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A Summary of Recent Breakthroughs in Micro- and Nano-Machining Technologies

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Abstract

In the twenty-first century, a new and advanced technology is being developed: miniaturization of gadgets. Miniaturization of devices is necessitated in several fields by the development of micro- and nano-scale components. From sub micron to several hundred microns, these components offer a high tolerance for a range of technical materials. A few examples of these fields include: optics, electrical devices, medicine, biotechnology, and aviation. As part of this study, researchers looked at the most current advances in micro cutting, micro electrical discharge, laser, and focused Ion Beam Machining (FIBM) technologies. During the comparison of four distinct machining methods, other criteria such as the material of the work piece, the minimum feature size, the maximum aspect ratio, and the surface polish were also taken into consideration.

Keywords—*micro machining, cutting, Electro discharge machining (EDM), laser machining, focused ion beam (FIB)*

Introduction

The usage of micro-scale components and devices has increased in recent years, particularly in the sectors of electronics, communication, optics, avionics, medicine and cars [1,2]. Examples of micro-machinery devices include medical implants, medication delivery systems, and diagnostic equipment. It is not uncommon for these items to be constructed from micro- and sub-micrometer-sized parts. In the wake of this requirement for micro- and nano-machining technologies, a lot of manufacturing research has taken place. This new trend necessitates the development of a new micro-manufacturing platform capable of not only combining several fabrication processes, but also creating new micro- and nano-machining technologies in the process. For low cost and high throughput, micro-manufacturing platforms are expected to create a wide range of materials. Lithography-based microelectromechanical systems (MEMS) have emerged as the most commonly utilised micro- and nano-manufacturing technologies in recent decades [5].” Two-dimensional or even two-and-a-half-dimensional micro structures can only be created using a few number of materials and techniques. Unfortunately, MEMS can not handle complicated three-dimensional micro structures composed of a wide range of materials

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because of this constraint. For these reasons, new micro and nano machining methods were created. Micro-electro discharge machining (micro-EDM), micro-cutting, and laser micro-machining are all examined in this study. Micromachining using a focused ion beam (FIB) [5,8,9].

Classification of Micro- and Nano-Machining Technologies

"Micro- or nano machining is the manufacture of components or products with at least one feature size in the micrometre or nanometer range." There have been a large variety of micro and nano machining technologies created during the last two decades based on diverse principles. Several techniques of classification have been devised in order to sort these innovations. Examples of micromachining techniques summarised and categorised by parameters are Masuzawa [10], for example. Micro- and nano-manufacturing processes were classified by Madou [11] as either lithographic or non lithographic. [12] Brinksmeier and coauthors. MET and MST have been characterized by Brousseau et al. [13] and Qiu et al. [14] as "micro-engineering technologies" (MET). To create MEMS, MST techniques like as photo lithography, electroplating, silicon micro-manipulation, micro-electroforming, and chemical etching are often used. When it comes to mechanical machining processes such as cutting and milling, as well as laser and micro-EDM machining, the term "met" is more often used. In order to generate precise mechanical components and surfaces, the MET might be used. It is possible to categorise micro- and nano machining processes as silicon-based or nonsilicon-based manufacturing technologies, based on the materials they process. According to Dimov and Brousseau [15] and their colleagues, these technologies were categorised on the basis of the processing dimension. FIB machining and micro-cutting are two examples of one-dimensional machining techniques. These technologies manufacture tiny components by eliminating material in a single dimension. Examples of two-dimensional methods that employ masks to create micro structures in a plane include photo/UV lithography, X-ray lithography, and electron beam lithography. In addition to volume structure, the most prevalent uses of three-dimensional technology are surface modification and deposition. There are four subcategories here: physical vapour deposition, chemical vapour deposition, nano-imprint lithography (NIL), and micro-injection moulding (MIM) (NIL). All of these technologies are examples of one-dimensional micro-machining technologies that have recently been developed.

