Chapter 5

Machining Burrs Formation & Deburring of Aluminium Alloys

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Additional information is available at the end of the chapter

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1. Introduction

Although the machinability of most aluminium alloys can be classified as relatively easy when the tool wear and the cutting energy are considered, these materials could however raise some concerns when the chip formation and the burr formation are of concern. Burr formation, a phenomenon similar to chip generation, is a common problem that occurs in several industrial sectors, such as the aerospace and automobile sectors. It has also been among the most troublesome impediments to high productivity and automation, and largely affects the machined part quality. To ensure competitiveness, precise and burr-free components with tight tolerances and better surface finish are demanded. Intensive research conducted during the last decades has laid out the mechanisms of burr formation and deburring in a very comprehensive fashion, and has introduced integrated strategies for burr prevention and minimization. Despite all the improvements realized, there are still many challenges encountered in understanding, modeling and optimizing the burr formation process and size, through production growth and cycle time reduction. Furthermore, acquiring a solid knowledge on deburring methods and the links between them and burr size is strongly recommended.

This chapter reviews burrs formation and the factors governing them, including the workpiece material, the tooling, the machining parameters and the machinining strategy. A case study on the effect of heat treatments on drilling burr size is also presented and is followed by some deburring and edge finishing techniques commonly used for machined aluminum parts. The main advantages, disadvantages and limitations of these edge finishing operations are also presented.

2. Overview of burr formation

Burr formation is one of the major issues currently facing manufacturing industries. During the process of plastic deformation, the material is stretched past the point of elastic deformation, where it can no longer return to its original shape and size. If there is already a crack present in the material, the stretching will continue to increase the size of the crack eventually causing it to fracture [1]. Therefore, burrs forming during machining are defined as projections of material beyond the workpiece limits [2]. It is very important to limit burr formation rather than deburring them in a subsequent finishing operation [3]. Burr consists of an undesirable extended surface over the workpiece [4] or a missing portion on the workpiece edge (negative burr, see Figure 2), which should be avoided or at least minimized.

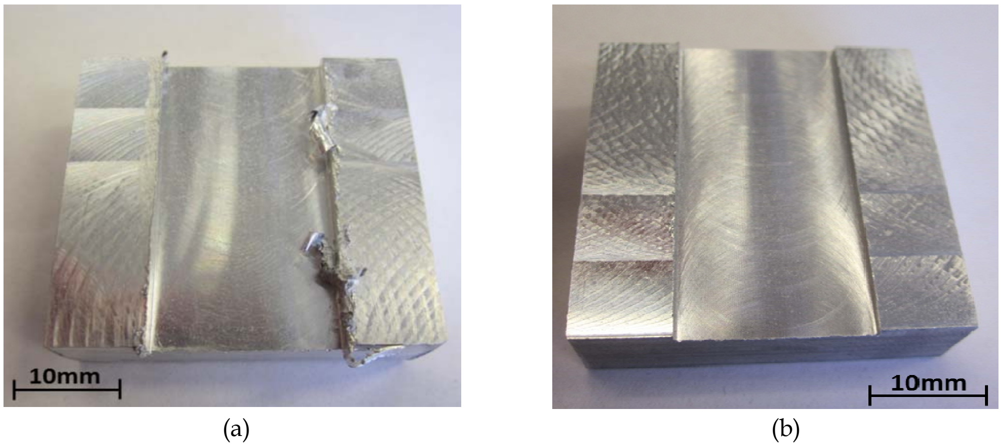

Figure 1. Slot-milled machined parts with (a) large burr formation, (b) burr formation with tiny scales

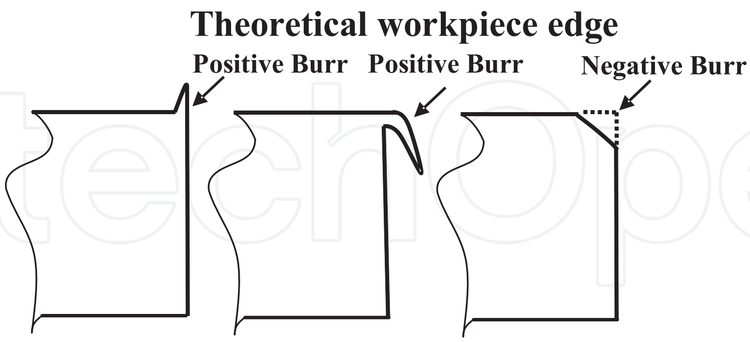

Figure 2. Examples of burr definition (*adapted from* [4])

Several authors have contributed to the advancement of knowledge on burr formation mechanisms, among which Gillespie [2], Aurich et al. [3], Pekelharing [5], Sofronas [6]Nakayama and Arai [7], Chern and Dornfeld [8], and Hashimura et al [9, 10]. Currently, numerous burr descriptions exist, depending on the application, manufacturing process, formation mechanism, shape and material properties [3]. The four main types of machining

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burrs are the Poisson burr, the Rollover burr, the Tear burr and the Cut-off burr [4]. According to [11], Poisson burr is formed as a result of the material's tendency to bulge sidewise. Narayanaswami and Dornfleld [12] called this phenomenon a side burr, because, according to engineering mechanics, the *Poisson effect* is only present in the elastic range.

Two types of burrs known as primary and secondary burrs were introduced by Kishimoto et al.[13]. Beier [14] described a secondary burr as remaining material at the edge of a part after deburring process. From [3], secondary burrs formed after the breakage of the primary burrs. However, they are smaller than depth of cut, while primary burrs are larger [13]. Nakayama and Arai [7] described the burr formation in various machining processes by combining two classification systems as: [1] by direct concerning of cutting edge; [2] by mode and direction of burr formation. The various types of machining burrs are shown in Figure 3. Interested readers on different types of machining burrs are referred to [3].

