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ORIGINAL ARTICLE

Mechanical deburring and edge-finishing processes for aluminum parts—a review

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Abstract Burr formation is considered as a detrimental phenomenon that not only decreases the machined part surface and assembly quality, but also increases the production cost. To conduct burr removal from machined edges and holes, the costly and non-desirable secondary operation, so-called deburring, is demanded. The complexity and severity of deburring processes depend on several factors, including burr size, location, and the material to be deburred. Due to vast applications of aluminum alloys in numerous manufacturing sectors including automotive and aerospace industries, adequate knowledge of the most widely used deburring processes on aluminum alloys is demanded. However, surprisingly, despite the acute demands by numerous manufacturing sectors, no state of the art was found in the open literature about applicable deburring and edge-finishing methods for aluminum work parts. This lack is intended to be remedied in this work by providing an insight into the most widely used deburring and edge-finishing processes for aluminum work parts. To that end, several deburring classifications were proposed. The main highly used category of deburring techniques is mechanical deburring process which is related to the removal of various kinds of burr shapes and size by means of mechanical abrasion. In fact, mechanical deburring processes are the most widely used techniques due to versatility, flexibility, deburring rate, and acceptable cost. Among mechanical deburring methods, several methods including robotic, CNC, and manual deburring were presented in this work. A brief insight into the application of several other non-classified mechanical deburring processes was also presented. In addition, knowing that an accurate selection of deburring methods is highly dependent to proper understanding of the burr formation, therefore, an overview of burr formation mechanism, morphology, shape, and, in principle, those factors governing burr formation are also presented, followed by experimental, numerical, and analytical models of burr formation morphology and size. Other general concerns, including the use of lubricant and its effects on deburring performance, must be identified. The future demands of precision deburring are challenging, not only for machine tools and deburring tools, but also for high-precision machining researchers. Close collaborations between machine tool builders, CAD/CAM programmers for precision tool path planning, and deburring and edge-finishing R & D community are highly demanded towards the successful movement to the next generation of precision deburring and edge finishing.

Keywords Aluminum alloy · Burr · Deburring · Edge finishing

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1 Introduction

According to open literature, superficial knowledge of the influencing cutting factors on burr formation and the effective solutions for complete or partial avoidance and/or reduction of burr formation may eventually lead to reduced work part resistance, tool life, and productivity rate [1]. Therefore, theoretical and practical solutions for burr formation avoidance or otherwise the use of secondary operations known as deburring becomes essential. According to [2], the main critical factors on deburring complexity are burr location and length, number of edges, and material to be deburred. According to review of the literature, there are over 100 deburring processes proposed so far [3]. As noted in [4], it is very difficult to secure an excellent edge quality following deburring process. To better select the deburring processes, several classifications were proposed in [3, 5, 6]. The most complete one was proposed by Gillespie [3], incorporating most of manual to high-technology deburring processes. He [3] identified over 120 deburring and edge-finishing processes and indicated that the deburring processes can be classified within four main categories of mechanical, thermal, chemical, and electrical deburring processes. Consequently, comprehensive investigations on factors governing deburring selection by means of minimizing the non-desirable expenses are strongly necessary. As noted in [7–9], laser deburring and micro-electrical discharge machining have very low destructive effects on the work part edges. However, thermal degradation of the workpiece, low operating speed, and time-consuming numerical control (NC) programming are the major drawbacks of the processes. Similarly, it was observed that the use of electrochemical deburring led to unintended damages to functional surfaces of the work parts, although this process can be useful for simultaneous deburring of multiple burr edges. According to [10, 11], abrasive jet methods are efficient for small burrs in brittle materials. According to Ko et al. [12] and Kim and Kwak [13], magnetic abrasive grinding exhibited excellent surface finish in the deburred edges. A new deburring process utilizing magneto-rheological fluid in the production of micromolds was used in [14]. These abrasive methods were however limited to micro-burrs only, and several others issues with regards to residual abrasive particles are expected. Moreover, despite the type of material used, the deburring intersecting hole is among the major concerns when dealing with high-precision deburring and edge-finishing. This becomes more complicated when the burr sizes at intersecting holes are classified as large scales. In this case, the use of advanced custom-designed cutting/deburring tools/machines and strategies on the basis of mechanical cutting and abrasion becomes apparent.

Another affecting factor on the adequate selection of deburring methods is the type of work part. Due to vast applications of aluminum alloys (AAs) in numerous industrial sectors, adequate knowledge of the burr formation mechanism and morphology, as well as the most widely used deburring processes on AAs is highly demanded. In fact, as compared to steel and titanium alloys, high cutting speed and low cutting forces are the major observations when machining AAs [15, 16]. In other words, AAs are classified as easy-to-cut materials with a relatively high level of machinability. However, other machinability attributes including chip characteristics, tool life, surface finish chip disposal, and burr formation are of major concern when machining AAs are the subject of investigation [17]. The latter tends to affect the quality and accuracy of the deburring processes [18, 19]. Up until now, the machinability attributes of several easy- to difficult-to-cut materials, in particular, burr formation mechanism and morphology, in brittle and ductile materials are very well-understood, and sophisticated approaches for adequate prevention and minimization were introduced [20–31]. However, these approaches are generally limited to material and machining modes used. In fact, the burr sizes in aluminum work parts vary when machining mode and cutting conditions are changed (see Figs. 1 and 2). If appropriate cutting conditions are used, the generated burrs in aluminum work parts can be excessively big (Fig. 1a) or negligible in size, while they cannot be even observed by the naked eyes (see Fig. 1b).

As noted in [32], adequate selection of experimental parameters may lead to less requirement of deburring and edge-finishing operations when machining AAs. Although this subject was extensively studied in the literature [33–39], however, in comparison, fewer amounts of works reported the deburring and edge-finishing methods on aluminum work parts. Knowing that deburring processes are complicated, costly, time-consuming, difficult to automate, and, in principle, non-value adding, therefore, further investigations on burr formation mechanism and morphology as well adequate understanding and optimum selection of deburring processes are of concern [40]. Moreover, the major side effects of deburring processes on aluminum work parts may appear on dimensions, tensile residual stress, smut, discoloration, surface passivation, and generation of new burrs. In addition, the rate at which the work parts are rejected due to the presence of burrs is also among the essential criteria for deburring selection [17]. According to review of the literature [3, 8, 41, 42], deburring processes by means of mechanical abrasion seem to be more efficient than other methods in terms of simplicity and removal speed when large-burr removal at hard-to-reach places is intended. Therefore, in addition to an overview of burr formation mechanism, morphology, and shape, the most widely used deburring and edge-finishing methods on the aluminum work parts will be presented in this work. Also, a brief insight into the application of several other non-classified mechanical deburring processes was also presented. The conclusion and future prospects are then presented. The research outcomes are thought

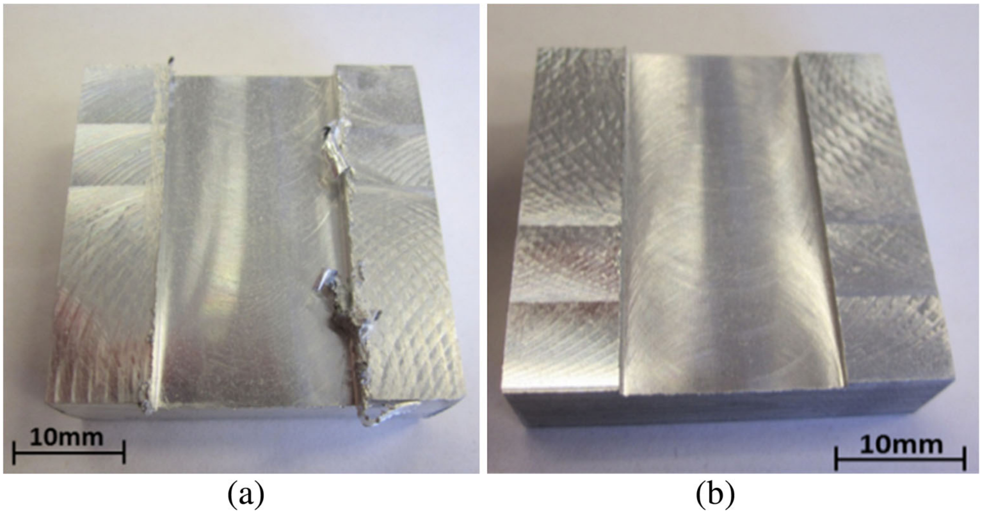


Fig. 1 Slot-milled 6061-T6 aluminum machined part with **a** large burrs and **b** acceptable burr size (Adapted from [1])

to be beneficial for an adequate selection of deburring processes, cost reduction, and production rate improvement.

2 Overview of burr formation

The burr formation mechanism in metal cutting was initially described by Pekelharing [43]. As shown in Fig. 3, the burr is known as the edge of a workpiece with an overhang greater than 0 [26]. In order to gain an adequate description of the burr, a new term, called "burr value," comprising several burr size attributes was defined (Fig. 3) and proposed in [5]. As noted in [44], the most widely used burr size attributes are burr height and thickness which in principle are widely used for tool replacement, schedule arrangement, and burr removal difficulty evaluation. According to [1, 45], the longitudinal profile of the burr is not commonly used to define the burrs as it is not highly informative in most cases. Instead, the burr thickness (b_t) is frequently used to define the deburring time and methods [17, 26].

2.1 Burr formation mechanism

It is agreed upon that acquiring a good understanding of burr formation mechanism and morphology is demanded prior to using deburring and edge-finishing methods. According to open literature, burr formation mechanism in various machining modes has been extensively studied by numerous leading authors, including Pekelharing [43], Sofronas [47], Gillespie [3], Nakayama and Arai [21], Chern and Dornfeld [48], Hashimura et al. [49, 50], Aurich et al. [26], and Niknam et al. [1, 17, 31, 38, 39, 45, 51–55]. According to Pekelharing [43], the negative-shear zone causes the exit failure of cutting tools and eventually root type burr formation in milling operations. Sofronas [47] declared that plastic deformation flow during the cutting process is the main cause of burr formation. Gillespie who is considered as the pioneer in the field of burr characterization, deburring, and edge finishing could present an analytical model, capable of predicting the burr properties [56]. He later proposed the six main physical processes leading to burr formation [3]. Three stages of burr formation mechanism in orthogonal cutting, including (1) initiation, (2) burr development, and (3) final burr formation, were proposed in [21]. Nakayama and Arai

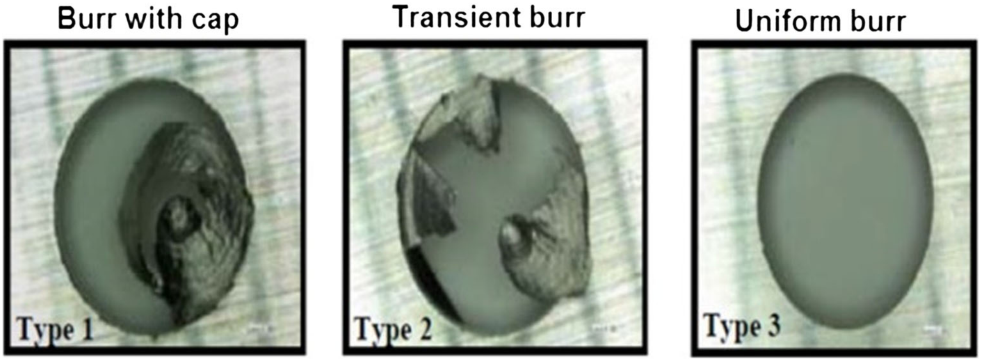


Fig. 2 Exit burrs when drilling 6061-T6 aluminum work parts (Adapted from [46])

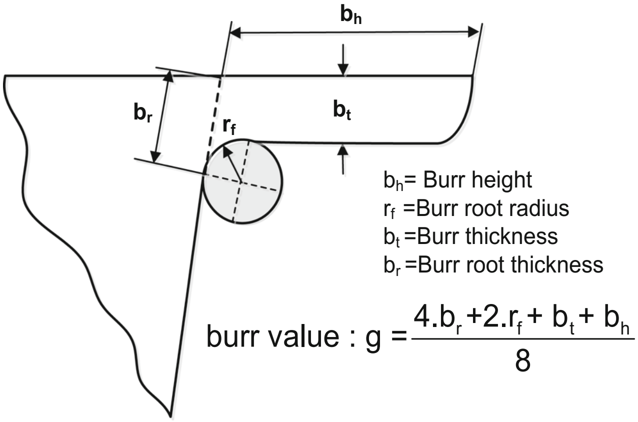


Fig. 3 Measurement values of burr (Adapted from [5])

proposed a simple model of the burr formation mechanism that comprises (1) initiation, (2) transition, and (3) push-out stages. A burr breakout model based on SEM observations in micro-machining tests was presented [48]. According to Hashimura et al. [50], in addition to cutting conditions, the tool and workpiece geometries and the mechanical properties of the workpiece are regarded as the critical factors affecting the burr formation mechanism, shapes, locations, and generation sources. The individual stages of burr formation in ductile and brittle materials as depicted in Fig. 4 were also proposed in [50]. In addition to the abovementioned work, factors governing milling burr formation size and morphology as well as optimum process parameter selection when milling aluminum alloys were comprehensively studied and reported by Niknam et al. [1, 29–31, 37–39, 45, 51, 52, 55, 57]. However, several solutions, including analytical, numerical, and experimental modeling algorithms and strategies, were proposed for this purpose. The main achievements related to modeling burr formation morphology and size attributes in milling operations which are classified as the most complex machining operations are presented in the following passages.

