

Analysis of Small Holes Manufacturing for Optomechanical Components

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Small holes can be manufactured by several ways. It is important to define in what dimensions the small holes vary. Anyway, drilling is one of the oldest technologies of holes manufacturing. In small dimensions we use the term microdrilling for description. Beside this conventional way of manufacture there are also unconventional methods. Microdrilling bits very often break before they are worn. Therefore, the tool life of these bits is quite unexpectable. It is due to relatively high load against the drill bit strength. So, it is important to choose proper drill bit material, cutting geometry, construction, process liquid, clamping and cutting conditions. These parameters are important for achieving ideal conditions for microdrilling. Even a tiny change in pre-set parameters can lead to destruction of these delicate tools. Fiber arrays are designed and manufactured for precise positioning of optical fibers in row (1D) or in plate (2D). Fiber arrays can contain most of fibers including polarization maintaining fibers (PMF).

Keywords: microdrilling, microdrilling bit, optomechanics, fiber array

1 Conventional and unconventional methods of small holes machining

Small holes can be manufactured by many ways. It is important to define in what dimensions the small holes vary. Anyway, drilling is one of the oldest technologies of small holes manufacturing. Beside the conventional ways of manufacturing there are also unconventional methods. Review of technologies is in table below (Tab.1.).

Tab. 1 Technology review

Conventional methods:	Unconventional methods:
Spiral micro drill bit	Laser
Spade micro drill bit	Electron beam
D shaped micro drill bit	Ultrasonic vibrations
One flute micro drill bit	EDM
Step micro drill bit	ECM
Coated micro drill bit	SACE

1.1 Conventional technology – micro drilling

Drilling is type of chip forming process where blind or throughcoming holes of given diameter in different materials are made. For drilling we use drill bits tools and drilling machines as machine tools.

Microdrilling comes out from simple drilling and is different in the size of drilled holes. There is no given limit value but generally we can say that machining of holes 1 mm in diameter and smaller is considered as microdrilling. Companies define the holes diameter by themselves.

Term „microdrilling“ was introduced as result of

task where the hole size was in few micrometers. Exact definition of microdrilling relates to diameter with no specific size. Each manufacturer and researcher define hole diameter different way with no specific standard. For example, Small hole drilling company declares their ability to microdrill holes from 0.03 mm up to 2.99 mm with precision of placing and depth of drilled hole ± 0.01 mm. The Rotana company presents diameters from 0.1 mm up to 3 mm. Zheng and co. States that micro drill bit diameter varies from 0.03 mm up to 1 mm. In these cases, we can see, that the definition is different for every company and researcher. Therefore, it is good to keep the common definition to prevent ambiguity between many opinions. Based on many studies we can say that microdrilling is drilling where the hole diameter is smaller or equal to 1 mm [1].

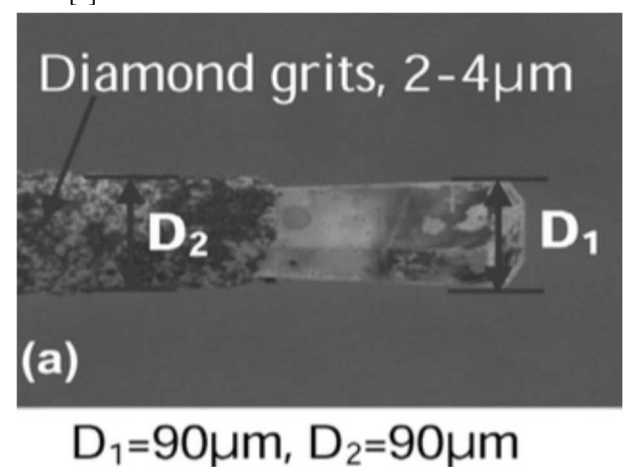


Fig. 1 Combinatory microdrilling bit with diamond coating [2]

1.2 Unconventional technologies

Advantage of laser beam – as one of unconventional methods – are mainly in its applicability on wide area of materials that are not possible to manufacture with other methods or it is difficult to do so. Materials like glass, ceramics, polymers or kevlar and carbon composites. [3,27]

