6061: 37.7

				Al5035,Al7075: 15.08
Kilickap et al [135]	Al-7075	5	F: 0.1. 0.2, 0.3	0.1
			S: 4, 12, 20	4
Huang et al. [170]	Al 6061	8	F: 0.2, 0.15, 0.1	0.1
			S*: 50,63,75	50
Kundu et al [98]	Aluminum alloy	9	F: 0.032, 0.08 , 0.125	0.032
			S: 12.5, 20, 32	20
Zedan et al [23]	Al 6061-T6	9.525	F: 0.15, 0.25, 0.35	0.15
			S: 30, 60, 120, 150, 240, and 300	240
Sreenivasulu et al [171]	Al 2014	8, 10, 12	F**: 0.04-0.03-0.02, 0.04-0.03-0.025, 0.06-0.04-0.03	0.033
			S*: 12-15-18,17-22-26,18-26-30	18-26-30
Dornfeld et al. [26]	Ti-6AI-4V	6.35	F: 0.0254, 0.0508, 0762	little influence
			S: 120, 140	little influence
Abdelhafeez et al. [162]	Ti-6Al-4V	6.35	F: 0.07, 0.14, 0.21	0.14
			S: 10, 20, 30	30
Shetty et al. [139]	Ti- 6Al-4V	6.35	F: 0.05, 0.1, 0.15	0.05
			S: 10, 15, 20	10
Prabukarthi et al. [154, 153]	Ti- 6Al-4V	5	F: 0.05, 0.09, 0.13	0.13
			S*: 11, 13, 16	16
Patil et al. [24]	Ti- 6Al-4V	10	F: 0.06, 0.08, 0.1	0.1
			S*: 38, 50, 63	38
Zhu et al. [172]	Ti- 6Al-4V	3.6	F: 0.02, 0.05, 0.13, 0.2, 0.23	0.05
			S: 20, 26, 40.5, 55, 61	26
Waqar et al. [140]	Ti- 6Al-4V	6	F: 0.05, 0.1, 0.15	0.05
			S*: 15, 19, 23	15
Glasin et al. [141]	GLARE composites	6	F**: 0.1-0.05-0.03, 0.2-0.1-0.07, 0.3-0.15-0.1	0.05
			S*:57,113,170	113
Giasin et al. [142]	GLARE composites	6	F**: 0.1-0.03-0.02-0.01, 0.3-0.1-0.05-0.01, 0.6-0.2-0.1-0.07	0.02
			S*: 19, 57,113,170	113
Ekici et al. [107]	Al/10B C composites	5	F: 0.08, 0.012, 0.16	0.16
			S: 18, 25, 35	18
Thakre et al. [110]	Aluminum silicon carbide	10	F: 0.1, 0.15, 0.2	0.1
			S: 40, 60, 80	Negligible effect
Rajmohan et al. [143]	Hybrid metal matrix	6	F**: 0.05-0.025-0.017, 0.1-0.05-0.03, 0.15-0.075-0.05	0.05
			S*: 19,38,57	19
Palanisamy et al. [144]	Al–Gr composites	6	F: 0.06, 0.08, 0.1	0.06
			S*: 11,16,21	11
Thakre et al. [110]	Metal matrix composites	10	F: 0.0254 and 0.0762	0.0762
			S*: 12 to 24	12
Uysal et al [146]	Polymer materials	8	F: 0.1, 0.2, 0.3	0.1
			S: 40, 80, 120	120
Rubio et al [21]	Sandwich composite	5	F: 0.05, 0.10, 0.15, 0.25	0.05
			S: 24, 48, 72	72
Soo et al [147]	CFRP/AA7010 stacks	6.38	F: 0.15, 0.30	0.15
			S: 60,120	120