2.2 Burr formation modeling

One other approach to predict the burr formation morphology and size and ultimately simplifying the deburring process selection is to use advanced modeling techniques, including analytical, computational, and experimental approaches which have shown successful implementations in various kinds of machining operations. The major related research works in this domain are presented as follows.

2.2.1 Analytical modeling

Among modeling approaches, due to the complexity of burr formation mechanism, analytical modeling of burr formation is considered as a challenging subject. This becomes harder when burr formation modeling during cutting tool entrance and exit of the work part is intended [58]. Several advanced modeling algorithms were proposed, and certain levels of approximations and simplifications were used to establish analytical models of burr formation morphology and size [2, 22, 48, 49, 59–61]. Effects of various input parameters such as various exit angles and nose geometries were incorporated into models [60]. Subsequently, the slip line method was proposed to model exit burr formation in orthogonal cutting [59]. This work was later expanded in wider scopes [22], and burr formation in orthogonal cutting with three stages of burr initiation, development, and formation were presented. Subsequently, a tool entrance/exit model was proposed in [2]. Chern and Dornfeld [48] noted the direct effects of plastic bending and shearing of the negative deformation on burr formation/breakout in orthogonal cutting operation. The fracture strain from McClintock's ductile fracture criterion was used in [61] to model material exhibiting fracture during burr formation. A transition from primary to secondary burrs according to tool engagement condition was presented in [49], which led to a burr size prediction system, known as exit order sequence (EOS). The proposed method has been widely used in face-milling process [62]. Micro-burr formation modeling and control were studied in [28, 41, 63–66]. Special attention was paid into the effects of chip size on burr formation morphology and size. According to review of the literature [30], it can be stated that analytical modeling of burr size by means of burr size prediction is considered as an extremely challenging subject due to the effects of multiple parameters that are very difficult to model explicitly. Therefore, in most of the reported analytical models in the open literature [22, 45, 48, 52, 58, 61, 67, 68], orthogonal cutting was considered, the effects of flute geometry were neglected, and the normal yield stress were neglected in all cutting conditions used.

2.2.2 Numerical methods

Among numerical methods, FEM for metal cutting simulation was the main source of attention and it has been widely used to analyze tool design and forming processes [69]. The effects of process parameters (see Fig. 5) on the hard-to-measure responses such as contact stresses on the tool faces (flank and rake), cutting temperature at the tool–chip and tool–workpiece interfaces, chip temperature, and sliding velocities between the chip and the tool can be presented by FEM models. The improved understanding of the cutting physics in this domain has led the researchers in academic and industrial institutions to simulate the cutting forces, stresses, tool temperature, chip formation, and burr formation [69]. Extensive understandings of FEM modeling of burr formation morphology and size by means of burr size reduction have been reported in the open literature [59].

Rapid developments of new models of material behavior under high strain rate led to a wide range of FEM applications

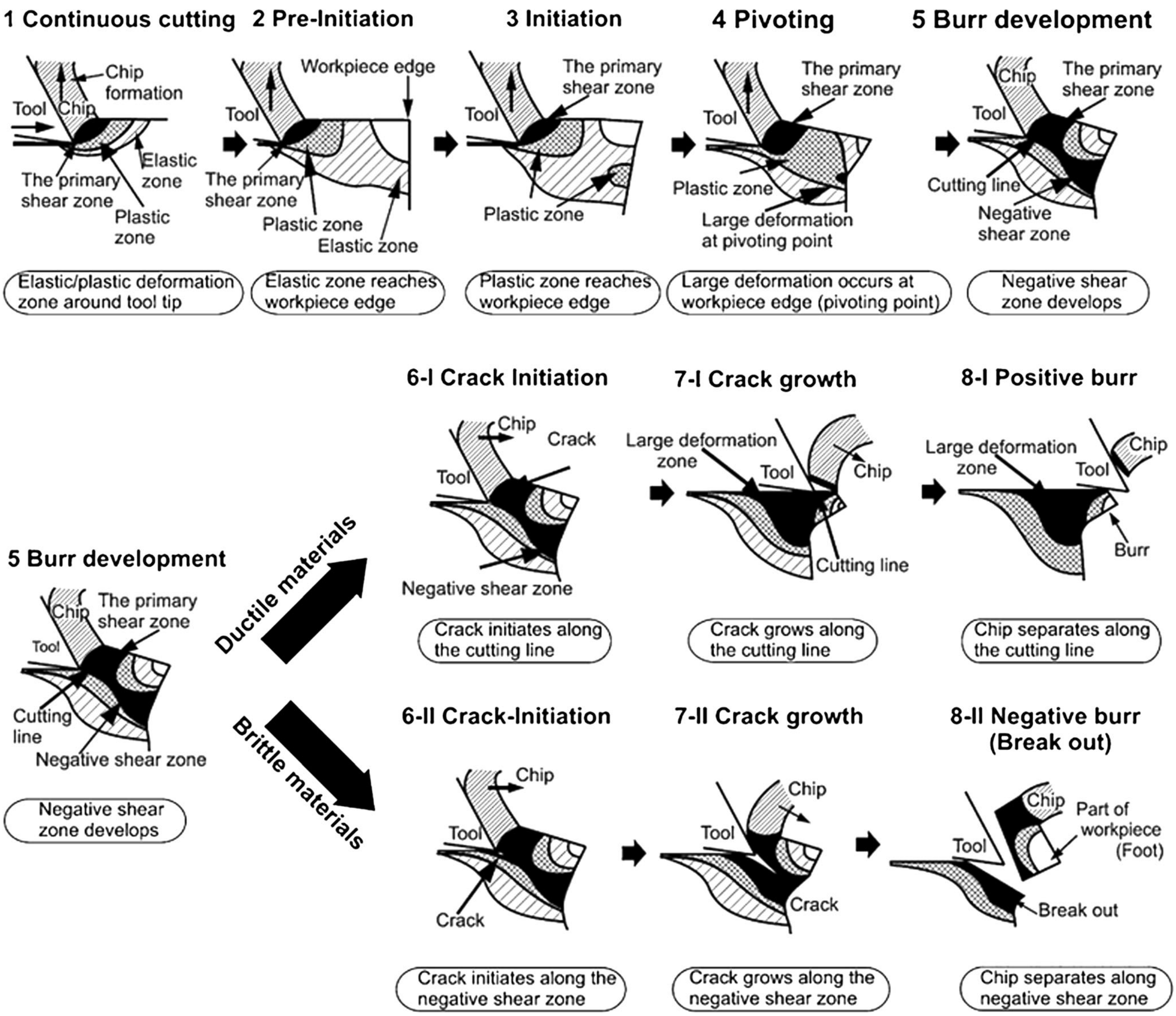


Fig. 4 Overview of burr formation mechanism in brittle and ductile materials (Adapted from [50])

in chip formation characterization, burr formation, and cutting force modeling (see Fig. 6) becoming more accurate and representative [70]. Burr formation modeling using FEM was initiated by Park [71], which presented finite element (FE)-based *ABAQUS/Explicit*. The sharp cutting tool and the element separation criterion were used where work material and the cutting tool were considered as rigid bodies. The effects of exit angle, rake angle, and backup materials on burr formation processes were later presented in [72]. Hashimura et al. [49] developed a basic model of burr formation in orthogonal cutting and confirmed the models on elastic–plastic basis.

The high negative hydrostatic pressure was observed in the transition from steady-state cutting operation to burr formation [73]. The exact meaning of hydrostatic pressure and its effects on various aspects of burr formation are not yet discovered. Chu et al. [74] proposed a milling burr-predicting system using a burr control chart (burr-predicting system). The 2D FE models of burr formation in orthogonal cutting on the basis of implicit Lagrangian codes were presented in [75]. As confirmed in [75], stress distribution, strain, strain rate, and temperature variations can be modeled and calculated with FEM. However, a significant difference was observed among computational values of burr size attributes (thickness and height) and those measured experimentally. The complexity of chip formation mechanism is regarded as the main reason of difference between experimental and modeling results.

The material plastic properties (i.e., flow stress as a function of strain, strain rate, and temperature) under specific machining operation are the main required elements for successful FEM modeling. Due to a wide range of limitations, the 3D FE models of burr formation were reported only in few studies [76–78], in high-interaction machining operations, including macro and micro millings, which are rarely available [26, 41, 59,

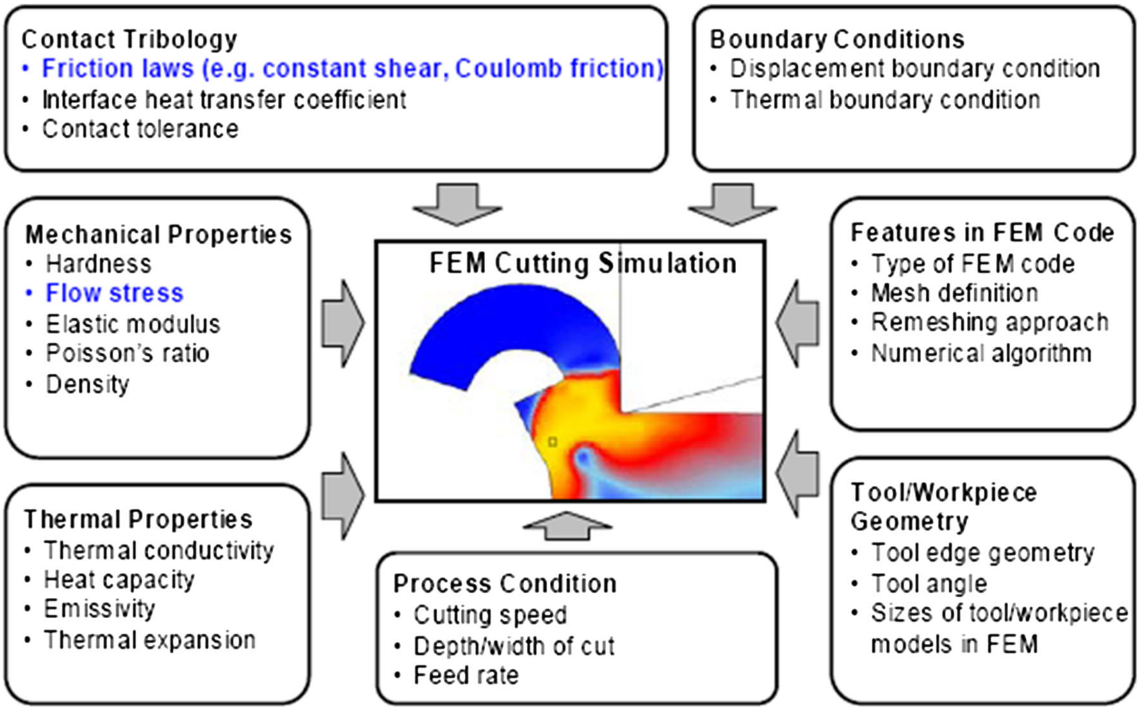


Fig. 5 Factors governing FEM simulation of metal cutting (Adapted from [69])

75]. A comprehensive overview of the FE modeling of burr formation in turning, drilling, and non-traditional machining operations is presented in [26]. However, despite reported progress in this domain, the accuracy of input boundary conditions has a direct influence on the accuracy of modeling results. This can be considered as the main critic drawn against FEM. Unfortunately, the knowledge of input boundary conditions and material plastic properties is not yet advanced. Therefore, despite the machining operation used, they are usually simplified in modeling works. Consequently, the experimental results are not strongly correlated with computational results in many situations.