(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)

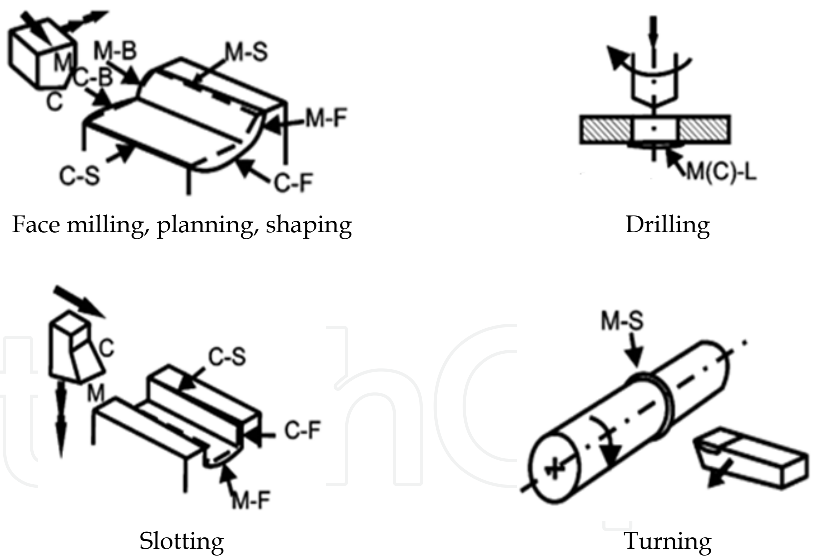


Figure 3. Types of machining burr [3]

As can be seen in Figure 4, to better describe the burr, a new term called "burr value" was defined in [15]. It contains the burr root thickness (b_r), burr height (b_h), burr thickness (b_t) and burr root radius (r_f). However, measuring and/or estimating all these parameters to calculate the burr value is very difficult and time-consuming. Furthermore, it would appear that the burr value can also not be used as an efficient parameter to better select a deburring method. Of all the burr parameters, the burr height and thickness are used to determine the burr removal difficulties [16].

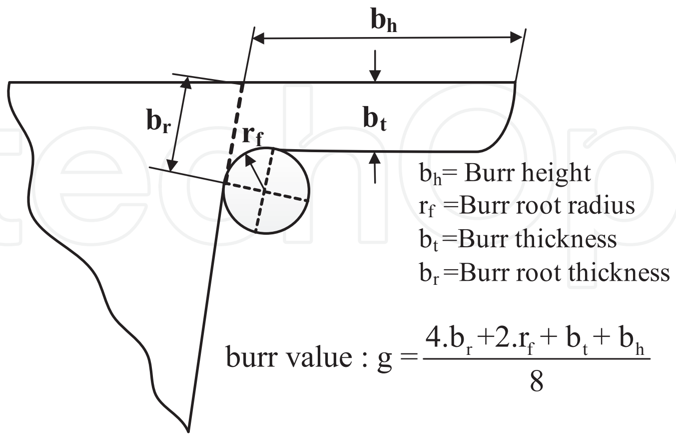


Figure 4. Measurement values of a burr (*adapted from* [15])

3. Factors governing burr formation

Burr formation is a crucial issue in industrial circles. Previous studies have shown that burr formation is almost impossible to avoid [17]. Gillespie and blotter [18] observed that burr formation cannot be avoided solely by changing the feed rate, the cutting speed and the tool geometry. Burrs in drilling perform an important role on product quality and may cause reliability problems and performance degradation. Burrs are formed both at the entrance and at the exit of the workpiece [19]. The exit burr is important as it is larger in size and is most difficult to remove causing deburring problems. Therefore, many of studies paid their attention to exit burrs in drilling and milling operations [19-27]. Sofronas [6] summarized several factors governing drilling burr formation. According to [3, 6, 28], the following are the principal factors governing milling burr formation:

1. Machined part (geometry, dimension, mechanical properties, etc.);
2. Cutting parameters (cutting speed, feed rate, depth of cut, etc.);
3. Cutting tool (material, shape, geometry, rake angle, lead angle, helix angle, etc.);
4. Machine tool (rotational speed, dynamic strength, etc.);
5. Manufacturing strategy (tool path, coolant, back cutting, lubrication, MQL, etc.).

This summary is however still limited due to the complex interaction effects that exist between process parameters, since their degree of influence on burr formation varies considerably simply by adding or removing cutting parameters and/or changing the material. In other words, factors governing burr formation cannot easily be classified as direct and indirect factors [29]. The following lines present the dominant process parameters influencing the burr formation mechanism and size.

3.1. Workpiece materials and conditions

Machined part properties (e.g., chemical, mechanical properties) have significant effects on the burr formation process. The dominant mechanical properties usually reported in the literature are hardness, ductility, yield strength and elongation [30]. According to [3], higher ductility materials tend to generate larger burrs, but limited if not none burr formation is anticipated when the material is restricted to deform in the force direction. According to [31], the machining of ductile materials tends to form larger burrs, particularly at higher levels of cutting speed and feed rate. According to Ko and Lee [32], material properties had more effect on the drilling burr size than feed rate. Analytical models proposed in [27, 33] were capable to predict the size and type of exit burrs in milling and drilling of ductile materials. Niknam and Songmene [27], while modeling and studying the burr formation during millings of AA6061-T6 and AA2024-T321 found that the exit burr thickness, which control the deburring difficulties and the deburring cycle time, is highly sensitive to material mechanical properties such as yield strength and to the cutting force. When the material is brittle, fractured burrs (negative burrs) are formed on the edge part. This phenomenon can be reinforced at higher cutting speeds and feed rates, creating irregular burrs. The workpiece edge angle is the most prominent geometrical element of the workpiece that highly affects the burr formation mechanism. According to [34, 35], cutting tests on the edge angle lower than 90º generate long and thin burrs, while short and thick burrs are formed on parts with edge angles of 90º or larger. An increase in the temperature hardens most materials, and consequently affects the machining and deburring performance, even if the burrs created are small. According to [2], taking steps to prevent plastic deformation reduces the incidence of burr formation. His proposed methods include laser treatments, hard machining, localized mechanical processes, and chemical and thermal treatments. In addition, chamfering on the external edges of the machined part before the cutting operation is an excellent approach to prevent material deformation at the part edge, and consequently achieve burr size reduction [17]. The burr form and height in drilling are dependent on the material properties and cutting conditions [36]. Images showing typical exit hole appearance are presented in Figure 5 as a function of feed rate. As shown in the following example, the AA6061 High Strength (AA6061HS) contained higher levels of the major alloy addition to promote increased age hardening response. The AA6262 and AA4XXX compositions were based on AA6061 but contained additions of 0.5 wt% Pb-0.4 wt% Bi and 8% Si respectively.

The worst case for burr was obtained for the AA4XXX-T6 alloy (Figure 5] which is the most ductile one. The burr observed was a transient burr type. The other alloys exhibited a uniform burr (type I) or crown burr (type II):

- The AA6262-T6 and AA6061-T6HS alloys produced only uniform burrs (type II).
- The AA4XXX-T6 and AA6061-T6 alloys produced both uniform burrs (Type II) and transient or crown burrs (type I). The latter are generally difficult to remove.

- The AA4XXX-T6 was problematic in terms of exit burr height.