Kamboj et at [99]	Al6063/15%/SiC composite	8 ,12	F: 0.05, 0.15, 0.25	0.05
			S: 37.68, 103.62, 150.72	150.72
Kadivar et al [127]	Metal matrix composites	12	F: 0.08, 0.18, 0.32	0.18
			S*: 5,27,53	27
Shusheng Bi et al [163]	Stacked metal materials	6	F: 0.05, 0.075, 0.1	0.075
			S*:9,19,28,38	38
Liang et al [164]	Stacked metal materials	6	F: 0.05, 0.075, 0.1	0.075
			S*: 9,19,28,38	38
Basavarajappa et al [65]	Metal matrix composite	10	F: 0.05, 0.15, 0.25	0.05
			S*: 31,63,94	31
Rajmohan et al [148]	Hybrid metal matrix composite	6	F**: 0.05-0.025-0.017, 0.1-0.05-0.03, 0.15-0.075-0.05	0.03
			S*: 19,38,57	35
Saravanakumar et al [66]	Particle reinforced hybrid composite	6, 10	F**:0.05-0.017, 0.15-0.05	0.017
			S*: 19-31,57-97	57-97
Kuo et al [156]	Ti-6Al–4 V/CFRP/AA7050	6.38	F: 0.05, 0.08	0.08
			S: 30, 120, 120	Negligible effect
Hassan et al [173]	CFRP aluminum Stack	4.826	F: 0.05, 0.1	0.1
			S*: 23,39	39
Xavier et al [84]	Metal matrix composite	5	F: 0.05, 0.15, 0.2	0.05
			S*: 60, 74, 90	90
Parkash et al [157]	Al-Fly ash composite	10	F: 0.035, 0.07, 0.14	0.07
			S: 20, 40, 60	60
Shivapragash et al [174]	Al-TiBr2 composite	0.6	F: 0.5, 1.0, 1.5	1.5
			S*: 2,3,4	2
Jindal [175]	Poly methyl methacrylate strip	0.2	F: 0.14, 0.22, 0.34	0.14
Timata et al. [151]	Forging brass	18	F**: 0.2-0.16-0.12, 0.24-0.2-0.17, 0.3-0.24-0.21	0.2
			S*: 24, 28, 33	24
F: feed in mm/rev, S: speed in m/min or rpm, *indicates speed converted to m/min from rpm, ** indicates feed converted to mm/rev from mm/min				