Basic characteristic properties of laser beam are the coherence, monochromaticity and low divergency of beam. These properties allow us to focus the laser beam into small point and achieve high areal energy density (up to $10^8 \text{ W}\cdot\text{cm}^{-2}$) that is important for part machining. [5,28]

Most often used types of lasers for drilling and microdrilling are solid-state Nd-YAG and Yb-YAG lasers or neodymium-doped (Nd) or Ytterbium-doped (Yb) yttrium aluminum garnet laser. Both are slowly replaced by CO₂ lasers with same effectivity but smaller heat affected area. The wavelength of these lasers is around 1060 nm with a minimum drilled hole diameter of 0.1 mm and an accuracy of 0.001 mm. [4]

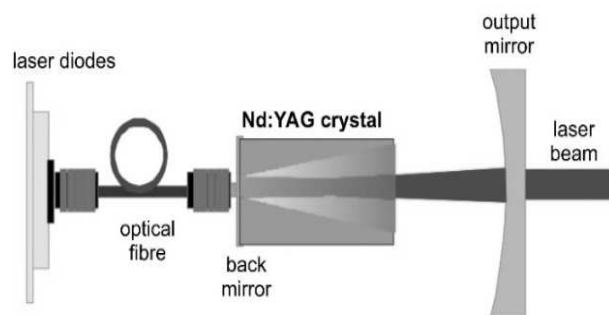


Fig. 2 Diagram of a solid-state Nd:YAG laser [6]

For microholes is currently available for example the technology of microEDM (electroerosive machining), laser, mechanical drilling etc. Among these technologies the EDM is one of the most effective unconventional technologies. It is a non-contact process, suitable for machining very hard and very strong materials, so called HRSA materials (otherwise considered to be „Difficult to cut“ materials). With this method we can create both holes and difficult 3D shapes. In this method electric discharges are created that are moving between the tool (one electrode) and conductive workpiece material (other electrode) that is submerged into dielectric liquid. Heat that is created with sparks allows melting and evaporating the workpiece material and eroding the electrode [7].

As already written it is a very effective method for drilling of deep holes but extensive use in mass production is currently not possible. The main reason is the unstable nature of this process, control of fragments removal, tool wear and low material removal rate. The main disadvantage of this process is the tool wear that is caused by high heat that leads to increase

of cost of manufacturing. On the contrary the advantage is the ability to make complex shapes with high precision, lack of mechanical forces and deformations. For characterization of output of this process from the erosion speed point of view we use the so called Material removal rate (MRR). For the reason of above stated disadvantages is necessary to precisely select the working condition for effective working process. Among the factors that influence the effectivity belongs i.e.:

- Process parameters (voltage, current, pulses)
- Type of dielectric liquid
- Tool properties
- Material properties [7,8]

For that reason experimental research is made in order to improve the EDM process. For example it was discovered that the thermal properties of workpiece material affect the quality and precision of holes. In this experiment was compared sintered carbide (WC-Co) and stainless steel (SUS 304). Properties like low thermal conductivity, high disposition to quenching and high ductility under increased temperature are lowering the quality of drilling and dimensional stability by their unstable process (lower the MRR). [7]