Cutting-Edge Technology

Micro-cutting

In many ways, micro-cutting is quite similar to classic macro-cutting in terms of its machining principles. Using micro-tools with geometrically defined cutter edges, it is a kind of mechanical micro-machining that is used to remove materials. Ultra-precision or micro-machines with specific designs are required to carry out this technique. Using micro-cutting, which can reach micro form accuracy and nanoscale quality in a variety of technical materials [16–18], micro-components or micro-features are often created. A wide range of micro-cutting operations are possible, including turning and milling as well as drilling and grinding at the tiny level. Utilizing several types of micro-cutting procedures, a broad variety of micro-component geometries and surface qualities may be produced When micro-cutting replaces conventional macro-cutting, there are additional hurdles to overcome in terms of predictability, output, and productivity [30]. Because of the significant reduction in size, micro cutting has a number of unique properties. In addition, there are features such as a minimum chip thickness and minimal cutting chip creation. In macro-cutting, the cutting tool's edge radius is used to its utmost extent, resulting in a deeper cut. Macro-chip models presuppose complete removal of work piece surfaces and the development of a cutting chip, which is seldom the case in practise. “Cutting at a negative rake angle is common in micro-cutting when the depth of cut is equal to or less than the cutting tool's edge radius. The same negative rake angle applies to micro and macro grinding as a result. An increase in the quantity of shearing and ploughing forces may be attributed to an increase in elastic-plastic deformation of work piece materials in micro cutting. During micro-cutting, work piece material may exhibit pure elastic deformation, as proven by Liu et al [6,33] and Bissacco et al [34]. Kim et al. [35] developed a novel kind of non-detached chip when the tool cutting depth exceeded the minimum chip thickness. When the cut depth falls below a certain chip thickness, the surface material merely deforms elastically, resulting in no cutting chips. In order to achieve successful cutting, the minimum chip thickness has a significant impact on cutting chip creation and growth. For a minimum chip, Weule et al. [36] suggest that both the cutting tool's edge radius and the material's properties are significant. Surface roughness may be measured once the depth of cut exceeds the minimum chip thickness by analysing the elastically deformed material's spring back. The minimal chip thickness may be predicted using an analytical model developed by Liu et al. [37], which is reliant on the thermo-mechanical parameters of the machined material, such as cutting temperatures, stresses, and strain rates. According to Vogler et al. [38,39], using a finite element modelling approach, the minimum chip thickness of steel is roughly 0.2 and 0.3 times the edge radius of pearlite and ferrite cutting tools, respectively, in terms of chip thickness. In light of this finding, it is reasonable to assume that the material properties have an impact on the minimum chip thickness. Work piece-to-cutting-tool friction was studied by Son et al. [40]” in order to develop an analytical model for estimating the minimum chip thickness. Cutting tool edge radius and tool-to-workpiece friction angle were shown to have a direct association with the thickness of the smallest chip. WTC micro aspherical moulds were produced by Chen et al. using parametric research and micro-grinding technology. They discovered that the grinding trace spacing had a greater impact on the surface quality of ground inserts than the thickness of an undeformed nano metric chip. For micro grinding wheels, they created a new truing and dressing procedure which improved grain packing density and wheel form accuracy to an acceptable level. A 200-mm micro aspherical insert with a form and surface polish error of 4 nm was produced using these methods. Researchers have studied the effects of tool deflection, bending stress, and chip formation on micro-cutting cutting's force [41]. Studying cutting force differences between macro and micro cutting was done by Kim et al. (31). The shear plane is the location where shear occurs when macro-cutting is used. Micro-cutting saw a constant rise in shear stress. In order to account for the elastic recovery of work piece material, micro-cutting force models were created. This resulted in the cutting tool moving along its clearance face. According to Liu et al. [6], the cutting tool's induced vibration and the machined material's elastic recovery both have a significant impact on the cutting force's amplitude at low feed rates. It was found that the elastic deflection of the machined material resulted in forced cutting tool vibration when feed rates were too low. For example, Bao and Tansel provided a cutting force model that takes into consideration tool tip trajectory for computing the chip thickness of machined material [42,43]. “Because of the significant differences between macro cutting and micro cutting, both the negative rake angle of the cutting tool and the elastic-plastic deformation of the work piece material were not taken into account while micro cutting was being done. Cutting force interaction with tool deformation is crucial in micro-cutting. Cutting force models have been developed by Dow et al. [41], Duan et al. [44], and Ma et al. [45] to correct for the inaccuracy generated by cutting-tool deflection in micro cutting. Cutting tools have a significant impact on surface quality and the size of micro-component features while micro-cutting.” There has been a lot of advancement in micro-cutting instruments over the last several decades. It is standard practise to use diamond materials in the micromachining of ferrous materials [46]. Tungsten carbide is often used in micro-milling and micro-drilling instruments. [47]. Ultra-precision grinding is currently used to make commercially available micro-cutting tools with helix angles of up to 50 mm [48].] Tool strength and machining limitations may be improved by using zero-helix angles on micro cutting tools with a diameter under 50 mm [23,48]. [23,48]. Onikura et al. [49] “employed ultrasonic vibration grinding to make carbide tools with an 11 mm diameter in order to reduce grinding forces without breaking the cutting tools. Milling tools with a diameter of 25 mm and different cutting blades were made by Adams et al. [50] using FIB sputtering.” [50 Micro channels with a diameter of 25 microns were created using these approaches. Millimeters are used to measure both depth and breadth. In their study, Egashira et al. [51] employed EDM. 3 mm diameter tungsten carbide cemented drilling and milling equipment to be developed These tools were used to create various items. holes and slots with a diameter of 4 mm, a breadth of 4 mm, and a depth of 3 mm.