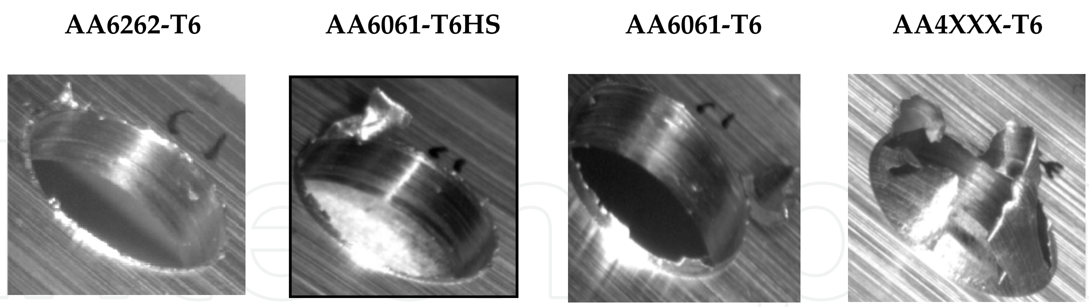


Figure 5. Optical microscopy images of exit burrs observed on drilled holes as a function of feed rate (cutting speed: 45.7 m/min; Feed rate: 0.0508 mm/rev) [36]

3.2. Cutting conditions

According to [37], burr height varies irregularly with changing cutting conditions. Increasing the cutting speed leads to reduced burr size. In addition, milling operations at higher feed rates reduces the burr size, while creating secondary burrs that are easier to remove. From [38], when the machined part surface is hardened in high speed machining, a transition from ductile to brittle behavior may occur. This phenomenon may lead to decreased burr height. Chern [39] analyzed burr formation during the face milling of aluminum alloys. He found that secondary burr formation is dominated by the depth of cut and the feed rate. Nakayama and Arai [7] showed that the burr size can be reduced by limiting the undeformed chip thickness. The cutting conditions, tool and workpiece geometry may reduce the shear strain supported by the chip, therefore possibly leading to burr reduction. Kim and Dornfeld [31] showed that higher levels of depth of cut generally increase the burr size. Longer burrs in the cutting direction are formed when larger corner radii are used. Olvera and Barrow [40] found that the exit angle and the depth of cut influence the exit burr in the cutting direction, whereas the depth of cut is the main factor affecting the exit burr in the feed direction. According to [41, 42], the use of high levels of axial depth of cut increases the possibility of burr size minimization, but may also cause inevitable damage to the cutting tool, the machine and machined part functionality. Therefore, the use of very high and/or low cutting parameters levels is not suggested during milling operations. Ko and Lee [32] used multiple materials in drilling processes and they concluded that the burr thickness is independent of the feed rate.

As shown in [36], the lower the feed rate, the higher the burr height obtained (Figure 6]. The AA4XXX produced most of the times high size burrs and only in very limited cases, the burr size was comparable to others alloys tested. At lower speeds, the burr size observed was higher compared the one obtained at high cutting speed; this denotes a possible interaction of the feed rate and the cutting speed on burr formation.

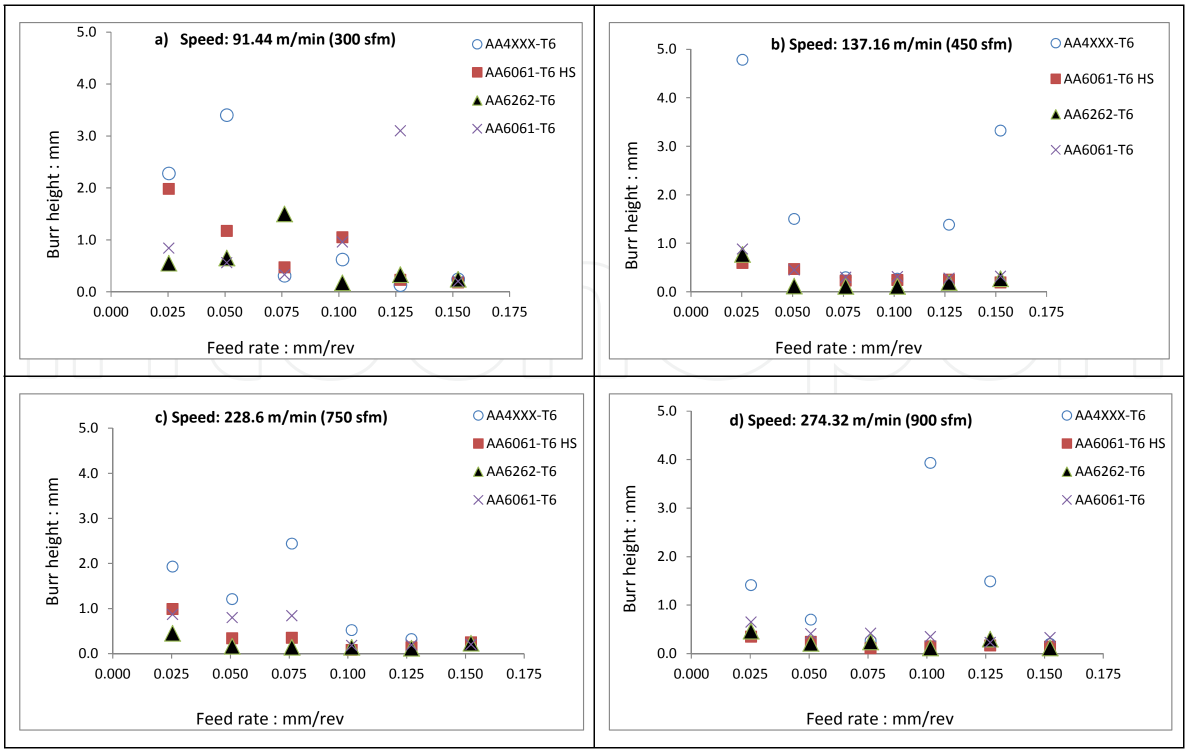
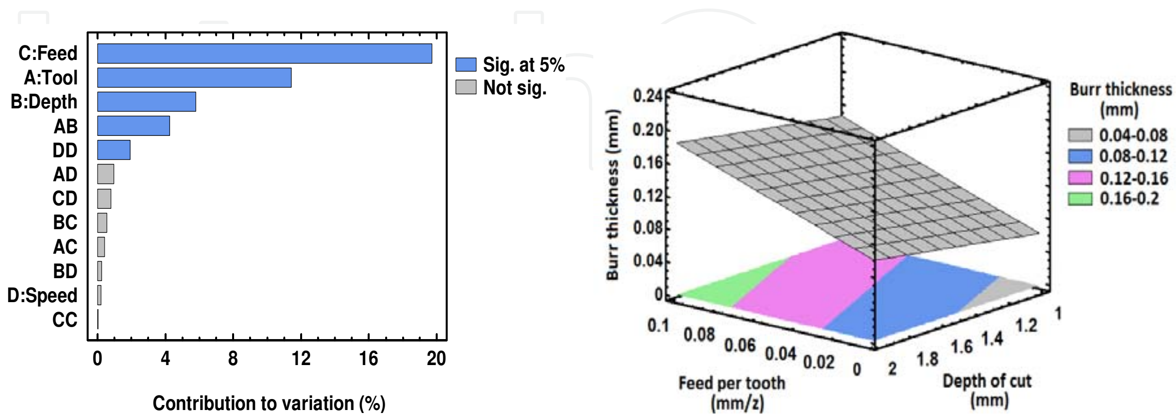


