INNOVATIONS IN MICRO/NANO PATTERNING USING TOOL-BASED METHODS

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ABSTRACT: In recent years, the trend in miniaturization of products has been pervasive in areas such as information technology, biotechnology, and the environmental and medical industries. Micro/Nano patterning is the key supporting technology that has to be developed to meet the challenges posed by product miniaturization requirements and the industrial realization of nanotechnology. Micro/Nano patterning techniques can be based on energy beams or solid cutting tools (tool-based micro-machining). Tool-based micro/nano patterning is a relatively new area; however, over the last two decades, owing to the predominant trend in the miniaturization of products, micro/nano patterning using tool-based techniques has become a key supportive technology. The energy beam-based patterning process (electron-beam lithography) has some limitations due to poor control of 3D structures, low material removal rate, and low aspect ratio. Moreover, these processes require special facilities, and the maximum achievable thickness is relatively small. Some of these limitations can be overcome by a tool-based approach using ultra-precision machine tools and solid tools as cutting elements to produce the micro-features with well-controlled shape and tolerances. These micro/nano machining-based patterning techniques have been achieved through a paradigm shift in the ideas and processes of conventional machining. In this paper, an attempt has been made to present the recent innovations in tool-based micro/nano patterning processes.

ABSTRAK: Pada tahun kebelakangan ini, trend dalam pengecilan saiz produk telah menguasai pelbagai bidang seperti teknologi maklumat, bioteknologi dan industri alam sekitar dan perubatan. Pencorakan mikro/nano merupakan teknologi sokongan utama yang perlu dibangunkan bagi menghadapi cabaran keperluan pengecilan produk dan kesedaran industri nanoteknologi. Teknik pencorakan mikro/nano boleh dilakukan dengan teknik yang berasaskan rasuk tenaga atau alat pemotong yang kukuh (pemesinan mikro berasaskan alat). Pencorakan mikro/nano berasaskan alat adalah perkara yang agak baru; namun dalam tempoh dua dekad kebelakangan ini, oleh kerana trend pengecilan produk semakin berpengaruh, pencorakan mikro/nano menggunakan teknik berasaskan alat telah menjadi satu teknologi sokongan yang utama. Proses pencorakan berasaskan rasuk tenaga (rasuk-elektron litografi) mempunyai beberapa batasan kerana kawalan lemah terhadap struktur 3D, kadar pembuangan bahan adalah rendah dan nisbah aspek adalah rendah. Selain itu, proses ini memerlukan kemudahan khas, dan ketebalan maksimum yang boleh dicapai adalah agak kecil. Sebahagian daripada kelemahan kaedah ini boleh diatasi dengan pendekatan berasaskan-alat, menggunakan alat mesin ultra-precision dan peralatan yang padu sebagai elemen pemotong bagi menghasilkan ciri mikro yang mempunyai bentuk dikawal dengan baik serta had yang boleh diterima. Teknik pencorakan mikro/nano berasaskan pemesinan telah dicapai melalui satu anjakan paradigma dalam idea dan proses pemesinan konvensional. Dalam kertas ini, suatu percubaan telah dibuat untuk mengemukakan inovasi terkini dalam proses pencorakan mikro/nano berasaskan alat.

KEYWORDS: *patterning; micro-machining; nano-machining; ultra precision machining; combined machining; hybrid machining*

1. INTRODUCTION

Owing to recent trends in the miniaturization of products in areas such as information technology, biotechnology, and the environmental, medical and optics industries, the micro/nano patterning process using tool-based micro/nano machining is becoming a key supportive technology. Micro/Nano patterning using tool-based micro/nano machining includes precision machining processes such as turning, milling, and electrical discharge machining. In most of these processes, material removal is done at the micron level; however, material removal at the submicron level is also achievable using a precision diamond-tool-based machining process. The key advantages of patterning using such a process are that almost every material, including metals, plastics, and semiconductors, can be machined with no limitation for high aspect ratio. On the other hand, microstructures produced by photolithography have the limitations of low aspect ratio and quasi-3D structure [1, 2]. It is possible to fabricate high-aspect-ratio components with submicron structure by the *lithographie galvanoformung und abformung* (LIGA) process (German – a combination of lithography, electroplating, and molding) using the synchrotron radiation process and focused ion beam (FIB) machining process. However, present laboratory-scale and industrial fabrication techniques using LIGA require special and extremely expensive facilities like a synchrotron system and the machining of expensive masks that have hindered the quick and economical fabrication of micro parts. Furthermore, such processes offer an extremely low dimensional range, and often they are not required for a particular application. The major drawback of the tool-based process is the limitation on machinable sizes; however, this limitation can be overcome in some cases through a hybridized/compound machining process. For example, a combination of conventional turning and nonconventional electrical discharge machining can be used to produce micro hole patterns. Thanks to such innovations in recent years, micro patterning using micro machining has become widely accepted for various applications. Moreover, in recent years, thanks to the advance in diamond-tool-based machining, for example FTS diamond turning, high precision-level patterning has been achieved. Consequently, it is possible to manufacture high-precision master tooling for many high-precision roll-to-roll manufacturing processes. If semiconductors and optical devices can be fabricated by roll-to-roll manufacturing on large substrates, then many devices could be fabricated at a fraction of the cost of the traditional manufacturing process. All of these advances in micro/nano patterning processes have been achieved as a result of revolutionary innovations in machine tools. In this paper, an attempt has been made to present the recent advances in the machine tools and the machining processes for micro/nano patterning using a tool-based approach.

2. DEVELOPMENT OF STATE-OF-THE-ART MACHINE TOOLS

Micro/Nano patterning with a tool-based micro/nano machining process has become increasingly popular because of a growing demand for industrial products, with an increased number of functions, and with reduced dimensions, higher dimensional accuracy, and better surface finish. In order to achieve such micro/nano patterning using a machining process, it is necessary to realize a thermally stable machine tool structure. Shinno et al. presented an actual design concept of a thermally and dynamically stable machine tool structure [3]. The stable machine tool structure shown in Fig. 1 is achieved if the following attributes are present: (1) desirable structural design of a machine tool for micro- and nanometer-scale processing, (2) isolation of the error sources, (3) minimization of the error sources, and (4) control of the error sources. Key design factors to be considered include independent metrology frame, symmetric machine structure, heat flow control, minimization of Abbe offset, perfect noncontact structure, and active vibration control [3].

