ARCHIVE OF MECHANICAL ENGINEERING

VOL. LXV 2018 Number 1

DOI: 10.24425/119413

Key words: WEDM, ECM, Micro-EDM, recast layer, micro-gear

TINA CHAUDHARY [1], *ARSHAD NOOR SIDDIQUEE* [2], *ARINDAM KUMAR CHANDA* [3], *ZAHID AKHTAR KHAN* [2]

ON MICROMACHINING WITH A FOCUS ON MINIATURE GEARS BY NON CONVENTIONAL PROCESSES: A STATUS REPORT

Recent developments in automation and technology have revolutionized the way products are made. It is directly seen in the evolution of part miniaturization in the sectors such as aerospace, electronics, biomedicine and medical implants. Micromachining is a promising technology to fulfill the need of miniaturization. A review has been done on the micromachining processes such as micro electric discharge machining (micro-EDM) and wire EDM (WEDM), micro electrochemical machining (micro-ECM). Recent literature were studied and categorized in terms of materials, process parameters, performances, product manufactured, and miniature product generation. Starting with brief introduction to micromachining, classifications and applications, technical aspects of discussions from the literature have been presented on key factors such as parameters and the response variables. Important aspects of recast layer, heat effected zone, micro-hardness, micro cracks, residual stress, etc., have been given. A special focus is given to the status of the research on micro-gear manufacturing. Comparison has been made between other conventional process suitable for micro-gear manufacturing and WEDM. The miniature gear machined by WEDM shows the defect-free microstructure, better surface finish, thin recast layer and improved gear quality parameters such as profile and pitch. Finally, the research gaps and future research directions have been presented.

1. Micromachining

Requirement of meso-scale (500 mm to 1000 mm) and micro-scale (1 mm to 500 mm) products is rapidly increasing in aeronautical, automobile, biomedical, nuclear, optical, and semiconductor field [1]. Micro-manufacturing facilitates the

[1] *Department of Mechanical and Automation Engineering, Indira Gandhi Delhi Technical University for Women, Kashmere Gate, Delhi, India. Email: tina.mech.auto@gmail.com*

[2] *Department of Mechanical Engineering, Jamia Millia Islamia (a Central University), New Delhi, India*

[3] *Department of Mechanical and Automation Engineering, G.B. Pant Engineering College, New Delhi, India*

use of miniature features in products such as fuel injection nozzles, semiconductor devices, biotechnology products, medical tools for investigation, and medical surgery [2]. Present day micro-manufacturing processes are broadly classified as lithographic and non-lithographic techniques [3]. Photolithography is evolving as an important technology that supports micro-manufacturing, but it has several limitations for high aspect ratio structures, use of work materials and high initial investment etc. [4]. Non-lithographic techniques typically not only overcome such limitations but also have an advantage over lithography in terms of cost, materials choice, relative accuracy and complexity of product geometry.

Non-lithographic techniques are broadly classified into three types, i.e., advanced micromachining, mechanical micromachining, forming and moulding, and finishing processes [5, 6]. Mechanical micromachining includes the micro-cutting using conventional micromachining tools. This includes processes such as micro-drilling, micro-turning and micro-milling processes, etc. Based on source of energy, advanced micromachining techniques can be further subdivided into groups, i.e., based on energy (i.e., mechanical, thermal and electrochemical energy). There are further subdivisions under each of these sub-categories.

Mechanical energy may be supplied in several forms such as ultrasonic vibrations, abrasive jet, abrasive water jet, and water jet [3]. Use of thermal energy during micromachining may comprise of high energy beams such as in ion beam machining, electron beam machining, laser beam machining, plasma arc machining etc.; and high energy sparks such as in electric discharge micromachining, wire-electric discharge micromachining, and micro-wire electric discharge grinding. Energy in chemical form is also used for the purpose of micromachining such as in electrochemical micromachining, petrochemical micromachining [3].