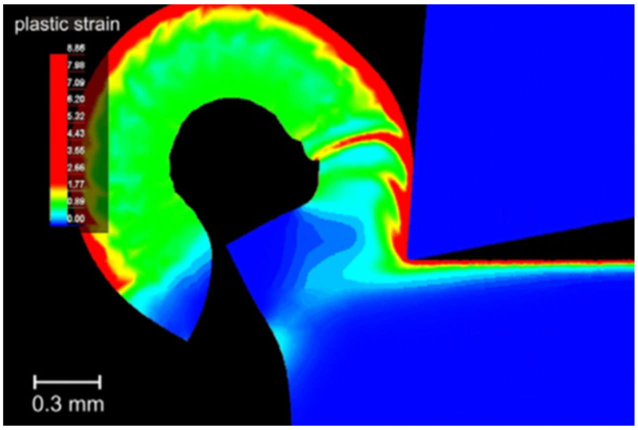


Fig. 6 Simulation results of burr formation in orthogonal cutting using FEM (Adapted from [69])

2.2.3 *Experimental studying/modeling*

In addition to analytical and numerical modeling works reported in the open literature, an extensive amount of studies was devoted to experimental characterization of the factors governing burr size attributes [56, 79–90]. For instance, the effects of tool geometry, various workpiece materials, cutting parameters, and tool path were investigated in [56]. The influences of tool wear, cutting speed, and coolant on the burr size during face milling of cast iron and aluminum alloys were investigated in [85, 86]. Various tool materials and wear conditions were observed in face milling of gray cast iron [87]. The effects of cutting speed, feed rate, material hardness, tool wear, and cutting tool exit angle on the burr formation during face milling of AAs were reported in [88]. As noted in [89], the dominant process parameters on cutting direction burrs are cutting parameters such as cutting tool geometry as well as work part mechanical and chemical properties. Furthermore, most of the existing research works in the literature characterized the burr size attributes, in particular, burr height. However, the burr thickness is of interest from a deburring perspective, because it describes the time and method necessary for deburring [90]. In addition, the use of statistical tools to determine the dominant process parameters on burrs has not been widely reported in the open literature [1, 27, 37, 51]. The dominant cutting parameters on each burr were also found different. In addition, no relationship could be formulated between burr thickness and height [1].

Finally, it could be stated that the effects of numerous process parameters on burr formation morphology and size are limited to the tool material and cutting operation used. A large number of experiments are then necessary to establish an operational window to examine the factors governing burr size attributes, which are however considered as an expensive and time-consuming approach [30].

2.3 Burr shapes

A descriptive overview of burr shapes on the basis of the manufacturing method used, formation mechanism, work part shape, and mechanical properties was proposed by Aurich et al. [26]. The four types of burrs, mainly known as Poisson burr, rollover burr, tear burr, and cutoff burr (Fig. 7), were presented in [40]. As noted in [91], the material's tendency to bulge sidewise is the main cause of Poisson burr formation, which is also called as side burr [2]. Fundamentally, the rollover burr is a chip that in fact is bent rather than sheared at the end of a cut. This, therefore, tends to create large burrs which are typically known as exit burrs. As a result of material tearing from the workpiece rather than complete shearing, the tear burr is formed, which is similar to the burrs formed in punching operations. Consequently, as a result of workpiece separation from the raw material, cutoff burr formation may occur [56].

Primary and secondary burrs were defined in [79]. Later, Beier [92] called secondary burrs as the materials which remained on the machined part edge after the deburring process. However, they are smaller than the depth of cut, while primary burrs are larger [79]. To conduct easier and more adequate deburring performance, in particular on the milled part edges, burr size minimization is of interest. This can be achieved when transition from primary burrs to secondary ones is simplified [30]. The side burrs were studied in [21], and their classification was proposed according to the direction and the mode of burr formation. The cutting edge, the mode, and the direction of burr formation are the main factors affecting the generation of the presented burrs in Fig. 8 [14].

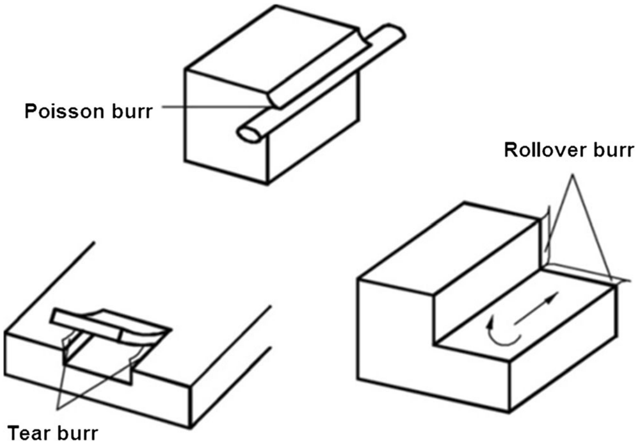


Fig. 7 Poisson, tear, and rollover burrs (Adapted from [26])

2.4 Burr formation and deburring difficulties

Remarkable concerns associated with burr formation and deburring operations have been noted in the review of the literature as follows:

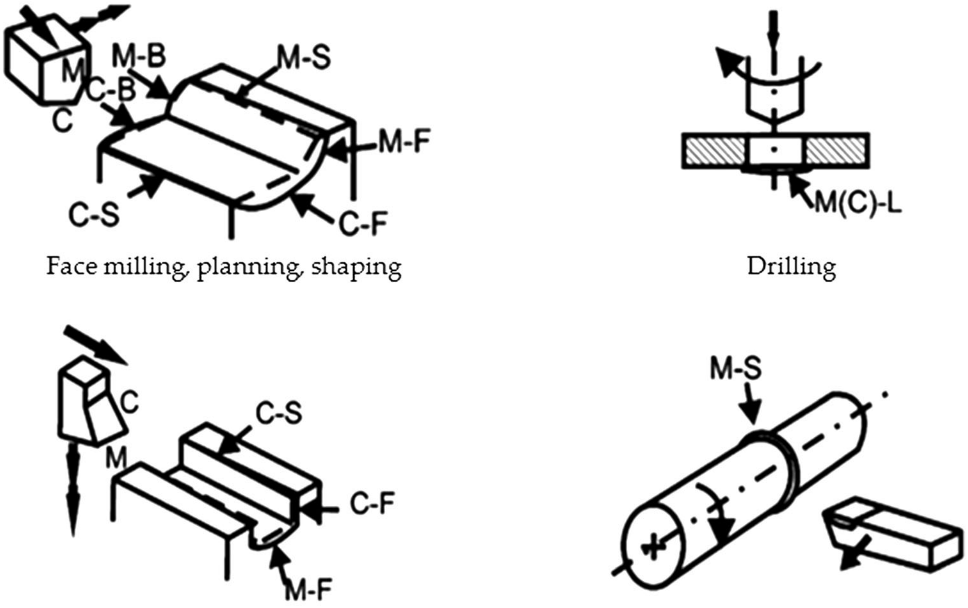
1. Minor labor injuries which appeared during assembly operations
2. Source of debris, which in turn reduces the useful life of the machined part
3. Reduction in the part resistance, tool life, and performance efficiency [22]
4. Creation of failure and hazard during assembly operations of various kinds of machined parts
5. The risk of adhering burrs and debris separation from the work part, which eventually may lead to failure during assembly and destructive damage to the product (e.g., motor)

Burr removal or deburring is usually necessary, despite being considered as a time-consuming and a non-productive process, which in fact may constitute around 30% of the cost of finished parts [3]. In order to secure appropriate edge and surface qualities, several deburring processes are in general combined together. Considering that deburring processes are hard to automate [40] and their performance affects both surface and edge of the work pars [3], it is highly suggested to propose suitable approaches to avoid/minimize the burr formation rather than using deburring tools in consequent finishing operations. Considering that the burr size is a major element affecting tool wear, specific attention has been paid to the adequate selection of deburring tools/strategies when machining AAs [26].

3 Deburring operations

As noted in [4], it is very difficult to secure an excellent edge quality following deburring process. To better select the deburring processes, several classifications were proposed in [3, 5, 6]. The most complete one was proposed by Gillespie [3], incorporating most of manual to high-technology deburring processes. He [3] identified over 120 deburring and edge-finishing processes and indicated that the deburring processes could be classified into the four main categories of mechanical, thermal, chemical, and electrical deburring processes. According to Table 1, the ten most frequently used industrial deburring processes were introduced in [3]. This is in agreement with observations made in [7–14]. In fact, as

(1) Cutting edge directly concerned	
Major cutting edge	M
Corner or minor cuttign edge	C
(2) Mode of the diection of formation	
Backward flow	B (Backward or entrance flow)
Sideward flow	S (Sideward burr)
Forward flow	F (Forward or exit burr)
Leaning to feed direction	L (Leaned burr)



Face milling, planning, shaping

Drilling

Slotting

Turning

Fig. 8 Various forms of burrs (Adapted from [26])

reported in [7–14], the main drawbacks of several deburring methods including electrochemical, abrasive jet, and magnetic deburrings are unintended damages to functional surfaces of the work parts and limited burr removal capability in the micro level. This becomes more complicated when large-burr removal at intersecting holes is demanded. Therefore, proposing advanced custom-designed cutting/deburirng tools/machines and strategies on the basis of mechanical cutting and abrasion becomes apparent. In addition, the effects of lubrication on deburring performance must be identified [93]. According to Table 1, processes 1–8 are classified as mechanical deburring processes. It should be however noted that the work part geometry and mechanical properties are the key elements to classify the deburring tools and processes. In fact, machined part properties (e.g., chemical, mechanical properties) such as hardness, ductility, yield strength, and elongation have significant effects on burr formation morphology, deburring, and edge-finishing difficulties [59]. This, therefore, implies adequate selection of deburring process. To have that accomplished, the first approach was proposed in [5]. A software was also developed for this purpose by Loi [94]. The developed deburring database software comprises certain parameters including burr shape, surface roughness, workpiece properties, weight, and volume. An industrial system was also proposed in [95] to address the research objectives aforementioned. As previously noted, all abovementioned industrial deburring processes constitute certain levels of side effects

Table 1 The most commonly used deburring processes

No.	Deburring operation mode
1	Manual deburring
2	Brush deburring
3	Bonded abrasive deburring
4	Abrasive jet deburring
5	NC/CNC deburring
6	Barrel deburring
7	Centrifugal barrel finishing
8	Robotic deburring
9	Electrochemical deburring
10	Vibratory finishing

Source: [3]

on the specimens. This work indeed does not intend to indicate the main features, benefits, drawbacks, and restrictions of the deburring methods. Moreover, in reference to the research scopes and outlines defined in this work, only the most commonly used deburring processes on aluminum work parts, with specific concentration on the mechanical deburring processes, will be presented in the following sections.

3.1 Mechanical deburring processes

Burr removal is in general conducted by means of mechanical abrasion during mechanical deburring processes. Several deburring tools including abrasive wheel, brush, or solid tools, such as robot arms and grippers [96, 97], were proposed for direct installation at the machine–tool station. The commonly used mechanical deburring processes on aluminum work parts are presented in the following sections.

3.1.1 Manual or hand deburring

Hand deburring Due to several advantages such as flexibility, low cost, and poor level of technology demanded, the manual or hand deburring (Fig. 9) is still considered as the most frequent deburring operation, although [3] it is more observed with a high waste rate, fatigue, frustration, etc. Moreover, manual deburring is currently applied by non-qualified operators in dry condition within numerous industrial sectors. Furthermore, in addition to worker injuries, a major problem with mechanical hand deburring is piece-to-piece discrepancy [98] which tends to increase the waste rate and prolongs the duration of the production process. Despite the difficulties aforementioned, this technique is still widely used in numerous industrial sectors.