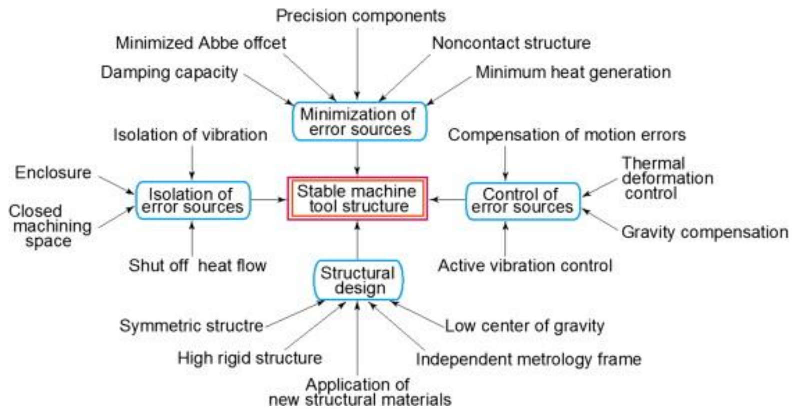

Fig. 1: Concept of stable mechanical tool structure for micro and nanometer-scale processing [3].

In order to rationally meet such processing requirements, micro/nano machining tools capable of producing micro/nano patterning have been produced by the leading machine tool manufacturers and by advanced research institutes around the world. Machine tools for micro/nano patterning could be divided into two types. The first type is used for micro-level components, such as high-aspect-ratio micro components. Commonly used machine tools in this area include micro-EDM, micro turning, micro drilling, and micro milling. The second type is machine tools and processes capable of performing nano finished patterning, and could be defined as those tools which generate surfaces suitable for optical functions. However, this definition does not limit the machine from being used to make surfaces and features intended for mechanical functions.

2.1 Machine Tools for Micro Patterning

Among conventional and nonconventional micro machining techniques, micro-EDM is the process most commonly used for patterning. In this area, the leading machine tool manufacturers are Sarix, Smal Tec, Mikrotools, and Takashima. Figure 2 shows a micro-EDM machine from Sarix, and a micro-EDM and nano grinding machine from Small Tec.

Fig. 2: SarixMikro EDM machine (left); Small Tec micro-EDM and Nano grinding machine (right) [4, 5].

The key problem of micro patterning using machine tools is that often a single machining process cannot fulfill all the requirements because of the limitations of that process. Most machine tools capable of nonconventional machining are not designed to perform conventional machining processes. In recent years, therefore, research institutions and machine tool manufacturers have focused on the development of compound/hybrid machine tools capable of performing two or more manufacturing processes in one single setup/platform. Rahman et al. reported that, to achieve effective implementation of compound and hybrid micromachining techniques, four important areas need to be addressed, as shown in Fig. 3 [6].

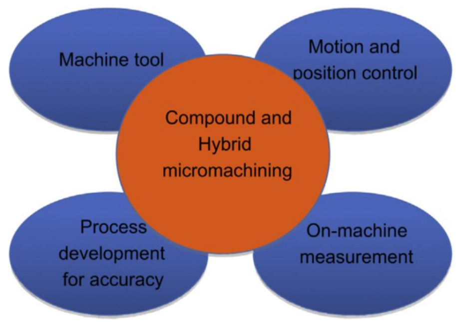

Fig. 3: The technologies required for successful development of compound and hybrid micromachining processes [6].

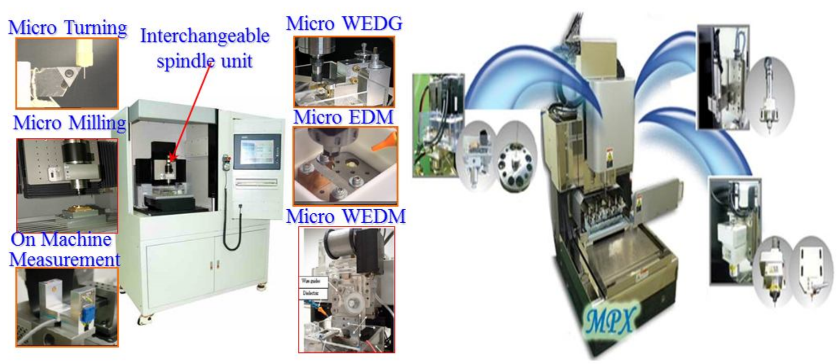

Fig. 4: Integrated multi-process machine tool from Mikrotools (left); multiple function machine from Takashima (right) [6, 7].

Therefore, the first and most important requirement for the development of the compound and hybrid machining processes is the development of a multipurpose machine tool or the integration of facilities for performing two or more manufacturing processes in one single setup and platform. Leading machine tool manufacturers and research institutions have developed machine tools suitable for compound/hybrid machining. The world’s first integrated multi-process machine tool for micro machining has been developed at the National University of Singapore (Machine Model: DT – 110). Multiple types of micro machining, e.g. micro turning, micro milling, micro-EDM, and micro-ECM, can be carried out on the same machine (Fig. 4). This highly flexible machine ensures high rigidity for precision machining. The special features of the developed machine include: (a) miniature machine design, (b) low noise and low heat generation, (c) high resolution with full feedback (resolution of 0.02 µm and accuracy of +/-1.0 µm), and (d) the ability to handle multiple processes, such as µ-EDM, µ-ECM, µ-milling, µ- turning and µ-drilling. This technology is patented and licensed to Mikrotools Pte Ltd, a spin-off company of the National University of Singapore.

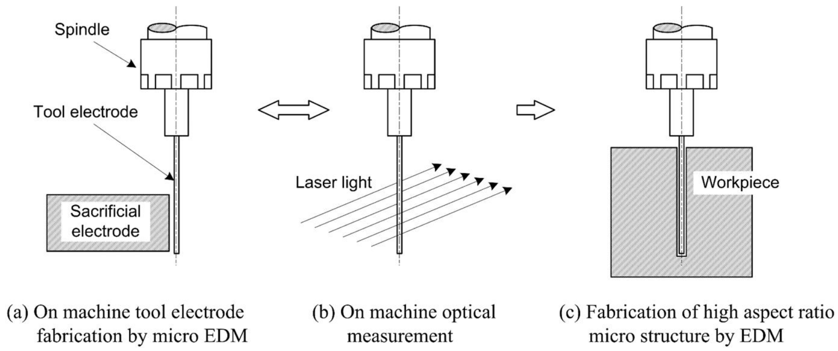

Fig. 5: Micro-EDM with on-machine-tool fabrication and on-machine-tool inspection steps in Mikrotools DT – 110 machine [8].