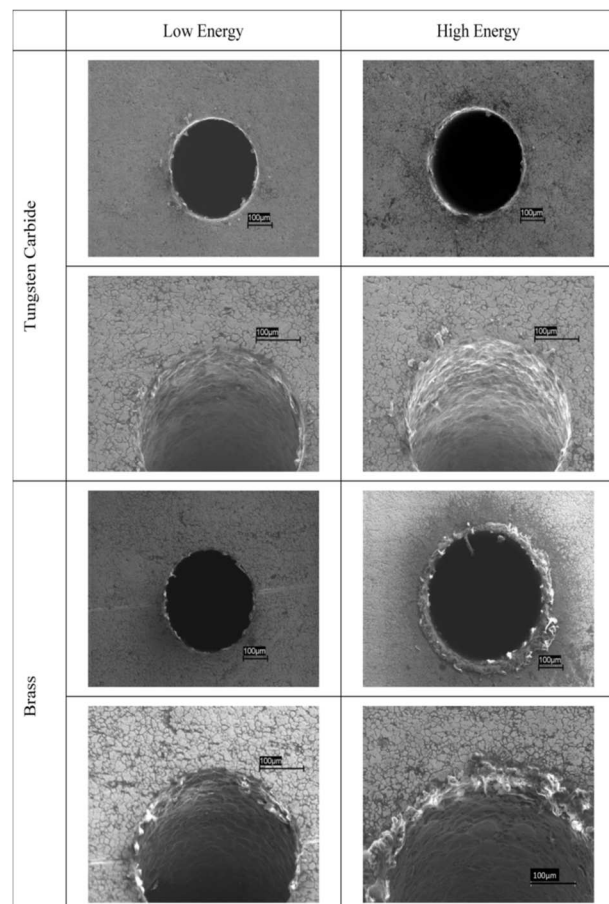


Fig. 3 Micro-drilled holes for different energies and electrodes [7]

Technology of drilling with use of electron beam uses kinetic energy of the stream of accelerated electrons. The essence of this method is transformation of kinetic energy from the electrons that hit the surface into thermal energy leading to melting of surface. Material is evaporating from surface and continually deepening hole is created. Beam penetrates the surface and stops in certain depth. Generated thermal energy concentrates under surface and causes the eruptive evaporation of material.

Vapours from evaporated material are ionized and cause new foculation in the place of impact. Characteristic feature of this method is significant ration between width and depth of hole.

Working mode is contact of electron beam with surface of workpiece. We recognize continual or pulse work mode. Exact drilling is achieved with use of the pulse mode where the pulse time is from 2 μ s to 0.01 s with pulse frequency 500 to 10 000 Hz. [9,10]

Electron beam is often used for microdrilling. Minimum hole diameter is stated to be 0.015 mm. Such thin holes are drilled with high speed and it is possible to make up to 4000 holes per second. At deep hole drilling with ratio of length to diameter up to 100 it is necessary to use the beam with diameter 2x up to 4x smaller in comparison to drilled hole diameter. Tolerance of the drilled hole diameter is from 5 to 20 % of its diameter. [10]

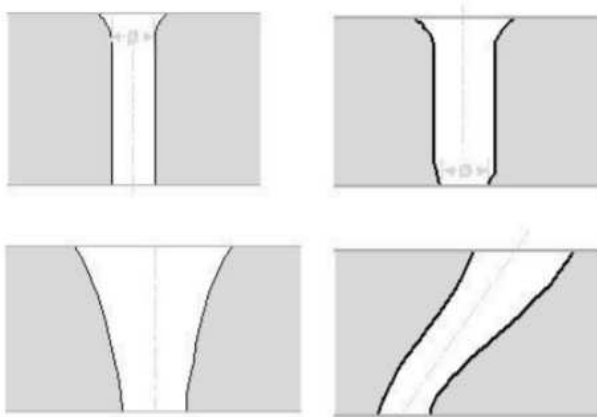


Fig. 4 Profiles of holes made with the “drill on fly” method [13]

The „drill on fly“ method is using the electron beam and it exact bending against the workpiece. If the beam during one pulse is focused on the same place of impact it will create the hole with round diameter. Change will happen with changing place of impact by using relative movement between the laser beam and machined workpiece. In this case we achieve a non-rotational hole. With this method we can create complex shape surfaces in holes. [11,12]

Source of electrons is autoemission or thermoemission. Autoemission sources are emitting electron from cathode due to action of strong electric field.

Disadvantage of autoemission is need of ultra vacuum that causing more abundant use of thermoemission. At thermoemission the electron beam is generated from surface of cathode heated to high temperature. The so called „electron gun“ is formed by heated tungsten cathode and anode. Electrons emitted from cathode are accelerated with appropriate anode to the speed equal to 2/3 of the speed of light.

Generated electron beam must be focused to the smallest possible area to increase the energy density. Foculation is made with use of electromagnetic lenses. The resulting energy density is approximately $10^8 \text{ W}\cdot\text{cm}^{-2}$. [10,11]

Electrochemical machining (ECM) is a method of chipless machining of materials that are electrically conductive. This method is using the knowledge of impact of electric current to electrolyte. The principle is based on the physical phenomenon called electrolysis. Electrochemical machining is further connected with Faraday's laws, thermodynamics of galvanic cells and theory of electrolytes. [14]

The workpiece connected as anode is merged into the electrolyte. With closed circuit we get a reaction where the cations of electrolyte are reacting with anions of metal and thus removing the metal from anode. Tool (cathode) is copying the shape of the wanted product.