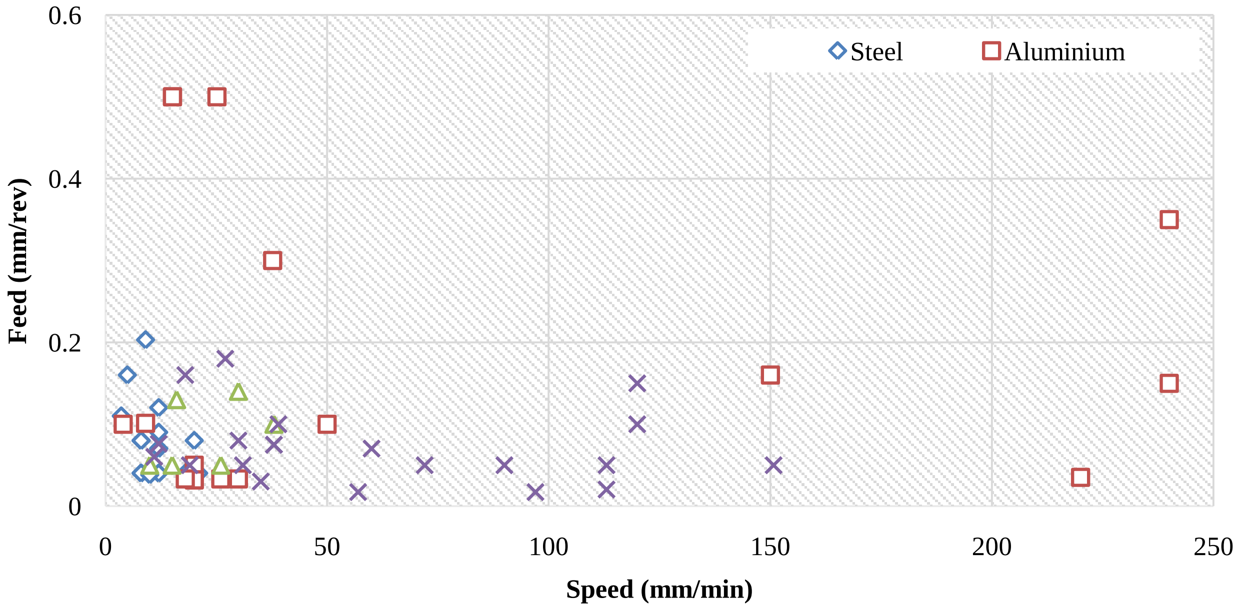


Fig. 4 Optimum combinations of feed-speed observed by different research groups for different materials

4.6 Drill Geometry

The burr size is influenced by drill geometry such as point angle, clearance angle, helix angle, point style and number of flutes. Table 7 and 8 summarizes the observations of different studies on point angle, helix angle and clearance angle.

Most of the studies observed that drills having higher point angle produce smaller size burrs. The higher point angle confirms the maximum lip movement in the earliest possible time. It avoids the strain hardening as well as the change in the chip flow direction. Also, this ensures that the material below the drill bit is more prone to cut rather than simply flow toward the feed direction. Its lows down the yielding of work material towards the feed direction and thus, results in smaller burrs[115, 110].The studies, which tested point angle in the range of 90° to 140°, recommended point angle in between 125°-140° for smaller burr size [36, 115, 110, 176, 152]. Heisel et al.[177] tested point angle in the range of 155° to 185° and found that the exit burr size is a minimum with 155° point angle. Few studies have disclosed some controversial observations, such as Shetty et al. [139] found that smaller point angle is better for titanium alloy. The author tested point angle in the range of 90° to 118° and found that 90° is best suited for titanium alloys. Similarly, Uysal et al. [146] found that 80° is best for polymer in test range of 80° to 120° whileQinglong et al. [149]found that 78° is best for the T800S/CFRP in the testing range of 78° to 113°. Manjunatha[30]further found that the effect of point angle on burr height and burr thickness is different. The author recommended a smaller point angle (127°) for a smaller burr height, while a higher point angle (132°) is recommended for a smaller burr thickness.

Higher helix angle has been recommended by many studies to minimize the burr size and shape. The reason could be lower torque and thrust force required for drills with high helix angles. Gillespie et al. [60] experimentally tested drills with 27.5° and 37.5° helix angles and found that 37.5° helix angle produces a minimum burr. The author found a 50% reduction in burr height and a 20% reduction in burr thickness with 37.5° helix angle. Similar findings have been disclosed by Zhu et al. [7] also. While Dornfeld et al. [26]have reported some controversial results wherein the authors observed 51% and 20% improvement in burr height and thickness after reducing the helix angle of the drill from 35° to 30°.Ballow et al. [104]studied the effect of change in helix angle controlled by point angle on the shape and size of the drill burrs. The author found that low helix angle is better with high point angle, whereas a high helix angle is better with low point angle.

Many studieshave found that a low value of clearance angle is advantageous to reduce the burr size and shape[7, 30, 116, 128]. The reason could be that low clearance angle provides sufficient support for drilling edges which helps in easy breakage of the chips and lowers the burr size.

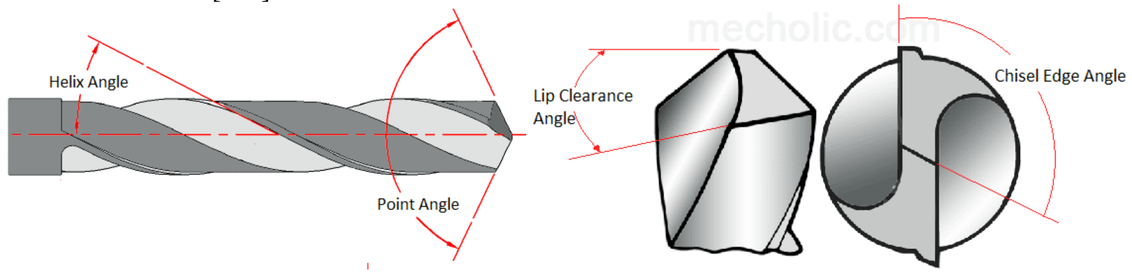
Studieson drill wear have observed that burr formation is exponentially increased with drill wear, particularly with higher cornerwear.These observations hold true for all type of cutting conditions [92,104, 176-181]. With the higher tool wear, cutting becomes inefficient which results in higher cutting forces along with higher temperature and power consumption[182]. High cutting force and temperature conditions produce crown burrs as discussed in section 3.