2.2 Machine Tools for Nano Patterning

Nano-level patterning is usually achieved using diamond as a tool to generate precision surfaces on a nanometer scale. In this area, diamond turning has been widely accepted by the industry for more than three decades. Diamond turning machines are often equipped with Fast Tool Servo (FTS) for its advantages in surface finish and precision level. Current turnkey machines have a resolution of up to below 1 nm. However, only a few suppliers in the world can produce such machine tools. The two major market shareholders are Ametek Precitech and Moore Nanotechnology Systems, both located in Keene, New Hampshire. At present, these two companies produce two-axis diamond turning machines for simpler applications like contact lens making, as well as multi-axis machines for much more complex applications such as functional free-form surface generation [9]. As with the development of multi-axis machines, an ultra-precision vertical axis has enabled the process of patterning using a diamond micro milling technique. With the further development of more advanced linear motors, hydrostatic slide guides, high resolution grate scales, and high-performance CNC motion control systems, the accuracy and performance of diamond turning will be continuously improved for more complex applications. Figure 6 shows two multi-axis machines, built by Ametek Precitech and Moore [10, 11].

Fig. 6: Examples of multi-axis diamond turning machines:
Nanoform 700 Ultra (left) [10], and Nanotech 350FG (right) [11].

Over the years, a lot of development has taken place in the machine tool industry for ultra-precision machining whereby the resolution of machine movement has reached sub-nanometer scale. However, the challenge of making an affordable ultra-precision machine tool has not been adequately addressed, and no significant research has been carried out in this area. A project was initiated to design, develop and fabricate a highly affordable ultra-precision machine tool at the National University of Singapore [12], and a high-speed and low-cost desktop ultra-precision lathe has been reported. This was achieved by incorporating a Fast/Fine Tool Servo (FTS) system on a precision machine that is to be designed and fabricated using mainstream components at low cost. The machine components and elements are arranged as shown in Fig. 7. The arrangement features a high-speed aerostatic work spindle of 15,000 rpm in a T-base 2-axis system mounted on a granite base. A piezoelectric actuator which can actuate forward and backward in very high resolution is used to drive the FTS system in the *z*-axis direction.

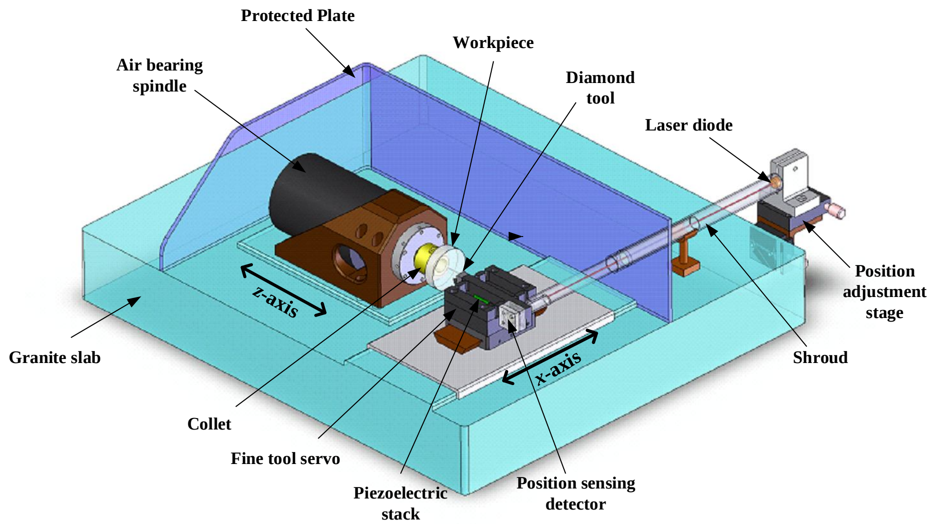

Fig. 7: FTS-High speed diamond turning machine (UPL –Series) [12].

3. MACHINING PROCESS FOR MICRO PATTERNING

An innovative patterning process is the key supportive technology that has to be developed to meet the challenges posed by the requirements of product miniaturization. In conventional micro-machining operations such as milling, turning, and drilling, machining forces influence the accuracy of the finished micro parts. However, researchers have tried to mitigate this issue by implementing simple engineering solutions. Usually, if a manufacturing engineer is asked to fabricate a micro shaft that is 50 µm in diameter and 10 mm in length, the engineer will argue that it is impossible. The usual reason why such a narrow shaft cannot be machined is the insufficient stiffness of the product, which will deflect because of the cutting force, because the engineer will think only of a turning process from the free end of the blank up to the desired length by longitudinal turning, and in this process these dimensions cannot be achieved. However, Aziz et al. showed that engineers tend to forget that the problems of both deflection and cutting force can be solved by applying fundamental engineering knowledge. As shown in Eq. (1) and Eq. (2), they can control the deflection by calculating the step size, which will ensure that even a 50 µm shaft will be able to withstand the deflection without yielding. If step turning is carried out as shown in Fig. 8a (Path B instead of Path A), then the machining of a narrow shaft can be performed easily. Machined shafts are shown in Fig. 8b [13].

Deflection, $\delta = \frac{Fl^3}{3EI} = \frac{64Fl^3}{3\pi E d^4}$ (1) Bending stress, $\sigma = \frac{32Fl}{\pi d^3}$ (2)

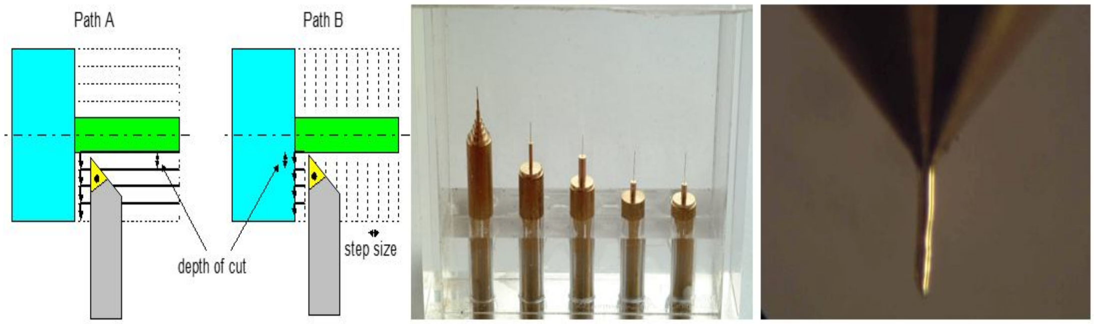

Fig. 8: (a) Two possible ways to do turning; (b) Micro shafts of diameter 50 microns; (c) Bending of micro shafts in conventional turning below 50 microns [13].

Although step cutting force could be applied to control the deflection in a certain range, in conventional machining a fully straight shaft below 50µm diameter is difficult to achieve (Fig. 8c). Because of this limit on machinable sizes, conventional micro machining is not suitable for high-aspect-ratio micro patterning. On the other hand, non-conventional machining processes such as micro-EDM and micro-ECM have become available over the last two decades as methods for manufacturing microparts and micro patterns. Key benefits are the absence of cutting force, and flexibility for machining irrespective of the material's hardness. Through optimization of the process parameters, high-aspect-ratio micro patterning can be achieved using these nonconventional micro-machining processes. For example, Khalid et al. performed processing of a carbon nanotube forest configuration of a high-aspect-ratio 3D micro-structure. High-frequency pulses were developed to process the nanotube to target shapes in a forest [14]. The optimal dispensation level was established in air with 30 V voltage and 60 mA current for a 10 µm discharge gap. A 5 µm feature in forests with an aspect ratio of 20 has been reported at minimized discharge energy and gap.