Fig. 9 Manual deburring (Adapted from [98])

Manual metal cutting/deburring tools/machines According to [41, 42], deburring-based cutting tools seem to be more efficient than other methods in terms of simplicity and removal speed when intended to remove large burrs at hard-to-reach places. Manual metal cutting/deburring tools/machines can be classified into end-finishing, single-purpose, and multiple-purpose machines. These machines have been widely used for deburring, brushing, grinding, polishing, and buffing of aluminum-made work parts [3]. A deburring tool (Fig. 10) with a spherical cutting head mounted on a pivot shaft was constructed for burr removal in intersecting holes of aluminum-made work parts [99]. Despite the adequate performance observed, however, due to vibration, irregular cutting was detected at higher speeds of revolution. Further studies to reduce the irregular cuttings are still required. Figure 11 shows the drilling edges in 6061-T6 aluminum specimens before and after the deburring process. It exhibited that drilling an exit burr is highly affected by the exit angle. Kim et al. [100] developed a combined drilling/deburring tool which could be incorporated into a deburring cutter, mounted on a cantilever located within a cavity in the drill's shank. Successful experimental verifications were observed on aluminum alloys. Avila [97] described an Orbitool deburring device (Fig. 12) for chamfering the edge of cross-drilled hole intersections. The proposed tool could perform adequate burr removal with no damage to the hole's surface. He confirmed the adequacy of this device through experimental verification works on AA 6061-T6 components. The observations led to a general conclusion that this tool can be considered as an alternative

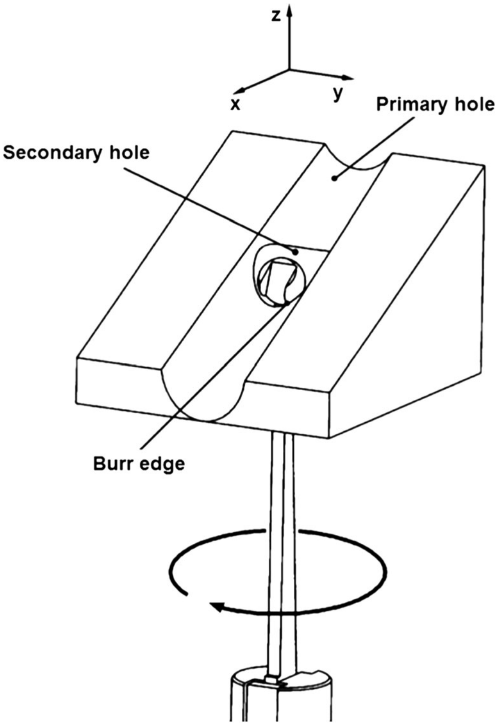


Fig. 10 New deburring tool proposed by (Adapted from [99])

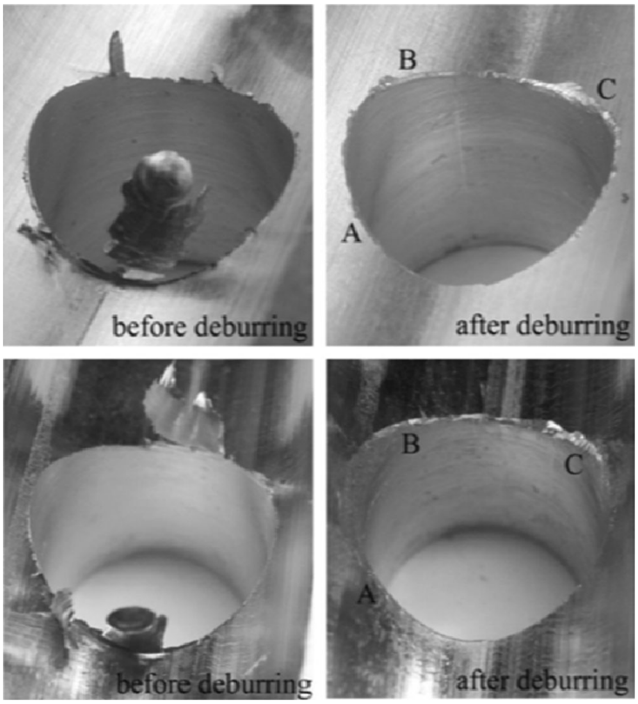


Fig. 11 Drilling edges before and after deburring in 6061-T6 aluminum specimens (Adapted from [99])

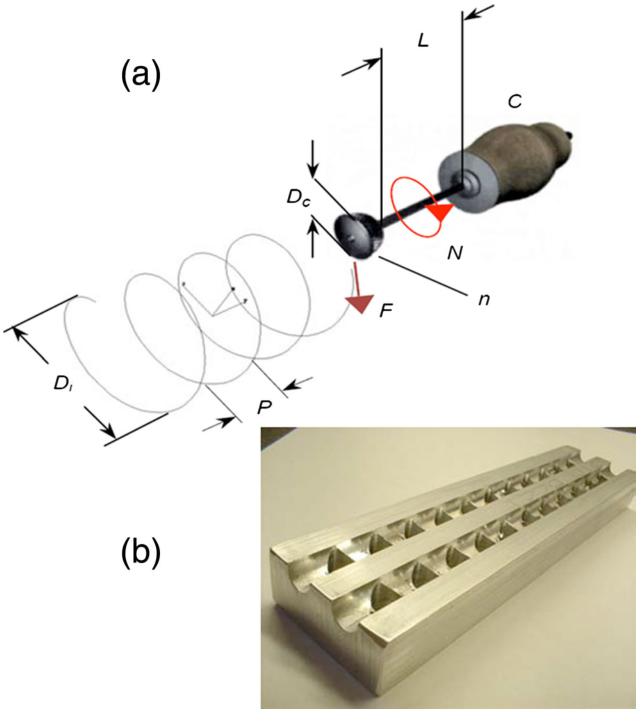


Fig. 13 **a** The Orbitool deburring process. **b** 6061-T6 aluminum work part (Adapted from [97])

approach to abrasive brush deburring. However, certain drawbacks such as relatively lower removal speed than abrasive brush deburring still remain as the source of attention (Fig. 13).

As can be seen in Fig. 14, a new method for deburring intersecting holes in high-speed condition was proposed in [101]. The two cutting edges incorporated into the tool are both supplied with coolant or air. Knowing that no spring has been used in the tool, relatively higher flexibility can be achieved by controlling the air or coolant pressure.

To overcome the reported shortcomings of existing deburring tools for generated burrs on the intersecting holes, a new deburring tool with hemispherical cutter head mounted on a pivoted shaft (Fig. 15) was designed and manufactured [41]. This tool is capable of reaching the burr edges located deep in the work part. Deburring tests with the optimized tool on the AA 6061-T6 specimens represented significant reduction on the surface irregularity by an index value change from 1.3 to 0.7 mm which is considered as an indication of easier burr removal at intersecting holes. However, the current design seems to be useful and efficient at lower speeds of deburring. An ideal design would offer higher speeds of deburring. Moreover, one of the main constraints of the current design is that the cutter head diameter is only limited to over 5 mm. Consequently, the deburring operation becomes very difficult with a diameter below 5 mm. These problems need to be addressed in future studies.

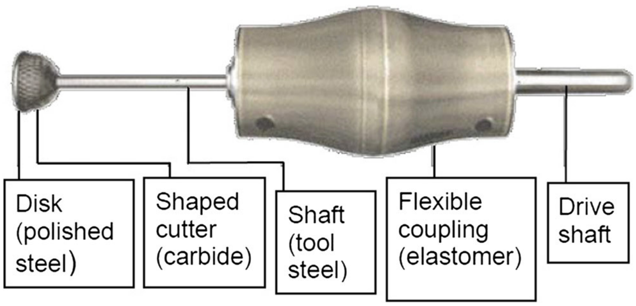


Fig. 12 The Orbitool and its components (Adapted from [97])

3.1.2 Abrasive fine-finishing technology

Abrasive fine-finishing technologies employ various kinds of tools at different operational conditions with great capabilities [102] and wide range of industrial applications. Figure 16 presents the abrasive finishing technologies which enable deburring and edge-finishing of various holes with complex paths and geometries in numerous components, including aluminum-made work parts. Surprisingly, superficial understanding of the finishing characteristics is noted. Therefore, the operators' skills play significant roles on the resulting finishing and edge-finishing conditions.

According to processing principle, the abrasive finishing technologies (Fig. 17) can be presented in two main classes: (1) motion-copying processes and (2) pressure-copying processes [42]. Using the first class, the material removal can be conducted up to the determined level of depth of cut which enables the control of form accuracy and dimension. In contrast, no depth of cut is determined in the latter technique and

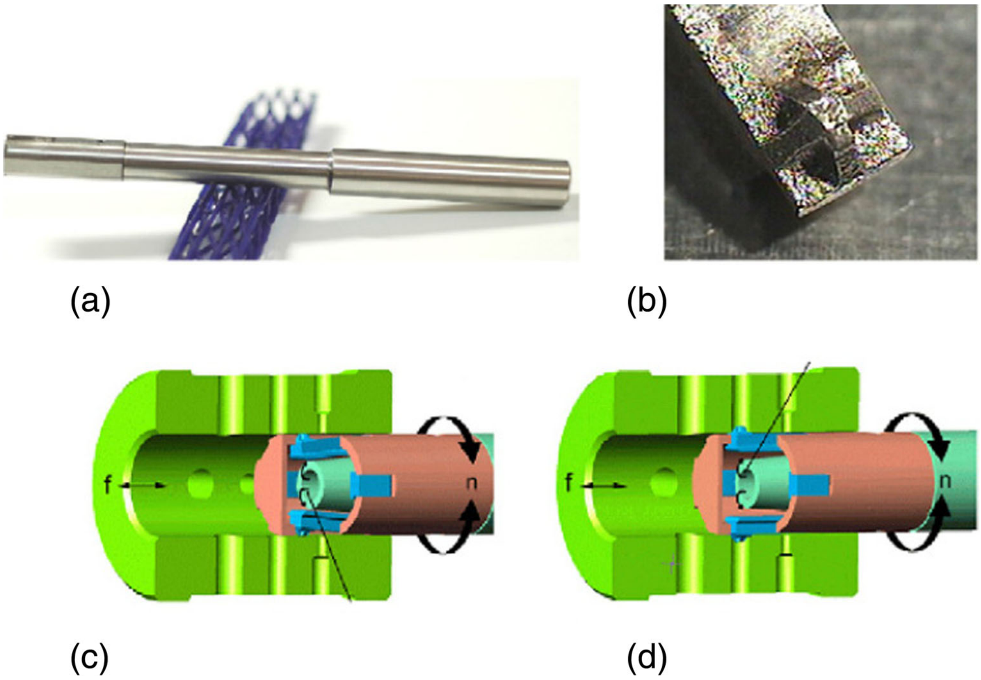


Fig. 14 Beier deburring tool. **a** Beier tool. **b** Cutting edge of the Beier tool. **c** Inner surface. **d** Intersecting hole (Adapted from [101])

material removal can be conducted by means of the pressure of the tools against the work parts. This may allow desired surface geometries and surface integrity while dimensional accuracy cannot be controlled adequately. Super finishing, honing, lapping, polishing, and buffing are representative of pressure-copying processes and are often used as post-grinding processes. Abrasive fine-finishing technologies can be classified based on the following criteria: (1) abrasive state, (2) tools used for the processes, and (3) finishing methods.

Bonded abrasive deburring Bonded abrasive deburring or sanding is considered as a multipurpose, flexible deburring technique that can be used in heavy stock removal applications. It performs well in manual and automated deburrings and surface flattening processes. Various modes of bonded abrasives are available (see Fig. Fig. 18) for lubricated and dry deburrings of aluminum alloys and different families of metals. According to [3], 3D abrasive products could show better burr removal in aluminum-drilled holes than that observed in stainless-steel parts. The most leading advantages of bonded abrasive deburring are relatively low operating cost, diversity of multiple proposed models, and noteworthy flexibility and adaptability to manual or automatic tools. However, the main drawbacks are limited lifetime, dust emission and new burr generation, destructive influences on residual stress and surface quality, and lack of contact with certain sides of the work part. Therefore, specific attention has been paid into proposing alternative methods with fewer side effects.