The removal rate depends on several factors:

- Smallest possible gap between the electrodes and keeping it at constant value for the whole time (cca 0.05 to 1 mm)
- Temperature
- Flow rate
- Electrolyte structure (typical using NaCl, NaNO₃, HCl, NaOH)

Materials that are considered to be badly machinable with the electromechanical machining are the alloys with higher content of carbon, dural alloys with silicon and grey cast iron that is almost unmachinable.

Holes with diameter smaller than 1 mm in materials that are difficult to machine are possible to manufacture with following methods of electrochemical machining:

- Electrolytical drilling with shaped tube (STEM = Shaped Tube Electrolytic Machining)
- Fine electrolytical drilling (ECF = Electrochemical Fine drilling)
- Electrolytical drilling with a focused stream of electrolyte (ESD = Electro-stream drilling) [13]

Ultrasound supported technology is ideal for machining of hard and brittle materials. This process is working effectively if the hardness of machined materials is higher than 40 HRC. [15]

Principle of ultrasonic machining is based on moving the tip of tool with ultrasonic vibrations and on dosing the abrasive suspension into the machining area. Abrasive particles in the machining area are getting the energy with ultrasonic oscillation along their axis. Oscillating tool is forcing the abrasive particles to hit the machined surface in the gap between the tool and the workpiece and to machine the work area. At the ultrasonic machining the material is removed in the form of microparticles that are formed with radial and lateral microcracks. [15,16]

Researchers in studies [17],[18],[19] described three basic mechanisms of material removal – mechanical abrasion as result of:

- Direct embossing of big abrasive particles – percussive effect
- Impact effect of smaller free moving abrasive particles in gaps created by bigger abrasive particles (called the „working gap“)
- Cavitational erosive effect where the gas bubble is collapsing in the working gap by absorbing the energy of ultrasonic vibrations

This process is used mainly for cutting and machining. In present many scientists are working on use of this technology also to manufacturing of microholes. At ultrasonic microdrilling are used the ultrasonic vibrations with frequency higher than 20 kHz to oscillate the tool or workpiece. Figure 5 (a) is showing the typical diagram of ultrasonic microdrilling process.

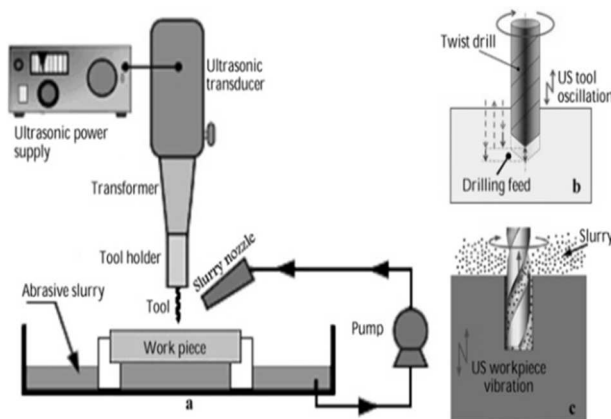


Fig. 5 Ultrasonic microdrilling

a) Setup of the machining process, b) tool oscillation a c) workpiece oscillation [20]

Figure 5 (b) is showing the tool oscillation when

the workpieces is fixed in position. Figure 5 (c) is showing the workpiece oscillation where the tool is rotating in fixed axial position. [20]

Main disadvantage of the ultrasonic microdrilling is low speed of drilling process. Although the hole quality is much better in comparison to other technologies the slow process is limiting the use in praxis. [20]

Chemical engraving with use of sparks (SACE – Spark assisted chemical engraving) that is also sometimes called ECDM – electrochemical discharge machining and ECSM – electrochemical sparks machining are examples from many technologies of micromachining of glass and ceramics. This unconventional technology is based on electrochemical discharges. [21]

Mechanism of microdrilling with SACE is based on electrochemical discharge. The drilling itself is made with thermal etching. Two electrodes are used where the smaller electrode is the tool that machines the workpiece and the bigger one is counter-electrode in the electrolytic solution created mostly with 30% mass solution of NaOH. [22,23]