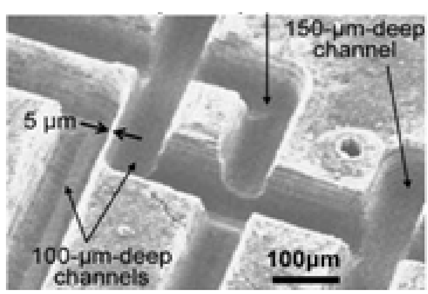

Fig. 9: Multi-level micro channel structures patterned in a CNT forest using micro-EDM [14].

Although stand-alone (single function) machine tools are used as major means to fabricate micro products, in many cases a single micro-machining process cannot fulfill all of the requirements of product miniaturization because of the limitations of that process. The major limitations are in relation to machinable sizes, accuracy, and surface roughness.

However, some limitations on machinable sizes can be overcome through hybridized/compound machining processes. There is no exact definition for a hybrid machining process. From time to time a number of definitions have been proposed by researchers. In 2014, the collaborative working group on hybrid processes of the College International pour la Recherche en Productique, or International Academy for Production Engineering (CIRP), put forward the following definition: hybrid machining processes are based on the simultaneous and controlled interaction of machining mechanisms and/or energy sources/tools having a significant effect on the process performance. The wording "simultaneous and controlled interaction" means that the processes/energy sources should interact more or less in the same processing zone and at the same time [15]. In this paper, on the basis of this definition, combined/ hybrid micro-machining processes are classified as

- Compound micro-machining processes for patterning
- Hybrid micro-machining processes for patterning.

This section provides a comprehensive review on the recent state-of-the-art innovations in tool-based combined/hybrid micromachining processes. Other patterning processes such as coating, laser micro machining, lithography, molding, etching, and assembly of films and substrates are non-tool-based approaches and are therefore not covered in this paper.

3.1 Compound Micromachining Process for Patterning

As presented earlier, a compound micro-machining process is a combination of two different machining processes in a single set-up applied one after another. This compound micro/nano machining can only be achieved through a paradigm shift in the ideas and processes of conventional machining. In recent years many attempts have been made in the compound micromachining area to combine conventional material-removal processes, such as turning and milling, with non-conventional machining processes like EDM, EDG, and ECM to fabricate micro parts with high dimensional accuracy.

3.1.1 Micro-EDM and Micro Turning

Micro turning has the capability to produce three-dimensional (3D) structures on microscale. The major drawback of the micro turning process is the limit of machinable sizes and the fact that the cutting forces influence machining accuracy. It is very difficult to achieve a straight shaft below 50 mm in diameter, and in many cases the tool either breaks or starts to wobble, owing to excessive radial cutting force on the micro shaft. Therefore, a compound process has been reported by Asad et al. [16] where the commercial cutting tool is modified using the micro-EDM process to reduce the force component responsible for breaking of the shaft.

This compound process is the combination of micro-EDM and micro turning in a single setup. First, a commercially available polycrystalline diamond (PCD) tool is modified by the micro-EDG process to reduce the nose radius of the cutting tool, thus minimizing the force component that causes shaft deflection during micro turning. Commercially available PCD inserts, designed for a light finishing cut, have a relatively large tool nose radius (e.g. 100 µm). This tool nose resolves the cutting force on the shaft into two components, namely Fx and Fy, as can be seen in Fig. 10a. The Fy component of the cutting force does the actual cutting, while the Fx component causes deflection of the micro shaft. A commercially available PCD insert is modified using the micro-EDG process to achieve a very sharp cutting edge, so as to reduce the Fx component of the cutting force significantly. This modification of the cutting tool makes it possible to achieve a straight shaft of much smaller diameter. The compound process combining micro-EDG and micro turning is presented schematically in Fig. 10b. A dual-cutter setup is arranged for micro turning, one with a round nose for initial turning up to 100 µm, then a sharp tool for a final cut up to 20 µm. After the micro turning process, the fabricated microelectrodes are used in machining of small and higher-aspect-ratio micro holes by micro-EDM on the same machine (Fig. 10c). Therefore, this compound process is in fact a combination of three steps: modifying the cutting tool using micro-EDG, fabricating micro shafts using micro turning, and applying fabricated shafts in micro-EDM drilling. Figure 11 illustrates the concept of the micro-turning–micro-EDM compound machining process. An electrode of required dimension is first fabricated by micro turning prior to micro-

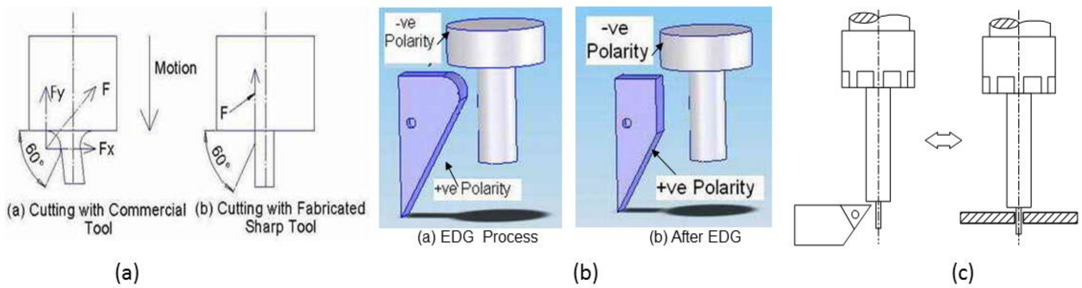

Fig. 10: (a) Modification of a conventional cutting tool using the micro-EDG (variant of micro-EDM) process; (b) a schematic representing the compound process combining modification of a cutting tool by micro-EDM and turning of a micro shaft by a modified tool tip; (c) compound process of fabricating a microelectrode using micro turning and applying a fabricated microelectrode in the micro-EDM drilling [16].

