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A review of modern advancements in micro drilling techniques

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Abstract

The demand for micro drilling with a diameter in a range of a few microns to several hundred microns is increasing in industries such as electronics, aerospace, medicine and automobiles, due to a significant uptake in the use of miniaturised products and devices. In order to satisfy the demand, a number of different micro drilling techniques have been developed. There has been, however, no report which explains, compares and contrasts all of these micro drilling techniques. This study examines the latest micro drilling methods and techniques, categorises them into different groups, highlights recent developments and new trends, and depicts the future requirements in the field of micro drilling. Both conventional and non-conventional micro drilling techniques used in modern age applications are categorized. Conventional micro drilling makes use of drill bits of different configurations such as twist, spade, D-shaped, single flute, compound drill and coated micro drill, while non-conventional micro drilling involves electrical, chemical, mechanical and thermal means which include laser, EDM, ECM, SACE, electron beam, ultrasonic vibration or combinations of these approaches. We present here, a comparative study of conventional and non-conventional micro drilling techniques in order to show the potential and versatility of various micro drilling methods.

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A REVIEW OF MODERN ADVANCEMENTS IN MICRO DRILLING TECHNIQUES

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ABSTRACT

The demand for micro drilling with a diameter in a range of a few microns to several hundred microns is increasing in industries such as electronics, aerospace, medicine and automobiles, due to a significant uptake in the use of miniaturised products and devices. In order to satisfy the demand, a number of different micro drilling techniques have been developed. There has been, however, no report which explains, compares and contrasts all of these micro drilling techniques. This study examines the latest micro drilling methods and techniques, categorises them into different groups, highlights recent developments and new trends, and depicts the future requirements in the field of micro drilling. Both conventional and non-conventional micro drilling techniques used in modern age applications are categorized. Conventional micro drilling makes use of drill bits of different configurations such as twist, spade, D-shaped, single flute, compound drill and coated micro drill, while non-conventional micro drilling involves electrical, chemical, mechanical and thermal means which include laser, EDM, ECM, SACE, electron beam, ultrasonic vibration or combinations of these approaches. We present here, a comparative study of conventional and non-conventional micro drilling techniques in order to show the potential and versatility of various micro drilling methods.

Keywords.

Micro drilling, Micro drill manufacturing technique, Conventional micro drilling, Non-conventional micro drilling.

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1 INTRODUCTION

Recently, the trend for producing miniaturised products and devices that are “smaller, faster and cheaper” [41] has become the main focus in industries such as electronics, aerospace, medicine and automobiles [13, 43, 44]. Miniaturised components such as PCB (printed circuit board), microscopic nozzles, micro dies and molds, chemical microreactors, tooth implantation, high-tech medical appliances, fuel filters and fuel ignition systems, are produced with the help of micro machining techniques [45–47]. Among those, micro drilling is one of the most fundamental micro machining techniques and is generally defined as the drilling of diameters between 1 μm and 1 mm. In line with the trend of miniaturisation, micro drilling is now being extensively used in areas such as precision engineering, micro-electro mechanical systems (MEMS), micro total analysis (μTAS), consumer products, biomedical and chemical engineering, optical displays, fluidics, wireless and optical communications, and PCB industries [45, 49–51]. Of all these industries, PCB makes the most use of micro drilling. As a key electronic component, a PCB requires hundreds, even thousands, of micro holes to connect the electronic parts according to a predetermined circuit design [52]. Driven by the continuously rising demand for smart phones, tablet computers and notebooks, digital cameras and video recorders, and other electronic devices, the PCB industry is growing very quickly worldwide. Research indicates that the PCB market is expected to grow with a compound annual growth rate (CAGR) of 4% over the period 2015–2020 [53–56].

While the products are becoming smaller, lighter, thinner, more multi-functional and higher density, there is a requirement for more lines and holes in a limited space, along with improved quality of holes. To achieve this goal, various researchers have been working to improve the performance of micro drilling in a wide range of areas including different manufacturing methods, fabrication materials used [57], shape and mechanical properties of micro drill [58–60], accuracy and quality of holes, inspection mechanisms [61–63], machine operating conditions (i.e. cutting speed, cutting load, and coolant), chip formation and removal process [64], heat generation [65], and coated micro drill. In particular, a number of different traditional as well as non-traditional micro drilling techniques have been employed to satisfy the ongoing demand for micro drilling based on the type of application, dimensional precision requirement, hole wall surface quality and speed of production. Each of these micro drilling techniques has its advantages and disadvantages, but so far no single study in the literature reviews, compares and contrasts the advantages and disadvantages of all these technologies.

The survey described in Rajan et al. [66] is limited to three micro drilling techniques: mechanical micro drilling, electro discharge machining (EDM) and laser micro drilling. Sen et al. [6] reviewed only the electrochemical machining (ECM) micro drilling techniques including electrochemical drilling (ECD), acid based ECM drilling processes, shaped tube electrolytic machining (STEM), capillary drilling (CD), electro-stream drilling (ESD), and jet electrolytic drilling (JED). They also compared EDM (electro discharge machining) micro drilling, laser micro drilling and various processes of ECM micro drilling, however, the comparison is limited only to a few non-conventional micro drilling techniques. Zheng et al. [67] reviewed micro drilling in PCB industries, including tool materials and geometries, thrust force and torque, damage and breakage of micro drilling. They mentioned several micro drilling techniques

such as EDM, vibration and laser drilling. Discussion on other drilling techniques, however, is limited. Kim et al. [68] reported on the manufacturing process of mechanical micro drills. They also covered various aspects of micro drilling that include the importance of micro drilling in the 21st century, shape design, and the longevity and cutting ability of a micro drill, but their paper only explains the features of mechanical micro drilling. All these previous works deal only with a few micro drilling techniques, and do not provide a clear overview of all available micro drilling techniques.

In this paper all the available micro drilling technologies are reviewed. It will first provide a chronological description of micro drill evolution and then explain the fundamental concepts of micro drilling, thus clarifying the ambiguity regarding the definition of micro drilling, geometrical attributes of a micro drill, advancements in materials used for micro drilling, and the manufacturing techniques of the most commercially available twist type micro drill. The review then surveys state-of-the-art micro drilling techniques and methods; classifies them into different groups; highlights recent advancements and ongoing new trends; illustrates future requirements, and sets out the existing shortcomings and provides recommendations to overcome these. The available micro drilling techniques are broadly classified into two groups, conventional and non-conventional. Conventional micro drilling makes use of drill bits of different configurations such as twist, spade, D-shaped, single flute, compound drill and coated micro drill. Non-conventional micro drilling involves electrical, chemical, mechanical and thermal means which include laser, EDM, ECM, SACE, electron beam, ultrasonic vibration and combinations of these approaches. A detailed comparison table is included at the end of both the conventional and non-conventional micro drilling techniques to compare the features of the different techniques along with their advantages and disadvantages.

2 MICRO DRILLING TECHNIQUES

2.1 Classification of micro drilling techniques

As broadly classified in this paper, micro drilling operation is performed in two ways, conventional and non-conventional. The conventional technique refers to micro holing where a drill bit is mounted on the spindle and rotates at high speed, goes through the workpiece and makes the micro hole. There are various types of micro drills depending on their shape and configuration can be seen below. The details of these types are discussed in subsequent sections.

Conventional micro drilling techniques:

- a. Twist type; (section 4.1)
- b. Spade; (section 4.2)
- c. D-shaped; (section 4.3)
- d. Single flute; (section 4.4)
- e. Compound tool micro drilling, and (section 4.5)
- f. Coated micro drill (section 4.6)

Non-conventional micro drilling, on the other hand, is comparatively new and is also being extensively used in many modern applications. Unlike the conventional way of using a drill bit, the non-

conventional micro drilling technique involves various means of electrical, chemical, mechanical, thermal operation and/or a combination of these processes. The non-conventional methods which are commonly used in modern applications can be summarised as follows. The detail of each category is explained in subsequent sections.

Non-Conventional micro drilling techniques:

- a. Laser; (section 5.1)
- b. EDM; (section 5.2)
- c. ECM; (section 5.3)
- d. SACE; (section 5.4)
- e. Electron beam; (section 5.5) and
- f. Ultrasonic Vibration (section 5.6)

2.2 History of micro drilling

Drilling, as one of the most commonly used machining techniques, has been used since ancient Egyptian times. Studies reveal that 25% of manufacturing time is involved in drilling processes [69]. It is estimated that approximately 250 million drill bits are used annually in the U.S. industry alone [69]. Needs for micro drilling were first realised in the 1940s [70] and afterwards attempts have been made to produce high quality micro drills. In 1958, Levin [71] produced a drilled hole as small as 0.015 mm with the help of an instrument lathe, which could be the first attempt to perform micro drilling. Between, 1960–1970 a limited number of works on micro range drilling were undertaken typically in Japan and the USA [72, 73]. The next decade can be seen as the commencement of micro drilling in the arena of both conventional as well as non-conventional micro drilling. Several different research experiments were carried out during period with, however, their scope was limited. Twist and spade type drills made of high speed steel and carbide materials were usually prepared by grinding and mostly used to drill holes with the size down to 0.025 mm. Lathes were used as the drilling machine resulting in an inadequate spindle speed. The work pieces at this time were limited to brass, steel, copper, stainless steel, gold, and plastics. Some theoretical investigations such as torque and thrust analysis in micro drilling were also conducted. Among the non-conventional approaches, only laser drilling was noticed in this decade [74–77]. In 1980, Sugawara [78] discussed different parameters of micro drilling including shape of the drill, feed rate, cutting speed, workpiece structure, chip formation and cutting forces. The work of Iwata et al. [79] published in 1981 reported a high speed steel micro deep drilling with the speed as high as 18000 rpm. From the late 1980s, the demand for making tiny holes has increased in order to cope with the large production of printed circuit moulds with the introduction of CNC (computer numerical control) and since then, there has been an innovative evolution of micro drilling with the purpose of meeting the continuously growing industrial demand in various sectors.

Non-conventional micro drilling, on the other hand, is comparatively newer approach than conventional. Among all the non-conventional techniques laser micro drilling was noticed to be utilized

in the decade of 1970s [75–77, 80]. Most laser drilling in this period were based on long pulse CO₂ and YAG laser system. In these systems material removal takes place by melt expulsion, which leads to poor dimensional accuracy and micro cracks on the wall of drilled holes. These drawbacks led to a limited usage of these technology. In the next decade, some of the drawbacks were solved by the advancement of low-power waveguide excimer lasers and frequency quadrupled Nd-YAG lasers [81–83], however, were limited to non-metallic materials and larger diameter of the holes. In this period some other non-conventional micro drilling technique such as EDM was reported to be used for micro drilling. In 1986, Kagaya et al. [84] has successfully examined EDM micro drilling on a variety of materials including S45C, SUS304, Cu, Bs, Pb and achieved micro holes as small as 0.17 mm in diameter with aspect ratio of 10–17. Between, 1990–2000 along with laser and EDM, micro drilling by means of ECM and ultrasonic vibration were also reported, however, with limited use [85–87]. Laser micro drilling, in this decade, were more focused on high precision and high aspect ratio micro drilling. Excimer laser based drilling on polymers and PCBs were reported to be popular among the researchers in this period [83, 88–90], while facing ongoing problems of micro drilling in metals. In 1999, Lazare [91] introduced UV laser based micro drilling and achieved aspect ratio as high as $\Phi/d \approx 600$, in a variety of materials including PMMA, PC, PET, PI, PS and PEEK. For micro drilling on metals, a number of attempts were made at the end of 1990s. Zhu et al. [92] investigated micro drilling of metal foils such as Al, Mo, Ti, Cu, Ag, Au and brass using femtosecond Ti: sapphire laser pulses. From 2000 onward not only laser micro drilling was reported to be widely used in industries on almost all types of materials including metals, but also all other types of non-conventional micro drilling techniques that include EDM, EDM, BE, SACE and ultrasonic vibration. Though the technology of BE and SACE were invented in 1952 and 1968 respectively, but their usage in order of micro drilling is reported from early of 21st century [73, 93].

2.3 Fundamental concepts of micro drilling

2.3.1 Definition

One of the basic operations of industrial machining is “drilling” i.e. making a hole inside the component. When the component becomes smaller and smaller, the hole size required eventually decreases to only a few microns. Hence the use of the term “micro drilling” is initiated, which is also known as miniaturised drill, micro perforation, small diameter drilling technology, micro hole drilling, making tiny holes, and micro hole machining.

The definition of micro drilling depends on the diameter of the hole. There is no specific standard to define micro drilling. Different researchers and manufacturers define micro drilling differently. Sphinx, the Swiss micro drill manufacturer, defined micro drilling as having a starting diameter of 0.05 mm and ranging to 2.5 mm [94]. Zhuang [28] defined a micro drill bit with a diameter less than 3.175 mm. Tibar et al. [95] defined micro drills as having a diameter less than 1mm. Kudla in [23, 96–98] defined micro drill with a diameter less than 500 μm and in some other articles Kudla et al. [20, 99–101] referred to a micro drill with a diameter less than 1 mm. According to Kondo et al. [102] the diameter

of micro drills is less 1 mm. Robertson [103] stated that tooling suppliers defined a micro drill as being 1 mm in diameter. Zheng et al. [104] reported that the diameter of microdrills is generally between 0.03–1mm. Abouridouane et al. [105] stated the diameter of drill in a micro range falls between $d = 50\ \mu\text{m}$ and 1 mm.