Electrochemical machining (ECM) which works on dissolution of metal electrochemically is also another advanced process which is used for micromachining applications. In ECM, the shape of electrode identifies the shape of machined surface and very high degree of finish is produced as the removal is through atom by atom dissolution of material [7]. In some of the latest variant of the process, electrolyte jet has also been tried instead of a metallic tool [8]. A high speed jet localizes the electrochemical dissolution easily and allows machining of micro indentations. Advanced finishing processes, such as micro/nano-finishing, include elastic emission finishing, abrasive flow finishing, magneto-rheological finishing, magnetic float polishing, magnetic abrasive finishing and so on [3]. Hybrid process is the combination of these micromachining processes to take the advantages of constituent processes. Hybrid processes include electric discharge grinding, electrochemical discharge machining, chemical mechanical polishing, electro chemical spark micromachining, electrolytic in process dressing and so on [9, 10]. Hybrid micromachining processes results in great improvements in responses such as MRR, SR, geometrical accuracy and tool life, etc. Hybrid micromachining process could be exceptionally beneficial to fabricate complex miniature parts with high machining efficiency. Combined hybrid micro machining has great prospects in fabricating complex micro parts with good accuracy and surface quality. ECDM milling, for example, is a favorable process for fabricating complex shapes with non conductive, hard and brittle materials. Furthermore, laser assisted micro milling can develop free form surfaces on non conductive hard and brittle materials. These micromachining processes can also combine with other sequential processes to improve machining rate, surface integrity and geometrical accuracy of the micro-parts [10]. Sequential micromachining process is the machining technique where two or more micromachining processes are enacted in a sequence on same or different tools. A recent research is geared towards sequential micro machining processes over single machine tool to reduce the realignment errors. The major advantages of sequential micromachining over the single machine tool are that it prevents the repositioning errors and enables higher levels of accuracy or tighter tolerances, and reduces rejection of machined parts. Multifunctional micro machining processes are attracting the global attention due to precise, reconfigurable and flexible manufacturing [6].

1.1. Major micromachining applications

One of the oldest and largest applications of micromachining is in the manufacturing of silicon-based semiconductor devices. Simply because these devices are produced by detailing micro- features on wafers of semiconductors which are hard and fragile, machining of these becomes very important. The silicon micromachining technology is based on three process, i.e., lithographic approach, direct etching and deposing processes. Silicon wafers can be machined with physical and chemical etching, and finally elements are released layer by layer from silicon substrate. This is non-contact method based on the masking and light exposure. The final components are obtained due to patterning of the workpiece surface with bidimensional approach [11–13].

Bulk micromachining of silicon products is a subtractive method employed in the silicon device fabrication using wet and dry etching. The material removal is obtained by chemical liquid solution in wet etching, while in dry etching it is obtained by chemical or physical plasma etching. In wet etching, isotropic and anisotropic etchants can be used. Etch of the stop methods are applied to control machining depth in silicon wafers. Dry etching uses physical methods such as ion milling and sputtering, chemical approaches and both etch processes combination like reactive ion beam etching, reactive ion etching (RIE) and deep RIE [11–13]. Surface machining is used to obtain the moveable structure from substrate, on the basis of selective etches of the thin sacrificial and structural layers. After developing sacrificial layer, the moveable component is released [12]. The main limits are process cost and two-dimensional based patterning. Materials and masks alignments are other problems.

1.2. Micro machining of features possessing high aspect ratio

LIGA (abbreviation of Lithographie Galvanoformung Abformung) is an X-ray source based common technique and is generally used for single moulds production for the replication of mostly plastic components [11]. In this, a conductive substrate is coated with polymers such as a layer of polymethyl methacrylate (PMMA) and then uncovered to X-ray synchrotron radiations for transfer of pattern from the mask. Small wavelength and intense radiations are used to reach deep penetrations. Further, electroplating process is performed. Finally, a high aspect ratio part is produced which can be used for applications such as in micro injection moulding, hot embossing or to replicate metallic or ceramic components [11]. Production cost is one of its main limitations of this process.