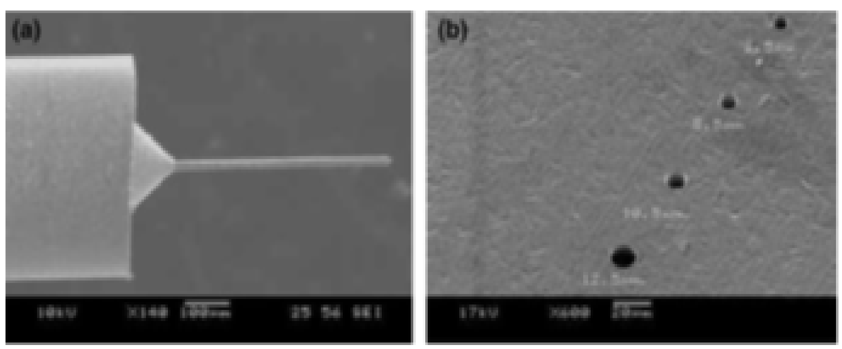

Fig. 11: (a) A 19-mm graphite electrode of 0.5 mm length fabricated by a micro-EDG–micro-turning compound process; (b) micro holes (up to 6.5 µm hole in 50 µm plate) fabricated with the microelectrode obtained by the micro-turning–micro-EDM drilling compound process [6].

EDM. Using this compound process, clamping error can be avoided, and deflection of the electrode can be minimized; consequently, the accuracy of machining can be improved. The fabricated microelectrode and machined micro holes pattern using the microelectrode are presented in Fig. 11a and Fig. 11b, respectively.

3.1.2 Micro-EDM and Micro Grinding

The fabrication of a miniaturized (sub-100 µm) grinding tool for difficult-to-cut materials like PCD and tungsten carbide (WC) is necessary for the machining of micro channels with an improved surface finish. The micro-EDM process is found to be capable of machining any difficult-to-cut materials down to the desired dimension. Therefore, a compound process is being developed [16] to solve the issues by combining the micro-EDM process with the micro grinding process. In this compound machining process, a PCD tool is fabricated on a machine in a desired shape using the block micro-EDG process. The PCD tool contains randomly distributed protrusions of diamond particles with dimensions around 1 μm that serve as the cutting edges for micromachining on glass. When the dimension of the PCD tool is reduced to the required dimension of the grinding tool by the micro-EDG process, the binder materials (usually nickel or WC) are removed because they are conductive, thus protruding the diamond particles, which are nonconductive. PCD with a cobalt binder, which can be shaped with micro-EDG, is emerging as a tool material for micro grinding of hard and brittle materials. The cobalt binder provides an electrically conductive network that can be removed with EDM. The diamond cutting edges are exposed as the discharges erode away the cobalt binder. Figure 12 shows the different steps of the micro-EDM–micro-grinding compound process with a machining example in BK-7 glass. As can be seen from Fig. 12c and Fig. 12d, the fabricated slot has a very fine and smooth surface, which is comparable to the surface obtained from ductile mode cutting of glass in macro scale.

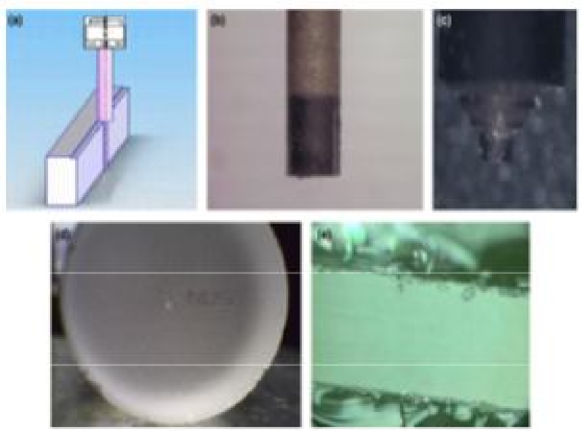

Fig. 12: (a) A schematic diagram showing the block micro-EDG process (a variant of micro-EDM); (b) a PCD tool before the micro-EDG process; (c) fabrication of a micro grinding tool with the micro-EDG process; (d) micro channels on glass machined by the micro grinding process with a fabricated PCD tool; and (e) surface finish of the microchannel in glass [16].

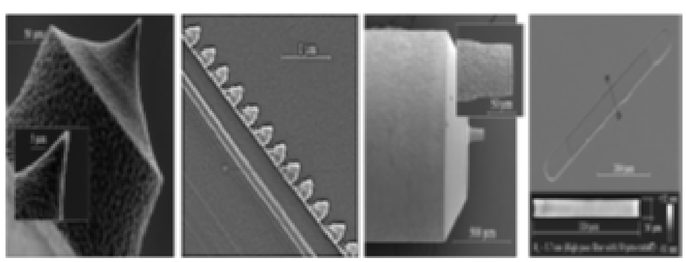

Fig. 13: (a) A PCD scratch tool produced with the WEDG process; (b) a scratch in ULE glass produced with the tool shown in (a); (c) a cylindrical 50 mm PCD tool used to cut pockets in ULE glass; and (d) a slot ground in ULE glass using the tool shown in (c)[17].

3.1.3 Coated EDM and Wire EDM

Ferraris et al. have demonstrated a process for manufacturing a high-aspect-ratio micro punching die pattern using a coated-EDM and wire-EDM combined process [18]. Initially, micro holes were drilled using a coated electrode. Commercial WC tubes, having a diameter of 130 -4/-6 µm and inner hole between 40 and µm were employed as tool electrodes to perform experiments with internal flushing. A parylene C coating was applied on the electrode via chemical vapor deposition. As compared to standard WC tools, parylene-C-coated tools showed better performance in terms of aspect ratio and low tool wear. It is reported that micro holes of about 0.18 mm in diameter and 10 mm in depth (AR 60) are achievable with 30-mm-long tools within 30 min [18]. This high-aspect-ratio micro drilling strategy is finally combined with micro wire EDM for fabricating a pattern on a micro punching die, as in Fig. 14.

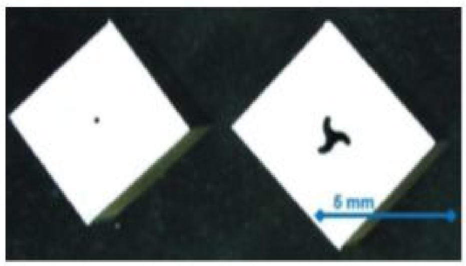

Fig. 14: Optical image of a pattern for micro punching (right) fabricated via micro wire EDM from a high-precision micro deep hole (left) drilled using a parylene-C-insulated tool electrode [18].

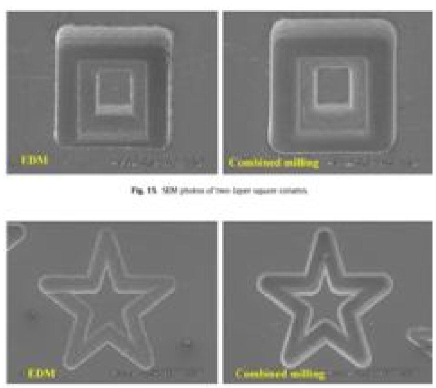

Fig. 15: EDM surface (left); improved surface after combined milling (right) [19].