We can see from the literature that the definition of micro drilling varies greatly between manufacturers and researchers. This creates confusion and arguments. It is beneficial, therefore, to follow a general definition in order to avoid the ambiguity among different opinions. It will facilitate to be more specific and help to distinguish between macro and micro drilling. Based on this study, a drill bit or a tiny hole can be termed as micro drilling if its diameter equals or below 1 mm. Due to the so called size effects, the physical appearance or the geometry of the drills are generally changed when the diameter of a micro drill is equal to or below 1 mm, in terms of nonappearance of steps in the margin, margin allowance, web thickness etc. as depicted in subsequent section. In addition, micro drills with diameter of 1 mm or below 1mm commonly suffer by the problem of breakage, while the drills with larger diameter is subject to wear out before any breakage occurs. Hence, a definition that can distinguish the changes of these features is helpful. The definition of micro drilling, however, is found not to be that much useful in some of non-conventional micro drilling such as laser and electron beam, since these technologies are mostly employed for a range of few tens of microns, but important for other types of non-conventional micro drilling such as EDM, ECM and ultrasonic vibration. When the hole diameter requirement is 1 mm or below 1 mm, the system is suffered by size effects which eventually needs special consideration of operating parameters, machine arrangements and precision and production rate.

2.3.2 Geometry of the micro drill

The majority of micro holing operations are performed by a twist type of micro drill. The life of such miniaturised drills is quite unpredictable. It has been observed that micro drills frequently break down before they wear out [99]. This is mainly because of the relatively great load on the drill compared to its strength. Even a slight change in processing parameters or increase in forces can cause catastrophic destruction of these fragile tools. This means that, selection of appropriate parameters including tool material, shape and geometry, and lubrication is of great importance in order to obtain satisfactory performance of the micro drill.

The geometry of a drill bit greatly affects the way it behaves during drilling. The influence of the shape and the geometry of a micro drill have been investigated by many researchers [49, 101, 106, 107]. Considering the differences in cross-sectional profiles of miniaturised twist drills, they can be classified into three main groups. The first group of drills with a diameter range of $0.5\ \text{mm} < d < 1\ \text{mm}$, is similar in shape to normal range drills. The only variation is the absence of the step in margin forming undercut. The second group of drills ranges between $0.2\ \text{mm} < d < 0.5\ \text{mm}$ in diameter, and is characterised by the nonappearance of the margin (the whole land surface is of the same diameter) and gradual enlargement of the web. The third group of drills have diameters less than 0.2 mm with a reinforced shank, in which the relative web thickness is considerably larger than that in the other

groups [99]. The geometric attributes of a microdrill were explained by Coombs [1] in 2007, as shown in Fig. 1. It can be seen that the land is the area remained after fluting. With the aim of reducing the amount of land that generates friction with the hole-wall (thus creating heat), drill bits are basically margin relieved. This means that the amount of land that remains in contact with hole-wall at the time of drilling is called the margin.

The broader the margin, the bigger the friction area and the greater the drilling temperature, causing higher extents of heat-related micro perforation quality faults for instance smear and plowing.

Fig. 1 Typical geometry of a micro drill [1-3]

The consequence of increasing land and web is a less in the flute area. Small flute space infers shorter amounts of available area to take away drilling chips, which subsequently increases drilling temperature as well. Another key issue is flute length which is measured by the depth of the drilled hole. Flute length is, in fact, a determining factor for the measurement of the stiffness of rigidity. Higher rigidity which comes with shorter flute length, offers perforation operation with more stability and enhanced tool life. Point angle determines the sharpness of the micro drill, and is also an important factor, particularly as it plays a significant role in the beginning of the micro drilling. It has effects on thrust force, torque, and cutting edge, which eventually determines the size of the chips produced. Wong et al. [108] discovered that with the proper point angle, the thrust force generated during drilling can be minimised and position error can be avoided. Heinemann et al. [109] have conducted several experiments to study the optimised point angle of the micro drill and found that point angles B (120°) and C (130°) have better performance in terms of higher tool life. According to tool manufacturers, however, an angle of 90° is frequently used in soft materials, while for harder material it ranges from 120° to 130° . Another important factor that greatly influences the performance of micro perforation is the helix angle as shown in Fig. 1. This is determined by the number of flutes, flute

clearance, web thickness and flute style. The most commonly used helix angle is 30°. Therefore a careful design is very important in order to avoid breakage and achieve higher performance.

2.3.3 Materials of micro drills

The latest developments in material science and manufacturing technologies have strongly augmented the freedom that a tool designer can enjoy when designing cutting tools and materials. By means of controlling material distribution at micro and nano-scale, metamaterials can be designed which can have extraordinary properties such as negative elastic modulus, electromagnetic and acoustic band gaps or super-hydrophobic surfaces. In similar manner, through powder metallurgy, alloys with refined grains can be manufactured with superior properties for instance high hardness, rigidity, and wear resistance at elevated temperatures. In this section the materials that are used for manufacturing micro drills and their cutting edge advances are described.

2.3.3.1 Tool material properties for modern micro drilling applications

During perforation, micro drills rotate at tremendously high speed and consequently friction causes very high temperatures. In addition, the chips formed during machining result in high stress on the cutting edges of the drill. These eventually lead to fatigue and subsequent breakage of micro drill. For this reason, selection of a suitable material for micro drill is crucial. For successful micro perforation, the drill materials must have following properties:

- Adequate material hardness, in order to withstand the cutting force at the tool/specimen interface and high temperature at the chip/tool interface.
- Excellent wear resistance, in order to avoid tool wear and extend tool life.
- Sufficient rigidity and toughness to prevent tool fracture and breakage.

The current trend in the market, is to produce near-net-shape workpieces which decreases the requirement of post drilling operations. Progressively high surface integrity and close-dimensional tolerance are essential to ensure that tools have lower wear as well as much tighter specification of tool dimensions. Another aspect that will need to be considered in future is the consistency of the micro drill performance, particularly in unmanned machining conditions.

2.3.3.2 Materials used for manufacturing modern micro drills

A wide variety of materials and alloys are used in macro scale drilling, but there is still a limited choice for micro drilling. Currently, the most common and commercially available micro drill materials include; tungsten carbides (WC), high speed steel (HSS), cermet, and polycrystalline diamond (PCD). Among them, WC and HSS are most widely used due to their favorable price to quality ratio [28].

2.3.3.2.1 Carbides

Sintered carbide tools, also known as hard metal tools or cemented carbide tools are made by a mixture of fine-grained tungsten carbide with cobalt at high temperature and pressure. Tantalum, titanium or vanadium carbides can also be mixed in small proportions. Carbides which refers to alloys, made with

the help of powder metallurgy methods are usually the best choice for a drill material. Cobalt (Co) is normally added as a binding element in the range of 6–15% by mass. WC is the main choice for manufacturing micro drills [110, 111], and is extensively used. The reason for the widespread usage of WC is its excellent material properties. Tungsten carbide is approximately two times stiffer than steel, with a Young's modulus in the range of 530–700 GPa. It has a high melting point at 2,870 °C (5,200 °F), and a boiling point of 6,000 °C (10,830 °F). WC is an extremely hard material, ranking about 9 on Mohs scale, and with a Vickers hardness value of around 2600. It has excellent wear resistance, higher rigidity (2 to 3 times higher than steel), very low coefficient of thermal expansion, and higher rupture strength. Because of these superior mechanical and thermal properties, WC micro drills provide higher cutting force (2–3 times higher than that of high speed steel), enhanced positional and dimensional accuracy, improved surface finish and increased production rate (4–12 times faster). These inherent properties lead to widespread usage of WC micro drills [112–114].

Despite these excellent material characteristics, WC micro drills also have some limitations. The necessity of precise machining conditions, high power consumption, reduced strength, and decreased fracture toughness are a few of these. The major drawback of WC micro drills, however, is their short tool life. Unlike macro drills, micro drills frequently break down before they wear out [68, 109]. This abridged tool life is due to the brittleness of WC in drilling. Since WC is very hard and brittle, it breaks down with even a tiny distortion. An excessive thrust force, imprecise alignment of machine and tools, inaccurate operational conditions, failure to remove chips, and inappropriate drill geometric parameters are the main reasons which cause buckling or deformation of the drill and which eventually cause micro drills to be broken down during drilling. This breaking down of the tool in the middle of operation is highly undesirable as it not only causes loss of the tool but also the workpiece. It also consumes extra labor and time. On the other hand, WC micro drills are expensive. A WC micro drill is 3–5 times more expensive than that of HSS. As industries in the modern age are highly concerned about the production cost, it is necessary to find a way to reduce the material cost as well as increase the tool life.

The focus in future can be given to the production of nano-sized WC powder down to 10 nm as well as the method of sintering and grain growth of nanocrystalline WC. Refined grain size of the WC leads to an increase in hardness, wear resistance and rigidity. The details of the development of nanocrystalline WC can be found in [115]. Other possibilities, in order to save the cost of using expensive WC and increase tool life, can be investigated in order to develop a composite micro drill. Two layers of materials can be used, the low cost inner core material will provide higher strength to withstand cutting force as well as reducing the material cost significantly and the outer sleeve material will perform the cutting action with excellent wear resistance, superior hardness and higher cutting speed [116, 117].

2.3.3.2.2 High Speed Steel

In addition to WC, HSS is also the preferred choice by many manufacturers because of its improved tool life and reduced cost. HSS is basically a high-content carbon steels containing a high proportion of alloy

elements like molybdenum (Mo), tungsten (W), vanadium (V) chromium (Cr) and cobalt (Co). In order to attain various mechanical properties, the amount of alloying elements is usually controlled and combined in a set amount. This can increase the hardness of the tool material and will allow the micro drill to last longer at high temperature. The major limitations of HSS include poor wear resistance, low hardness and a limited maximum working temperature of 500°C. There are a wide variety of HSS assigned names by American Iron and Steel Institute (AISI), but few of them are used for making micro drills. M1, and M2 and M7 are mainly used for cutting materials like carbon steel, aluminum and brass. The added cobalt in M35 and M42 creates better thermal properties than regular HSS, thus making it a better option for cutting harder materials [28, 111, 113].

Currently, HSS produced by powder metallurgy (known as HSS-PM), offers a high wear resistance, high toughness, and hardness. There is a recent trend towards making super high speed steel, termed as HSS-E. The powder metallurgy produced HSS-E-PM steel, containing cobalt alloy, gives a very homogeneous structure that has a direct positive effect on the consistently high performance capability of the micro precision drills. In future HSS-E-PM can be a good choice for manufacturing micro drills, but much research is needed in order to find the best way to acquire the desired properties. An exciting innovation would be to develop an HSS containing carbide alloy, which combines the advantages of HSS, flexibility for instance, with the advantages of carbides, for instance dimensional precision[118-120].

3 The manufacturing technique of twist type micro drill

Many researchers find it difficult to understand the process of manufacturing micro drills due to the dearth of articles which explain it in a simple way. Hence the manufacturing method using a twist type micro drill is presented schematically step by step. Fabrication of micro drills is performed with the application of abrasive machining techniques in the form of fine grinding. Special types of machine tools, precise measurement systems and ultra-fine grinding wheels are common requirements for fabricating small size micro drills. Fig. 2 shows a typical illustration of an abrasive grinding wheel used to grind the micro drills.

Fig. 2 Abrasive Grinding set-up for micro drill [23]

Manufacturing steps that are commonly followed to fabricate a micro drill is listed as follow.

Manufacturing steps of micro drill.

1. Cutting of rod for section
2. Center-less grinding of outer diameter
3. Profile grinding (Preliminary shaping of cutting part)
4. Point angle grinding (grinding of conical tip)
5. Taper grinding (Shaping of cutting part)
6. Final grinding of cutting part
7. Grinding of twisted grooves and margin (Making flutes and margin clearance)
8. Sharpening of cutting edges
9. Cleansing (remove dust and oil)
10. Inspection (dimension measurement)

Fig. 3 depicts the graphical representation of the manufacturing steps of micro drill. The WC rod, which is made from powder metallurgy, is cut into pieces with the desired dimensions as shown in Fig. 3-a. Centerless grinding is performed to shape the outer diameter of the blank rod as shown in Fig. 3-b. Profile grinding removes the burrs that might have been created during cutting at cross section of the blank rod, as shown in Fig. 3-c. At this stage chamfering is done at one end of the rod. The angle of the chamfering varies between 45 to 60°, depending on the manufacturers design. To create the drill point, point angle grinding is conducted in step-4 as seen in Fig. 3-d. Usually 120° point angle is made based on the design. The next step is to create the cutting part which is also known as body length. A taper grinding wheel is employed to the grind cut part, as can be seen in Fig. 3-e. As the cutting part needs to be very precise, a special type of ultra-fine grinding wheel is required. As shown in Fig. 3-f final grinding is done with the help of fine grinding wheel. In the next step flutes are made. Fig. 3-g shows the grinding of twisted -

Fig. 3 Manufacturing process of micro drill

grooves as well as margin. In Fig. 3-h sharpening of edges in flank area is performed in order to create cutting edges of micro drill. Four flank surfaces are normally made in a planar type twist micro drill. To remove oil and dust, the micro drills produced are passed through a cleaning process, as shown Fig. 3.-i. After cleaning, inspection is conducted to measure the dimensions.