Micro-EDM

Using high-frequency electrical discharges between the electrode tool and the work piece material, EDM is a thermo electric machining process for removing material from work pieces. Liquid dielectric baths are used to keep the two components immersed in one another. The ultimate objective of EDM development has been to produce micro metric characteristics. These advancements have resulted in the use of micro-EDM for making micro-components, tools, and components with micro-features. Accuracy materials like hardened steel, cemented carbide, and electrically conductive ceramics may be made by employing Micro-EDM to create sub micron precision. This is one of the best technologies for micro-structures with high aspect ratios because of its low cutting force and excellent repeatability." Micro-EDM was used to manufacture micro-features, which were then soldered together. For micro EDM, die-sinking is the most often used process. Other prominent methods include wire EDM, drill EDM, and milling. [13, 14] When it comes to tool manufacturing and dielectric fluid flushing [55–56], Micro EDM has a distinct advantage. However, it has distinct properties in tool design, discharge energy, and dielectric fluid flushing that set it apart from macro-EDM. Due to limitations in electrode handling, work piece electrode preparation, and machining process design, micro-EDM is more difficult to execute than typical macro-EDM [53].] In macro-EDM, the machining mistake induced by electrode wear is often overlooked. When using micro-EDM, the machining precision of micro-features is significantly reduced because of the electrode wear that occurs throughout the process. A team of researchers investigated the mechanism of electrode deterioration and the various techniques of adjusting for it. Pham et al. [53] Electrode wear compensation was crucial to achieve very fine micro features in micro EDM milling by examining the impact of many kinds of faults on the machining accuracy of micro EDM milling. The technique of micro-EDM milling they proposed was likewise free of complicated mathematical computations. When milling along Path 1, electrode wear is focused on the tool's edge and face, which means the cavity volume is only half-filled after the first pass. The Z contact parameter, which specifies where the electrode tip makes contact with the work piece, has been reset. Afterwards, the routes for the next milling runs are established (Paths 2 and 3). Using a freshly prepared electrode for final milling runs is the only option if electrode wear is negligible or non-existent. They studied the influence of numerous factors on electrode wear in micro EDM drilling utilising micro-rod and micro-tube electrodes. Electrode wear ratios were calculated using a straightforward approach after the researchers investigated several wear compensating methodologies. Machined geometrical deviations are the basis for this kind of operation. [59] Dimov and coworkers developed a novel layer-based micro-EDM milling tool path generating method. This approach combines the uniform wear method with adaptive slicing to correct for electrode wear by varying the thickness of the layer. To build sophisticated three-dimensional cavities, micro-EDM machining employed electrodes with basic shapes. In micro-EDM, Tasi and Masuzawa [60] evaluated the impact of electrode wear on various materials' thermal properties. "They found that the boiling point of an electrode has a significant influence on electrode wear. In the wake of this finding, they came up with an index to measure electrode material's erodibility. It was discovered by Uhlmann and