3.1.4 Sequential Micro-EDM and Micro-ECM

A sequential micro-EDM and micro-ECM process is the combination of micro-EDM and -ECM processes in a single set-up. The objective is to improve the surface finish generated by the micro-EDM, using micro-ECM as a secondary process. Usually, a surface machined by micro-EDM is relatively rough due to the micro craters and micro cracks produced by micro discharge. Zeng et al. reported on a milling process for a 3D micro structure combining micro-EDM and micro-ECM. Micro-EDM shaping and micro-ECM finishing processes were carried out in sequence on the same machine with the same electrode but with a different dielectric medium. The surface roughness of 0.707 µm Ra resulting from EDM is lowered to 0.143 µm Ra by applying micro-ECM finishing [19].

Figure 15 shows the pattern produced by the micro-EDM and micro-ECM combined process. For the 3D microstructure pattern, the combined process showed higher accuracy than that achieved merely by micro-ECM milling.

3.1.5 X-ray Lithography, Electroplating and Moulding (LIGA) and Micro-EDM

Micro-EDM has many advantages in terms of precision, surface quality, and complex 3D shape formation. However, micro-EDM has not achieved widespread use in product manufacturing, primarily because of its productivity drawbacks. For instance, to produce arrays of micro holes, a single electrode is used to machine one hole at a time. Moreover, if the number of holes is very high, the electrode may need to be changed in the middle of the machining process. To resolve this issue a compound micro-machining process has been developed by Takahata et al., which combines micro-EDM and LIGA. In this combined process, the LIGA process fabricates arrays of microelectrodes, and then those electrodes are used for the machining of a microstructure with a high-aspect-ratio holes pattern [20].

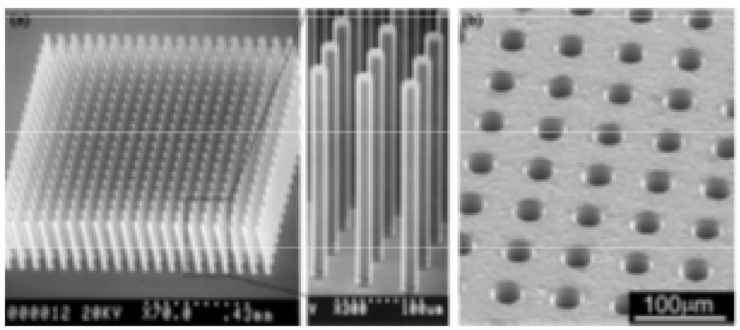

Fig. 16: (a) A 20 ×20 array of LIGA-fabricated copper electrodes;
(b) through-holes batch-machined in 50 mm thick stainless steel by
the micro-EDM process using the array of electrodes shown in (a) [20].

3.2 Hybrid Micro-machining Process for Patterning

As presented earlier, hybrid machining processes are based on the simultaneous and controlled interaction of machining mechanisms and/or energy sources/tools having a significant effect on the process performance [15]. Here the wording "simultaneous and controlled interaction" means that at least one machining process is superimposed with input from other types of machining process/energy source. In summary, the processes/energy sources should interact more or less in the same processing zone and at the same time.

3.2.1 Simultaneous EDM and ECM Process (SEDCM)

With the ceaseless demand towards smaller, thinner and lighter products, many innovations have been made in micromachining for micro and nano applications. Among these processes, micro-EDM and micro-ECM have the advantage of negligible cutting force due to the non-contact nature of the processes. Notwithstanding this advantage, each process has some undesirable effects which limit its capability. By appropriate combination of these two processes, their adverse effects could be significantly mitigated. However, micro-EDM operates in non-conductive dielectric fluid whereas micro-ECM employs conductive electrolyte. Because of these divergent requirements, micro-EDM and micro-ECM are usually used sequentially. This requires the repetitive change of machine tool or machining fluid, which hinders the practical use of micro-EDM and micro- ECM for micromachining. Hence, to overcome the aforementioned issues, a process combining micro-EDM and micro-ECM has been reported by Nguyen et al. to achieve improved performance on both surface finish and dimensional accuracy [21]. This hybrid machining process is named Simultaneous Micro-EDM and Micro-ECM (SEDCM). To resolve the machining fluid issue, low resistivity deionized water was used, which has characteristics of both conductive fluid and a dielectric fluid. In addition, short voltage pulses were also applied to localize the material dissolution zone for higher precision. By examining the effect of different pulse parameters, it was found that pulse-on time is the main factor affecting the effectiveness of localization or suppression of material dissolution. The material removal phenomenon of micro-EDM in low-resistivity deionized water was then investigated. It was observed that there is a conversion from mere micro-EDM to hybrid micro-EDM/ECM (SEDCM) when the federate is reduced. For predicting suitable machining conditions for SEDCM milling, an analytical model was proposed and developed which can indicate critical conditions for transitions of micro-EDM/SEDCM/micro-ECM milling in low-resistivity deionized water [21].

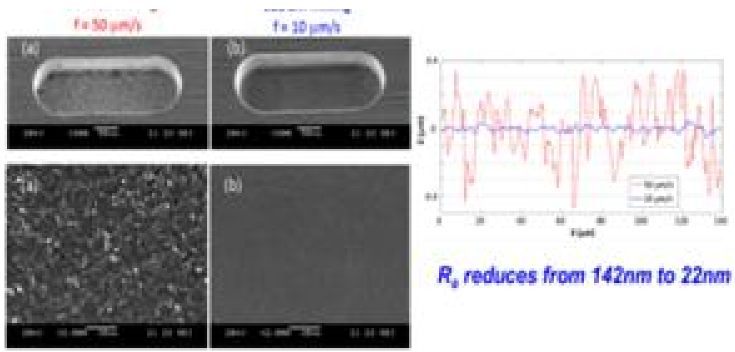

Fig. 17: Simultaneous EDM and ECM (SEDCM) process carried out in each cycle (EDM during on-time and ECM during off-time) to improve the surface finish to mirror finish (Machine Model: DT – 110) [21].

SEDCM was applied to milling to fabricate intricate 3D micro-shapes with enhanced surface finish and dimensional accuracy. Micro shapes with surface roughness as low as 22 nm Ra have been obtained as shown in Fig. 17.

3.2.2 Micro-electrochemical Discharge Machining

Micro–ECDM is a combination of electrochemical (EC) reaction and electro-discharge (ED) action. ECDM has been investigated by many researchers using different materials [22-26]. Figure 18 shows a 3D pattern produced by ECDM process in Pyrex glass.