The major limitation of this manufacturing technique is the long time required. Because of many steps required, it takes a long time to manufacture a single micro drill, causing the production rate to be small and requiring higher labor cost. It also requires a number of machines, the operation and maintenance of which is expensive. Therefore, development of an innovative manufacturing method of the micro drill could reduce the cost for both manufacturers and users. One way of doing this could be to use a forming method instead of abrasive machining. The micro-manufacturing process could involve a direct powder solidification extrusion forming technology, which simultaneously solidifies the powder as well as gives the final shape of the product. The micro die could be designed with a negative replica of the micro drill, and then passed through a forming process such as extrusion at the proper temperature and pressure. Successful research would reduce the costs from buying a rod and cutting into pieces to all different grinding steps. It has the potential to eliminate the expensive machines set up as well as save labor cost.

4 Advancements in conventional micro drilling

With the advancement in today's grinding techniques, it is possible to manufacture micro drills with a diameter smaller than a human hair. A record of making spade type micro drills with a diameter of $d=2.5\ \mu\text{m}$ was reported by National Jet Co. [18] using an ultra-precision abrasive technique. Another great achievement was Nisshin Seisakusho Tools [121] making a twist type micro drill of $d=10\mu\text{m}$. To meet the current demand, not only the size of the micro drill but also a wide range of other parameters are being studied in order to enhance the performance of micro drills. In commercial manufacturing companies the focus is mainly on the size, shape and materials of the micro drill, while researchers attention falls on the investigation of mechanical properties [99, 122], simulation and numerical analysis [58, 123], micro drill parameter optimisation [50, 124], surface texture of drills [69, 125], chip formation analysis [28, 64], lubrication methods [126, 127], inspection mechanisms [128, 129], re-sharpening processes [130, 131], perforation techniques in different types of specimen [132, 133], effects of coating [134, 135] and prevention of tool breakage [95, 136].

Mechanical strength of a micro drill is often insufficient due to large load compared to its strength and thus frequently break down before they wear out. During machining a drill is loaded with a torque, T , feed force F_f and radial F_r force. Improper realization of these forces could cause torsional deflection and elongation of the cutting part; compression and angular deflection; buckling and bending

deflection and eventually result to the failure of the drill. Therefore, a precise assessment of mechanical properties of micro drills is essential to reduce the chance of breakage [99, 122]. Manufacturing the micro drill and optimize the design parameters by trial and error method is time consuming and expensive. Many researchers, therefore, choose an analytical way to examine the stress distributions that develop in the drills during operation and optimize the geometry by minimizing the stresses. Finite Element Methods are widely used in order to simulate the model and predict the best choices of the geometry [58, 123]. For the sake of enhanced efficiency, there are a number of operational parameters such as spindle speed, feed rate, and precision of alignment, holding the micro drill in the spindle, coolant used and peck drilling, which can considerably affect the outcome of micro drilling. Understanding the effects of these parameters and applying them accurately during machining is necessary to optimize the drilling performance [50, 124]. Along with mechanical, the tribological properties and surface texture of a micro drill have a significant effect on the characteristics and performance of such drills. To improve the efficiency, adequate cares must be taken to produce a micro drill of smoother surface, sharp and burr-free edges. Surface texture, to a great extent, depends on different makes; the grinding technology and precision they use, this also leads to the efficiency and price of a micro drill [69, 125]. Lubrication is important to improve the cutting efficiency and drive away generated heat during operation and thus extend the tool life. Many researches have examined the effects of lubrication or metal working fluid (MPF) [126, 127, 137]. Since lubrication and MWF are concerned regarding the hazardous effect on environment and worker's health, many researchers are reported to focus on environment-friendly lubrication, compressed air lubrication, minimum quantity lubrication (MQL), nano-fluid MQL and so on [126, 127, 137]. When a micro drill breaks in the workpiece, it is not only difficult to take out the drill but also the workpiece is wasted. Therefore, changing the micro drill in advance is crucial in order to continue the production and eliminate such demurrage. To know the exact time of changing, however, is very difficult. A number of different techniques and approaches are reported to monitor the drilling operation or the condition of drill bit, that include monitoring of drilling torques, machine-vision assisted drilling condition inspection, optical inspection of drill point defects, and laser inspection of outer diameter run out [138–141]. With the trend of miniaturization, micro holes are required in a wide variety of products made of various different types of materials such as hard to soft metals, glasses, ceramics, polymers, PCBs, wood and stones. With the change of material properties, the machining condition and the requirement of drill properties also change. A substantial amount of work focusing the micro drilling phenomena on different types of materials are reported by many researchers [142–145].

4.1 Twist type micro drilling

There are various kinds of micro drills available on the market, as mentioned in the classification section. The three most popular types are: the twist, the flat and the D-shaped. Among these twist type micro drill has the most intricate, however also the most advantageous shape of the cutting part. In terms of application, this type of micro drill has the highest proportion of market demand. Flat type micro drills are the simplest and D-shaped micro drill is also much simpler than twist. Therefore, flat and D-shaped micro drills are very easy to manufacture, though their cutting properties are very limited and this leads them to be used in only a small number of applications.

The advancement of fabrication of ultra-small twist type micro drills is an ongoing process. Researchers particularly manufacturers are continuously improving the performance of micro drill while reducing

their size. In terms of miniaturisation the latest attainment is to fabricate a twist type micro with a diameter of $10\mu\text{m}$ by NS Tools [121]. Refined nano-grain WC powder was used as a micro drill material. The standard flute length achieved was approximately $10d$. The microscopic images are depicted by [21] and shown in Fig. 4.

Fig. 4 Ultra small twist micro drill, $d=10\mu\text{m}$, standard $l=10d$, made of WC [21]

Another achievement obtained by ATOM [146] is to fabricate a twist type micro drill of $d=20\mu\text{m}$. The drill is suitable for a wide range of work piece materials such as carbon steel, alloy steel, titanium, resin and aluminum. The standard flute length of micro drill is applicable, $l=10d$. MPK KEMMER [19] has produced a micro drill of $30\mu\text{m}$ of WC micro-grains. This tool is basically devoted to PCB perforation. SEM observation of such a small micro drill is presented in Fig. 5.

Fig. 5 Twist micro drill ($d=30\mu\text{m}$), made of micro-grain WC [19]

The

advantages offered by twist type of micro drills include high production rate, availability in the market, better dimensional accuracy and the most popular way of micro drilling. As shown in Fig. 6(a) and (c), micro holes produced by twist type of micro drill (material: Inconel 718) is of better quality compared to laser as mentioned in Fig. 6 (b) in terms of hole straightness and wall surface quality. The drawbacks of the twist type of micro drill are short tool life due to tendency of frequent tool breakage and limited diameter range. Fig. 6 (c) shows the uniformity of holes produced by twist micro drill of $500\mu\text{m}$ as well as an example of the effect of hole condition when a breakage of tool happens [25]. Usually twist types of micro drills break down before they wear out. Since the diameter ranges in few tens of microns, the drills cannot provide adequate mechanical strength to withstand the cutting force. A number of researchers have figured out the reasons for such breakage and how to improve the tool life of

miniature drills as well as prevent tool breakage [147–149]. The factors that affect micro drilling performance and improper application of which may induce tool breakage, include geometry or shape of the drill, tool point angle, helix angle, chip formation and removal, coolant used, starting hole or spot drilling, cutting conditions (spindle speed and feed rate), and neck drilling [127, 150, 151]. Optimal

Fig. 6 Micro holes in Inconel 718 material. a) Micro holes by twist type of micro drill [32], b) Micro holes by laser [32], c) Uniform micro holes and holes with tool breakage [25].

4.2 Spade type micro drilling

The tiniest kind of micro drill is the spade type. When the diameter of the drilled hole is less than 10 μm , the twist type micro drill is no longer capable of performing the task due to manufacturing difficulty of such small type twist micro drill. Spade type micro drills are used in that case though their cutting ability is more limited than twist type. Spade type of micro drill does not have helical flutes, making it difficult to remove the chips and that is the main reason for the poor cutting property of spade type of micro drills. The other problem is the absence of an end point. The end of the smallest micro drills is comprised of a cutting edge, which is called the chisel edge, formed by two primary intersecting planes of micro drills. This drawback, however, is also encountered in the smallest type twist of micro drills. The general geometry of spade type of micro drills is presented in Fig. 7-a, [34]. The cutting part of a spade type of micro drill of $d=12.5 \mu\text{m}$ is shown in Fig. 7-b, [21].

Fig. 7 Spade type of micro drill, (a) schematic of general geometry, and (b) cutting part of spade type of micro drill, $d=12.5\ \mu\text{m}$ [21, 34].

The latest innovation reported is to fabricate a spade type of micro drill with a diameter as small as $d=2.5\ \mu\text{m}$ by National Jet [18]. They are also able to make holes of a diameter of approximately $d=30\ \mu\text{m}$ inside a human hair of approximately $d = 70\ \mu\text{m}$, as shown in Fig. 8(a). To produce a micro hole with a diameter less than $10\ \mu\text{m}$, a spade type of micro drill can be a good alternative. Fig. 8 (b-c), represents another example of spade type of micro drill of $300\ \mu\text{m}$ diameter and micro holes made in SiC plate as reported by Ohnisi et al. [40]. They have investigated the performance of such spade type of micro drill in various operating conditions and attained good shapes of the hole under all conditions, however, they observed large chipping around the hole entrance and poor surface roughness of hole wall at high feed condition. Due to the simplicity of manufacturing, the cost of a spade type of micro drill is cheaper than that of a twist type of micro drill. Unfortunately, less attention has been paid to the industrialization of this product. A limited number of research works has been reported as well. Since the current industrial demand is continuously moving towards making tiny holes, further investigation in developing the

Fig. 8 Example of micro holes by spade micro drill a) Micro drilling inside human hair by National Jet [18], b) Spade type of micro drill of $300\ \mu\text{m}$ diameter [3, 40], c) micro holes produced by spade micro drills [40]

4.3 D-shaped micro drilling

Another type of micro drill is D-shaped (also known as half round micro drill [21, 152]). Typically D-shaped micro drills are used for micro perforation of less than $50\ \mu\text{m}$ in diameter. The geometry of the D-shaped micro drill is presented in Fig. 9 [153]. The contour is semi-cylindrical with one straight flute. The advantages of this type of micro drill include manufacturing simplicity and smaller diameter, however, their cutting performance is limited by poor chips removal [21, 152].

Fig. 9 Geometry of D-shaped micro drills [30].

Fig. 10 SEM image of 17 μ m diameter D-shaped micro drill, a) overview, b) close up view with clearance angle 20° and cutting edge radius 0.5 μ m [3, 13].

Fig. 11 Micro holes by D-shaped micro drill, a) micro-hole of 6.7 μ m diameter and 10 μ m depth, (feed rate 0.03 μ m/s) b) micro-hole of 10 μ m of diameter and 20 μ m depth (feed rate 0.05 μ m/s), c) micro-hole of 22 μ m and 90 μ m depth (feed rate 0.1 μ m/s) [13].

Egashira et al. [13] fabricated a D-shaped micro drill of 17 μ m in diameter by means of a micro-EDM machine equipped with Wire Electro Discharge Grinding (WEDG). With the help of this micro drill they were able to machine a micro hole on the silicon board. The micro drill has a 300 μ m shank made from cemented carbide material of 0.3 μ m grain size. The clearance angle and the cutting edge radius are approximately 20° and 0.5 μ m, respectively. The tool length is determined by the depth of the hole to be drilled with an additional length of about 10 μ m. SEM micro graph of the 17 μ m diameter micro drill is presented in Fig. 10 (a). Fig. 10 (b) presents the close up view parallel to the cutting edge with clearance angle of 20° and cutting edge radius of 0.5 μ m. They have fabricated some other sized of D-shaped micro drills with various lengths, however, the smallest achievement was to manufacture a micro drill of as tiny as of 6 μ m in diameter and 10 μ m in length. Fig. 11 (a) – (c) shows example of holes produced by D-shaped micro drill of diameters 6.7 μ m, 10 μ m and 20 μ m respectively at different depth of cut and feed ratio.

Like spade type micro drills, D-shaped micro drills are also not as popular as twist type micro drills. Very limited research has been reported which investigates the suitability of this type of micro drills. Considering the promising advantages that D-shaped type micro drills offer such as ease of manufacturing, small diameter and low cost, this is an area worthy of more investigation.

4.4 Single flute micro drilling

Conventional micro drills with two spiral flutes, greatly reduces the rigidity of the micro drill and thus limits the anti-breakage ability of the drill bit. To solve this problem, a single flute micro drill is designed. Some other significant advantages of single flute micro drill include reduced heat generation due to small (virtually half compared to twist type) contact area between chips and hole walls, ease of chip disposal, high aspect ratio attainment, decreased rate of breakage and high positional accuracy. In spite of providing such good features, there are some limitations as well. *Since in single flute micro drills, there is only one flute corresponding to one cutting edge area, which is typically half compared to twist type, the cutting speed is lower than that of twist type of micro drills when compared with the same spindle speed and feed rate.* The problem often encountered by single flute micro drill is the negative rake angle at the points of on cutting lips adjacent to micro drill axis. This negative rake angle makes the drill tip to be blunter, causing increased cutting force as well as friction force and elevated temperature [37, 52, 154]. The geometrical attribute of a single flute micro drill is presented in Fig. 12.

Fig. 12 Geometric diagram of single flute micro drill [17]

The single flute micro drill was first invented by Houser in 1996 [17]. With 10 claims, 3 figures and 39 embodiments, he described the invention basically devoted to micro perforation in printed circuit boards. After that, a small amount of work has been reported to improve the performance of single flute micro drills. Recently Lee et al. [37], have designed a single flute micro drill with the help of Solidworks and performed a geometrical analysis mathematically. The main benefit of this research is to extend the tool life compared to conventional twist type micro drill by enhancing drill strength and reducing the cutting torque developed during drilling operation. The new single flute micro drill is shown in Fig. 13.