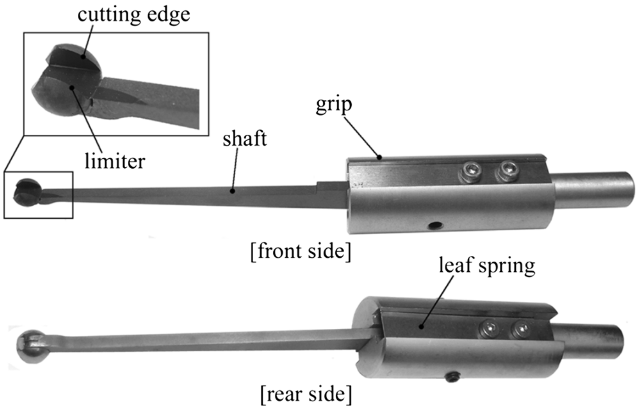


Fig. 15 Deburring tool and cutter head (Adapted from [41])

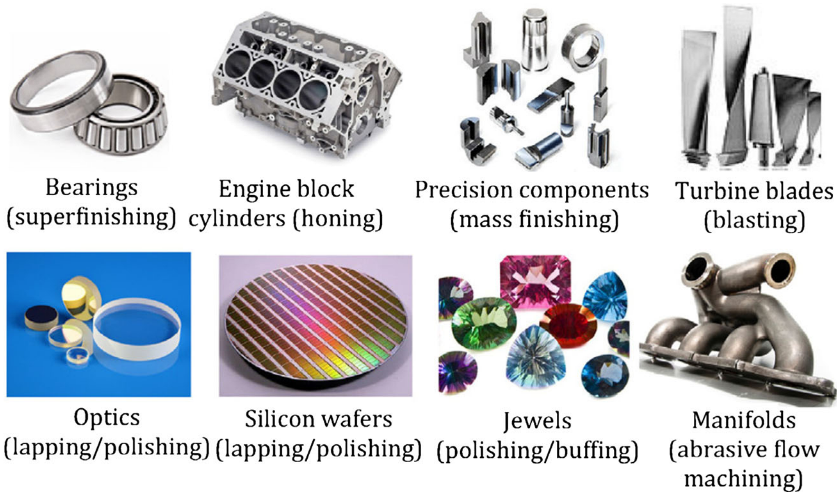
Unbounded abrasive finishing The main types of abrasive finishing operations are as follows [42]:

1. Abrasive blasting
2. Abrasive jet finishing
3. Abrasive flow machining (AFM)
4. Lapping, polishing, and buffing
5. Magnetic abrasive finishing (MAF)

Abrasive blasting is known as one of the subcomponents of the blast finishing which requires less labor than other deburring processes. The blasting equipment is designed to provide a concentrated stream that impacts specific edges. It has wide applications in cleaning, engraving (by sand erosion effects), and deburring complex and simple shapes. The main types of abrasive blasting deburring include

1. Conventional dry-blasting
2. Conventional wet-blasting

Fig. 16 An overview of the components finished by abrasive fine-finishing technology (Adapted from [42])

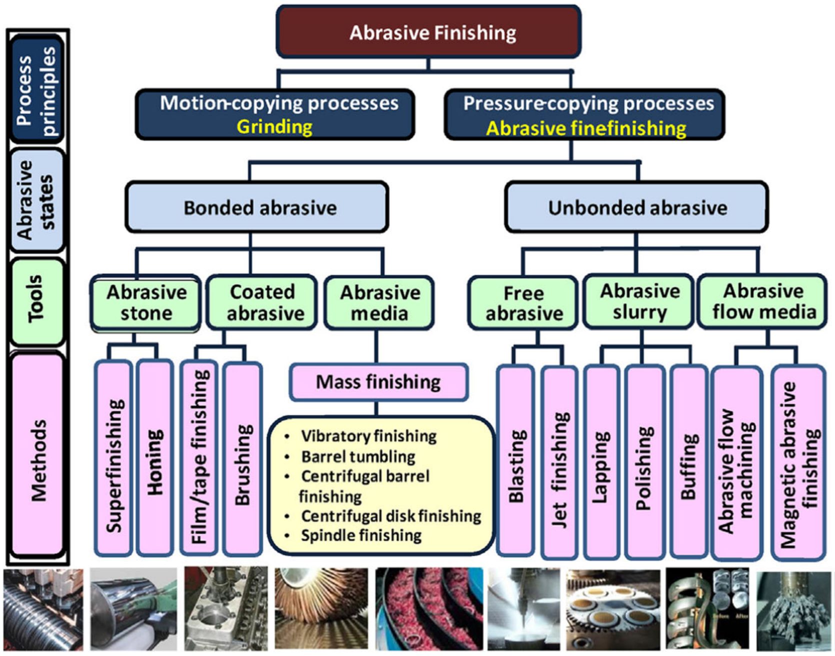


3. Micro-blasting

Conventional dry-blasting commonly uses air-blasting and centrifugal wheel (airless)-blasting. The work parts coated with grease or oil cannot be easily cleaned or finished by dry-blasting. Thus, the degreasing and drying should be performed prior to blasting. The functionality of automatic dry-blasting is examined in [103]. Wet-blasting or vapor-blasting uses the medium particle in slurry form and does not require the use of dust collector or ventilation tools. This method also provides a good surface finish. The main operational variables involved in wet-blasting are velocity and density of the blast slurry, abrasive type and size, angle of attachment, blast nozzle size, type and distance from work part, and desired work part quality level and production rate.

Micro-blasting, also known as abrasive jet machining (AJM) uses high-velocity stream of water/media for material removal purposes. The AJM technology was started over 40 years ago by simple cutting operation, and over the past decades, the technology and performance efficiency have been improved by achieving high water pressure (up to 400 MPa) [104]. Despite the capability of pressurizing the water, there are still many hard-to-solve challenges, especially when dealing with hard-to-machine materials such as ceramics and NiTi alloys [105, 106]. Consequently, the major applications were sectioning and engraving. Moreover, the process can be also used for cutting, deburring, cleaning, and edge finishing of various easy-to-cut materials, including aluminum alloys, with very low level of waste rate. The process is capable of burr removal from the root without forming radius at the part edges. To accomplish that, the parts should

Fig. 17 Classifications of abrasive fine-finishing technology (Adapted from [42])



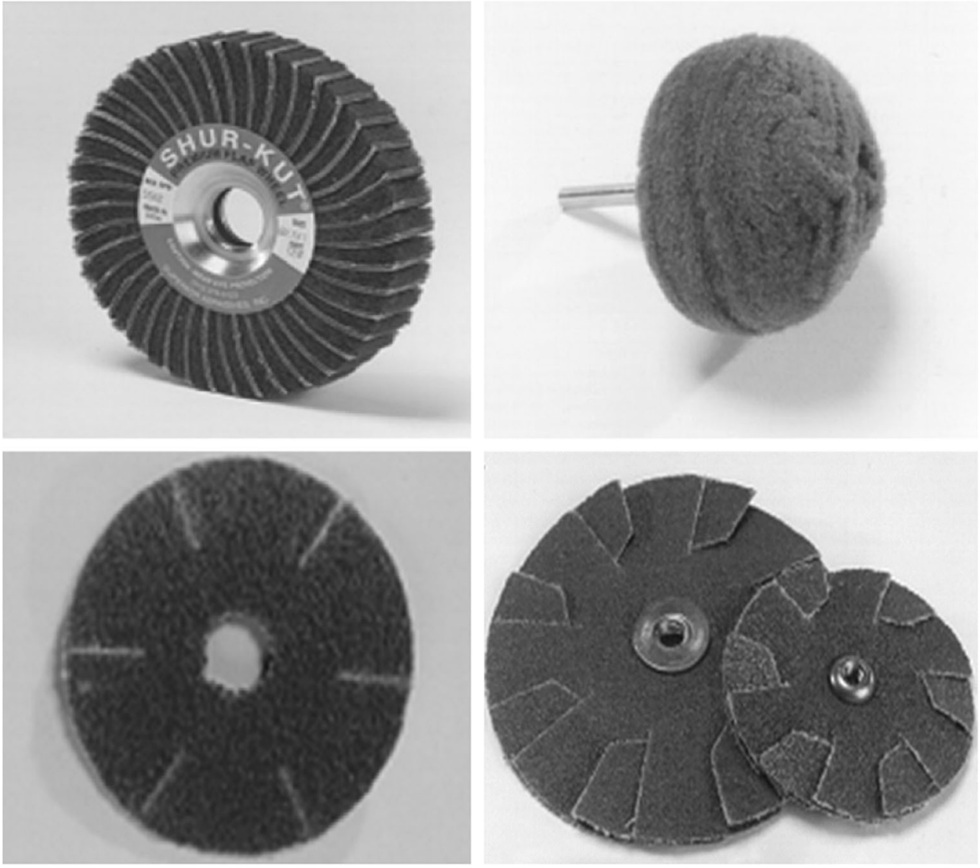


Fig. 18 Bonded abrasive-slotted tools for deburring applications (Adapted from [3])

be securely fastened during deburring process. Many sides of the work part can be deburred by a single orientation of the abrasive jet. This method is recommended for hard, brittle, and miniature materials. As noted by Balasubramaniam et al. [13, 107], tiny burrs formed in brittle materials can be removed by abrasive jets. This deburring method is fast, but usually, only one piece can be deburred at a time. Abrasive methods are restricted to micro-burrs, and the residual abrasive particles are considered as the main difficulties hindering the deburring performance. Furthermore, the consumed energy level is relatively low as compared to other methods. As shown in Table 2, the relative cutting (drilling) action on various materials with higher index numbers indicates greater efficiency. According to Table 2, the drilling efficiency of 2024-T4 aluminum alloys is larger than that of glass and stainless-steel AISI304 [3].

Other types of edge finishing and surface quality improvement methods are lapping and polishing. As shown in Fig. 19, granule, carrier fluid, workpiece, and platen are considered as the main components of the lapping and polishing processes. Material composition and fluid, in particular chemical and physical properties, play significant role in material removal. The main affecting parameters in lapping/polishing/buffing operations are cutting velocity and pressure. Because the process is a pressure-copying process, the feed velocity of the workpiece, as well as the cutting performance, is not directly adjustable.

Although several patents were introduced into use of MAF (Fig. 20), however, a wide range of applications as well as academic and industrial research works on MAF started in the 1970s [42]. The practical use of MAF in research groups was started in the 1980s, followed by public recognition of the mechanism and processing of MAF in 1990 [64]. In fact, rapid development of various kinds of magnetic abrasive tools, fluids, and magnetorheological fluid-based slurry led to a

Table 2 Relative cutting action of various materials

Material	Cutting index
Glass	0.6
Aluminum alloy 2024-T4	1.6
Stainless steel AISI304	0.9
Cold-rolled steel	1.0
Ferrite	3.0
Neoprene	0.05
Al_2O_3	0.4

Adapted from [3]

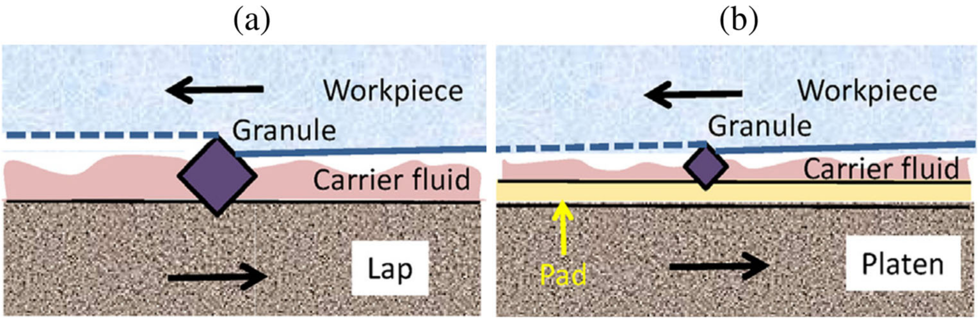


Fig. 19 Mechanisms of **a** lapping and **b** polishing (Adapted from [42])

wide range of MAF's practical applications in numerous industrial sectors. In addition to magnetic techniques and compound fluid-based slurry introduced in the 2000s, these smart fluid-based slurries have attracted considerable attentions in nanometer-scale finishing and deburring operations [42]. The rotating magnetic field with a permanent magnet tool can be used in finishing interior surfaces of tubular components, made of many kinds of metals. In fact, this method is very useful and efficient for finishing and deburring those tubes (e.g., elbows or bends) that are difficult to rotate at high speed.

3.1.3 Brush deburring

The diverse applications of the power-driven brush tools are, but not only restricted to, deburring, polishing, descaling, cleaning, edge blending, and texturizing. Brush deburring as presented in Fig. 21 is adaptable to manual or automatic tools, requiring only a limited level of operator interference. Other main advantages are high speed, safety, simplicity, low operating cost, and great flexibility for accommodating a variety of driving motors and fixtures. However, the main drawbacks and concerns that hinder the performance of brush deburring are particle and dust emission generations when applied on metal and plastic parts under dry conditions. This may cause environmental, health, and safety considerations. Other related drawbacks of this method are the possibility of new burr generation, risk of work part reshaping, and induced residual stress. As noted in [3, 108], brush deburring can be broadly applied for deburring and edge finishing of aluminum work parts, such as cylinder heads (see Figs. 22 and 23).

The main elements involved in brush deburring are brush style, design, materials, rotational speed, face width, coolant, burr size, location, and work part material [110].

3.1.4 NC/CNC machining centers

In order to attain better product quality, lower labor and production cost, and higher production rate, special concentration has been paid to the use of NC/CNC machines in various modes of precise deburring and edge-finishing applications on drilling holes and flat and curved surfaces. The NC/CNC machines are capable of providing automated, easy, and rapid attachment and detachment of brushing tools into the holder which in fact provide the simultaneous benefits of over 1000 standard cutting tools and various tooling conditions and in turn improve the flexibility and production rate and time. Other advantages of NC/CNC machines as compared to hand deburring are avoided repetitive motions and higher precision and accuracy which may lead to less work-related injuries. The combination of these elements may lead to significant reduction in production expenses [3]. Taking into account the abovementioned benefits, instead of a brushing tool, a movable water jet nozzle can be attached into NC/CNC machines, providing traversal motion around the machined part edges for deburring and edge-finishing applications (see Fig. 24). It is to underline that the latter method is only applicable when realistic but not widespread burr removal is demanded [26].