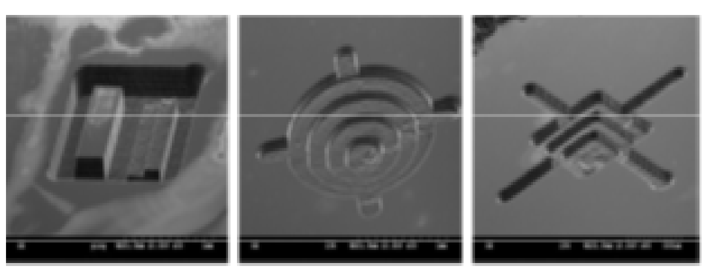

Fig. 18: Examples of 3D microstructure pattern in Pyrex glass [27].

In the ECDM process as a result of the electrochemical action there is a generation of positively charged ionic gas bubbles, e.g. hydrogen (H_2). As the DC power voltage is applied between the tool (or cathode) and the anode there is a breakdown of the insulating layer of the gas bubbles, resulting in material removal due to melting and vaporization of the work piece material.

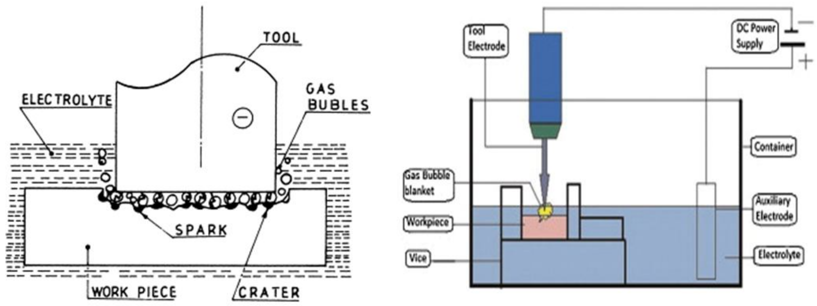

Fig. 19: Material removal mechanism of ECDM process (left) [28];
Schematic of ECDM process (right) [29].

3.2.3 Assisted Machining Process

In recent years, some assisted hybrid machining processes for patterning applications have been reported. In assistive hybrid types of machining process, the major machining process is superimposed with input from other types of energy such as ultrasonic vibration, laser, and magnetic, fluid. Two major assistive machining processes are vibration-assisted and heat-assisted. Researchers have used vibration-assisted machining for patenting in both conventional and nonconventional machining processes. In a conventional vibration-assisted process, reduction in average chippings and better groove shape are reported [30-32]. Figure 20 shows an example of the improvement of surface pattern with the aid of elliptical vibration-assisted cutting. Besides vibration-assisted machining, laser-assisted machining is receiving attention from researchers [33]. In the laser-assisted process, due to thermal softening at elevated temperature, high-strength materials which are otherwise difficult to machine are often easy to machine.

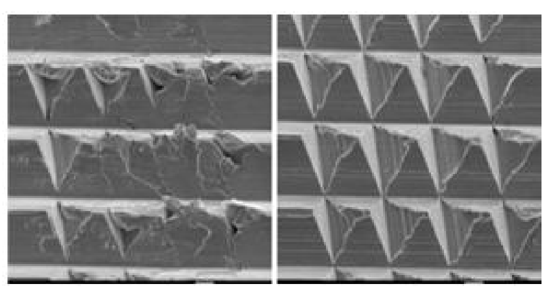

Fig. 20: Comparisons of pyramid patterns machined by conventional cutting (left)
and elliptical-vibration cutting (right) (work piece material: Inconel 600) [30].

4. MACHINING PROCESS FOR NANO FINISHED PATTERNING

The nano finished patterning process is used for producing surfaces suitable for optical functions, by the manufacturing of a master mould for a roll-to-roll manufacturing process. Previously, for optical-level surface generation, the most common process was single-point diamond turning. In recent years, with the advances in machine tools, some advanced processes have been developed for nano finished patterning.

4.1 Free-form Diamond Turning

The traditional single-point diamond turning process is limited to producing mirror finish on a rotationally symmetrical surface. However, by using fast-tool-servo technology it is possible to produce a pattern whose rotational Centre is not coincident with the centre of the part. Researchers have also reported other machining techniques, such as an automated Guilloche machining technique for non-rotationally-symmetrical patterns [34]. Early Fast Tool Servos were limited in the amount of off axis displacement that was possible. Recent innovations such as long-stroke fast-tool-servo technology enable off-axis displacement up to 1 mm at 100 Hz BW and 6 mm at 20 Hz BW [35].

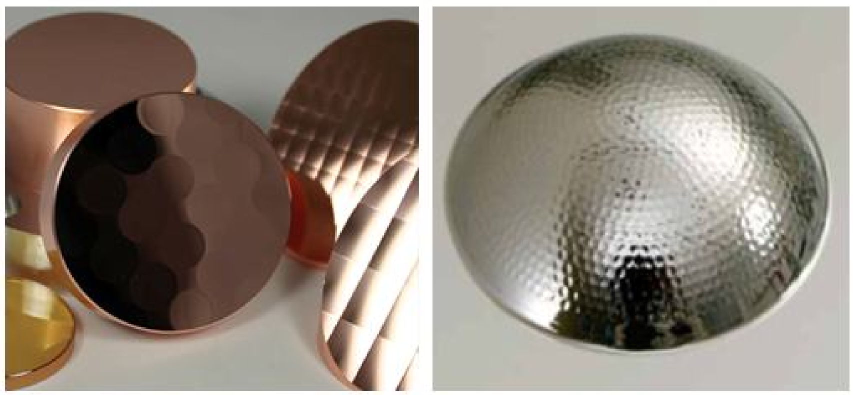

Fig. 21: FTS diamond-turned faceted mirrors (left); FTS diamond turned finished freeform micro-lens array mould insert containing 1,219 single spherical lenslets (right) [36, 37].

Non-rotationally-symmetrical applications often require displacement of more than a few mm. This problem can be tackled through innovated slow-slide servo technology, where the main linear slides of the machine can be controlled with precision of the main spindle rotation. Keong et al. have proposed a method to extend the limited stroke length of FTS without modifying an existing FTS system by generating a layered tool trajectory [38].

4.2 Diamond Micro Milling

Development of an ultra-precision vertical axis has enabled machining of optical surfaces using micro milling. Complex micro lens array patterns, gratings, and optical moulds can be manufactured in this process [35].

Fig. 22: Micro-lens array pattern generated by diamond micro milling of each lens individually [37].

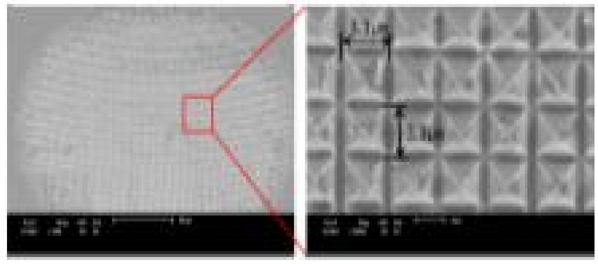

Fig. 23: Machined micro-array lens with a pyramid shape on the surface sample using a rotating cutting tool controlled by an electromagnetic actuator [39].