Roehner [61] that cutting-edge electrode materials might significantly reduce electrode wear. Polycrystalline diamond (PCD) and boron doped CVD-diamond (B-CVD) are examples of these materials (PCD). To better understand tool wear and the quality of the work piece surface, they investigated B-CVD and PCD processes. However, for industrial applications, additional study into the influence of micro-features and element concentration on material removal and wear mechanisms in PCD and B-CVD is required. The electrode wear compensation length was determined by comparing the expected material removal volume to the anticipated material removal volume in this study. An electro-thermal model was utilised by Aligiri et al. [62] to anticipate the amount of material removed in real time during micro-EDM drilling operations. According to Bissacco et al. [63], a novel micro-EDM milling electrode wear compensation method is based on discharge population characterisation and counting of the discharges. Electrode wear may be repaired via discharge counting without the need for pulse discrimination. Precision and reproducibility in micro-EDM rely heavily on the electrode preparation process [53]. As a consequence, tool-electrode preparation has received a lot of attention in recent years. For the purpose of simplifying the process of making electrodes on a machine, Wire electro-discharge grinding was suggested by Masuzawa et al. [64] as a novel method for grinding (WEDG). A travelling wire is used as a tool electrode in both WEDG and wire EDM; however, the wire guide and machining setup in WEDG are different from those in wire EDM [65].” These electrodes can be machined from materials that are less than 15 millimetres wide. Anode fabric, process strategy, and machine accuracy all had an effect on the surface polish, electrode quality, and angle percentage of the produced electrode, as studied by Rees et al. [65]. Each of WEDG's tungsten carbide and tungsten anodes can achieve high aspect ratio and outstanding surface wrap up, independently. A new technique based on an optical verification framework was also presented to improve the accuracy of device anodes. There are still certain concerns with traditional WEDM's Handle technique for wear emolument in micro-EDM processing [53]. It was later discovered that cathodes with high angle ratios may be produced by advancing nanoscale- and microscale-machining technologies. Concerns have been raised concerning the amount of effort required to deploy WEDG with a micro-EDM. EDT, EDG, and WEDG are three alternative methods for manufacturing round and hollow objects; they were examined in terms of pulse stability, hydrodynamic behaviour of dielectrics, machine-dependent crevice, and nourish control by Uhlmann et al. [66]. Aside from that, the surface quality of this consideration was not optimised. Adding a second rotating pivot to a micro-EDM machine, Qu et al. [67,68] enhanced standard WEDM by using a comparable technique to produce round and hollow components. Wire feed rate and section rotational speed were examined for their effects on machined component surface wrapping and roundness. A macro-component manufacturing method developed by the researchers is not immediately applicable to lower scale manufacturing. It is possible to execute WEDG using wire micro-EDM and a rotating submergible axle, according to Rees et al. [69] and Brousseau et al. [13]. When the terminal running wire was connected to the spinning test piece, a wire direct was not necessary. This method pushed the flexibility of machined round and hollow pieces to new heights. Under the same levels of release vitality, the use of WEDG set-up may provide much superior surface sharpness than standard WEDG.