Furthermore, laser-based systems are also efficient for micromachining of high aspect ratio features on a range of materials without any contact with workpiece [12]. Micro-holes, trenches, patterns and grooves can be produced on a workpiece with high degree of precision [13]. A short pulsed beam spot of laser instantly vaporizes the material and minimizes general problems related to heat affected zone (HAZ) and microcracks. It allows micro-drilling of holes [14] and achieves high aspect ratios up to 50 : 1. Femtosecond laser is the last step in laser micromachining research, through this high precision can be achieved with ultra-short pulse lasers suitable for micron features [15, 16]. Micro-ultrasonic machining is another process which can be used to drill high aspect ratio holes in hard and brittle material. It uses micro tool with ultrasonic vibration (less than 30–40 kHz) to mainly machine brittle and hard materials like ceramics, silicon, quartz, etc. [17–19]. A flow of abrasive slurry is often maintained between vibrating tool and workpiece. Micro-holes (15 μm) can be obtained in hard materials with ease by this technique. Holes of aspect ratios 10 : 1 one can achieve with greater tool diameters.

A versatile electric discharge machining (EDM) uses eroding action of discharge to remove material between tool and conducting workpiece. Electro-thermal erosion produces tiny craters both on workpiece and tool that are kept at a predefined minute gap. The crater so formed increases the gap which is maintained constant by advancing tool or work, and gradually tool shape is duplicated on the workpiece without any contact between micro-mechanical systems [20]. This technique is suitable for difficult to cut metals, alloys and conducting materials. During EDM, tool wear control is a challenge; also the recast layer on surface and micro-cracks are its major limitations. The EDM have common variants such as wire-EDM and sinking EDM, etc. Among other adaptations in the dielectric fluid, powder mixed dielectrics are becoming common, in which powder of various materials are mixed with dielectric fluid. When the powder dispersed dielectric flushes through the spark gap, particles of powder are arranged in the sparking area and often get collected forming cluster. The cluster formation bridges the gap between electrodes and causes early explosion. Faster sparking takes place within discharge and results in erosion from workpiece surface [21].

1.3. Mechanical micro-fabrication technology

Available bulk fabrication processes such as machining, forming, moulding and punching, etc., are in use to fabricate micro-parts. Active research in the field of micromachining is in optimization of processes for micro-turning, micro-milling micro-drilling, and micro-grooving for a vast range of materials. Mechanical micromachining can be used to produce parts of dimension as small as 100 μm. It is difficult to extend it up to 50 μm because of higher machining forces due to size effect [22, 23]. Ultra-precise machines are used in micro-milling operations with motions controlled by linear encoder or laser interferometer to attain submicron resolutions. Spindle speeds for micromachining is of the order of several tens of thousands of rpm and the tool needs to be chucked into the sophisticated precision bearing for minimization of radial errors. Similar approach is applied during turning of cylindrical workpieces micro-grooving or micro- threading and for circular grooving micromachining on the plane surfaces [24, 25]. Burr formation, dynamics and tool wear/failure are pertinent problems in these techniques. The main problems to develop this technology are correct tool shaping, process control, and correct selection of the machining parameters in micro level.

Drilling for micro-holes, turning for micro-pins, and miniature 3D shapes and fly cutting for micro-convex shapes are some typical mechanical micromachining processes. Grooves, holes and 3D convex structures can be fabricated using a micro end-mill [26–30]. Fabrication of micro-pins is possible by micro-turning, but there are inherent difficulties due to deformation of workpiece. Several types of micro-parts with surfaces of revolution can be fabricated using the conventional ultra-precision turning. Thus, conventional micromachining methods continue to be used to produce micro-parts with micro-steps [31, 32] and fly cutting is used for machining of grooves [33]. Fabrication of microgrooves and micro-pins, etc., are commonly produced by micro-grinding. The main requirement is reduction of thickness of grinding wheel up to the resolution of product. For micro-grinding tools, very small grains are essential. Diamond and CBN grains of submicron-order are highly desirable for precise product geometry [27, 34, 35].

Metal and ceramic powder injection moldings are the recent developments used to fabricate ready-to-use micro parts [36, 37]. These techniques use micro-mold insert which are injected with a feed stock comprising of metals/alloys/ceramics and suitable binder to produce green. The green is debinded selectively stepwise to remove the binder. Debinded parts are then finally sintered to produce the finished product [38]. A large number of micro-sized holes can be produced by micro-punching. Fabrication of micro die and punch and setting them with the precise clearance during operation are the major challenges of micro-punching. No effective method has been developed for multiple punches die set fabrication for micro-punching [39, 40].