As shown in Fig. 25, a polishing/deburring machine, consisting of two subsystems, was designed on the basis of

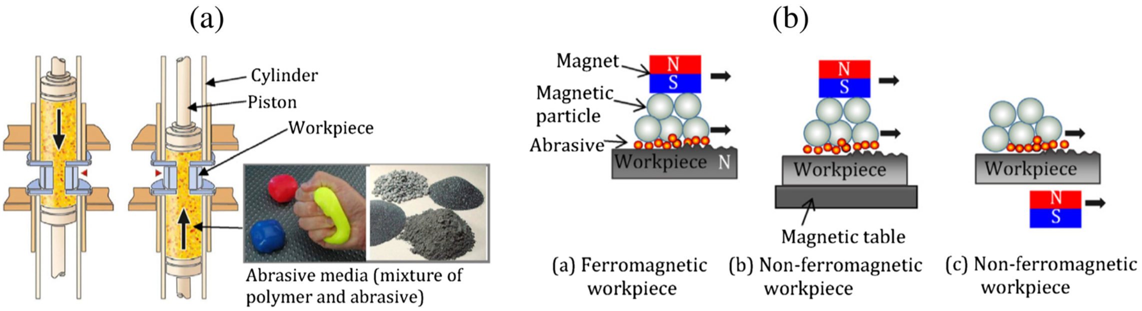


Fig. 20 **a** Overview of AFM setup. **b** MAF processing (Adapted from [42])

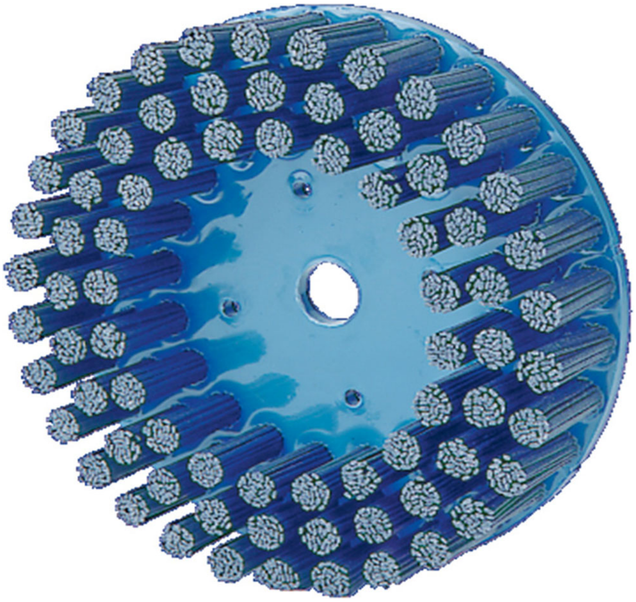
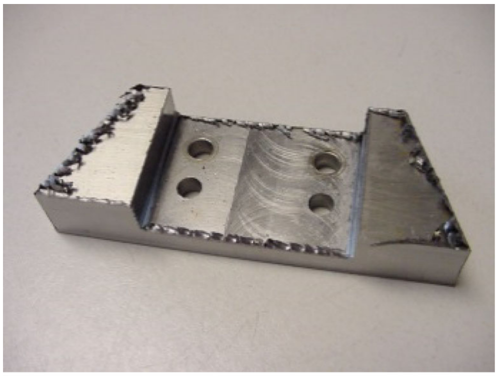
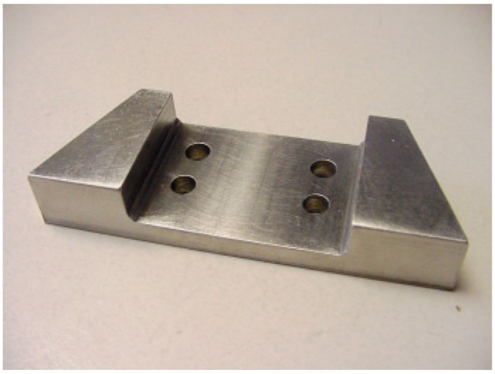


Fig. 21 Deburring and edge-finishing brush (Adapted from [26])

the tripod principle [111]. The first subsystem is a five-axis machine tool which is applied to control the tool/part motion. The second subsystem is also a compliant tool head for tool force control. The experimental results confirmed the capability of automated polishing/deburring of different types of aluminum work parts. Furthermore, high-quality cast or forged surfaces are not thought to be made with NC/CNC machines. A complete overview of the main concerns related to deburring with NC/CNC machines is presented in [3].

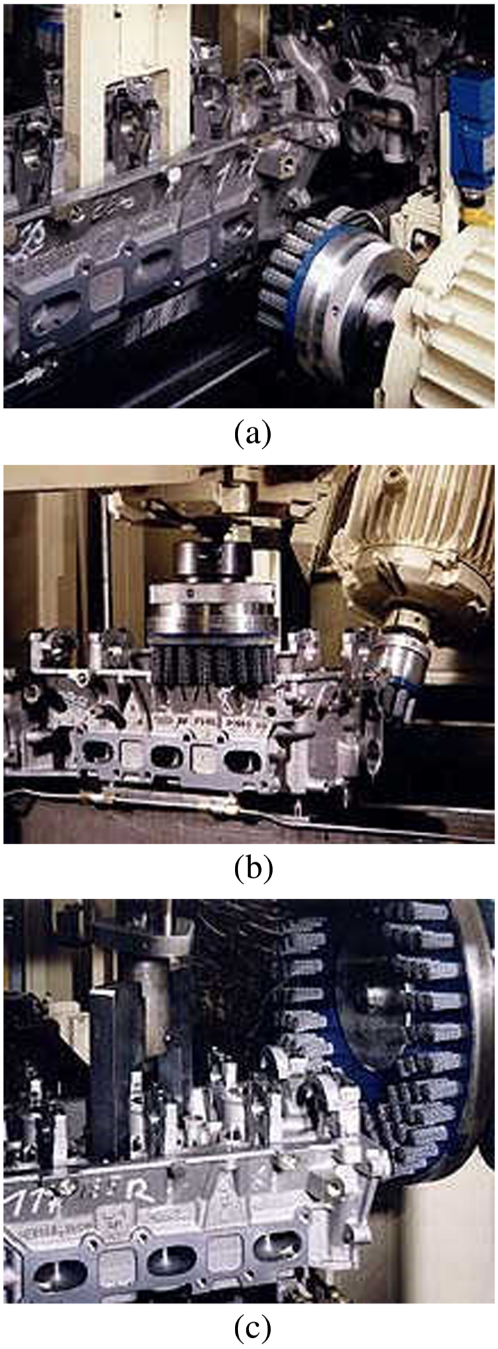


(a) Before deburring



(b) After deburring

Fig. 22 The 6061-T6 aluminum machined part edges **a** before and **b** after deburring (Adapted from [109])



(a)

(b)

(c)

Fig. 23 Brush deburring of the aluminum cylinder head using various brushing tools (Adapted from [108])

3.1.5 Robotic deburring

The wide range of applications of robots in numerous manufacturing divisions and sectors, including polishing,

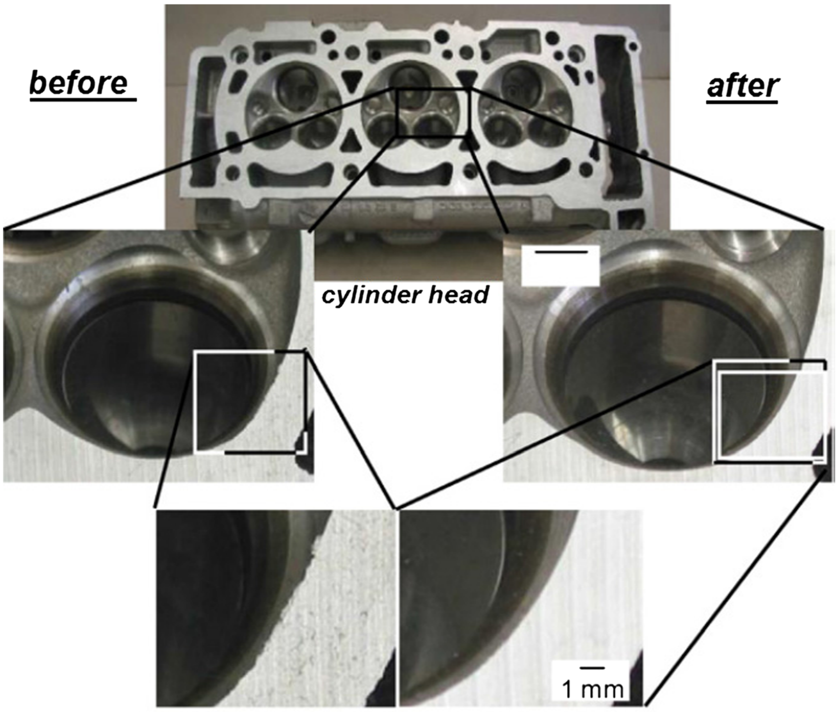


Fig. 24 Overview of water jet-deburring of aluminum cylinder heads (Adapted from [26])

edge finishing, and deburring, was reported in [112–124]. It is a delicate and promising topic which receives increased daily attentions. The main features and advantages of the robots are, but not limited to, no time limit restriction (three shifts a day), capability of accurate replication of the same motions, work part processing faster than humans, capability of manipulating heavier, higher-powered tools for faster finishing process, and accurate performance in hazardous, noisy, and ergonomically unsuitable situations (see Fig. 26) [112, 113]. Robotic deburring in principle is applied to decrease the work load and secure an adequate workpiece quality level. The main applications of robots are within but not limited to the main following areas: (1) simple-shape deburring and chamfering, (2) contouring, and (3) sensor-controlled countering. A robotic deburring structure for various industrial applications in numerous sectors was presented in [116]. Robotic deburring of a gearbox casting made from aluminum alloys is shown in [117]. An on-line path generation method using an industrial robot (see Fig. 27) was proposed and implemented for deburring of cast aluminum wheels [112]. The capability of the automatic generation of the six-degrees-of-freedom (DOF) tool paths is the main feature of this method. This may improve the accuracy and efficiency of deburring process.

Robotic deburring on the basis of tungsten-cemented carbide rotary files was presented in [119]. In this work [119], a deburring method using a feedback system based on robot position uncertainty control approach is introduced. Successful verification results on aluminum

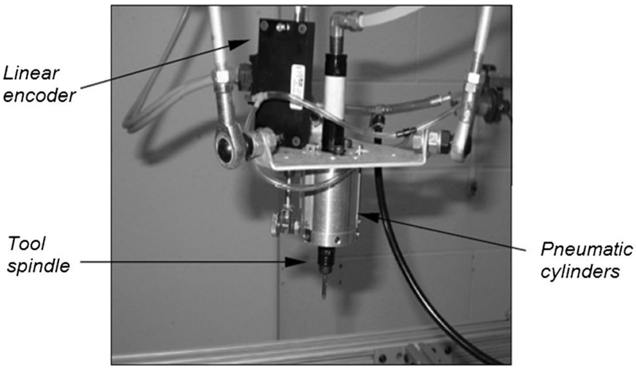


Fig. 25 Deburring tool head adaptable on a CNC machine center spindle (Adapted from [111])

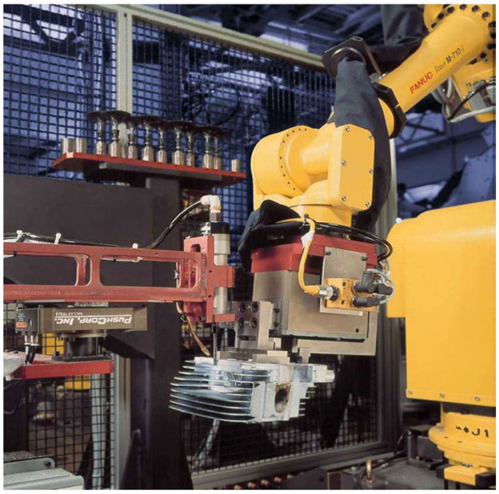


Fig. 26 Robot deburring on an aluminum motorcycle cylinder head (Adapted from [117])

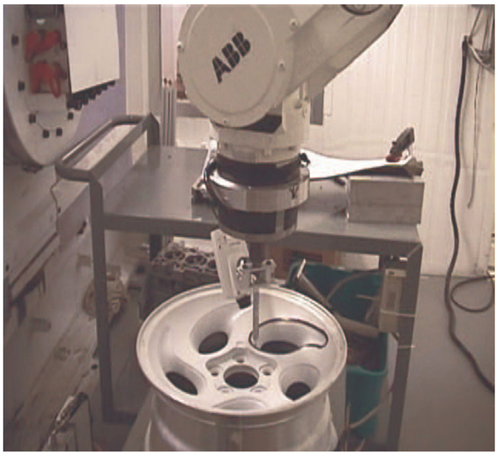


Fig. 27 A deburred and polished aluminum wheel (Adapted from [112])

work parts were observed. The fundamental aspects of acoustic emission (AE) applications within chamfering and deburring processes were introduced by Dornfeld [120]. The adequacy of proposed approaches was verified through experimental works on 6061-T6 aluminum work parts. A robot-integrated finishing and deburring process is proposed in [123]. An extrusion die made of AA 6061-T6 was automatically finished, and excellent surface quality was achieved (Fig. 28). Furthermore, evaluations were conducted to quantify the existing issues related to robot accuracy. Regardless of the acceptable finishing results, due to robot accuracy, the finishing process could not be conducted as similar as the manual finishing processes. Consequently, poorer surface quality as compared to what has been planned resulted. Robot accuracy in high-precision deburring and finishing operations is still considered as a major issue which needs additional investigations.