Currently only a few manufacturers are producing single flute micro drills industrially, though it has not gotten mass popularity yet. In the future investigation, the optimised geometry of single flute micro drill, proper helix angle and web thickness, processing of chip formation and removal, and enhancing the cutting speed can be very interesting field of research.

Fig. 13 3D design of single flute micro drill [37]

4.5 Compound micro drill

The name has come from the dual operations of micro drilling followed by the deburring process which the compound micro drill performs. Conventional micro drills usually machine a miniature hole with micro burrs around the hole. These burrs cause considerable problems. To remove these burrs, a deburring operation is usually performed after machining the holes, however, this causes other problems. The deburring tool has to be in an accurate position, fitting exactly inside the micro hole, and this is very difficult to achieve. It also consumes extra cost and time. Therefore, combining these two tasks together – micro drilling and deburring, by a single tool is very advantageous. The idea is presented in Fig. 14. It is noteworthy that the technique is applicable for the case of through holes. For no-through holes the deburring part cannot reach the other end of the holes and thus cannot perform the deburring

Fig. 14 Compound micro drill [27]

Onishi et al. [38], have fabricated compound micro drills of 80 μm in diameter furnished with abrasive diamond grain electroplated on the first half of the drill. The influence of diamond grits and the geometry of the drilling part have also been investigated by drilling into stainless steel. Different sizes of diamond grains ranging from 2–5 μm , have been electroplated on several sizes of base drill parts. Three

different types of compound micro drills are fabricated as mentioned in Fig. 15. Type-A consists of a 90 μm drill and substrate part with 2–4 μm diamond grit electroplated on the substrate. Type-B consists of a 80 μm drill and substrate part with 5–10 μm diamond grit electroplated on the substrate. Type-C consists of a 90 μm drill part and 80 μm substrate part with 5–10 μm diamond grit electroplated on the substrate. They have concluded that the burr removal was more successful in type-A and type-B than that of type-C.

Fig. 15 Compound micro drills a) type A, b) type B, and c) type C [38]

Aziz et al. [29] have examined the minimization of burr formation and improvement of surface roughness of micro holes by means of compound micro drills and compared the result with the holes machined by commercially available twist type of micro drills. As shown in Fig. 16, they have reported that the micro holes machined by compound micro drills have a smoother wall surface compared to the holes machined by twist micro drills. As can be observed from Fig. 16 (b) and (d) burr formation at both entrance and exit is minimized compared to the commercial twist drill as shown in Fig. 16 (a) and (c) respectively. Therefore, compound micro drills can be a suitable alternative for the through type micro holes where better surface quality and minimum burr formation is desired.

Fig. 16 Comparison of the burr formation and surface quality machined by commercially available twist drill and compound micro drills [29].

4.6 Coated micro drills

In order to improve the performance of the micro drill, numerous researchers have worked on coating the treatment of micro drills. A suitable surface engineering technique is adopted for depositing the coating material with the desired properties on the surface of the micro drill cutting part. Generally a very thin layer of 0.002–0.015 mm coating of harder material is deposited on the surface [28]. This coating layer can significantly improve the surface properties of micro drills by enhancing hardness, lubrication ability, heat and wear resistance. Common materials which are used in the coating of micro

drills include diamonds (e.g. diamond like carbon (DLC), micro crystalline diamond (MCD), fine grade diamond (FGD), nano-crystalline diamond (NCD), boron doped diamond (BDD)), Zirconium (e.g. Zr-Ti-N, Zr-C-H, Zr-C:H:N_x), Chromium (e.g. Cr₂N, Cr₂WCN), Carbon (C:W_x%), Titanium (e.g. Ti, TiN, TiCN), Aluminum (e.g. AlN, Al₂O₃) [155–159]. These coating materials are applied in mono/ multi-layer by means of several methods as mentioned in Table–1.

Table 1: Micro drill coating techniques

SN	Coating techniques	Acronym	Common coating materials	Coating temp	Citations
1	Physical vapor deposition	PVD	TiN, TiCN, TiAlN, TiZrN, CrN	300 – 600°	[155, 160]
2	Chemical vapor deposition	CVD	Diamond, Al ₂ O ₃ , TiCN	900–1100°	[161]
3	Medium-temperature chemical vapor deposition	MTCVD	TiCN	750–900°	[160]
4	Unbalanced magnetron	UBM	a-C:W _x %, TiN, AlN	Room–200°	[162, 163]
5	Closed-field unbalanced magnetron sputtering ion plating system	CFUBM	Zr-C:H:N _x %, Zr-Ti-N	Room–300°	[16, 164]
6	Physical vapor deposition–electron cyclotron resonance–chemical vapor deposition	PVD–ECRCVD	Ti, TiN, TiCN, DLC	300 – 600°	[165, 166]
7	Hot filament chemical vapor deposition	HFCVD	NCD, BDD, MCD FGD	750 – 950 °	[167, 168]
8	Atomic Layer Deposition	ALD	Al ₂ O ₃	Room – 400°	[169]
9	Coaxial excited microwave plasma system	CEMP	DLC	600 – 800°	[170]
10	Filtered cathodic vacuum arc	FCVA	Ta-C	Room temp.	[171]

The main advantage of coating is to enhance the tool life. Kao [16] coated a WC micro drill of 0.2mm diameter with Zr-C:H:x% by close field unbalanced magnetron (CFUBM) and examined the tool life in PCB specimens. Fig. 17 (a) and (b) show the micro drills wear morphologies after machining of 2000 holes, uncoated and Zr-C:H:N_{17%} – coated respectively. During drilling operation, uncoated micro drills (Fig. 17 (a)) adhere intermittently to PCB materials and therefore chips are accumulated on cutting and flutes, leading to dulling of the cutting edges and deterioration of machining quality as cutting proceeds. SEM micrograph of Zr-C:H:N_{17%} – coated micro drill (Fig. 17 (b)) reveals that coating improves lubrication effect between workpiece and micro drill and thus prevents accumulation of chips on cutting edges as well as flute during machining. In addition, a significant amount of coating is still seen in the micrographs of coated micro drills (the black region Fig. 17-b) after drilling 2000 holes. Fig. 17 (c) represents an SEM micrograph of 2000th hole drilled by uncoated micro drill, and Fig. 17 (d)–(f) represents micrographs of 2000th, 6000th and 10,000th micro holes drilled by coated micro drill, respectively. Fig. 17 (c) shows the presence of considerable burring in and around the 2000th drilled hole, i.e. the uncoated micro-drill exhibits a poor machining. By contrast, the 2000th hole machined by Zr-C:H:N_{17%} coated micro drill shows nearly no signs of burring (Fig. 17 (d)).

Although there are considerable advantages of depositing coating material on micro drill in terms of extended tool life, there are some drawbacks as well. The shortcoming of coating may appear even if the coating amount is as thin as 0.002 mm, it can affect drilling performance with the increase in the dimension of the drill tip and a decrease in the sharpness of the cutting edge. Heinemann et al [109] reported that a miniature drill coated with the help of a standard arc–evaporation method, while

inexpensive, generated an unacceptable surface finish. Even if an advanced coating technology is implemented with a thickness of less than 0.0015 mm which is currently possible, an experienced Waters engineer mentioned that the tool life gained is not as beneficial at cost-performance ratio [167, 172].

Fig. 17 Wear morphologies of coated and uncoated micro-drills following drilling of 2000 holes: (a) uncoated drill and (b) Zr – C:H.N17%-coated drill. (c) typical damage around 2000th hole machined using uncoated micro-drill; (d) typical damage around 2000th holes machined using Zr – C:H.N17% coated micro-drill, (e) 6000th coated (f) 10,000th coated [16].

Even though there are some disagreements regarding the pros and cons of using coating, many researchers and also industries are considering this as a promising technology in the future. Ueng et al. [165, 166] fabricated Ti/TiN/TiCN/DLC and diamond like carbon coatings on 0.4 mm diameter micro drills and found that the tool life of those drills was increased significantly by about 2.5 times compared with the uncoated ones. Shen et al. [167] developed NCD coated micro drills of 0.4 mm diameter. They examined the different thickness of the coating ranging from 1,3,5 and 8 μm , and found that tool life considerably increased, the greater the thickness the longer the tool life. Lei et al. [168] fabricated a diamond coated micro drill of 0.25 mm in diameter with an effect of boron doped diamond interlayer. They found that the tool life of micro drill increased to 2–3 times the normal.

Considering the current industrial demand and research trend, the development of coating technology will continue to lead the market as price now remains the main concern, coating technique certainly extends tool life. Specifically, super-hard coatings such as diamond and PCBN, are becoming more and more popular. Sometimes the advancement in coating technology is faster than users can accept, acclimate, and incorporate new capabilities. The key progress in the performance of micro drilling operations can be achieved only by understanding the complete physical potential delivered by micro drill coatings. Among such research works, ample attention must be paid on the role of the physical

properties of the tool and work materials and in order to achieve the optimum drill–chip contact conditions, comprising thermal and tribological relationships [173].

4.7 Key factors in micro drilling

Frequent tool breakage and quality of micro holes are the most discussed issues in conventional micro drilling perspectives. Since the dimension is in the range of microns, the drill cannot provide adequate mechanical strength to withstand the cutting force. This is why micro drill breaks down long before they wear out. In addition, precise hole quality requirement is often very crucial depending on the type of application. A number of researchers have attempted to figure out the reasons of tool breakage, ways to improve the tool life and prevent tool breakage, and improve the hole quality. The key factors relating to tool life and hole quality, that came out from their investigation can be summarized as follows.

1. Formation of chips, (section 4.7.1)
2. Burr formation, (section 4.7.2)
3. Cutting edge radius, (section 4.7.3)
4. Coolant, (section 4.7.4)
5. Starting hole or spot drilling, (section 4.7.5)
6. Cutting conditions i.e. spindle speed and feed rate, (section 4.7.6)
7. Tool point angle, (section 4.7.7) and
8. Peck drilling, (section 4.7.8)

4.7.1 Consequences of chip formation in micro drilling

Since drilling is a process of material removal, chip elimination is one of the most important factors that needs to be taken into account. Particularly in the case of micro deep drilling, chips are not easy to remove, and often encountered jamming inside flutes, which produces additional stress and heat, and eventually causes breakage of micro drill.

Tool failure that happens due to improper chip removal can be classified into three main categories, 1) Mechanical effect, 2) Thermal effect, and 3) Adhesion effect [174]. Mechanical effect is caused by sliding action between cutting edges and workpiece surface. During sliding, grains that are in contact become debilitated at their grain boundaries and ultimately lead to premature failure. The 2nd source of breakage is the thermal effect. When the chips are jammed inside the hole, it generates heat, causing the cutting edge to be softened at higher temperature, deform the shape and ultimately lead to tool breakage. The third source is adhesion often termed as built-up-edge (BUE). BUE is the accumulation of workpiece material over the cutting edge of the drill. In this scenario chip is adhered to the drill bit and change the geometry of the tool. This reduces radius cutting edge area, sharpness of the tool, shrinks chip removal space and generate high friction, stress and heat and eventually result to tool failure.

Chips that formed during micro drilling are produced in different shapes as represented in Fig. 18 [28]. Generally it is in medium shape during entrance as seen Fig. 18 (a), and shorter in Fig. 18 (b), and longer at the exit Fig.18 (c). It is reported that chips with long curly shapes tend to adhere in the gap of flute which avert coolant from going inside to decrease temperature and perform lubrication at the tip of drill. Shorter chips are more prone to be jammed the space of flutes and produce more stress and heat eventually shorten tool life. Medium size chips are comparatively better for micro drilling, though

further investigations are required to optimize the adjustment in order to produce perfect shape of chip as well as chip removal rate.

Fig. 18 Formation of chips at different stage of micro drilling, a) entrance, b) middle, c) exit [28]

4.7.2 Burr formation

Another phenomenon similar to chip formation as discussed in previous section, is the formation of burrs at entry and/or exit of a micro hole. Formation of burrs at entrance is caused by lateral extrusion action and at exit by rubbing the margins of the drill [175]. In micro drilling process, however, the main concern is exit burr due to bulk volume and large size than that at entry side [176]. Formation of burrs generate several problems for product quality and accuracy, hazards in handling of machined parts, and can negatively interfere the assembly process [177]. Deburring is a difficult, time consuming and expensive operation, and in some cases, due to part fragility and edge tolerance, deburring of micro holes is not possible. In addition, sharp burrs have a significant risk of safe handling as it can cause lacerations to fingers or hands. Sometimes, burrs can come in loose forms and can cause damage of the product. Therefore, burr minimization or elimination is very important drilling. Understanding the phenomenon of burr formation and its dominant parameters are essential for predicting and reducing burr formation [175–177].

Formation of burrs depend on a number of different factors such as workpiece material properties; micro drill geometry and material; and cutting conditions [178, 179]. Hashimur et al. [178] reported that burr formation increase with the increase of materials ductility. The geometry of micro drill affects burr sizes. The burr thickness and height reduces with the increment of point and helix angle. With the increase of feed rate and cutting speed, the size of burr increases [180, 181]. The burrs can have different shapes, however, there are three basic types of burr shapes as reported by [182, 183]. Fig. 19 shows 3 different types of burr shapes that usually form during micro drilling. Fig. 19 (a) represents an ideal case with a very little burr formation, Fig. 19 (b)–(d) represent uniform, transient and crown burrs. The uniform burr has relatively small and uniform burr height and thickness around the hole periphery. The crown burr has a larger and irregular height distribution around the hole. The transient burr is a type of burr formed in the transient stage between the uniform and the crown burrs [26, 182, 183].