It has been also reported that helical, split point, spiral point, chamfered, round and step drills form smaller burrs as compared to the conventional drills. These modified geometries reduce thrust generated during the drilling process which could be the main reason for the formation of smaller exit burrs [144,183-187].

In Table 8, the various recommendations as regards to drill geometries for least burr has been compiled. Ko et al.[59]studied the performance of chamfered, round and step drills on four different materials and found that step drill with 40° step angle produces the smallest burr. Similar findings have been noted for step drill by Ko et al. [183], Kamboj et al. [99], Kim et al.[188],Palanisamy et al. [144] and Hellstern et al.[184] in their respective research. The reason could be that the uncut portion of the work material at exit surface is reduced due to the step drill geometry. Palanisamy et al. [144] further recommended that one mm step size in step drill is an optimum value for reducing the burr size to a minimum level. Rao et al. [189] recommended step diameter and length should be about 70% and 60% of drill diameter for minimum exit burrs.Li et al. [185] compared the burr formation of the spiral drill with the conventional twist drill in their study. The authors found that burr formed in the spiral drill is very small as compared to the crown burrs generated in conventional twist drill. Dornfeld et al. [26]found that helical point drill produces lower burr size as compared to the split point drill. The reason could be the lower thrust force generated due to S-shaped web and short drill point length over the twist drill. The studies which considered the burr formation with two and three flute drills found that three flute drills produce small burrs as compared to two flute drills [133][190]. The reason could be the lower thrust force generated due to the three flute drill. The studies observed that the thrust force required for three flute drill is about 50% of the force generated using a two flute drill. Pawar et al. [118]have found controversial results in their research wherein the authors have found fewer burrs and better drill quality with two flute drills on GLARE as compared to the three flute and multi-faceted drills. Recently developed brad and spur drills produce smallest burrs in composites (CFRF [105], sandwich material[191]) over the twist, step, core, and dagger drills. The state of research reveals that different drill geometries have the potential to reduce the burr size to a minimum level, but researchers have not considered all the possible options on a single platform. Thus, more detailed studiesneedto be carried out in which all possible geometries are considered on a single platform for a wide range of materials to reveal the best geometry which produces the least burr without affecting drill quality.

Table 7: Effect of drill geometry on burr formation

Drill Nomenclature [192]



Drill geometry	Researchers observations	
Point angle	Large is better	[26, 158, 115, 58, 128, 129, 110, 144, 176, 152]
	Small is better	[139, 103]
Rake angle or Helix angle	Large is better	[7, 60, 193]
	Small is better	[26]
Clearance angle	Small is better	[30, 158, 115, 116, 128, 129, 10]

Table 8: Recommendations from different researchers for point, helix and clearance angle