A robotic deburring system (Fig. 29) based on using vision sensors for identifying the orientation, position, and shape of the work parts was proposed in [124]. The proposed system does not require the contour shape data from CAD profile. The image-processing system is proposed to capture the images from the work parts. The image processing is then conducted to determine those edges which require deburring (Fig. 30). With respect to each work part, the robot language program can be generated automatically from the workpiece shape data and finishing condition data. Therefore, the time-consuming and costly batch production programs via the so-called "teach" or "offline" programming methodologies would not be demanded. One of the main factors hindering the capability of the proposed method is the time and effort required for calibration when the work part size and deburring place are changed.

Figure 31 presents a robot arm joint with a deburring brush [125]. Hirabayashi et al. [126] proposed deburring robots, capable for automatic deburring of elevator guide rails. In practice, advanced robots equipped with five-axis-compliant tools are accomplished to remove most of the burrs, but not all [3].

3.1.6 Other commercial deburring processes

In addition to the most highly used deburring processes as aforementioned, several other deburring processes with high potential of applications on aluminum work parts were presented in [3]. Among them, an inductor creating a co-current magnetic field was used as a deburring method for milled surfaces [127]. Ultrasonic deburring of aluminum work parts with and without abrasive was reported in [128]. It was found that the distance between the horn and the workpiece and the size of abrasive are the governing factors on ultrasonic deburring. The deburring without abrasive led to unsuccessful performance (Fig. 32), while better results were observed when using abrasive (Fig. 33). The type of abrasive used has

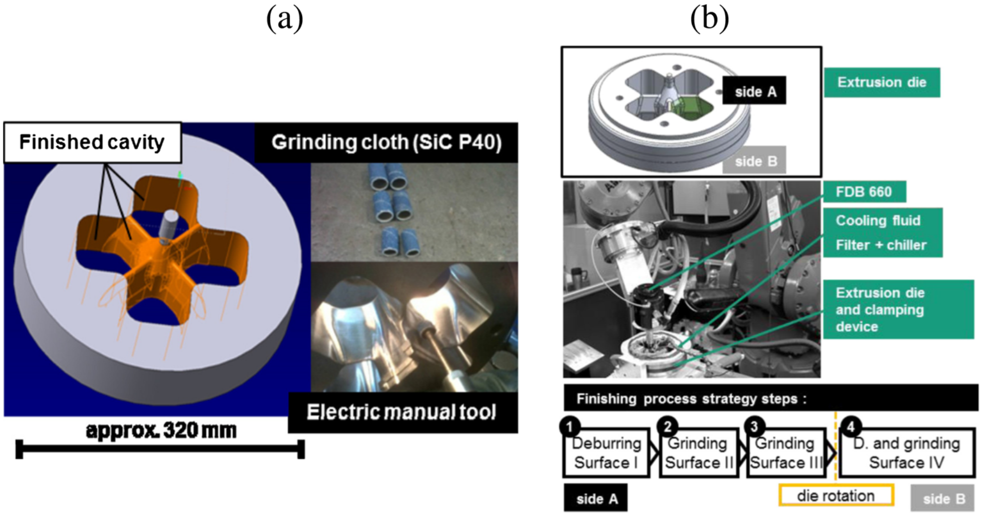


Fig. 28 **a** Aluminum-made extrusion die and manual abrasive tool. **b** Test bench configuration and proposed finishing strategy steps (Adapted from [123])

Fig. 29 Robotic deburring-based vision sensors (Adapted from [124])

a very significant effect on deburring performance. However, the low capability of large-burr removal hinders the wide applications of ultrasonic deburring [42]. A deburring method (Fig. 34) on the basis of the enhanced ultrasonic cavitation deprived of abrasives was proposed in [129], and successful deburring performance was observed on 6061-T6 aluminum work parts (Fig. 35). The degassed water was used in [129] as the testing liquid which seems to provide less temperature. Consequently, it was observed that using enhanced ultrasonic cavitation bubbles without abrasive led to easier burr removal. Despite the benefits aforementioned, the erosion characteristic of ultrasonic cavitation often erodes the work part during the process of deburring. To remedy this difficulty, ultrasonic system driven by a sweep frequency is the ideal approach that can reduce or avoid erosion caused by cavitation bubbles.

As expected, micro-burr removal was presented in [130, 131]. The electrochemical deburring (ECD) could be used in deburring conductive metals of any size or shape, including aluminum alloys [3]. This method is ideal when the removal of inaccessible burrs in aluminum work parts as well as surface generation, free of scratch, is demanded. However, the ECD applied to aluminum alloys with high silicon contents generates textured rather than smooth surface. Furthermore and as noted earlier, the use of electrochemical deburring led to unintended damages to functional surfaces of work parts, although this process can be useful for simultaneous deburring of multiple burr edges [42].

According to [3], thermal energy deburring (TEM) is used for deburring of heat sinks made of aluminum alloys. This technique is also used for thick-burr removal of thin components. Other methods such as electropolishing can be only applied for small-burr removal. Polycarbonate shots are mainly used for deburring aluminum-machined parts, such as transmission parts, pistons, and gears [3]. Within the precision laser deburring, it has been underlined that the silicon caoutchouc method is capable of measuring the cross-sectional profiles of the burrs when universal projector and AE were used as the feedback-sensing techniques [79, 132]. As noted earlier, the thermal degradation of the workpiece, low operation speed, high operating cost, and time-consuming NC programming are the major drawbacks of laser deburring.

One of the major reported techniques for burr removal in aluminum work parts is mass finishing. This approach includes vibratory finishing, barrel deburring, roll-flow finishing, centrifugal barrel finishing, and centrifugal disc finishing which in fact incorporates the combination of mechanical and electrical deburring processes. The overview of advantages and disadvantages of these methods is presented in [3]. Surprisingly, very little scientific research has been published in the 50+ years of mass finishing technology development [30, 42, 110]. This could be due to a superficial understanding of the tremendous costs and expenses related to mass finishing which not only increase the machining expenses, but also increase the lead time and decrease the production rate. Therefore, specific attention has been paid in the last few years on the practical and fundamental aspects of mass finishing.

4 Conclusion

In principle, the presence of burr formation is considered as a common observation in machining operations. The burr size and formation morphology highly depend on many factors including alloy composition and machining parameters, such

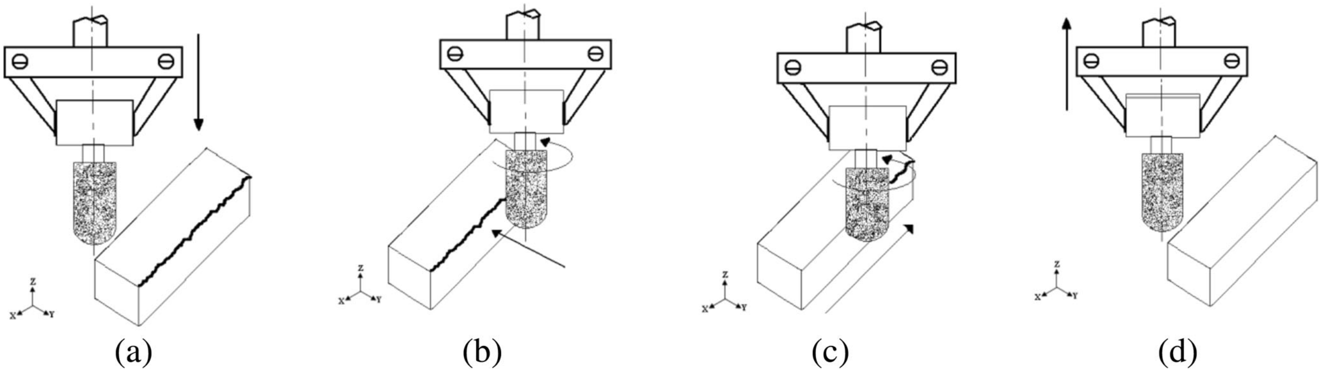


Fig. 30 **a** Surface detection. **b** Edge detection. **c** Finishing task. **d** Withdrawal motion (Adapted from [124])

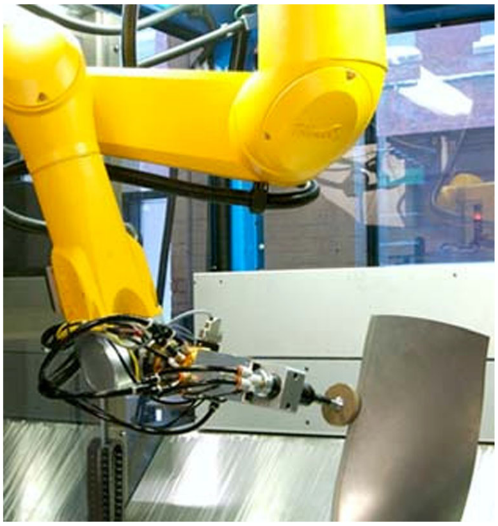
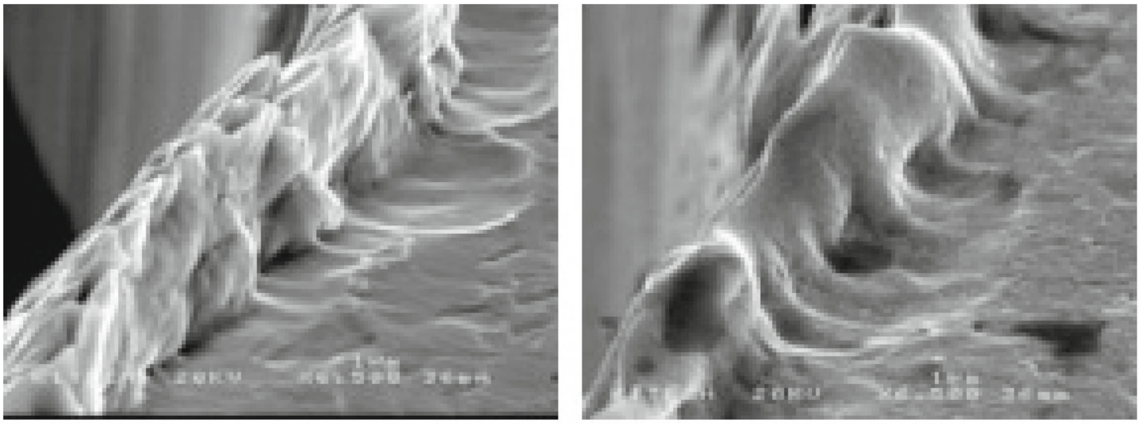


Fig. 31 A brush deburring machine on the basis of the robotic arm (Adapted from [125])

as tooling used, as well as lubrication strategies. However, although burr formation morphology and mechanism are very well-understood, those factors governing burr formation are not clearly defined yet. Knowing that deburring and edge finishing are considered as time-consuming, non-productive, and non-value adding processes, particular attentions are then required to use appropriate methods for adequate selection of deburring techniques. Among deburring techniques, mechanical deburring processes are the most highly used ones due to versatility, flexibility, deburring rate, and acceptable cost. Due to vast applications of aluminum alloys in numerous industrial sectors, the most practical mechanical deburring processes on aluminum works parts were presented in this work.