Electrochemical discharges are present when the voltage is higher than the critical value that is depending of the geometry and concentration of used electrolyte. Typical values of critical voltage are around 30 V. As soon as the critical voltage is reached first bubbles are generated in the area of tool electrode. They start to grow rapidly and gather to create the gas film (layer) that isolates the tool electrode from electrolyte. Electrical field in this gas film is quite high (regularly 106 - 108 V / m), to allow the electrical discharges between the electrode of electrolyte. Heat generated by these discharges and most probably some chemical etching are working together on eroding the workpiece. Workpiece must be placed in close distance from electrode (less than 25 μm for glass). [24]

Microdrilling to glass is difficult task and moreover in case of microdrilling with high sides ratio. The reason is the brittleness and non-conductive nature of glass. Traditional microdrilling takes relatively longer and achieves lower surface quality. On the other hand the thermal processes like laser microdrilling can provide higher output with respect speed of machining but there are often present problems in heat affected area and microcracks generation.

Procedures of chemical etching are also not suitable for microdrilling of glass because they are slow and difficult for making microholes with high depth-diameter ratio. From this point of view the SACE technology that is based on etching using the heat provide a promising solution for microdrilling in brittle materials. Limitation of this technology is that is suitable mostly for brittle materials.

Tab. 2 Comparison of individual technologies

	Laser	EDM	ECM	EBMD	SACE	Ultrasonic
Hole Ø	[µm]:					
normally	50-400	>100	>50	80-200	>300	100-500
Min.	1	5	8	50	200	5
L-D ratio:						
Normally	10:1	10:1	8:1	10:1	5:1	10:1
Max.	600:1	30:1	250:1	25:1	8.8:1	31:1
Drilling speed [mm/s]:						
Normally	<1	<0.05	<0.125	<1	0.03	-
Max.	6000	0.1	0.83	18000	0,1	-
Surface roughness:	roughest	rough	moderately rough	rough	Moderate rough	smoothest
Workpiece material:	Any difficult to cut	Electrically conductive	Electrically conductive	Any hard and brittle	Electrically non-conductive	Harder than 40 HRC
Chip removal:	Melting and evaporation	Melting and washing with dielectric	Metal dissolving in solution	Melting and evaporating	Melting and washing with electrolyte	Removal with suspension
Advantage:	High speed	Drilling of complex shapes	Better surface quality	High speed	Suitable for brittle material	Excellent surface quality
	High accuracy	Materials difficult to cut	Faster than EDM	No tool wear	Simple and flexible equipment	Better lubrication between tool and work-piece
Disadvantage:	Poor quality and hole rounding	Lower control of material removal mechanism	Less precise	High initial investments	Suitable only for brittle materials	Low speed
	Cost of equipment and its maintenance	Rapid tool wear / electrode costs	Not suitable for complex shapes	Need of qualified operators	Suitable only for nonconductive materials	Not suitable for complex shapes

2 Microdrilling

In previous chapter the term microdrilling was defined. This chapter is about specifications, strategies and sequence of operation steps. At the beginning it is

need to define cutting tools that are necessary for this technology.

Microdrilling bits often break before they get worn. Therefore, the tool life of these bits is quite unpredictable. It is caused by quite big load against its

strength. Therefore it is important to choose wisely the drill bit tool material, the cutting geometry, construction, cooling liquid, clamping and cutting conditions. These parameters influence the ability to maintain ideal conditions for microdrilling. Even a negligible change of parameters can lead to destruction of these delicate tools.

Microdrill bit geometry significantly influence the way how the microdrilling bit operates. According to differences in cross-section profiles the drill bits are ordered in three groups. First groups with diameter from $0.5 \text{ mm} < d < 1 \text{ mm}$ has similar shape as normal drill bits. In second group with diameters from $0.2 \text{ mm} < d < 0.5 \text{ mm}$ the drill bits have the same diameter on whole surface. In third groups belong all drill bits with diameter $d < 0.2 \text{ mm}$ with reduced shank. According the manufacturers is best choice to use drill bits with point angle value in range from 120° to 130° for harder workpiece materials and around 90° for softer materials. Another important factor is the helix angle that is usually 30° . Another issue is the friction that should be the lowest possible not to increase the temperature. Flutes (grooves) are quite tiny that causes bad flow of chips and thus higher probability of temperature increase. Another important factor is also the length of helix because with increasing length the drill bit rigidity lowers.