1.4. Mechanical micro-fabrication technology

Among most micro-sized features, micro-holes are most common. Parts with such small-sized hole are used in various products including biomedical filters, fluidic filters, suture needles [22], ink jet nozzles for printer, fuel injected nozzles, high pressure creating orifices, optical apertures, pneumatic sensors, micropipettes and guides for spinning nozzles, etc. Micro-holes are manufactured using micro-machining processes, as shown in Fig. 1 and Fig. 2.

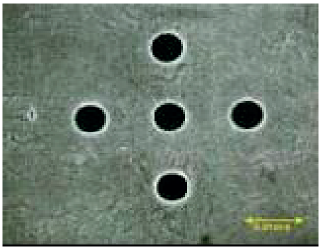

Fig. 1. Micro-holes manufactured by EDM

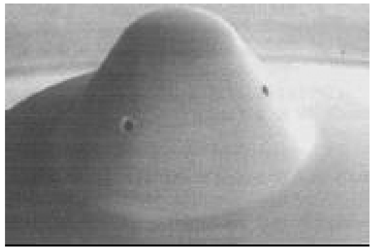

Fig. 2. Fuel injection nozzle cap holes machined by FS laser [41]

Apart from micro-holes, micro-pins are finding huge applications and their use is rising steeply. The use of micro pins in products such as PCBs, micro-jacks, electronics parts, assembly of moulding and packaging, etc., is steeply increasing. These pins are fabricated from various materials including brass, stainless steel, titanium, etc. Pins of these types can be very easy to produce using recent technologies such as Wire Electric Discharge Grinding, as shown in Fig. 3 [42, 43], and they have very good reproducibility. Parts such as ink jet nozzles for printers are the products used in bulk and are fabricated from stainless steel sheet/foils as this material is cost-effective and corrosion-resistant. Thickness of foil is of the order of 100–200 μm with an aspect ratio of 2 to 4 for the 50 μm diameter holes [44].

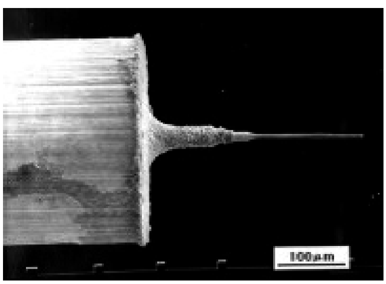

Fig. 3. Micro pin fabricated by WEDG

Large-scale developments in the ICT enable sophisticated communication, and computing systems have given way for demand in the products with such features as micro slots, micro grooves and micro slits, etc. Parts with profiles such as micro-recesses and other such features are widely used in products such as spinneret orifices in textile industries, dies for fabrication of micro electrode for the micro EDM, etc., [33]. Grooves with micrometer cross section are manufactured by ultra-precision single-point diamond turning [31]. Micro-sized structures can also be produced with micro end-mill cutting [27]. Grooves and slits of the order of 100 μm in width can be generated using FS lasers in different materials, like shape memory alloys (SMA) and copper [41], etc. Very precise beams and suspensions are the extension of slit fabrication for sensor devices such as resonators and accelerometers. Beams with 80 μm × 80 μm cross-section and suspensions 35 μm wide can be fabricated by EDM [45, 46]. Channels 60 μm wide and 900 μm deep for micro reaction systems are produced by electro-discharge grinding [47].

There is a great future ahead for entire products being manufactured in its 3D miniature form such as miniature power systems, drives which involve use of precise instrumentation, watches, micro-motors, micro gears and pumps. Such miniature devices categorized under micro electromechanical systems (MEMS) find large scale use of what is known as micro-bearing bracket employed for staying bearing [33]. Micro-gear pumps are being fabricated by LIGA subjected to EDM using copper electrode [47, 48]. Micro-turbine blades of diameter 600 μm and micro-turbine rotors are fabricated by SLS techniques [49, 50]. Air turbine rotor (diameter 400 μm) is manufactured by EDM [51] and 3D curved (50 μm thick) ribs can be produced by wire EDM [52, 53]. Micro-scissors and micro-forceps of Ni-Ti alloy have been cut out using WEDM with a very thin wire electrode [54]. Stepped gears of carbonyl iron with details of 80 μm are produced using inserts made by LIGA [36].