Drill Geometry	Reference	Work Material	Factor range tested	Recommendations for least burr
Point Angle	Gaitonde et al.[158, 115, 116][124][125]	AISI316L	118°, 126°, 134°	134°
	Gaitonde et al. [111]	AISI304	118°, 126°, 134°	126°
	Gaitonde et al. [132]	AISI 1018	118°, 122°, 126°, 130°, 134°	134°
	Gaitonde et al. [194][168]	Mild steel	118°, 122°, 126°, 130°, 134°	134°
	Syed et al [190]	Ti6Al4V	118°, 140°, 150°	150°
	Dornfeld et al. [26]	Ti6Al4V	123° ,139°	139°
	Shetty et al. [139]	Ti6Al4V	90°, 104°, 118°	90°
	Cantero et al. [176]	Ti6Al4V	118°, 135°	135°
	Celik [58]	Ti6Al4V	90°, 118°, 130°, 140°	140°
	Farid et al [195]	Inconel 718	120°, 125°, 130°	130°
	Dey et al. [160]	Aluminum bar	86°, 104°, 118°	118°
	Sreenivasulu et al [169]	Al6061	100°, 110°, 118°	118°
	Kilickap et al [135]	Al-7075	90°, 118°, 135°	135°
	Sreenivasulu et al [171]	Al-2014	100°, 110°, 118°	118°
	Thakre et al. [110]	Al6061-Sic	96°, 118°, 140°	140°
	Rajmohan et al. [144]	Al356/SiC-mica	100°, 110°, 118°	118°
	Heisel[177]	CFRP	155°, 175°, 185°	155°
	Uysal et al.[146]	Polymer	80°, 120°	80°
	Qinglong et al. [149]	T800S/CFRP	113°, 78°	78°
	Heisel et al. [196]	CFRP	155°,175°,178°, 185°	155°
	Parkash et al. [157]	Composite	80°, 100°,135°	100°
	Hassan et al. [173]	Carbon Fiber	110°, 130°	130°
	Vijayan et al. [150]	Carbon Fiber	110°,115°, 120°	113.5°

Clearance angle	Gaitonde et al. [158, 115, 116, 128, 129]	AISI316L	8° ,10°, 12°	8°
	Gaitonde et al [125][111]	AISI 316L	8°, 9°, 10°, 11°, 12°	10°
	Gaitonde et al[106]	AISI 1018 steel	8°, 9°, 10°, 11° , 12°	10°
	Gaitonde et al [194][168]	Mild steel	8° , 10°, 12°	8°
	Dornfeld et al. [26]	Ti6Al4V	10° , 12°, 14°	12°
	Sreenivasulu et al. [10]	Ti6Al4V	4° , 6°, 8°	4°
	Manunatha[30]	AL6001-T6	12° , 14°, 16°	13°
	Sreenivasulu et al [169]	Al-7075	4° , 6°, 8°	6°
	Sreenivasulu et al [197]	Al-6061	4°, 6°, 8°	6°
	Sreenivasulu et al [171]	Al-2014	4°, 6°, 8°	6°
	Heisel et al. [177]	CFRP	6° , 7°, 8°	7°
	Hassan et al [173]	CFRP/Aluminum	6°, 8°	6°
Rake or Helix angle	Zhu et al. [7]	Stainless steel	10° ,20° and 30°	30°
	Dornfeld et al. [26]	Ti6Al4V	30° and 35°	30°
	Gillespie [60]	Na	27.5° and 35.5°	35.5°

Table 9: Summary of researchers recommended drill geometries for least burr

Reference	Work material	Conventio-nal/Twist drill	Split point drill	Helical point drill	Spiral point drill	Step drill	Chamfer/ Double cone drill	Dagger drill	Round / Multi point drill	Core drill	Brad & spur drill	Recommended drill geometry for least burr
Dornfeld et al. [26]	Ti6Al4V	✓	✓	✓								Helical point drill
Ko et al. [59]	SM45C Steel	✓					✓		✓			Step drill
Li et al. [185, 198]	Ti6Al4V	✓			✓							Spiral point drill
Tamura et al. [199]	CFRP	✓					✓					Conventional drill
Zhu et al. [113]	Ti6Al4V stack					✓	✓		✓			Double cone drill
Qinglong et al. [149]	CFRP laminates	✓						✓				Dagger drill
Xu et al. [105]	CFRF	✓						✓			✓	Brad and spur drill
Rezende et al.[191]	Sandwich Material	✓				✓		✓		✓	✓	Brad and spur drill

5. Burr control strategies

In the following section, various strategies to minimize the drilling burrs are discussed. There is no single widely accepted strategy, which can completely eliminate the burrs in drilling, but the burrs can be reduced significantly by choosing appropriate drilling strategies whichcontributeinreduction of the deburring cost and time significantly.