Figure 6. Burr height progression as a function of feed rate, cutting speed and workpiece materials [36]

The effects of cutting parameters on top, entrance and exit burr thickness and height during the slot milling of AA 2024-T351 and AA 6061-T6 were statistically investigated in [24, 25, 43]. Among the investigated burrs, exit up milling thickness could be controlled by cutting process parameters, such as feed per tooth, depth of cut and cutting tool (see Fig.7(a)). While other burrs, such as exit up milling burr height, are affected by interactive between process parameters, nor direct effects.



(a) (b)

Figure 7. (a) Pareto chart and 3D contour plot of exit up milling burr thickness of AA 6061-T6 [21]

It is believed that the burr formation mechanism depends highly on the chip formation mechanism [27]. Cutting forces and chip thickness $h(\varphi)$ are highly affected by the feed rate, the depth of cut, and the tool and workpiece geometry. Therefore, it could be inferred that burr formation is influenced by cutting forces [17]. The direction and intensity of cutting forces affect the volume of the chip generated, and can also play an important role in material deformation. The influence of cutting forces on drilling and milling burr formation has been reported in [27, 29, 44, 45]. According to [46], the variation of exit up milling burr thickness (B_t) is highly correlated with changes in tangential cutting force [Figure 8]. According [46], the burr thickness (B_t) and cutting force F_t could be linearly formulated as a function of depth of cut and feed per tooth.

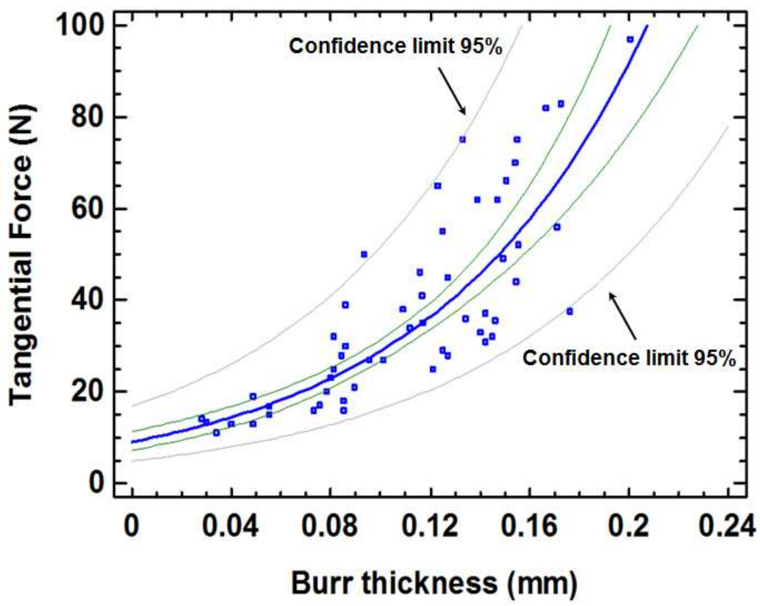


Figure 8. Exponential regression model between F_t and B_1 thickness [46]

Considering the research works presented in this section on factors governing burr formation, it could be inferred that due to complex mechanisms of burr formation and direct and interactive effects between process parameters, a large number of experiments is required to evaluate the effects of process parameters on burr formation and size [47]. The combination of statistical and experimental approaches is a good method to better understand the burr formation mechanism and to define the factors governing milling burrs. Furthermore, knowing that the best setting levels of process parameters needed to minimize each response are not similar, the question is how to obtain the best setting levels of process parameters to reach the optimum or near-optimum burr size. This issue becomes more complex as for a given machined part; cutting parameter optimization for burr size minimization alone may frequently deteriorate other machining performances, such as tool life and surface roughness. Therefore, the use of optimization methods for the correct selection of process parameters is strongly recommended [48]. According [21, 49, 50] achieving better surface finish and acceptable burr size in milling and drilling operations at the same time is possible when using optimization tools such as the desirability function and Taguchi method.

3.3. Cutting tool geometry

Pande and Relekar [51] studied the influence of drill diameter, feed, length to diameter ratio, and material hardness on burr height and thickness. It was determined that a drill tool diameter in range of 8-10 mm resulted in the low values of burr height. Bansal [52] found that using inserts with positive axial rake and negative radial rake angles led to satisfactory burr size and surface quality. According to [24], slot milling with a larger insert nose radius ($R\varepsilon$) leads to bigger exit bottom burr and smaller exit up milling side burr. In addition, when a larger $R\varepsilon$, pretty close to the axial depth of cut is used, a primary exit bottom burr formation is expected. Consequently, a smaller exit up milling side burr is generated. Avila and Dornfeld [37] showed that tool geometry and in-plane exit angle Ψ have significant effects on burr size and edge breakout during the face milling of aluminum-silicon alloys (AlSi9Cu3 and AlSi7Mg). Tripathi and Dornfeld [53] reported the possibility of burr-free conditions when using diamond end mill tools at high cutting speeds. According to [18], the use of sharp cutting edge tools with positive rake angle avoids built-up edge (BUE) formation, thus reducing the burr size. According to [42], tool coating has a negligible influence on face milling burrs. However, a certain level of coating influence on slot milling burrs was observed in [24]. According to [31, 54, 55], the tool condition and cutting parameters used, in particular, the feed rate, are the main governing factors affecting burr formation. For instance, a sharp cutting edge tool with a positive rake angle in the case of a milling operation avoids built-up edge formation, thus decreasing burr formation [18]. As presented in [54], tool wear increases the contact area of the burr-tool interface, and consequently, increases the cutting forces and stress distributions (Figure 9). Tool wear may physically occur on two sides of the cutting tool, mainly on the rake face and the flank face, thereby forming crater wear and flank wear. According to Choi et al. [56], tool wear highly affects the burr formation process when the tool enters and exits the machined part. Large entrance burrs formed when using worn tools resulted by different kinematic engagement rather than back cutting.