To date, many attempts have been reported in order to prevent or minimise the burr formation. These include varying the feed rate and cutting velocity during machining [178, 179], usage of suitable coolant and lubrication [184], coating of micro drills [185], optimizing drill geometry [186], ultrasonic assisted micro drilling [187], employing a hybrid system such as combining laser followed by micro drilling [55] and using a special design of micro drill such as compound micro drill [188]. Since burr

formation, to a great extent, depends on workpiece material, tool geometry and cutting conditions, an appropriate selection of them, can significantly reduce burr formation in micro drilling.

Fig. 19 Types of burrs in micro drilling a) virtually burr free b) uniform burr, c) transient burr, d) crown burr [26].

4.7.3 Cutting edge radius

The cutting edge radius plays a significant role in the performance of a micro drill and quality of micro holes. It has been observed that the reduction in cutting edges, caused by abrasive wear, lead to chipping and clogging of micro drill and eventually result to failure due to fracture propagation [13, 189]. Aramchareon et al. [190] have reported that increase in cutting edge radius lead to size effect and can substantially influence cutting forces, chip formation, chip thickness and the quality of wall surface finish. Nair [25] has examined the effect of cutting edge of 500 μm diameter WC micro drill. Fig. 20 (a) (c) show the sharp cutting edge of new drill, cutting edge after 118 micro holes and bad quality of hole by forming burr respectively. He concluded that the cutting edge radius increases with the increment of cutting speed and feed rate. This increase in cutting edge radius hampered the dimensional accuracy and surface integrity of the micro hole as evidenced by SEM micrograph shown in Fig. 20 (c). Excessive wear was characterised with the increasing of drill cutting edge radius. Cutting edge radius, therefore, greatly influences the finished product quality and tool life. An increase in cutting edge radius lead to the size effects come into play [191, 192].

Fig. 20 Cutting edge radius of 0.5mm micro drills before and after drilling of 118 holes: a) new drill, b) drill after 118 holes, c) burr formation [25]

4.7.4 Effect of coolant in micro drilling

Usage of coolant or cutting fluid, is a common technique being employed during machining. Coolant helps to drive away the chips as well as reduces the generated heat. In case of miniature drilling, however, coolant does not perform as effectively as in macro drilling [28]. Many researchers have investigated for proper selection of coolant conditions that include type of coolant, flow rate and angle of nozzle. A coolant with lower viscosity, higher thermal diffusivity, and good lubricity is recommended to attain optimal performance during micro drilling [174]. The drop size of cutting fluid is important factor, due to ease of penetrability, small droplets can dissipate heat more effectively. In general, drop size of coolant depends on supplied air pressure and volume of cutting fluid for atomization; higher the air pressure and flow rate, the more uniform and smaller droplet size will be. The proper angle of nozzle can be derived from the following equation:

$$\frac{P}{V^{1/3}} = \left[\frac{24}{\pi} \times \left(\frac{(1-K \times \cos^2 \theta)^{3/2}}{2-3 \times \cos \theta + \cos^3 \theta} \right) \right]^{1/3} \quad (1)$$

In Eq. 1, P is the desired droplet diameter (mm), V is the droplet volume (mm³), θ is the contact angle (°) and K is 0 for θ between 90° and 180°, 1 for θ between 0° and 90°, respectively [174].

4.7.5 Effect of spot drilling

This is observed that the initial few turns play significant role in successful micro drilling process. This feature is more important in micro drilling, since a micro drill carries higher eccentric load compared to larger diameter drill. Any irregular shape or roughness on the surface of the workpiece might result lateral sliding, resulting in a deviation from the path of alignment, raising bending force and change the direction of the tool axis and ultimately cause the tool breakage [28].

To avoid this problem, spot drilling is recommended by many researchers. Spot drilling facilitates a chance for micro drill to construct more contact area with workpiece which helps micro drill to set in exact position more precisely at primary stage. Once the drill tip fits in proper position, drills margin and cutting edges guide the drill to go forward, that ensures hole's straightness to be machined and prevent any lateral sliding or positional error [28, 193].

4.7.6 Cutting conditions in micro drilling

Cutting conditions, also called machine conditions, basically refer to spindle speed and feed rate that are provided by the machine which perform drilling operation. These two factors are keys to optimize machining productivity. Another important factor is Material Removal Rate (MRR), which can be calculated by the multiplication of spindle speed, feed rate and cross sectional area of drill as expressed in Eq. 2. Higher material removal rate will take less time to complete the drilling. Consequently faster drilling causes extra pressure load on the drill bit and ultimately could break the tool. Therefore, an accurate measurement is very essential. To calculate spindle speed Eq. 3 is used.

$$MRR = NfA = Nf\pi r^2 \quad (2)$$

$$N = \frac{V}{\pi D} \quad (3)$$

where N is the spindle speed (rpm), f is the feed rate (in µm/s), r is the drill radius, V is the cutting speed (fpm or m/min) and D is the drill diameter, respectively. To calculate optimized feed rate, various

opinions have been reported among researchers. However machinery's handbook [174] has mentioned following equation, derived by converting chip load of cutting edge to feed rate. The value of chip load is determined by empirical values.

$$f = C_L \times n \quad (4)$$

where C_L denotes chip load of cutting edge (mm/tooth) and n is the number of cutting flutes (teeth/rev), respectively. Generally with the variation of properties of workpiece material, tool properties and drilling process adopted, tool manufacturers facilitate their own technologies to meet customers demand.

4.7.7 Tool point angle

Tool point angle plays significant role at the commencement of drilling process. Researchers as well as manufacturers have conducted numerous study to find out the optimized tool point angle. Wong et. al. [108] figured out that by decreasing point angle, thrust force that generated during drilling can be minimized and position error can be escaped. Heinemann et al. [109] has conducted several experiment to study the optimized point angle of micro drill and found that point angle B (120°) and C (130°) have better performance in terms of higher tool life.

4.7.8 Peck drilling

Micro drills, by nature, are made slender with low rigidity and very high length to diameter ratio. When the drill penetrates deeper inside the specimen, thrust force increases sharply, as reported by Kim et al. [194], and thus enhances the possibility of breakage. Peck drilling is technique that can reduce the dramatic increment of thrust force and help extent tool life. The operation involves a periodic retract and re-insert of micro drill into the workpiece as illustrated in Fig. 21. It helps avoid the flute space from jamming by accrual of chips. In addition, the periodic insertions during machining permits the drill to cool down and also allows to be re-lubricated in order to drive away the heat in a more effective way, and thus prevent tool breakage.

Fig. 21 The illustration of Peck drilling

4.7.9 Strategy to prevent tool breakage

In general, drill failure occurs when the stresses developed due to cutting operation and added disturbances are higher than the limit of micro drill strength. As discussed in previous sections, numerous attempts have been made considering a number of different factors in order to prevent or

minimize tool failure. A common technique suitable for conventional micro drilling techniques at any operating conditions is proposed by Kudla [20] as shown in Fig. 22.

Fig. 22 Strategy for prevention of micro drill breakage [20]

4.8 Summary of conventional micro drilling.

Macro drilling and micro drilling are identical in many aspects, even though miniaturisation of drill size introduces numerous problems which have substantial effect on the micro drilling process and output. The main differences between micro drilling and macro drilling include larger shank diameter, web thickness, high rotational speeds leading to large vibrations and different modes of failure [195]. Micro drills suffer from breakage problem much more than normal ranged drills as drill bit of larger diameter usually fail due to wear out, long before the breakage takes place [128], whereas micro drills break long before they wear out [196]. In micro drills, the diameter of the shank is generally larger than drill diameter **in the flute region because of the minimum diameter that can be successfully held by the spindle**. This is because the strength that comes from the micro drill flute is not sufficient to hold the bit in the spindle. This is unlike macro drills where normally, the shank diameter and cutting part diameter remain the same size. To enhance the strength of flutes, the web thickness of micro drills is increased [21] comparing to macro drills. The other difference is that the length to diameter ratio is larger in case of micro drills than that macro drills to acquire high aspect ratio. Usually micro drills run at higher rotational speed and this makes them even more vulnerable to breakage. To ensure higher productivity, better quality and proper safety, avoiding micro drill breakage is crucial. Drill breakage that takes place in micro drilling is mostly due to excessive thrust force and/or torque that is generated during the application of higher cutting force [97]. This means that the

analysis of the mechanical features of micro drills such as torque-torsion analysis, mathematical modeling, rotating and bending characteristics, cutting force effects, tool wear mechanics and fracture features is essential in order to improve the performance of micro drilling and prevent breakage. Micro drilling performance can also vary from company to company due to their own different manufacturing technology.

Another important aspect must to be mentioned in regard to the quality and performance of conventional micro drills of all types is the microstructure of the micro drill materials. Even the same material with different grain distribution of atoms can have a big effect on the material properties and thus directly contribute to the performance and durability of micro drills. It has been reported that the hardness of the micro drills made from nano-sized powders is considerably higher than when conventional micro range powders are used. There is strong evidence that the sintered materials made from ultrafine grain sizes possess extremely high flexural strength [115].

In the future, whatever the type of micro drills considered, selection of appropriate materials with ultra-fine grain size and an optimised manufacturing method will be of great importance, as these directly influence the cost, performance and durability of the micro drills. With the advancement of simulation technology, micro drilling parameters can be simulated to examine their effects and performance before practical fabrication. Molecular dynamics or powder simulation can be implemented to verify the effectiveness of ultra-fine micro grains to enhance the mechanical properties of micro drills. The possibility of adapting a different manufacturing technique than grinding and machining can be examined with the help of advanced simulation technique. For example, simulation of a forming method to manufacture micro drills by means of a direct powder solidification-extrusion forming technology could open a new horizon of producing micro drills, if the simulation is successful.

4.9 Comparison of different conventional micro drilling techniques

Table 2: Comparison of the capabilities of conventional micro drilling techniques

	Twist	Spade	D-shaped	single	Compound	**Coated
Hole size(μm) [21, 168, 188]						
<i>Common</i>	> 50 μm	10-50 μm	10-50 μm	> 50 μm	> 90 μm	2-15 μm (Thickness)
<i>Min</i>	10 μm [121]	2.5 μm [18]	6.7 μm [13]	40 μm	80 μm	2 μm
Aspect ratio [27, 52]						
<i>Typical</i>	< 10 d	5-10 d	2 – 5 d	5-10 d	5-10 d	N/A
<i>Max</i>	24 d [107]	17 d	8 d [152]	12.5 d	-	N/A
Spindle (rotational) speed (k rpm) [40, 52, 123]						
<i>Typical</i>	30-200 Depending on drill diameter & materials	10 -25	3 – 10	50 – 100	20 – 40	Depends on basic drill type
<i>Max</i>	350 [123]	80 [40]	-	350 [52]	-	-
Point angle (deg.) [108, 197]						
<i>Typical</i>	90-140	118-135	N/A	70-130	90-130	N/A
<i>Best performance</i>	120-130	~ 120 [40]	-	-	118 [29]	-

	[109]					
Helix angle (deg.)						
<i>Typical</i>	20-50 [106]	N/A	0 - 20 (clearance angle)	30-70 [17]	N/A	N/A
<i>Best performance</i>	35-45 [2, 123]	-	-	-	-	-
Feed rate						
<i>Min (μm/s)</i>	50 [125]	0.16 [40]	0.03 [13]	50	16 [38]	No effect on feed rate
<i>Max (mm/s)</i>	200 [194]	13 [40]	12 [13]	-	0.5 [188]	-
Tool life	Low	Average	Average	High	Average	Increased by 2 – 5 times
Chip removal	Fastest	Slow	Slow	Fast	Slow	Helps to accelerate
Commercial availability	High	Medium	Medium	Low	On research	High
Fabrication material	HSS, WC, Cermet, PCD	HSS-E, WC	HSS-E, WC	HSS, WC	WC	Diamonds, Zr, Cr, C, Ti, and Al alloys
Shape complexity	Most	Simple	Simple	Medium	Medium	Varies on drill type and deposition technique
Wall surface integrity	Minimum burr	More burr formation	More burr formation	Better	Best	Reduce burr formation
Advantages	<ul style="list-style-type: none"> - Most commercially popular - Wide range diameter availability - High cutting speed - Easier chip removal - Better dimensional accuracy 	<ul style="list-style-type: none"> - Manufacturing simplicity - Cheaper - Smaller diameter attainment 	<ul style="list-style-type: none"> - Manufacturing simplicity - Cheaper - Smaller diameter attainment 	<ul style="list-style-type: none"> - Reduced heat generation - Better mechanical strength - High aspect ratio attainment - Better tool life 	<ul style="list-style-type: none"> - Excellent surface finish - Simple geometric shape 	<ul style="list-style-type: none"> - Increases tool life - Less heat and wear resistance - Lubrication ability
Disadvantages	<ul style="list-style-type: none"> - Manufacturing complexity - Poor mechanical strength - Limited diameter range - Shorter tool life - Higher heat generation 	<ul style="list-style-type: none"> - Poor chip removal - Low production rate - Limited market availability 	<ul style="list-style-type: none"> - Poor chip removal - Low production rate - Limited market availability 	<ul style="list-style-type: none"> - Lower production rate - Limited diameter range - Not available in the market - Slow chip removal 	<ul style="list-style-type: none"> - Slower production - Difficulty if making deburring part - Not available in the market 	<ul style="list-style-type: none"> - Decreases sharpness of micro drill - Poor surface finish - Additional cost of coating deposition

** This column does not refer to a different drilling techniques like others rather a treatment that can be implemented to all conventional micro drilling techniques.