5.1 Ultrasonic assisted drilling

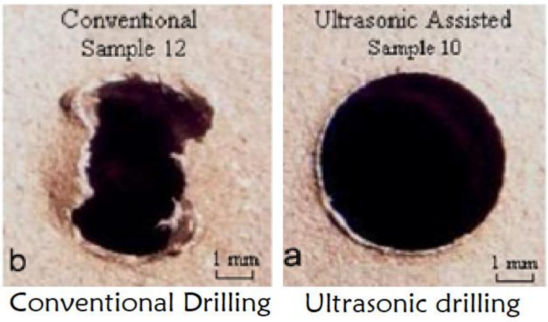
The vibration assisted drilling (VAD) is a new technique developed to minimize the drilling burrs in the different group of materials. In this method, a piezoelectric actuator applies controlled vibrations (high frequency (f) and optimized amplitude (Å)) to the drill in the feed direction. The controlled vibrations produce multiple impact interaction between drill and the formed chips. It results in lower thrust force and discontinuous finer chips. It can also reduce the burr size [127, 200-204].Fig. 5 shows the different examples of exit burr formed in conventional and ultrasonic drilling at same cutting parameters, drill geometries and drilling environments for various materials.

Babitsky et al. [205]used controlled vibrations (ƒ: 20 KHz and Å: 10 µm) on aluminum, copper, mild steel and composite and found reduction or even complete elimination of the burrs on both the entrance and exit face of the workpiece. Similar findings have been noted for drilling burr byChern et al.(Aluminum alloy,ƒ: 21 KHz and Å: 2 µm) [206], Takeyama et al. (Aluminum, Glass fiber reinforced plastics, ƒ: ultrasonic and Å: 7-13.5 µm)[207], Simon et al. (A1100-0 aluminum, ƒ: 4-12 KHz and Å: 2 µm) [75], Chang et al. (Al 6061-T6, ƒ: 4-12 KHz and Å: 2 µm)[208], Onawumi et al. (CFRP/Ti stack, ƒ: 22 KHz and Å: 15.1µm)[203], Kadivar et al. (Al/SiC metal matrix composite, ƒ: 22 KHz and Å: fixed)[127]andAzarhoushang et al. (Inconel 738, ƒ: 21 KHz and Å: 3-10 µm) [209]in their respective studies.Takeyama et al.[207]used vibrations with amplitude of 7 and 13.5 µmin drilling and found higher burr reduction for vibrations with 13.5 µm amplitude. Simon et al. [75] noted that optimized vibration parameters (frequency and amplitude) depend on cutting conditions like speed, feed, etc. The author noted that burr size is highly dependent on frequency and burr reduction is possible only above a threshold value. The author also observed that vibrations improve productivity by allowing higher spindle speed and feed without increasing burr size.Adachiet al. [210] noted that the burr size is not influenced by increase in the number of drilled holes after applying low frequency controlled vibrations. Recently, Lotfi et al. [95] combined the MQL and vibrations together and found this combined approach to be much superior then MQL or vibrations alone in improving the drilling quality. The author further noted that MQL-VAD approach produced burr-less holes.

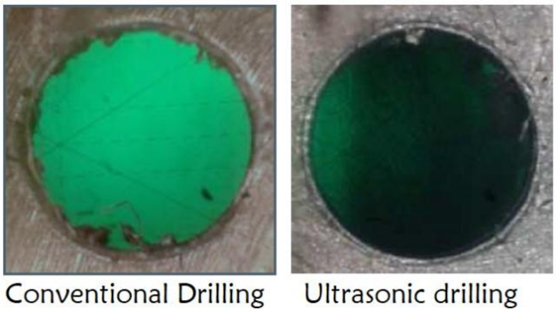
The presence of controlled axial vibrations in drilling improves the drilling quality and productivity for a wide range of materials. Although complex design of piezoelectric devices limits efficient use of vibrations in drilling, it enables testing wide range of vibrations parameters like frequency, amplitude and oscillation modes(sin, square, etc.,)on a single platform. Recently magnetic bearing spindles have been developed, which facilitated CNC control of frequency, amplitude and oscillation modes[211].This technology gives freedom to optimize the VAD process for individual product or application so as to produce burr-less holes.