A lot of different microdrill bits types are available in the market. Mostly often are used spiral drill bits, spade drill bits and D shaped drill bits. Most complex but also most suitable shape of cutting part has the spiral drill bit that is also most demanded on market. Spade drill bit and D shaped drill bit are in comparison much simpler and easier to manufacture. They have limited cutting properties and therefore they are rarely used.

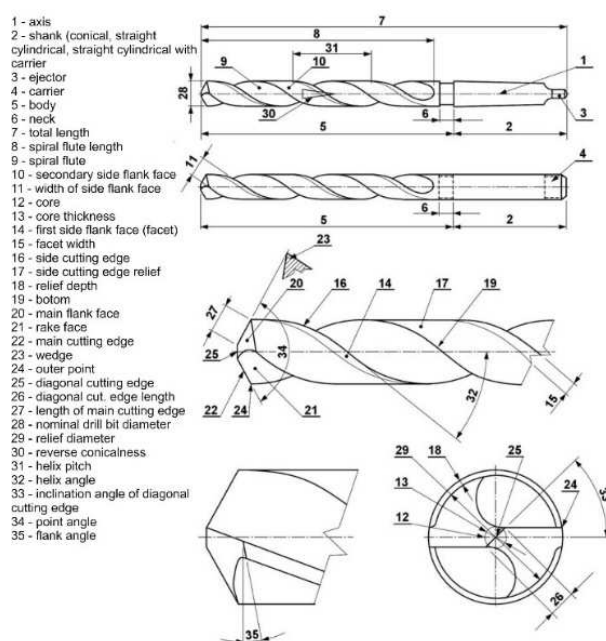


Fig. 6 Tool features description [25]

3 Optomechanical parts – fiber arrays

Fiber arrays are made for very accurate positioning of optical fibers in a row (1D) or in a plane (2D). Fiber arrays may be made with most types of fibers including polarization maintaining (PM) fibers. Fibers end faces at fiber arrays may be polished at different angles according their application. The thickness of cover glass at 1D fiber arrays may be thinned up to $150 \mu\text{m}$ and the end faces can be covered with reflex or anti-reflex layers as well as by lens array. 2D fiber arrays can be housed in metal flanges and the other side of fibers may be terminated by optical connectors.

Fiber arrays are made of glass. Into sanded/polished glass discs are pulse lasered precise holes into with are subsequently sealed optical fibers in various patterns. Then the front face of the whole array is sanded/polished and coated with anti-reflex layer according the demand. Fiber arrays are most often made of quartz, borosilicate glass or Al_2O_3 . Fiber arrays can be according the specification placed into aluminum (anodized) respectively stainless-steel holders for subsequent attachment in given application. On assembled matrix array distances between the actual and the ideal position of fiber holes are measured. [26]

4 Conclusion

The article analyzes in detail and describes possible technologies of small holes manufacturing. These technologies are considered for use in optomechanical parts manufacturing particularly of fiber arrays. Optomechanical parts have the prescribed high accuracy and are also subject to high requirements in terms of surface quality. It is often the case that there is a prescription for SPI A1 quality in the production documentation. It is a prescription according to the standard used in the plastics industry and for the field of mechanical engineering it is defined as a super high-gloss surface. The corresponding parameter $R_a = 0.012 - 0.025 \mu\text{m}$ is given in roughness units. Dimensions are usually prescribed with a thousandth specification. Currently based on table Tab.2 that the microdrilling is the most suitable technology. As noticed in chapter 2 most used tool are spiral drill bits. Spiral drill bit is a tool designed for making holes in material. Most often we can encounter double edged drill bits with two opposite helical flutes for chip removal. Helical grooved body allows also effective cooling. Helix angle against the tool axis is selected according drilled material and is in the range from 10° to 45° . Geometry of the tool cutting edge is very important and affects the size of cutting forces, quality of machined surface and the tool life of the cutting edge itself. Future research in the field of microholes drilling will focus on use of other types of microdrilling bits on geometry of tool and use of tool materials with high precision and machined surface quality.

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