5 Advancements in non-conventional micro drilling

Non-conventional micro drilling is defined as the micro drilling processes where no conventional micro drill bit is used. The methodologies followed for non-conventional micro drilling include laser, electro discharge machining (EDM), electron beams, electro chemical, and spark assisted chemical engraving (SACE). Of these laser drilling is found to be most popular based on this study. However, each technique has its own advantages as well as disadvantages in terms of cost, machining efficiency, precision, workable materials, and minimum achievable dimensions [198]. In this section six major non-conventional micro drilling technologies are examined. These include:

- Laser micro drilling; (section 5.1)
- EDM micro drilling; (section 5.2)
- Electro Chemical micro drilling; (section 5.3)
- Electron beam; (section 5.4)
- Spark Assisted Chemical Engraving (SACE); (section 5.5) and
- Ultrasonic Vibration (section 5.6)

5.1 Laser micro drilling

Laser micro drilling is a machining technique which employs a controlled ablation mechanism. Fig. 23 represents a schematic diagram of the process. A high density beam is focused on a point on the specimen so as to melt and vaporize the materials in its path. The diameter of the holes ranges from one micron to several hundred of microns. The mechanism involves different operating parameters which include the characteristics of the laser (frequency, wavelength and energy density), configuration of the machining process (assisting gas type and its pressure) and the specification of materials (composition and thickness). In principle, the laser micro holing operation occurs in two phases (i) photo-chemical, (ii) photo thermal. In photo chemical phase, laser photon energy falls directly on the material and causes it to break down the bonds and this results in the material being ejected from the volume under illumination. In the photo-thermal phase, the temperature rises above the melting or evaporation point due to absorption of laser energy by the material, and this results in the material being driven away by rapid boiling or evaporation [42, 199–202].

Fig. 23 Typical schematic diagram of Laser micro drilling [8, 9]

Researchers have gone through various techniques and methodologies to examine the feasibility of using laser energy with the purpose of micro drilling. Numerous factors have been considered these include the type of laser, the system development, the finite element method (FEM) simulation and analytical modelling, morphologies as well as the elemental composition of the machined holes, a wide variety of materials as work pieces, perforation quality optimisation, under water laser micro drilling, production time and energy required and cost reduction. The types of laser generally used for micro drilling include the UV laser (short, ultra-short pulse), the Nd: YAG (with or without diode pump, in various wavelengths), the CO₂ laser, the active fiber laser, the gold vapour laser, the diode array laser, the Nd-VO₄ laser, the excimer laser, the LD pumped THG-YAG laser and the copper vapour laser. Typical pulse durations for laser ablation are in the nano, pico and femto second ranges [203–205].

Among non-conventional micro drilling techniques, laser drilling is one of the most popular method. Laser micro drilling is well suited for generating micro holes in complex shape parts, widely used for advanced hard or difficult to cut materials for instance ceramics, glass and super alloy composites. Among major applications, laser micro drilling is the most widely used in aeronautical engineering, automobiles, semiconductor and biomedical industries. Typical examples include aircraft engine turbine blades, automotive fuel filters, cooling holes in turbine components, combustion chambers, surgical needles, microfluidic devices, micro-pumps, micro-sensors, micro-chemical-reactors, and micro-heat-exchangers [200, 206–208]. Laser micro drilling has developed as a potential substitute to overcome the shortcomings of conventional machining with the inherent advantages of high aspect ratio, localised treatment capability, operational precision, reduced costs compared to lithographic techniques, and high speed production rate. The drawbacks include poor hole quality and higher production cost compared to traditional micro drilling. The reason for reduced perforation quality is the excessive thermal residual stresses induced in and around the heat affected zone due to the difference in cooling rates and thermal shrinkage between the surface and interior regions of the material at the time of laser drilling. This phenomenon leads to surface and sub-surface cracking of the treated component and may also lead to fracture because of thermal shock [209–213]. A number researchers have studied the quality of holes achieved by laser micro drilling and compared with others, as discussed in subsequent sections.

Imran et al. [15] have investigated the quality of holes achieved by three micro drilling techniques, namely EDM, laser (Nd:YAG) and conventional (twist, WC, 400 µm diameter) and compared the results. They have used a rectangular 2.2 mm thick Inconel 718 alloy as specimen material. As shown in Fig. 24, laser drilled hole observed to be the worst quality (out of roundness ~27–31 µm), compared to 7–9 µm for EDM and 6–7 µm for conventional one. They have also reported that the shape down the length of the hole is not uniform in case of laser drilled hole. Fig. 24 (b) – (e) represent the backscatter electron (BSE) images of encircled area A, B and C. The recast layers of 6–12 µm and 9–45 µm are observed for EDM and laser respectively. Fig. 24 (b)–(d) also reveal the presence of micro cracks in the recast layer formed due to rapid shrinkage of solidifying material. In contrast, twist micro drill does not introduce any recast zone, however, characterized by forming an ultra-fine grained layer followed by a deformed grain structure as shown in Fig. 24 (e). Table 2 summarizes the characteristics of hole quality of the three micro drilling techniques. Similar observations were also conducted by Okasha et al. [55], Allen et al. [214] and Kuriakose et al. [215].

Fig. 24 The hole geometry and recast layer of EDM, Laser and conventional, a) hole geometry – EDM, b) hole geometry–laser, c) hole geometry–conventional, d) recast layer–EDM, e) recast layer–laser, f) recast layer–conventional [15].

Table 3: Hole quality comparison of EDM, laser and conventional twist [15]

Micro hole features	Micro drilling techniques		
	EDM	Laser	Conventional (twist)
Out of roundness	7–9 μm	27–31 μm	6–7 μm
Surface roughness (inside hole–visual)	Rougher than conventional	Roughest of all	0.1–0.25 μm
Edge profile	6–12 μm recast layer	9–45 μm recast layer	No recast, 3–6 μm thickness fine grained zone
Observed anomalies	Radial micro cracks	Radial micro cracks	No micro cracks, Exit burrs
Micro drilling time	15 min	< 1 s	~ 8 s

Another important factor to be considered during laser micro drilling is the presence of spatter. Laser drilled holes are innately associated with the deposition of spatters, due to unfinished expulsion of emitted material from the drilling site which consequently re-solidifies and adheres to the specimen surface around the hole periphery [216, 217]. Furthermore, removal of generated spatters require additional post machining or finishing processes and subsequently cause to additional process complexity, production time and cost [217, 218]. A number of different techniques based on chemical or physical anti spatter mechanism have been reported either to reduce or prevent spatter generation. Chemical techniques include spraying of selected solutions over the workpiece surface before drilling [219], applying a coating material [220], using a shielding gas nozzle [221] and chemical etching after the drilling process [222, 223]. Physical approaches include the use of a vibration technique to enhance molten material fluidity as reported by [224], masking the material surface with the help of paraffin wax or silicon grease [216], employing a surfactant fluid in order to prevent wetting of melted material on specimen surface [225, 226]. Moreover, with the help of an optimized selection of cutting edge laser processing parameters, spatter generation can also be reduced significantly [218].

Recently ultrafast lasers are gaining much popularity to overcome the shortcoming of traditional lasers. Ultrafast e.g. femtosecond (fs) lasers are dramatically different techniques by their basic working principle [227]. For traditional long pulse lasers, as discussed earlier, the ablation of materials takes place primarily through melt expulsion driven by the vapor pressure and recoil pressure of light. In Fig 25 (a), the black area represents the heat affected zone (HAZ). The blue lines indicate the shock waves generated by the light pulses. The continuous wave (CW) at the left, removes the material primarily by melting and creates a large HAZ. The ns laser at the center, uses the same principle, however, creates a smaller HAZ. In both cases, the melt layer is re-solidified, resulting in a geometric changes to the holes by forming recast layer and spatter. In contrast (Fig. 25 (a)-right), fs laser uses a pulse duration much shorter than the timescale for energy transfer between free electrons and the material lattice, resulting the absorbed energy heats the material very quickly past the melting point directly to the vapor phase with its kinetic energy [22]. Therefore, the material is removed by direct vaporization away from the surface without formation of a spatter or recast layer. This provides negligible HAZ and very fine and sharp features of the holes. Fig. 25 (b) and (c) represent the holes produced by ns and fs, as reported by [42]. Similar investigations were conducted by Tunnermann et al. [48] as shown in Fig. 25 (d) and (e) by ns and fs lasers respectively. Results from both the experiments reveal that the quality of holes achieved by fs lasers are much better than ns lasers. Visibly no spatter or recast was observed in Fig. 25 (c) and (e).

Fig. 25 a) Laser material interaction basic for different types of lasers, [22] b) – c) laser micro drilling comparison in steel for ns and fs, respectively [42], d) – e) laser micro drilling comparison 3.3 ns and 200 fs, respectively [48]

In future research, the focus can be on the production of high aspect ratio micro holes, improvement of the quality of holes in terms of dimensional accuracy, easier removal of debris and recast layer after laser operation, consumption of less power and control of the processing parameters. Employment of optimised processing parameters in a right way is directly related to the final product with improved quality in laser micro drilling. These parameters include pulse frequency, laser power, laser focal length, lamp current, laser irradiation time, air pressure, pulse width and surrounding gas condition. Proper controlling of such parameters can directly influence the success of laser micro drilling operation [210, 228, 229]. In addition, many researchers are also paying their attentions to fs laser micro drilling. Femtosecond laser can be used for a wide variety of materials such as metals, semiconductors, transparent materials, untrahard materials, polymers and tissues. The sources of fs

lasers, however, are traditional solid-state lasers, which are expensive, bulky and require regular maintenance. This drawbacks can be partially be overcome by fs fiber laser, which is less expensive, more compact, reliable and require minimum maintenance. Although abundant researches on micro drilling by fs exist, drilling high aspect ratio micro holes with minimal or no thermal damage still remains a major challenge [206, 230].

5.2 EDM micro drilling

Micro drilling with the help of EDM technology (MEDD) is a complex procedure performed with the simultaneous effects of thermal, chemical, mechanical and electrical operations, as shown in Fig. 26. Hence, the electrical energy is utilised to create high frequency discrete sparks for removing the material due to thermal energy of the sparks. The sparks are generated in the gap between two electrodes held a small distance from each other in a dielectric medium and a high potential difference is applied across them. Thus the localized zone becomes highly heated and the material starts to melt and vaporize. The ablated material is swiftly solidified and driven away from the inter-electrode gap in the form of debris particles by means of high pressure dielectric liquid circulated through the machining gap [198, 231–234].

Fig. 26 Typical Schematic diagram of EDM [4, 5]

Micro drilling with the help of EDM technology frequently called micro-electrical discharge drilling (MEDD), is actually a micro-electrical discharge machining (MEDM) process. Recently the use of this method for micro scale drilling has been extended. It employs a micro wire as the electrode to pass through the work piece to copy its mirror image in the work piece and eventually making a hole inside. The technology is suitable for complex geometrical shapes and difficult-to-machine materials of any hardness and toughness as long as it is electrically conductive, for instance tool steels, aerospace alloys and WC. This special feature makes this method be one of the most preferred non-traditional manufacturing technologies. Other advantages include negligible cutting force and the availability of electrodes. The electrodes required for MEDD can be easily manufactured with the help of electrode materials such as copper-tungsten and graphite materials using different techniques. Another promising feature of EDM micro drilling is the capacity to produce high aspect ratio micro holes compared to those of conventional ones. Plenty of research works have been reported that deals with EDM micro drilling into different materials and with high aspect ratios of micro holes. Egashira et al. [235] reported the smallest achieved diameter to be 0.5 μm using a silicon electrodes. The quality of

micro holes achieved by EDM is presented in Fig. 24 (a) and (d). It can be observed that the roundness and surface quality are close to conventional, however, much better than that of laser. A small region of recast layer with very micro cracks are observed. The disadvantages of this technology include unstable nature of machining process, inadequate control over material removal mechanism, poor surface quality since the material is removed through the processes of melting and vaporization resulting machined surface having thermally damaged layers or micro cracks in it, quick tool wear and lower material removal rate (MRR) causing a reduced output. As mentioned in Table 2, time taken by EDM for drilling a micro hole of 500 μm in a 2.2 mm thick Inconel plate, is much higher (15 m) compared to twist (8 s) and laser (<1 s) [15]. During the EDM process, the electrodes wear rapidly due to elevated temperature in the working area and this increase the production cost. Nowadays, along with research interest, EDM micro drilling has found wide applications in industry. This includes mould and die manufacturing, biomedicine, the automotive industry, aeronautics or aerospace engineering. Typical examples include inkjet printer nozzles; wire drawing dies; spinneret holes for synthetic fibres; cooling holes in plane turbine blades; fuel injection nozzles in automotive industries; dental, surgical implants and drug delivery orifices in medical purposes; cutting-tool cooling channels; and micro-hole drilling of hard, brittle and difficult-to-cut materials. [4, 236–242].