Aluminum [205]

Al2024-T6[212]



Inconel 738-LC [209]



Stainless Steel[201]

Fig. 5Examples of exit burr formed in conventional and ultrasonic drilling at same cutting parameters, drill geometries and drilling environments for various materials.

5.2 Use backup material

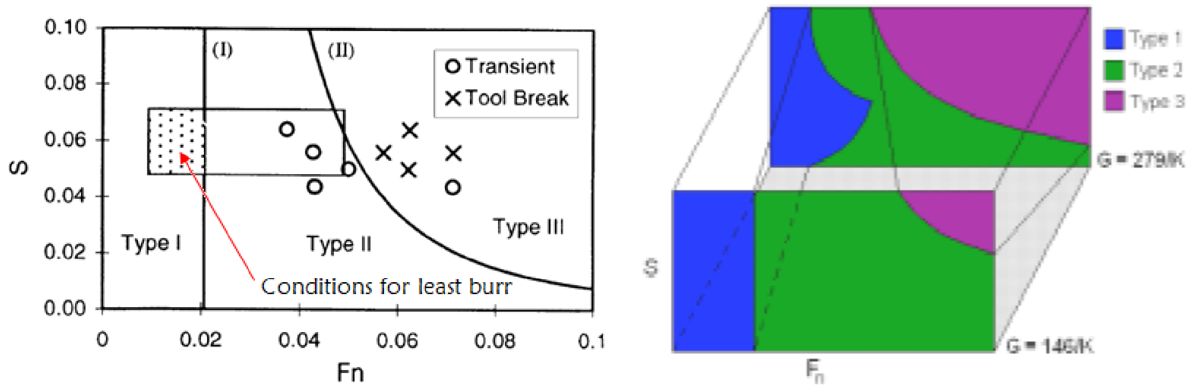
This approach is used in many industries to reduce exit burrs, particularly in drilling on composites [161, 213-215] and circuit boards [216-218]. In this approach, workpiece material or material which is slightly stiffer than the workpiecematerial is used as a backup support underneath the part being drilled. This approach can reduce the burr formation at the exit of the hole significantly. The reason could be the extra stiffness provided by backup support at the exit[219, 220]. This extra stiffness could restrict or delay the downward bending deflection caused by thrust force during drilling and promote continuous cutting and thus, minimize the burr size[221].Gillespie et al. [60] first time used the consumable backup plugs in cross-hole drilling and found a 50% improvement in burr morphology. The studies use a backup support which is same as the work material in aluminum [89] and low alloy steel [90] drilling found the consistent low burrs at a hole exit with a wide range of process parameters.

5.3 Pre-drilling and chamfering

A study has been carried out into the effect of pre-drilling and chamfering on the predrilled hole by Mahdy[222] in 2000. The author found that predrilling and enlarging tactics reduce the burr up to 75% compared to direct drilling. The reason could be reduced volume of displaced material [223, 222]. These studies also found zero burrs, when predrilled chamfer diameter is maintained to a final diameter of the drilled hole. However, this is the least used strategy in the industry. It reduces productivity and increases overall drilling cost which maybe the main reason for its least use.

5.4 Use of drilling burr control chart

In this approach, experimental data is organized into an useable databank to predict burr size based on drilling parameters. Dornfeld et al.[1]derivedfor the first time a control chart based on the experimental data available for steel alloys in their study. The author used speeds, feeds and drill sizes to build a two-dimensional control chart. As an example, Fig. 6a shows the two-dimensional control chart for a low alloy steel. This control chart shows the approximate boundaries between the three burr types. The dotted box in the chart indicates recommended process conditions for least burrs in low alloy steel. This approach is more material specific. To resolve this problem Link [224, 63] proposed a three-dimensional control chart in which the author adds the third axis as the material property index. Fig. 6b shows the three-dimensional control chart proposed by Link. This chart gives a very good guideline for industries to choose drilling conditions which produces predefined burr size. Limited drilling control charts have been developed by researchers (Steel alloys [1, 5], Copper and Brass[22], PCB [225]) thus, more studies have to be carried out in which control charts are developed for a wide range of materials and which accommodate different drilling environments, drill bit materials, and their properties as well.