Laser micro-machining

To melt and evaporate unwanted elements from the work piece using lasers, laser micro-machining might be a widely-used energy-based method [70]. Micro-manufacturing using lasers is a very effective method because to its wide range, low heat input and high adjustability [14]. Penetration, cutting, processing, and surface texturing may all be done using lasers incorporated within a multi-axis micromachining framework. To machine micro-components composed of various materials, including metals, polymers, glasses, and ceramics, this method is suitable [71]. It is mostly used for drilling, cutting, and processing in the field of laser micro-machining, in that order. Incredibly, laser micro-milling is gradually becoming recognised as an essential micro manufacturing breakthrough in quick prototyping, component downsizing for a variety of applications, and serial production of micro-devices via group manufacturing techniques [71,73]. Using a laser micro-drill, you can make very precise micro-holes. The two most common types of laser micro-drilling are called percussion boring and trepan boring, respectively. Percussion drilling is often used to create micro-holes, in which the laser point stays fixed on the work piece material and a series of beats are fired. A micro-diameter hole's depends on the laser spot size, which may vary from a few micro metres to several micro metres in diameter. Because the gap width at the laser beam's departure is narrower than the gap width at the laser's entry, the laser penetrating micro-hole is tapered. Optimizing the handling parameters may enhance the reduced form [75,76]. The tiniest micro-holes generated by the Lightmotif B.V. Organization are sub-microns wide at the laser exit. Ultrasonic vibrators used in conjunction with laser penetration energized the work fabric, according to Zheng and Huang [77]. According to the researchers, compared to laser penetration that did not use ultrasonic vibration assistance, they saw significant improvements in the angle proportion and wall surface wrap up of micro holes produced by this technique. Using trepan laser micro-drilling innovation, the laser bar can cut the work piece fabric around the circle of the gap to manufacture gaps larger than the laser spot measure.

Trepan laser micro-drilling was used to create these micro-holes, which result in perfectly smooth dividers free of burrs. Trepan laser micro-drilling has a comparable machining guideline to that of laser micro-cutting. Through the use of beat lasers, this method also removes fabric from the work piece, allowing for very accurate cuts with excellent surface quality and no injury [78].] When laser micro-cutting employs rapid galvanometer scanners, precise, adaptive, and fast cutting shapes may be achieved quickly. Laser micro milling of high quality requires precise control of the laser settings and improvement of the filter design. When it comes to laser micro-milling, Petkov et al. suggested that ultrashort beats and lengthy beats are two of the most common methods of removing material off the surface of a material. When it comes to pulse length, femtosecond and picosecond are the two most often used terms, however lengthy beats also refer to nanoseconds and longer. Because the duration of laser beat is smaller than the time necessary for electrons and nuclear cross sections to achieve thermal equilibrium, laser removal may be regarded a solid-plasma or solid-vapor motion, with little or no heat-affected zone, in this manner.[80,81] Laser micro-milling with lengthy beats produces a recast layer by swiftly dispersing heat into the work fabric. Additionally, there are many abandons, including micro fractures and debris, surface layer damage, stun waves and recast layers [82]. To better understand the surface properties and micro structures of a Nitinol alloy, Huang et al. [83] used femtosecond laser micro-milling. As a result of their experiments they were able to produce a product with much improved surface quality, as well as thinner re-deposited fabric and heat impacted layers. Surface quality may be improved by using ultrashort pulses of laser micro-milling. Micro-machining of ceramic components using laser micro-milling with microsecond beats has been studied by Pham et al. [73]. They found that this method can produce micro components with highlight sizes of up to 40 nano meters. “In any event, their study was still in its early phases and did not reveal the fabric evacuation component and the interactions between the laser pillar and the work piece included in the machining handle. Demonstration of the fabric removal process in laser removal was established by Dobrev and colleagues [84]. In this demonstration, they demonstrated the arrangement component of cavity surrenders on metal materials machined using microsecond laser pulses. As a final step, laser micro-milling was used to manufacture ceramics and silicon nitride micro-components.” Past laser micro-milling projects have shown the precision of laser micro-machining on the micro metre scale. Work piece composition and surface finishing, as well as process conditions, all have an impact on cutting accuracy and surface quality.