A number of research works have been investigated and optimised the parameters of the micro EDM drilling process. During MEDD, there are several factors which directly affect the operational performance. These factors can be associated either with the process parameters (for example voltage, peak current, pulse duration and spark gap) or with the system (for example type of dielectric fluid, tool properties, chemical and physical material properties). It has also been noted that the thermal properties of a specimen have a significant influence on the quality and accuracy of the micro holes drilled by EDM [5]. Many researchers are working to improve of MRR, electrode wear rate (EWR) and relative wear (RW) with the aim of contributing to high quality product at lower cost and duration. Development of systems introducing newer EDM micro drilling machines or ideas/techniques are also continuously being studied at both the scientific as well as the corporate level in order to meet the industrial demand particularly in the field of aviation, automotive, and medical applications [239, 243–246].

5.3 Electro chemical micro drilling

ECMD is basically an anodic dissolution process, where material removal takes place in a way similar to electroplating. A schematic diagram of this is presented in Fig. 27 [247, 248]. The workpiece to be micro drilled acts as an anode whereas the tool acts as a cathode. The anode and the cathode are separated with the help of an electrolyte, usually a salt solution. When the tool is fed maintaining a particular distance from the workpiece and a pulsed voltage is applied through the electrolyte then according to Faraday's law, the anode i.e. the workpiece starts to dissolve locally. Hence, a negative mirror image is generated inside the workpiece and this produces micro holes [249, 250]. Presently, researches are working on both aspects of system development and parameter optimization. Investigation devoted to system development includes the voltage applied, the concentration of electrolytes, the pulse frequencies, the pulse duration, the machining depths and the tool feeding rates.

Parameter optimization, on the other hand, involves the hole diameter, the aspect ratio, conicity, hole overcut, and surface finish [248, 251, 252].

Fig. 27 Typical schematic of ECM micro drilling [6, 7]

Electro Chemical Machining (ECM) was patented by Gusseff in 1929 [253]. Since then, it has become more and more popular in both the area of scientific research and manufacturing industries. Much research has been published on ECM, but a limited number of papers dealing with micro drilling using ECM technology has been reported [7, 249]. Micro range holes made with the help of ECM or ECMM (electrochemical micro machining) is termed as electrochemical micro drilling (ECMD) [254, 255]. Currently ECMD appears to be a very promising technology because of the advantages it offers. These include inexpensive setup, high material removal rate (MRR) regardless of material hardness, no tool wear, no residual stresses on the surfaces of the drilled products, better precision and control, rapid machining time, minimal roughness on the machined surface and its being environmentally acceptable. Chemically resistant materials which are broadly being used in electronic and biomedical applications such as titanium, super alloys, copper alloys, and stainless steel can also be micro drilled by this method.

Fig. 28 (a) – (h) represent a comparison of hole quality achieved by ECM and other processes. Non-conventional techniques including ECM, EDM and laser, do not satisfy high quality of hole requirements with respect to either geometrical characteristics (viz. overcut, taper, wall surface finish) or metallurgical characteristics (viz. heat affected zone, presence of micro crack and recast layer). Liu et al. [7] drilled micro holes in stainless steel by means ECM. As shown in Fig. 28 (a)–(b) the hole is characterized by poor roundness and rough wall surface finish. EDM and laser (Fig. 28 (c)–(d) [31], and Fig. 28 (e)–(f) [33]) involve material removal by heating the material to melting and vaporization phase, which ultimately lead to the formation of heat affected zone resulting metallurgical damage or micro cracks on the surface. In contrast micro hole (Fig. 28 (g)–(h) [26]) by conventional twist gives better hole roundness and smooth surface finish. EDM and twist, however, are limited by small aspect ratio

comparing to ECM. In many applications depending on type, material condition and high aspect ratio, ECM is considered the only viable process [6].

Fig. 28 Comparison of ECM micro drilling techniques in steel with EDM, laser and twist a) – b) ECM drilled micro hole and cross sectional view [7], c) – d) EDM drilled micro hole and cross sectional view [31], e) – f) laser drilled micro hole and cross sectional view [6, 33], g) – h) conventional-twist drilled micro hole [26].

Chemical machining or electrochemical machining is actually a thermal-free process which obviously results in no micro crack or thermal residual stresses remaining on the machined surface [250, 256]. The major drawbacks of ECMD are the failure of tool insulation and stray removal. Insulation failure in ECMD occurs primarily due to clogging in the holes because of the use of salt electrolytes. The stray removal that generally occurs on the internal side wall of the holes has a considerable effect on the reliability of the process [6]. In addition, the precision it offers is not as that of conventional micro drilling. The biggest markets for ECMD products are mainly electronics, medicine, automotive, optics, biotechnology, communications, and avionics industries. Typical examples include pressure sensors, compact disk players, air bags and ink jet printers.

5.4 Electron Beam micro drilling

Electron beam micro drilling is a thermal drilling process performed under vacuum conditions [257]. This is necessary because when the beam comes in contact with air, it may react with the air molecules and will lose energy. In the EBMD process, the cathode is connected to a high voltage power supply that produces the required electrons. Then the speed of the electrons is accelerated with the help of an electrical field applied between the cathode and anode at a very high potential difference. A modulating electrode is used to control the intensity of EB. Fig. 29-a shows the schematic of the full process. After being generated, the highly accelerated and concentrated EB are focused on the specimen by means of an electromagnetic lens. The energized beam instantly melts and vaporizes the workpiece material at the point of impact. Typically within just a few thousands of a second the EB drills a fine channel

through the specimen. Fig. 29-b presents the steps involved in creating the holes. At the reverse side, a backing material is used to drive out molten material and help keep the hole size uniform. As soon as the EB penetrates through the specimen, the backing materials react to the beam and produce a very large volume of gas which blows up the molten material out of the drilled hole [257–262].

Fig. 29 Electron Beam Micro Drilling (a) schematic of operational set up, (b) EBMD process, and (c) Typical example of EBMD [35, 36]

Karl Steigerwald discovered the process accidentally when he was working with a high resolution electron microscope in 1948 [93]. Soon after that he developed a micro drilling system at Carl Zeiss, and later a company in the name of Steigerwald Strahlechnik was founded which produces micro holes ranging from 50 μm to 1 mm [260]. Electron Beam (EB) drilling is similar to laser drilling in that the energy is generated and accurately focused on the specimen to melt and vaporize the drilling area. Today's cutting edge technology of EB involves two basic types of operations, single pulse mode called "perforation" and a multi pulse mode used to expand the hole shape. The perforation type micro drilling technique, however, is more extensively used due to a higher productivity rate when compared to laser, EDM or ECM.

Cost comparisons among different micro drilling techniques are difficult, considering the varied nature of these processes and the variation of post processing procedures that may be necessary [6]. For holes with low aspect ratios, the cost of EDM, ECM and conventional, is low, however, for higher aspect ratios their cost increases abruptly. Fig. 30 presents one such cost comparison on the basis of relative percentage taking into account the varying ranges of the aspect ratio values. The comparison is performed for micro holes in the range of 250–750 microns diameter drilled individually and with no allowance for deburring or for secondary operations [24].

Though the basic principal of EBD was invented long ago, the production of micro drills on a mass scale using this technology is comparatively new. In future, this method has a large potential particularly in

those applications where more than 10,000 holes are necessary in a single part. As material hardness is not an issue, for drilling micro holes in difficult-to-cut and complex shape parts EBD can be one of the best choices.

Fig. 30 EBMD hole array and cross sectional view of 0.5 mm thickness steel sheet a) SEM images of entrance , b) SEM images of exit holes, c)-d) cross sectional view of micro holes [24].

5.5 Spark Assisted Chemical Engraving micro drilling

The mechanism of SACE micro drilling is based on electro chemical discharge, and machining takes place on account of thermal assisted etching. As shown in Fig.-26, two electrodes are employed, the bigger one acts as a work piece and smaller one as tool, in an electrolyte solution typically made of 30 wt% NaOH. A potential difference is applied between cell terminals, when it reaches to a critical value (typically 30 V), bubbles grow up densely in the tool-electrode zone and coalesce into gas film. This electrochemical discharge causes the temperature to rise about 500–600 °C in the machining zone. This quickens the etching process of the work piece by means of OH radicals supplied in the electrolyte solution. The reaction that takes place is mentioned in Fig. 17 [39, 263–266].

Figure 31 Typical mechanism of SACE micro drilling [39]

Spark Assisted Chemical Engraving (SACE) is also known as Electro Chemical Discharge Machining and Electro Chemical Spark Machining. The system was developed by Kurafuji et al. in 1968 [73], for glass micro holing, but later was adopted to machine other non-conductive materials such as quartz, and ceramics. Micro drilling in glass substances is a challenging task and this is particularly the case with high aspect ratio micro drilling. The reasons for this are the brittleness and the nonconductive nature of glass. Traditional micro drilling takes relatively longer time, and achieves poor surface quality. On the other hand, thermal processes such as like laser micro drilling, can provide better performance on account of machining speed but frequently face the difficulty of abating heat affected areas, and of causing micro cracks. Chemical etching procedures are also not so suitable for glass micro drilling as it appears to be very slow and too difficult to generate high aspect ratio micro holes. In this regard SACE which is based on thermal assisted etching can provide a promising solution to micro drilling in brittle materials. The limitation it has is that the technology is mostly suitable for brittle materials only. More study is needed for it to be utilized for mass production in industrial point of view [73, 263, 267]. Fig. 32 shows an example of micro holes obtained by SACE. Gao et al. [10] have machined micro holes on a 2mm thick Pyrex glass plate with the help of a 200 μm tungsten carbide tool and achieved a micro hole of entrance and exit diameter 245 μm and 210 μm respectively with an aspect ratio of 8.8. As can be observed from the figure, the quality of hole is suffered by poor roundness and presence of micro cracks, however, the cross sectional view reveals that the hole is comparatively straight.

Fig. 32 SACE drilled micro holes on Pyrex glass a) cross sectional view, b) entrance, c) exit [10].

Till date two strategies are used for SACE micro machining, gravity feed and constant velocity feed micro drilling. Gravity feed is found to be the most popular among researchers, wherein a constant force is applied on the tool-electrode. This strategy has been shown to be very successful in micro drilling of a diameter of 200 μm , with minimal surface cracks. This is especially true if it is combined with tool-rotation and pulsed voltage application, it provides appreciable surface homogeneity. A limited amount of research has been done on constant velocity feed micro drilling. Investigations into the kinematics of the tool on micro drilling performance employing various tool rotational speeds as well as feed rates, are seen as major concerns. Electrolyte use has been found to be influential on the geometry

of micro holes in terms of entrance and exit diameters. The ability of constant velocity feed micro drilling to generate complex shaped products, for instance micro-threads used for removable tubing interconnections, has drawn certain attention towards deeper investigation of this micro drilling method [10, 11, 39, 268, 269].

5.6 Micro drilling by virtue of ultrasonic vibration

Ultrasonically assisted machining technique was first introduced by Kumabe et al. [11, 270]. After invention, the technique has been using for machining and cutting purposes. Nowadays, however, many researchers are working to use this technology to produce micro holes. It employs an ultrasonic (US) vibration either to oscillate tool or workpiece with a frequency higher than 20 kHz. Fig. 33-a shows a typical schematic diagram of ultrasonic micro drilling process. Fig. 33-b illustrates the oscillation of tool while workpiece is fixed. Fig. 33-c shows the vibration of work piece while tool is rotating in a fixed position.

Fig. 33 Ultrasonic micro drilling, (a) US machining process set-up, (b) Tool vibration, and c) WP vibration [11, 12]

Advancement in the arena of micro drilling includes the usage of ultrasonic vibration. This can be used individually to produce a miniaturised hole or can be added to another fundamental perforation technique, either conventional or non-conventional. This feature is very effective in improving machinability e.g. excellent quality of the hole surface, it produces high aspect ratio, reduces the cutting force and facilitates chip removal. Typical examples of applications include high precision medical equipments, Micro Total Analysis System (μ -TAS), Micro Electro Mechanical System (MEMS), lab on a chip devices and many others [11, 12, 271–273].

Chern et al. [14] examined the effects of ultrasonic oscillation on the micro hole quality of AL 6061 by means of a 0.5 mm diameter twist micro drill (Fig. 34 (a)–(d)). Fig. 34 (c) shows that the burr formation

on the hole periphery significantly reduced compared to without vibration as shown in Fig. 34 (a). Fig. 34 (d) reveals that the surface finish on hole wall also improved considerably because of US. In addition, they figured out that the oversize, roundness and centre displacement of drilled micro-hole centre have been improved in ultrasonic vibration micro drilling. Hung et al. [12] produced micro holes inside a high nickel ally using a helical micro-tool by micro-EDM combined with ultrasonic vibration. They were able to significantly reduce EDM gap, taper and machining time for deep micro-hole drilling. They also produced holes with higher surface quality. Aziz et al. [274] conducted ultrasonically assisted micro drilling for stainless steel by employing micro long flat drills of a diameter 20 μm . They were able to enhance the performance of the tool when ultrasonic vibration was applied. Rusli et al. [275] examined the performance of micro drilling by means of ultrasonic assisted ECM in a glass substrate. They found that ultrasonic vibration has three effects, changing the discharge characteristics by varying the gas bubbles and formation of gas film, improving electrode circulation by the use of a high pressure electrolyte, and attaching the tool electrode to workpiece. Hara et al. [11] have conducted an experiment of ultrasonically assisted micro drilling in an acrylic resin for μ -TAS. Fig. 35 shows microphotographs of cross sectional view of drilled hole and surface roughness profile. It is observed that US assisted micro hole can attain smooth and adhesion free hole wall surface; surface roughness obtained is 0.11 μmRz . In contrast, the hole surface roughness without US is 0.34 μmRz .