(a) (b)

Fig. 6(a) Two-dimensional control chart for low alloy steel; S (S=10-5 d * N; where d is drill diameter (mm) and N spindle speed (rpm) and Fn,[1]. (b) Three-dimensional control chart [224]

Conclusions

The 'burr-free edge' of the drilled hole is primarily characterized by part quality because it influences the part performance during its service life. The review on the state-of-the-art of burrs in a drilling process leads to following major conclusions, including current research gaps and future research direction:-

- According to the general observations of researchers, drilling exit burr size is closely related to the extent of thrust force produced during the drilling operation and the stiffness provided by the work material at the drill exit (as a consequence of the tool/work orientation of exit surface and/or physical properties of the work material).
- Number of studies have showed thatburr minimizationis possible through control of thrust forces, optimizing process parameters (like speed, feed, cutting fluid, etc.), drill geometries (coating, point angle, helix angle, lip angle, sharpness etc.), addition of controlled vibrations or use of optimum cutting environments (wet, mist or MQL, cryogenic, etc.,) in drilling process.

- The review reveals that the effect of process parameters like speed and feed on burr size is mainly dependent on material. According to the major observations, low feed-speed is favorable for burr minimization in different grades of steel, copper, and brass among the tested range. Whereas, materials like aluminum and composites produce least burrs with low feed conditions, while do not show any particular trend with the reduction of cutting speed. Further, material like titanium does not show any particular trend with a change in feed and cutting speed. Thus, the systematic study with a wide range of process parameters (feed and speed) is recommended for titanium alloys to reveal the trend.
- The review further reveals that the burr size could be controlled by optimizing the heat input at the cutting zone, and the different combinations of speed-feed have potential to generate optimum heat at the cutting zone.Fromproductivity point of view, lower speed-feed recommendation is undesirable. Thus, more research on different combinations of speed-feed, which contribute towards higher productivity along with optimum thermal input (which produces least burrs) in drilling is essential.
- The review also reveals that the presence of cutting fluids significantly minimizes burr formation in drilling. The studies found smallest burrs in cryogenic environment, but did not find much advantageous over the other methods like wet or MQLcooling (i.e. cryogenic burrs don't differ much than other methods).The review shows that MQL has potential to produce smaller burrs with least lubricant cost. The review reveals that only a few researchers have addressed MQL in their studies. Thus, further detailed studies should be carried out on MQL with reference to mass flow rate, different lubricant compositions and air pressure.
- According to the general observation by researchers, exit surface geometries have the potential to control the burr size and burr likely areas. Most of the exit surfaces of drilled holes in industrial applications are not flat i.e. they are curved or angled as per the assembly or application demand. It was found during the review that most of the research recommendations are based on flat exit surface. Thus, these recommendations are not directly useful for industrial applications. Hence, a further detailed study has to be carried out on exit surfaces which replicates real-life applications.
- According to general agreement on results, drill geometries have high potential to minimize burr. The recommended values are 127 – 155ºfor point angle and 37.5ºfor helix angle, respectively. It is also revealed that the step drill produces smallest burrs as compared to all the other drillgeometries. The review also shows that coatings have potential to reduce drilling burrs size, however all coating materials have not been tested on a single platform. Thus, further detailed study has to be carried out in which performance of different coating materials is studied on a single platform.
- There is no single widely accepted strategy, which can totally eliminate burrs in drilling but, drilling burr could be reduced to minimum level by adding controlled vibrations or using back up material and control charts. These controlled small burrs have the potential to reduce the deburring cost as well as manufacturing time significantly. Controlled predefined burrs will also facilitate use of automatic robotic deburring and/or electrochemical deburring systems in industries.

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