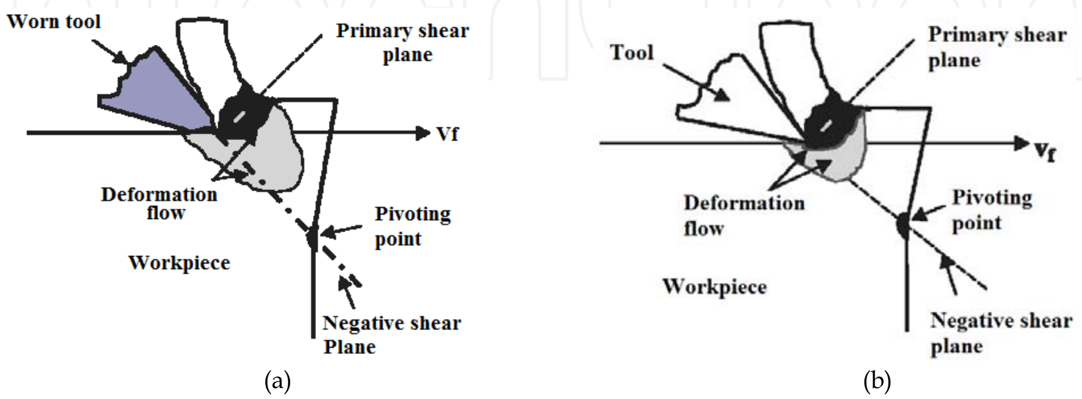


Figure 9. Shear angle and pivoting point for a (a) worn tool, (b) sharp tool (*adapted from* [54])

According to [18, 28, 31], using higher cutting speeds and feed rates when cutting certain materials may increase the cutting temperature and consequently reduce the tool life as a result of tool wear. When the strain rate of the material increases, it effectively enlarges the burr dimension. A similar problem may occur when using dry machining or inadequate tool geometry.

3.4. Machining strategy

According to [55, 57], an adequate selection of the machining strategy has positive effects on the burr formation mechanism. The main machining strategies proposed to date include:

1. Optimization of the tool path planning, including the machining direction and the tool engagement angle;
2. Using inserts and backup materials;
3. Using modified cutting parameters;
4. Using coolant and lubrication.

To predict and control the burr size in milling, several algorithms were presented in [26, 58, 59] and eventually led to proposing tool path planning approaches for burr size minimization. The effect of back cutting on burr formation was reported in [60]. Przyklenk [34] proposed a new strategy for burr reduction by using dry ice snow to cool down the machined part edge. Shefelbine and Dornfeld [41, 61] stated that the use of coolant decreases the burr size, while larger burr is expected when using worn tools. According to [17], proper lubrication reduces friction between the workpiece and tool, and consequently, reduces the incidence of burr formation. However, as stated by Aurich et al.[62], in the case of certain materials, the use of lubricant hardens the burrs and complicates the deburring processes. Moreover, the use of cutting fluids seriously degrades the environmental air quality and increases machining costs by 16-20% [36]. One alternative approach with reduced cost and greater environmental benefits is dry machining. Some works have reported on dry milling [21, 43, 63-67] and dry, mist and lubricated drilling of aluminium alloys [29, 49, 68]. According to [69], the processes constitutes a suitable candidate for the machining of ductile materials, such as aluminum alloys.

4. Case study: Effect of artificial aging heat treatment on drilling burr size

Surprisingly, very limited information is available on the influence of material properties such as ductility, strength, and hardness on the burr formation during machining of aged aluminum alloys. In this chapter, the influence of heat treatment on the burr formation during drilling of Al-Si-Mg (A356) cast alloys is investigated. In order to study this effect systematically, the aluminium alloys were heat-treated to produce different precipitation states they were later machined under controlled conditions. This work was carried out in order improve part quality of drilled hole.

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4.1. Experimental procedure

A set of experiments were carried out on a high speed 3-axis CNC milling machine-tool (Power: 50 kW, Speed: 28000 rpm, Torque: 50 Nm). The cutting tool used is non-coated high speed steel twist drills (3/8 stub drill bright finish with 118 point angle). It should be mentioned here that a group of drills with the same batch were used throughout the tests in order to ensure uniformity of geometry, microstructure and properties for the cutting tools. The parts used for the experiment were rectangular blocks of A356 cast aluminum alloy 300 x100 x 20 mm in size, mounted on a special machining fixture. Cutting forces were measured using a three-axis table dynamometer (Kistler 9255-B). The tested material was A356 aluminum alloy which chemical composition is given in Table 1. Drilling tests were conducted at different cutting conditions as shown in Table 2. Experiments were repeated four times and the average values of burr sizes were used for further analysis. The burr height was recorded using Mitutoyo Height Gauges with a sensitivity of 0.0005 in (13 μm).

	Si %	Mg %	Fe %	Cu %	Mn %	Zn %	Al
A356	7	0.35	0.2	0.2	0.1	0.1	Balance

Table 1. Chemical composition of A356 alloy

Parameters	Condition
Material	A356 (300 mm x100 mm x 20 mm)
Tool	HSS twist drill-9.525 mm diameter , 118° point angle
Speed	60, 180, 300 m/min
Feed	0.15, mm/rev
Depth of cut	3 mm
Lube	None

Table 2. Machining parameters used

5. Results

5.1. Effect of heat treatment

The properties of aluminum casting alloys can be improved through the appropriate control of several metallurgical factors involved in the production of these castings [70]. Aging treatment is usually applied to improve the strength and hardness of the castings. Aging temperature and aging time are the two variables which control the characteristics of the phases precipitated during the aging treatment, and they ultimately also control the mechanical and machinability properties of the alloys. The A356 alloys were received in as-cast condition (T0), and the samples were then divided into five groups as follows: (i) two blocks in as-cast condition (T0); (ii) two blocks in T4 condition (Solution Heat-Treated " SHT "+Quenching); (iii) two blocks in T61 condition (SHT+Quenching+Artificial aging at 155°C for 5 hours); (iv) two block in T62 condition (SHT+Quenching+Artificial aging at 180°C for 5 hours); and (v) two blocks in T7 condition (SHT+Quenching+Artificial aging at 220°C for 5 hours). All the samples were solution heat-treated at 540˚C, for solution times of 8 hours. The solution-treated samples were then quenched in warm water (60˚C) to room temperature. For each given condition, all the samples were solution heat-treated and quenched at the same time leaving only the other conditions, such as natural and artificial aging time, as variables as shown in Figure 10. Figure 11 summarizes the hardness measurement implemented on the A356 aluminum alloy. The hardness measurements reveal that the peak hardness value varies between 85HRE and 90 HRE. Hence, it is believed that aging at 155˚C for 5 hours produces almost the same precipitation hardening as aging at 180˚C for 5 hours. Then hardness tends to decrease upon further aging. The variations of hardness when exposed to different aging temperatures are correlated with the number of Mg_2Si phases in which the hardness increases with an increase in the number of Mg_2Si phases.