FIB-machining

FIB machining may manufacture precise micro- and nano-features by removing unwanted work piece material layer by layer using a focused ion beam and in situ scanning electron microscopic (SEM) monitoring. Materials may be deposited using the FIB's Ion Beam Induced Deposition (IBID). Precursor gas is required for deposition. [86] Ion beams are a subset of ion beams, and they are used to irradiate the work piece's surface and the atoms inside it. With FIB micro-milling, you will get a boost in power. The final result is seen here. As soon as they acquire more energy than their surface binding potential, they start to sputter Micro-features may be created on practically any work piece material with high surface quality and dimensional precision using FIB micro-low milling's ion scattering effect. According to [13], the lateral dimensions of micro-features may be as small as 50 nm [13]. Electronic circuits may be modified, TEM specimens can be produced, and ICs can be debugged with the help of the FIB micro-milling technology [88–90].To manufacture micro-components of high quality and accuracy that may be employed in a wide range of applications, the FIB can be used [88,91,92]. In the micro-tool industry, FIB micro-milling is commonly employed because to its high precision and resolution capabilities. “This method creates less machining stress and damage layer compared to typical ultra-precision machining processes. To create micro-tools from non-planar materials, Picard et al. employed FIB micro-milling. In addition to the tungsten carbide and high-speed steel, these micro-tools included single crystal diamond. For the fabrication of micro-diffractive optical components, researchers Xu and colleagues [94] employed FIB micro-milling to create micro-cutting tools with edge radiuses of roughly 25 nm and complicated forms. Diamond cutting tools with nano metre edge radius were manufactured by direct writing of FIB micro-milling (FIB micro-milling). Micro-cutting tools may benefit from an improved process for increasing cutting ability and prolonging tool life, which might decrease FIB-induced damage. Recently, FIB micro-milling has been employed to create micro- and nano structures. On Ni-based substrates, Li et al. tested the FIB's capacity to grind micrometre and nanoscale features. The micro- and nano-features machined by the FIB micro-milling technology may be utilised to construct Ni-based masters for injection moulding and hot embossing rather than lithography-based pattern transfer methods. In the absence of mask removal or etching, FIB micro-milling may quickly produce silicon island arrays that are site-positioned. As well as nanoscale Si island arrays with hexagonal symmetry, they developed silicon islands in different shapes and sizes. For ZnO micro-cavity creation, Chang et al. [99] employed FIB micro milling to design a manufacturing procedure and fully examined the optical characteristics of different shaped micro-cavities.” Micro cavities based on ZnO may be produced with high quality utilising FIB micro-milling, according to their findings. Using FIB micro-milling, Lu et al. [100] investigated the fracture strength of the protective inter metallic layer on AZ91E Mg alloys by building a series of cantilevers of different diameters. There are several applications for FIB micro-milling in complex micro-structures made up of a variety of technological materials.

Comparison of micro- and nano-machining technologies

Processes such as micro cutting, micro-EDM, laser micromachining, and FIB machining were all explored in the study of micro and nano machining techniques. For the manufacturing of micro- and nano-components, certain machining processes are necessary.' On the basis of their material removal rates and the sorts of work pieces they are capable of processing, the four previously described processes are compared. In terms of efficiency, micro-cutting processes like micro-turning, micro-milling, micro-drilling, and micro-grinding are the most effective. It is possible to machine a wide variety of materials using these methods. In terms of feature size, micro-cutting has several limitations. It is still challenging to machine components with a diameter of less than 25 mm. One may easily produce ultra-high aspect-ratio micro holes of more than 30 using micro-EDM drilling technology. When using Micro-EDM, however, you must use conductive materials alone. When using laser micro machining, you may deal with the widest variety of materials possible. These two main ablation regimes have a direct influence on machining efficiency and feature size, which are determined by the duration of the laser pulses used. “Laser micro machining can achieve feature sizes of less than 3 micro metres using ultrashort pulses, but it also has the lowest material removal rate.” Engineering materials are no match for FIB machining's ability to fabricate components at the micro-and nano scales. “This technique is limited by the lowest rate of material removal of the four technologies. Although FIB machining and laser micro machining with ultrashort pulse lasers have moderate material removal rates, both technologies may offer a high-resolution removal process.” As a whole, these four methods of micro- and nano-component manufacturing complement one another.

Conclusions

Four of the most often used nano fabrication methods were the subject of research described in this publication. According to their efficiency, work piece materials, minimum feature size, maximum aspect ratio and polishing polishing were compared across four machining processes. Micro-cutting is the most efficient of the four machining processes available. This method has limitations when it comes to the smallest possible feature size. In Micro-EDM, you can get the most out of every square inch. Laser micro machining using ultrashort pulse lasers and FIB machining may be used to obtain submicrometric features.

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