Among most micro parts, micro-gears are most versatile and common components that are employed in several types of MEMS and NEMS, and other miniature products [33] such as watches, pumps, turbines, harmonic drives, medical/dental devises and equipment, and RC vehicles, micro-motors, business machines, electronic home appliances, measuring instruments and timing devices. There are several processes which are used to produce micro-gears such as micro-powder injection moulding, EDM and gear hobbing.

2. Electric Discharge Machining, a promising process for micromachining

Going by the literature, it is evident that EDM process is a highly suited process for micro-machining owing to relatively low cost of equipment, its ability to cut hard materials with ease, and process being accurate. EDM started with its initial equipment termed as sinker/sinking type EDM, which finds great application in die and mould making. In sinking EDM, the workpiece can be produced either by three dimensional movements of electrode or by replication of a shaped electrode tool, or by combination of both. The electrode is generally made of highly-conducting material (electrically and thermally both) such as copper, graphite, etc., and a constant spark gap maintained through a numerical control [21]. While the conventional EDMs are suitable for large productions which can be as large as weighing in several tens of kg, recent micro-EDMs are adapted to produce small/miniature parts with micro-features. There are four types of micro EDMs: micro wire-EDM (WEDM), micro die sinking EDM, micro-Electric Discharge Milling and micro-Electric Discharge Drilling. In micro WEDM, wire of diameter of the order of 0.02 mm is used as the electrode. In die sinking MEDM, a micro-feature containing electrode is used to cut mirror image on the workpiece. In milling micro-EDM, 5–10 μm diameter micro electrodes are used to generate 3D cavities. In drilling micro-EDM, microelectrodes (10 μm diameter) are used to drill miniature holes in the workpiece [21]. Incidentally, merits of EDM out weight its limitations and the progress of this process is way ahead as compared to competing processes. This is the reasons that this process has branched out in a large number of special purpose variants and finds very versatile applications. Because of its versatility, a detailed state of the art of research in various aspects of the process is presented in the following sections of this paper.

2.1. Wire Electric Discharge Machining (WEDM)

In WEDM, the material is removed from the job by supplying a string of discontinuous sparks between the job and circulating wire electrode separated by a dielectric fluid, which is entered into the machining area continuously. During WEDMing, thin wire (0.1–0.3 mm diameter) electrode is used and the workpiece is placed on CNC worktable. Wire electrode is supplied continuously by a microprocessor through the workpiece, which allows manufacturing complex shapes with extremely high accuracy. The wire has to perform a number of machining passes through the part to attain the higher surface quality and dimensional accuracy [21]. The dynamic process forces often result in frequent breakage of micro-sized wire and require manual involvements. Other issues in micro-WEDM include production of micro-holes to thread wire in workpiece. Also, the accuracy should be very high for positioning the holes. Wear and tear is another significant issue in micro-WEDM, because it causes frequent wire breakage [55].

2.2. Microparts made by WEDM

A typical micro-part, a steel pattern/tool, shown in Fig. 4, is used to make polymer product from DMMA monomer polymerized with 1.2% EGDM cross linker (AIBN is used as a initiator) [56]. This pattern possesses pillar dimensions of $23 \times 42 \times 400$ μm and distance between the pillars of 450 μm.

Numerous other micro-parts are in use, such as gear wheel manufactured using 30 μm tungsten wire electrode, as shown in Fig. 5. Gears like this are typically used in micro-motors which work with high torque and low rotational speed. The gear having 1 mm outer diameter, 6 mm height and a total of 8 of teeth is made from X38CrMoVS_1 steel [56].