Kim et al. proposed a new rotating spindle system with a rotating cutting tool controlled by an electromagnetic actuator. A PID controller was adopted to make the system stable, and adaptive feed forward cancellation is used to compensate effectively for the run-out of the spindle system during machining. The machining results show that this compensation improves the pattern accuracy [39].

4.3 Diamond Turning for Master Tooling

Ultra-precision diamond turning is the foundation for generating the master tooling for many roll-to-roll embossing processes. However, the roll-to-roll processing process for many applications is still in the development stage. If semiconductors and optical devices can be fabricated in this way on large substrates then many devices could be fabricated at a fraction of the cost of the traditional manufacturing process. In recent years, therefore, a few new machining processes for the preparation of master tooling for roll-to-roll embossing have been reported by researchers.

4.3.1 Direct Patterning of a Radial Fresnel Lens on a Roller Mould

The conventional FTS diamond turning process is not capable of machining steep circular grooves on the roller, because of the fixed tool–work piece relative position and limited degrees of freedom. A radial Fresnel lens comprises a series of central symmetric steep circular grooves. Therefore, direct diamond turning of radial Fresnel lens structures on a roller mould was considered unfeasible, due to their fixed tool–work piece relative position and limited degrees of freedom. Figure 24 schematically describes the inability of the ultra-precision diamond turning approach to generate radial Fresnel lens structures on a roller. The dark shaded zone represents the portion where the work material cannot be removed owing to the steep circular groove profiles and the fixed cutting angle.

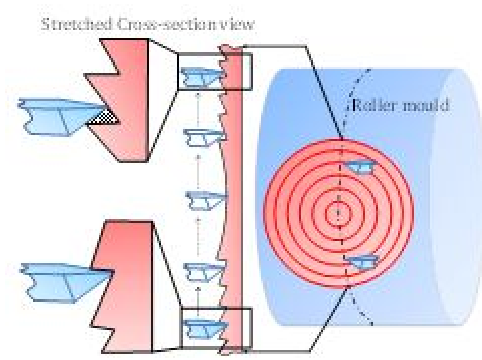

Fig. 24: Inability of the ultra-precision diamond turning method to machine a radial Fresnel lens on a roller [40].

A novel process named Synchronized Tool and Roller (STR) diamond machining has been reported by Huang et al. to solve the problem illustrated above which is currently faced by the industry [40]. A four-axis synchronized tool work piece interactive motion is designed to realize precise machining of the radial Fresnel lens microstructures containing steep circular grooves on the outer cylindrical surface.

The potential of the STR diamond machining process has been demonstrated by direct machining of a radial Fresnel lens structure with 10 mm diameter and 8.25 nm surface roughness on a roller mould in 8 h, which satisfies the industry's requirement of high-precision optical roller moulds.

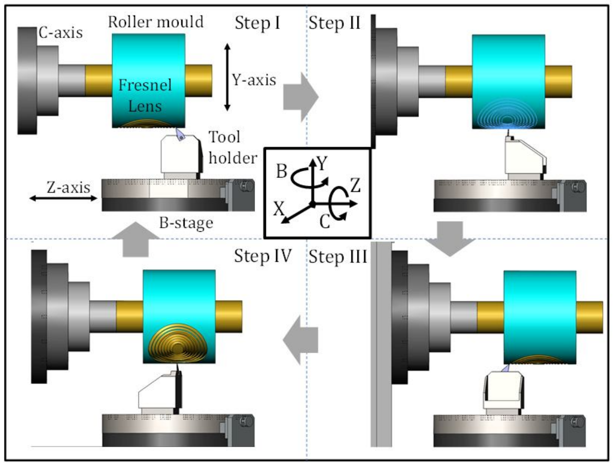

Fig. 25: 4-Axis integrated tool-work piece motion [40].

4.3.2 Engraving/Patterning for Roll-to-Roll Gravure Printing

Roll-to-roll gravure printing has received great attention in recent years owing to its superior performance compared with the conventional silicon-based semiconductor industry. Currently available roller gravures have a large gravure width (usually 25µm). So it is often difficult to scale down the printed line width, which is crucial for the film's circuit density, resolution and transparency. Zhang et al. proposed a novel method called diamond micro engraving to reduce the ink volume transfer read during the machining process. A V-shaped sharp diamond tool, two linear axes and one rotary axis of ultra-precision machine was used to miniaturize the line width to 7 µm [41].

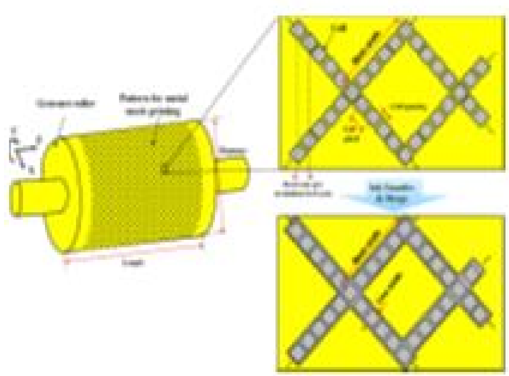

Fig.26: Gravure roller with a specified pattern for metal mesh printing [41].

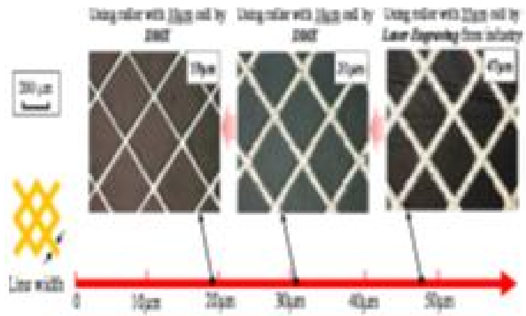

Fig. 27: Scaling down of printed line width using gravure rollers machined by DME [41].

The researchers demonstrated the performance of the DME-machined roller moulds. By replacing the laser-engraved roller with the gravure rollers machined by DME, the line width of printed metal mesh film, which works as a kind of transparent conductive film used in touch screen modules, was reduced from 47 µm to 19 µm, and its transmittance for visible light was increased from 65.2% to 80.4% [41].

5. CONCLUSION

In this paper, a short review on recent innovations in tool-based micro/nano patterning has been provided. Tool-based micro-and nanometer-scale processing is one of the core technologies for patterning applications. With the development of machine tools and machining processes, more tool-based patterning processes are finding applications in the areas previously dominated by lithography-based processes. Future machine tools for micro-and nanometer-scale processing require a machining capability of sub-nanometer-order resolution to find patterning applications in areas that are currently dominated by lithography-based processes.

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