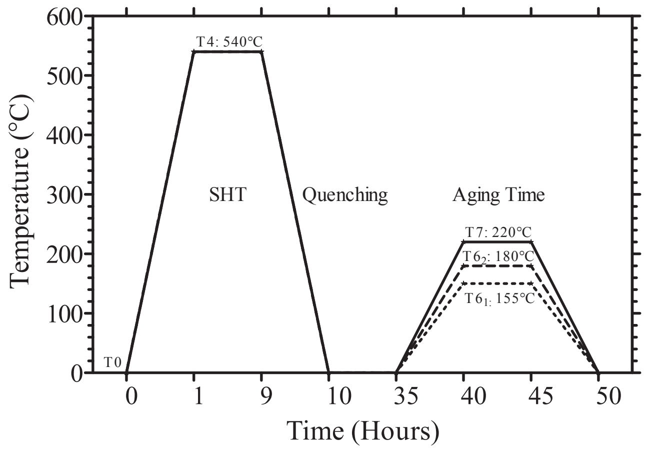


Figure 10. Different heat treatment conditions applied to the A356 alloy

Figures 12-13 show the effects of different heat treatments on the burr heights with various cutting speed and feed rate during machining A356 aluminum alloys in dry conditions. To emphasize the effect of heat treatments on the material properties and its effects on the burr height thus, the case study will be focused on dry conditions. The experimental results reveal that the A356-T61 aluminum alloy in peak aging condition produces the lowest burr height than other alloys, whereas the A356-T0 and A356-T4 in cast and SHT conditions were produced the highest level of burr formation. Generally, it is also observed that aging at low temperature, 155 ºC, was observed to produce the lowest level of the burr formation while the aging at higher temperatures, 180°C, and 220°C, respectively, are accompanied with an increase in the burr heights. The lowest level of burr height was observed in peak aging conditions A356-T61 alloy may be explained based on the fact that burr formation is closely re-

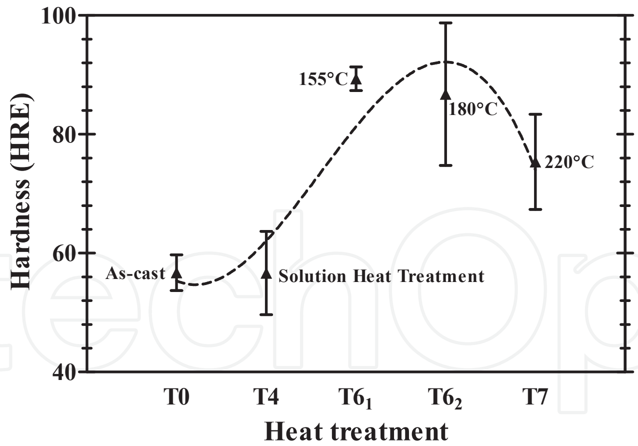


Figure 11. Evolution of the changes in the hardness values result in the heat treatment conditions

lated to the hardness of the workpiece, as well as to the deformability of the matrix around the Si particles. Thus, when the workpiece made of the A356-T61 alloy is hard (i.e. high tensile properties), thereby resisting deformation, and the work material is also difficult to deform in the shear zone ahead of the cutting edge and on the tool surface in such a way that the Si particles are secured firmly in position. Consequently, the particles have a strongly abrasive action on the tool cutting edge resulting in a high cutting force as well as in low level of burr formation.

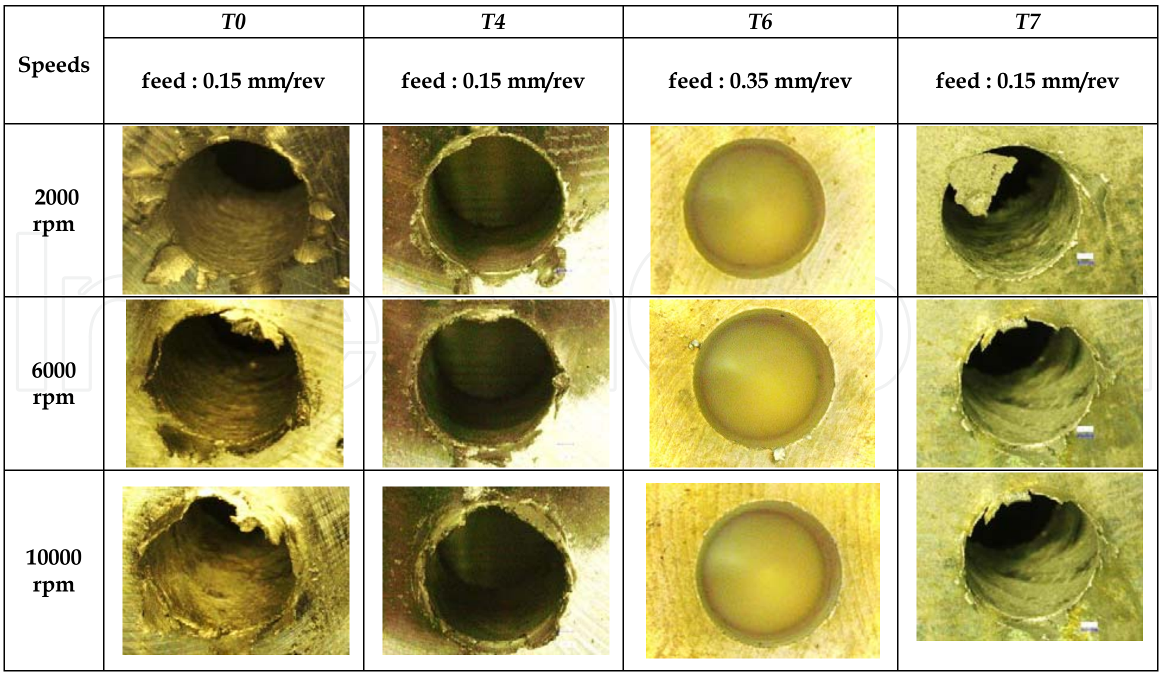


Figure 12. Influence of the heat treatments on the burr formation during the drilling of the A356 aluminum alloy with diffiren feed rate at (a) as-cast alloy condtion (T0), (b) T4 (c) T61 (d) T62 (e) T7 conditions