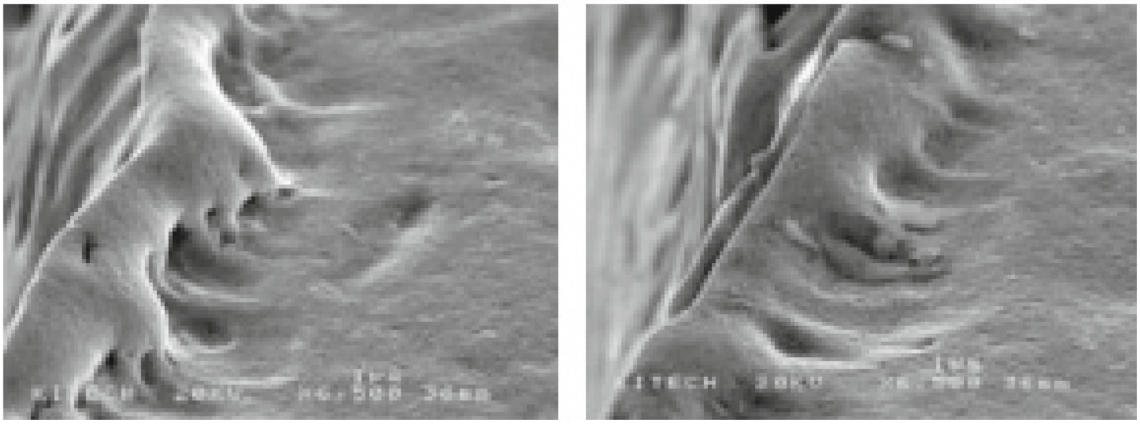
The following conclusions can be presented:

- It is agreed upon that burr formation is a serious concern on a product's quality, functionality, production rate, and cost as well as customer and supplier relations. In fact, burr formation morphology and size, as well as rapid tool wear are closely related when machining aluminum alloys.
- It should be noted that although it is believed that deburring operations tend to expand the production line (~ 30%), but the use of deburring process in several situations is mandatory and inevitable. One solution to overcome the abovementioned concern is to gain a comprehensive knowledge of the factors governing burr formation and



(a) Initial burr height = 8μm

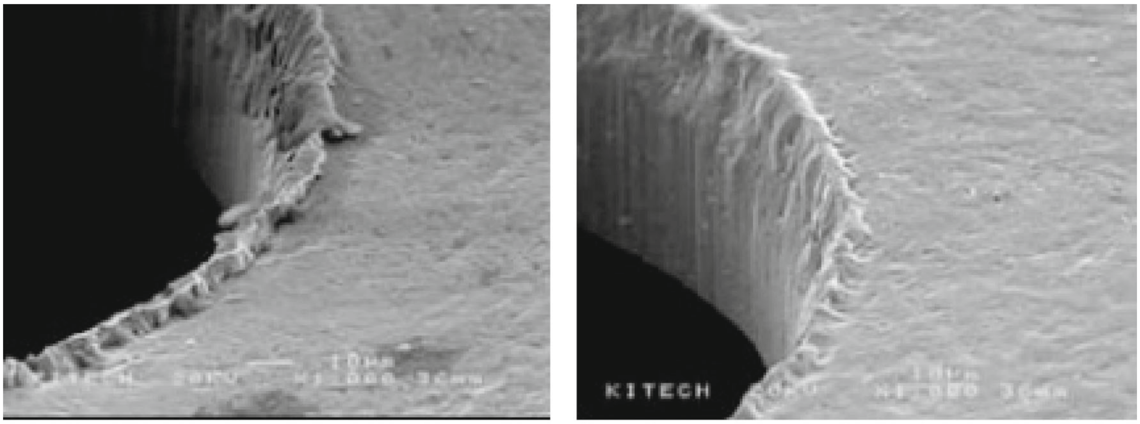
(b) After ultrasonic deburring during 30 sec



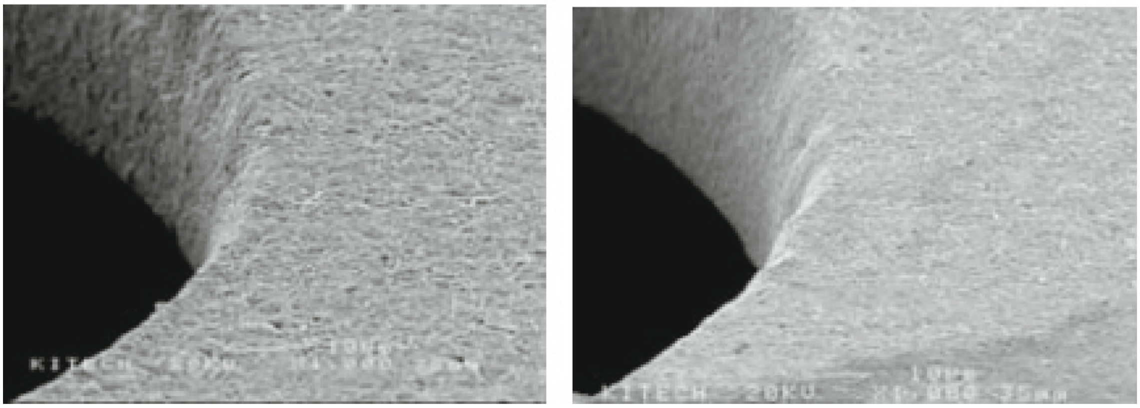
(c) After ultrasonic deburring during 60 sec

(d) After ultrasonic deburring during 120 sec

Fig. 32 Hole shape by SEM after ultrasonic deburring without abrasive (Adapted from [128])



(a) Using only water (b) Using abrasive type #8000



(c) Using abrasive type #325 (d) Using abrasive type #800

Fig. 33 Hole shape after ultrasonic deburring without abrasive and with abrasive (Adapted from [128])

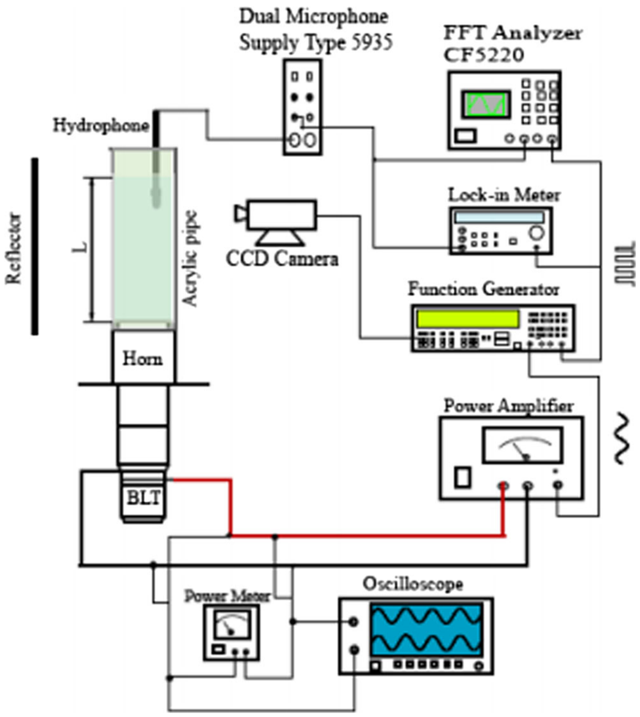


Fig. 34 Schematic diagram of experimental setup (Adapted from [129])

adequate selection of cutting parameters which may reduce the complexity of deburring performances. Unfortunately, low amount of comprehensive work is available about this subject. As noted earlier, surprisingly, due to a superficial understanding of the finishing characteristics, the operators' skills play significant roles on the resulting finishing and edge-finishing conditions. The main drawbacks of several deburring methods including manual, electrochemical, abrasive jet, and magnetic deburring as well as robotic deburring were presented. As noted in the open literature, in addition to unintended damages to functional surfaces of the work parts, most of the deburring methods are limited to micro-burrs. This becomes more complicated when large-burr removal at intersecting holes is demanded. Furthermore, robot accuracy in high-precision deburring and finishing operations is still considered as a major issue which needs additional investigations. Therefore, proposing advanced custom-designed cutting/deburirng tools/machines and strategies on the basis of mechanical cutting and abrasion becomes apparent.

- NC/CNC machines have received huge amount of attention for particular applications, including precise

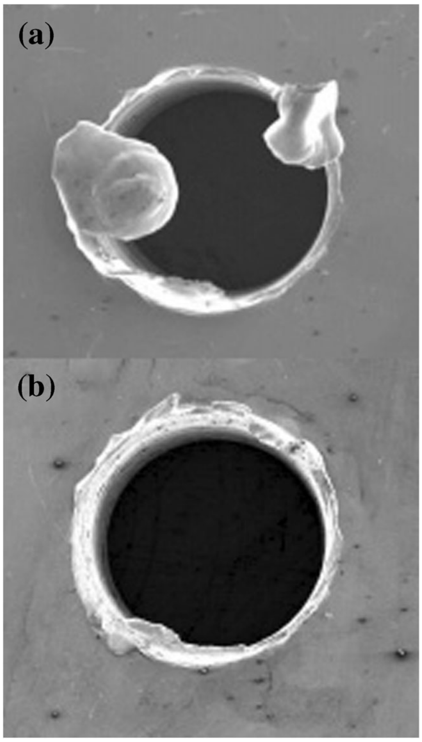


Fig. 35 The work part before and after ultrasonic deburring (Adapted from [129])

deburring and chamfering of holes and flat and curved surfaces of aluminum work parts. Although these methods can efficiently perform automated polishing/deburring of aluminum work parts, their application is limited to those work parts' reasonable but not complete burr removal demands. In addition, NC/CNC machines may not be used when high-quality deburring of the cast or forged surfaces is demanded.

- Other general concerns, including the use of lubricant and its effects on deburring performance, must be identified. For instance, the use of lubricant when machining certain materials tends to complicate burr removal and edge-finishing operations. This subject becomes more delicate when dealing with aluminum components, in particular those milled parts that contain various modes of burr formation morphologies and size. Comprehensive investigations in this domain are still required.
- In order to improve the deburring accuracy, appropriate arrangement and combination of several deburring processes are proposed. This indeed requires us to formulate direct relationships between burr size attributes, deburring processes, and deburring difficulty. Several solutions by means of formulating the abovementioned link are demanded which could be considered as the main source of attention in prospective research works.
- Another commercial mechanical deburring method is robotic deburring which is believed to have great potential applications in numerous industrial sectors. The main feature of robotic deburring is automated tool path generation (e.g., six DOFs) which leads to an accurate and efficient deburring performance. In this regard, on-line industrial robot path generation approach was developed. Successful implementation results were observed in the case of deburring cast aluminum wheels.

4.1 Future prospects

Although a solid base has been created in the area of burr analysis and characterization in the last decades, however, the deburring and edge-finishing technologies have not yet been applied in many industrial applications within the last decades. Several directions for research activities are however proposed which may establish a promising field for applied research works with rapid and efficient effects on various industrial sectors and micro-/nano-scale products with high demands that all require adequate cleaning without edge disturbances.

The future demands of precision deburring are challenging, not only for machine tools and deburring tools, but also for high-precision machining researchers. This, therefore, requires close collaborations between machine tool builders, CAD/CAM programmers for precision tool path planning, and deburring and edge-finishing R & D community. This would help towards successful movement to the next generation of precision deburring and edge finishing. In this regard, comprehensive knowledge of the factors governing burr formation and adequate selection of cutting parameters which may reduce the complexity of deburring performances are strongly demanded. Unfortunately, low amount of comprehensive work is available about this subject. This could be considered as a primary source of attention in forthcoming works.

Implementing adequate approaches to prevent, eliminate, or at least reduce the possibility of burr formation needs to be conducted; otherwise, the replacement of cutting tools is essential to avoid non-desirable expenses. This indeed requires adequate knowledge of the advantages and disadvantages of deburring processes. Furthermore, generating a relationship between burr size, location, and the main attributes of deburring processes needs to be investigated. Therefore, having an adequate awareness of deburring processes and formulating direct links between them and the burr size, by means of incorporating the effects of material properties, cutting parameters, and machining strategy, shall be studied by academic and industrial scopes by means of world-class applied research works. One of the subjects which received less amount of attentions is the deburring difficulties on the work parts received from lubricated machining. This could be an ideal subject for forthcoming articles.

Adequate awareness of deburring processes and formulating direct links between them and the burr size through incorporating the effects of material properties, cutting parameters, and machining strategy need to be studied through world-class applied research works within academic and industrial disciplines.

Specific attentions should be paid into non-mechanical deburring technologies. For instance, electrodischarge deburring using EDM machine is proposed. For successful utilization of EDM deburring, as aforementioned, the effects of various parameters on the deburring performance must be identified. For instance, the effects of various electrode materials and shapes on the final quality of deburred parts need to be studied.

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