Fig. 34 Micrographs for comparison of micro holes in Al 6061 with and ultrasonic vibration a) top view without US, b) cross sectional view without US, c) top view with US, d) cross sectional view with US [14].

Fig. 35 Surface roughness profile of micro holes in acrylic resin a) – b) conventional micro drilling, c)–d) US assisted micro drilling [11]

The main drawback of ultrasonically assisted micro drilling technique is the slow production rate. Though the hole quality is much better than other techniques, the slow process limits the application of this technique. Processing parameters are also reported to be optimized, resulting in an abridged scope of work in the future.

5.7 Summary of non-conventional micro drilling techniques

Non-conventional techniques reported in this paper have the potential for very versatile usage in modern day applications such as medical, engineering and different branches of science. Various types of metal cutting, machining and welding are also performed using these technologies. A limited number of these technologies are devoted to conduct miniaturized perforation. The overall technological advancement is sometimes more or less than the requirement of micro drilling to meet the ongoing demands. Therefore, dedicated research into developing these non-conventional techniques is necessary to satisfy the growing needs of micro drilling.

Laser micro drilling, though it is the most popular one, has a number of drawbacks. These include poor dimensional accuracy, formation of debris or a recast layer which need to be removed, presence of thermal residual stresses causing micro cracks in the hole and higher production cost. Some of these shortcomings can be eliminated by implementing appropriate process parameters. The process parameters include the source of laser, focal length of laser, laser current and power, irradiation time, pulse width, air pressure and the condition of surrounding gas. By controlling these parameters the performance of laser micro drilling can be significantly improved.

The second popular non-conventional technique of micro drilling is EDM micro drilling. As long as the workpiece is electrically conductive, the technology can be used for any geometrical shape or difficult-to-cut materials of any hardness. Material removal during the process, however, is still a challenging task to properly control and because of this the method suffers from the problem of micro cracks and poor surface finish. As mentioned in section 5.3, in order to improve the performance of EDM micro drilling, both the process and system parameters need to be precisely controlled.

Recently, ECMD is getting much attention due to its various advantages such as higher material rate, inexpensive set-up, higher production rate compared to EDM and environmental friendliness. Tool insulation and stray removal are still a big challenge for this technology. Dimensional accuracy is also still not as high as the conventional one. Further investigation is needed in order to improve the system and optimize the parameters for mitigating the shortcomings of ECMD.

Electron beam micro drilling and ultrasonic vibration micro drilling are comparatively new techniques for producing micro holes. EBD is basically developed to produce bulk micro holing for complex shape or difficult to machine materials. The technology can be equipped with a programmable CNC

controlled machine. Micro drilling by means of ultrasonic vibration, on the other hand, is mainly used for producing excellent quality micro holes but this is useful for certain specific applications. The feature can be added to other types of micro drilling methods in order to achieve a superior quality hole wall surface.

5.8 Comparison of different non-conventional micro drilling techniques

Table-4: Comparison of the capabilities of non-conventional micro drilling techniques

	Laser	EDM	ECM	SACE	EBMD	Ultrasonic
Hole size(μm)						
<i>Common</i>	50 – 400	> 100	> 50	> 300	80 –200	100 – 500
<i>Min</i>	1 [276]	5 [242, 277]	8 [278]	200 [266]	50 [258]	5 [279]
Aspect ratio						
<i>Typical</i>	10 : 1	10 : 1	8 : 1	5 : 1	10 : 1	10 : 1
<i>Max</i>	600 :1 [280]	30 : 1	250 : 1	8.8 : 1	25 : 1	31 : 1
Drilling speed						
<i>Common</i>	0.1 – 3 (s/hole)	0.01 (mm^3/m)	0.125 mm/s	0.03 mm/s	10 holes/s	N/A
<i>Max</i>	0.001 s/hole	0.06 (mm^3/m)	0.83 mm/s	0.1 mm/s	3000 holes/s	N/A
<i>Speed comparison</i>	Fast	Slowest	Medium	Slow	Fastest	Slow
Surface roughness (inside hole)	Roughest	Rough	Medium	Medium	Rough	Smoothest
Edge profile	9 –45 μm recast layer	6–12 μm recast layer	No	No	5 μm recast layer	No
Operating voltage	Depends on type of laser	30 – 150	10 – 30	25 – 35	120–300 keV, between poles	25 – 60
Pulse Frequency (kHz)	0.4 – 30	80 – 800	1 – 15 (MHz)	0–0.1, negligible effect	2 – 3	20 – 60
Work material	Any, difficult-to-machine	Electrically conductive	Electrically conductive	Electrically Non-conductive	Any, hard and brittle	Harder than 40 R_c
Chip removal	Melt and vaporize	Melt and Drain by dielectric	Metal dissolute in solution	Melt and drain by electrolyte	Melt and vaporize	Carried away by slurry
Commercial availability	High	Medium	Medium	Low	Low	Medium
Complex shapes	Yes	Yes	No	No	Yes	No
Wall surface integrity	Heat affected surface	Heat and thermal affected	No residual stress	Minimal residual stresses	Heat affected	No residual stress
Advantages	– High speed production	– Complex shapes	– Excellent surface	– Suitable for brittle	– Extreme high speed production	– Increase relative cutting Speed

	<ul style="list-style-type: none"> - High aspect ratio - Localised treatment capability, - Operational precisions, - Reduced costs comparing to lithographic technique 	drilling <ul style="list-style-type: none"> - Difficult-to-machine materials - Negligible cutting force - Availability of electrodes - High aspect ratio 	quality <ul style="list-style-type: none"> - inexpensive setup - Higher production than EDM - No tool wear - no residual stresses, better precision and control, - Environment friendly 	material <ul style="list-style-type: none"> - Better surface qualities - Operational Simplicity & flexibility, - High, aspect ratio, - Low structural damage (micro-cracks) 	<ul style="list-style-type: none"> - Automatic - Complex shape - Can be precisely focused - No contact between tool and work - No Tool wear - No physical damage to work piece. - Machining any material 	<ul style="list-style-type: none"> - Better lubrication between tool and workpiece - irregular contact reduces temperature - excellent surface quality - Easy chip removal
Disadvantages	<ul style="list-style-type: none"> - Poor hole quality - Higher production cost - Expensive setup 	<ul style="list-style-type: none"> - Less control on material removal mechanism - Unstable nature of machining - Poor surface quality - Quick tool wear - Slow production - Electrode cost 	<ul style="list-style-type: none"> - Difficulty in tool insulation & stray removal - Less precision - Not suitable for complex shape 	<ul style="list-style-type: none"> - only suitable for brittle materials - Difficulty in flushing machining spot - only suitable for non-conductive materials 	<ul style="list-style-type: none"> - High initial investment - Skilled operators needed - Poor hole quality - Higher Power consumption - Limited size of w/p - Limited accuracy 	<ul style="list-style-type: none"> - Slow production rate - Not suitable for complex shape

6 CONCLUSIONS AND RECOMMENDATIONS

In this work, the cutting edge technologies used for micro drilling in wide variety of different applications, have been listed and reviewed. The techniques are classified into two broad categories, conventional and non-conventional. The conventional method is to employ a micro drill bit of different shapes and geometric configurations. There are six types of conventional micro drilling. These are twist, spade, D-shaped, single flute, compound, and coated micro drill. Of these six types, the twist type micro drill is the most popular one. The detailed manufacturing steps of twist micro drill are described in this study. *The key factors that play important role in successful micro drilling operations are presented and explained with graphical examples.* The techniques that do not require a drill bit are called as non-conventional micro drilling. Six types of non-conventional micro drilling techniques have been reported in this study; which include Laser, EDM, ECM, SACE, EBM and Ultrasonic vibration micro drilling. Each of the techniques is discussed *with figures* by explaining their working principle, pros and cons, challenges and future prospects. Out of all the non-conventional techniques, laser micro drilling is found to be the most popular one. *Two synoptic tables are presented in order to compare and contrast various features, advantages and disadvantages of different methods for both conventional and non-conventional micro drilling techniques. The key recommendations that can be drawn from this study are summarized as follows.*

- Due to size effects, the behaviour of conventional micro drills is different from that of macro drills, as micro drilling parameters (such as shape and geometry of the micro drill, tool point angle, helix angle, chip formation and removal, effect of coolant used, starting hole or spot drilling, and favorable cutting conditions i.e. spindle speed and feed rate) need to be very carefully designed. Getting aid from today's advanced simulation software to optimise these parameters is highly recommended before manufacturing it in order to save time, effort and cost [2, 60, 281].
- As the material of conventional micro drills plays a significant role in their performance and durability, choosing the correct material is very important. Using micro grain and ultra-fine grain powder in order to produce micro drills can provide excellent quality materials with superior hardness and wear resistance. Corresponding powder metallurgy can also be simulated by virtue of molecular dynamics or powder simulation [28, 117, 282].
- Conventional micro drills are fabricated by means of an abrasive grinding. This involves several manufacturing steps, requiring a precise grinding wheel and machine, consuming higher labor cost and longer time. Developing an innovative direct micro forming method, by virtue of which, micro drills of any types could be made in a direct powder solidification-extrusion forming method without the usage of a grinding wheel, would be able to save both cost and time.
- Conventional micro drills are usually made of tungsten carbide and high speed steel. WC, in particular, is the most popular one due to its superior mechanical properties for instance high hardness, better wear resistance, and higher melting point. The problem of WC, however, is that

it is brittle and often cause breakage of a tool. A composite micro drill of outer material WC to provide adequate hardness and wear resistance, and a high strength steel inner material to provide strength for withstanding the breakage, could significantly improve the tool life and thus save a considerable amount of cost [116, 283].

- Spade type micro drills can be very promising in the case of micro drilling of a diameter less than 10 μm . This is basically due to manufacturing simplicity. This means that further investigation into this type of micro drilling has great potential [21, 274].
- D-shaped micro drills are necessary in some precision applications. However, manufacturing ultra-small D-shaped micro drill still remains a challenge. Usually they are fabricated by EDM. Development of a grinding set-up for making such tiny D-shaped micro drill, even better producing them by a direct forming method could be an interesting area of research, by avoiding the expensive arrangement for EDM [13].
- Non-conventional techniques often encounter problems in terms of quality, cost and time. On the other hand, no fundamental micro holing technologies have recently been discovered. This means that, a hybrid machining process combining more than one process could solve many difficulties. Researchers have already begun investigating the results of the combined methods, but there is much research still to be done.
- Due to the advantage of high speed, laser micro drilling has always shown to be a good choice in industrial application. The drawbacks of poor surface finish, recast layer and spatter formation can be reduced by optimizing the process parameters as discussed in section 5.7 [199, 202, 284].
- Short pulse e.g. femtosecond laser micro drilling are gaining much attention in these days, due to the advantage of minimal spatter, micro cracks and recast layer formation. The expensive source of solid state lasers can be replace by comparatively less expensive fiber laser [48, 204, 206].
- EDM micro drilling is suitable for any geometrically complicated parts as long the specimen is electrically conductive. With the current advancement, the technology is still lacking an improved method for material removal, increase the production speed and minimize the electrode wear. In addition, presence of micro cracks and poor roundness require much investigation to improve the hole quality [5, 231, 239].
- ECM in contrast to EDM facilitate high material removal rate. This method is also chosen for environment friendliness. However, insulation of tools and stray removal still remain a major challenge for this technology [254, 256, 285].
- For bulk production of micro holes, where high quality of hole is not essential, EBMD is a better choice. The technology is preferable for complex shape parts or difficult-to-cut materials. EBMD is not so popular yet in the market, only a few machines are available in the world, however has a great potential to catch the market in the future [258, 261].
- In the applications where ultimate quality of holes are required, ultrasonic vibration micro drilling is the best option. A wide variety of tool type and size can be employed in this approach. The technology, however, is limited by its slow production rate. To increase its applicability, further investigation is necessary in order to improve the production rate [11, 286, 287].

- In conclusion, since the market is so vast facilitating a number of alternatives, to select an appropriate technology for micro drilling not only necessitate deep understanding about the available technologies, but also a number factors that need to be carefully considered. As mentioned in section 5.4, the cost comparison may be difficult in the beginning, therefore, the technology suitable for workpiece material and requirement of hole quality need be considered prior to cost estimation. For the specimen made of difficult-to-machine material or complex shape, a non-conventional micro drilling technique is recommended. If the production volume is large, a laser or EBMD will be a good choice for this type of materials. Hence, EBMD is used for limited aspect ratio, whereas laser micro drilling can be employed for obtaining high aspect ratio. However, if the hole quality also has to be considered, a f_s laser is more preferable. To reduce the cost fiber fs laser can be used. For lower production volume and medium quality of hole EDM or ECM can be chosen, if the specimen is electrically conductive. ECM is found more environment friendly and able to attain high aspect ratio. For non-conductive or brittle type material such as glass or acrylic, SACE is suggested. For other type of materials such as metals, polymers, PCBs, composites and woods, conventional micro drilling is suitable. When the diameter of a hole required goes down to 10 μm , spade or D-shaped type micro drill can perform the function. For the materials of hardness more than 40 R_c , US assisted micro drilling can provide excellent quality of micro holes. In the case when the quality of hole can be compromised, employing a coated micro drill can reduce the tooling cost significantly.

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