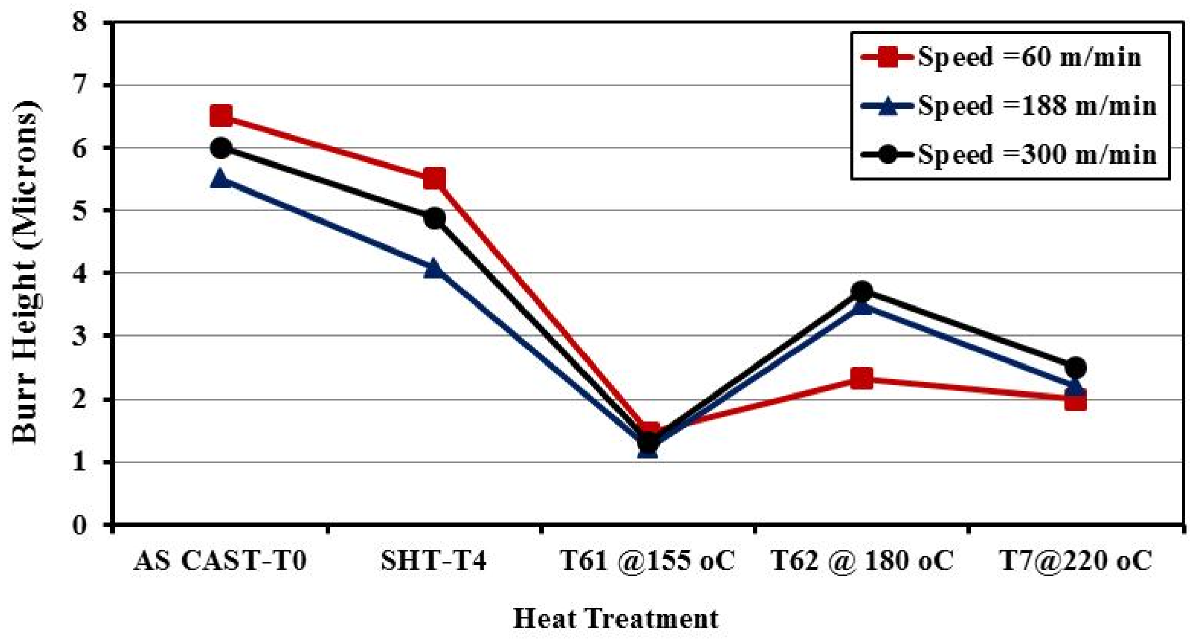


Figure 13. Influence of the heat treatments (T0, T4, T61, T62 and T7) and the cutting speed on the burr height during the dry drilling of the A356 alloy with feed rate 0.15 mm/rev.

6. Overview of deburring processes applicable to aluminium alloys

Burr removal is a non-value added process [3] and might represent as much as 30 percent of the cost of finished parts [2]. As deburring is non-productive and costly finishing process, it should be minimized or avoided. Any material leading to limited burr formation is therefore advantageous. Recent studies and literature have pointed out tremendous issues related to burr formation and deburring operations, including: [1] small finger injuries for assembly workers; [2] source of debris (bits of burrs) during operation, thereby reducing the life time of the machined part; [3] changing parts resistance and reduction of tool life and efficiency [44]; [4] presentation of hazard in handling of machined parts, which can interface with subsequent assembly operations ; and [5] the burrs that are adhered to the work part may become loose during operation, and consequently cause difficulties and damage.

Gillespie [2] has identified 122 deburring and edge finishing processes. To better select them, several classifications were proposed in [2, 15, 34]. The work of Gillespie [2] is the most complete work, encompassing all deburring methods, from manual deburring to high technology finishing systems using CNC and industrial robots. He [2] classified deburring processes under following categories of [1] Mechanical deburring processes; [2] Thermal deburring processes; [3] Chemical deburring processes and [4] Electrical deburring processes.

Mechanical deburring processes: During mechanical deburring processes, the burrs are reduced or removed by mechanical abrasion. This can be done manually, using abrasive, using a brush or a solid tool off-line or directly at the machine-tool station. Sometimes, a robot is also used. The overview of most highly used mechanical deburring methods on aluminum alloys will be presented in the following sections:

6.1. Manual deburring

Manual deburring is still known as the most widely used operation for many reasons, including extreme flexibility, low cost and lack of technology needed. According to [2], manual deburring is associated with wasting of time and asset, fatigue, frustration, etc. Moreover, in most of industrial sectors, manual deburring is implemented in dry conditions by non-qualified operators. This consequently increases the waste rate and delay in production lines.

6.2. Bonded-abrasive deburring

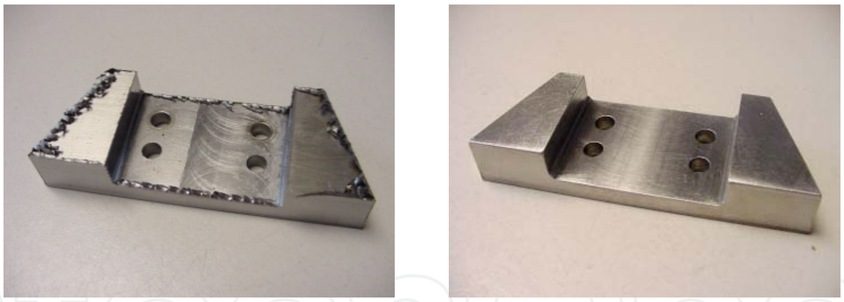
Bonded abrasive deburring *or sanding* is a versatile deburring technique which can be applied when heavy stock removal is intended. This method performs well in manual and automated operations that are used for deburring and surface smoothing. Many types of bonded abrasives are available for dry and lubricated deburring of aluminum alloys and metals work parts. The main benefits of bonded-abrasive deburring are low cost; large variety of models and great adaptability to manual or automatic equipment. On the other hand, the main disadvantages of this method include short life time, dust emission and new burrs, significant effects on residual stress and surface quality and lack of access to certain sides of the work part.

6.3. Brush deburring

The power driven brush tools have a wide range of applications in deburring, cleaning, descaling, polishing, edge blending and texturizing of the metal work parts. The brush deburring is considered as a fast, safe, simple, relatively inexpensive, and flexible deburring method, which could be also adaptable to manual or automatic equipment with little operator interference. The rotary action in brushing allows a great variety of driving motor and fixtures to be employed. The brush deburring involves several environmental, health and safety considerations, including particle and dust emission when using dry sanding of metal and plastic parts. The generation of new burr, new changes on the work part size, fatigue life and residual stress are the main disadvantages and side effects of brush deburring. As described in [2], brush deburring method is widely used for deburring of aluminum work parts, such as cylinder heads (see Figure 14). The main process variables involved in brush deburring include, brush style, brush design and materials, face width, coolant, brush rotational speed, burr size, burr location and work part material.

6.4. NC/CNC machining centers

Due to growing demands on higher production rate, improved quality and less labour and production cost, particular interest has been paid to use of NC/CNC machines for precise deburring and chamfering of holes, flat and curved surfaces. The NC/CNC machines can



(a) Before deburring (b) After deburring

Figure 14. Burr edges before (a) and after brush deburring(b) of AA 6061-T6 [71]

brush the machined parts by simply attaching the brushing tools (miniature or large scales) in a tool holder. It also allows the machine to change the tooling conditions and begins the cutting operations and simultaneously taking the advantage of over 1000 standard cutting tools, thus providing great flexibility. Other benefits of NC/CNC machines include prevention of repetitive motions in hand deburring, and lost time due to work-related injuries which may lead to a major cost saving in production line [2]. When using NC/CNC machines, it is also possible to pick up a movable water jet nozzle and traverse it around the machined part edges for deburring and edge finishing (see Figure 15). However this method can be used on the aluminum work parts which require reasonable but not complete burr removal [3]. A polishing/deburring machine is developed in [72], consisting of two subsystems. The first subsystem is a five-axis machine for tool/part motion control and the second subsystem is a compliant tool head for tool force control. Both subsystems are designed based on the tripod principle. According to experimental results, high precision automated polishing/deburring on aluminium work parts was observed. As pointed out in [3], NC/CNC machines may not produce high quality cast or forged surfaces. The main concerns when using NC/CNC machines are comprehensively presented in [2].

6.5. Robotic deburring

Robots can operate with no time limit; reproduce the same motions accurately; can process workpieces faster than humans; they can use heavier; higher-powered tools for faster finishing; they can work in hazardous; noisy and ergonomically unsuitable situations for humans. Robotic deburring is used to reduce the work load and guarantee an adequate workpiece quality level. Robotic applications fall into three general areas [1] simple-shape deburring and chamfering, [2] contouring and [3] sensor-controlled countering. A framework for robotic deburring applications in various industrial sectors was proposed in [73]. The use of robots for deburring operation was reported in [74, 75]. Robotic deburring of gearbox casting made from aluminum alloys is presented in [76]. In [77], an on-line industrial robot path generation method has been developed and implemented to generate robot paths for deburring cast aluminum wheels. This method could automatically generate six degree of freedom (DOF) tool paths for an accurate and efficient deburring process. Kazerooni [78] presented robotic deburring using tungsten cemented carbide rotary files. He introduced ro-

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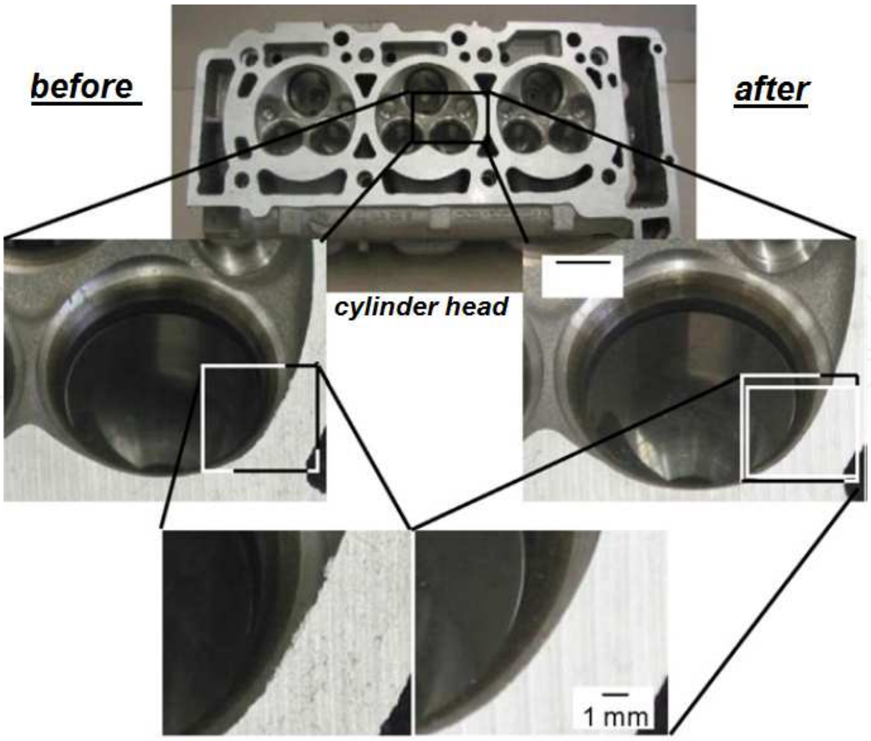

Figure 15. High pressure water jet deburring of aluminum cylinder heads [3]

bot-position uncertainties in deburring and a feed-back system working according to the prescribed controlled strategy. Experimental verifications on aluminum work parts have shown satisfactory results. Dornfeld [79] introduced the fundamental principles of acoustic emission (AE) applications in chamfering and deburring operations and verified his approach through experimental works on 6061-T6 aluminum alloys. Hirabayashi *et al.* [80] presented deburring robots equipped with force sensors for automatic deburring of elevator guide rails. The more widely used applications employ advanced robots that use five-axis compliant tools, capable to remove most, but not all burrs [2].

7. Conclusion

The development of aluminum alloys is often conditioned by aeronautical requirements, but still aluminum is considered as a suitable candidate for several applications in other sectors. However, through growing demands on part quality, functional performance and global competition, special attention has been paid to burr formation which appears to be one of the major troublesome impediments to machinability, part quality and high productivity of aluminium alloys.

In this chapter, overview of machining burr classifications and formation mechanisms as well as factors governing burr formation were presented. Furthermore, the effects of heat treatments on burr formation during drilling of aluminium alloys were presented, followed by introducing the most highly used mechanical deburring processes on aluminum work parts.

This work has led us to conclude that:

- There is a substantial need to reduce, prevent and eliminate burrs. Considering that the burr formation is inevitable phenomenon in machining operations, particular attention should be paid to burr control rather than burr avoidance. The main benefit would be to reduce the needs of deburring operations. However, using deburring operations in some cases is still mandatory.
- Most aluminium alloys, whether wroughts or casts, can experience burr formation during machining processes; The shape and the size of this burr will depend on the alloy composition and conditions, its mechanical properties, but also on type of machining operation, tooling used, machining parameters, and machining conditions and strategies. Using very low feed rates on a material with high ductility may generally lead to higher burr size.
- Development of simulation models of burr formation processes, coupled with advanced cutting force and temperature modeling algorithms, capable of indicating the interaction and dependencies of factors governing burr formation is suitable approach for better understating of factors governing each individual machining operation.
- The knowledge of each deburring method and the requirements of the finished products, in addition to burr size, mainly burr thickness are major parameters for correct selection of deburring method. For many cases, combination of several deburring processes is required to gain better results. Therefore, developing the links between burr sizes and deburring methods and deburring difficulty is a benefial approach for better selection of deburring methods, which infact reduce the non-desirable expenses.

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