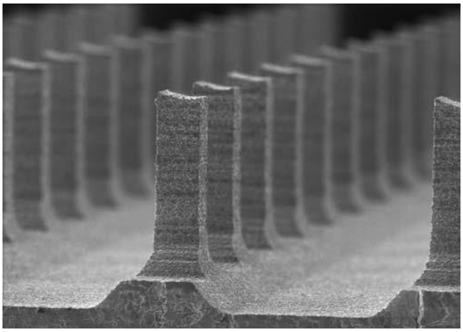

Fig. 4. Wire EDM mould tool using steel [56]

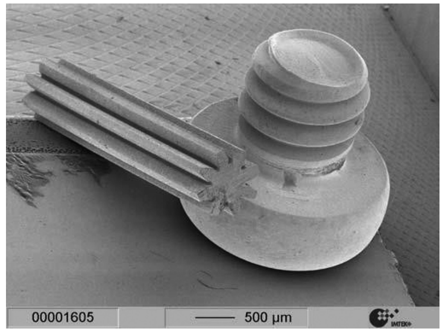

Fig. 5. Steel gear wheel [56]

Several other textured/micro-featured surface are shown in Figs 6–8. Fig. 6 depicts a moulding fabricated from stainless steel. The micro-features in these parts are machined with 100 µm zinc wire coated with brass [56].

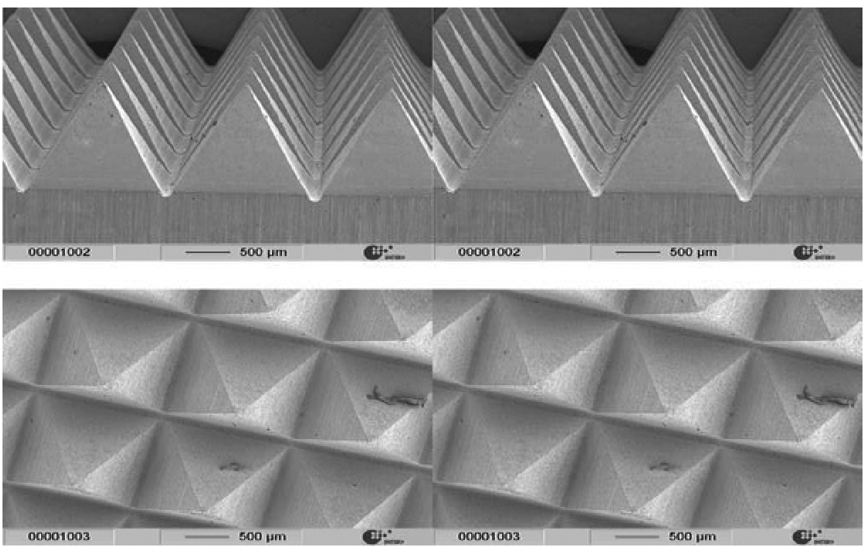

Fig. 6. Micro-feature details of stainless steel [56]

Ceramic micro-parts manufactured by WEDM have very high hardness and high temperature resistance, excellent corrosion resistance and low surface abrasion [56]. A typical gear wheel made of siliconized silicon carbide ceramic and machined from 30 µm wire electrode is shown in Fig. 7. The wheel has a 10 mm height, outer diameter of 1mm and a total of 8 numbers of teeth.

The WEDM has also been used in carbon paper structuring for miniature fuel cells as shown in Fig. 8. The channel of size 500 µm × 500 µm is machined with tungsten wire of 50 μm diameter. Such small channels improve the interchanging of H_2–O_2 reaction in fuel cells. Reaction energy is converted into electrical power using porous and conductible diffusion layer [56].

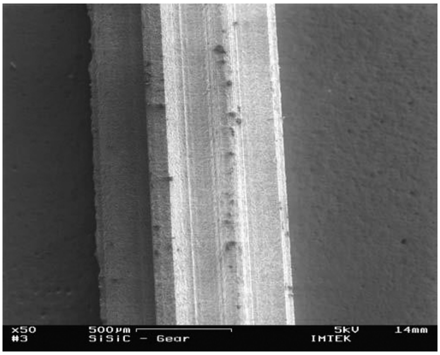

Fig. 7. Gear wheel using siliconized silicon carbide ceramic [56]

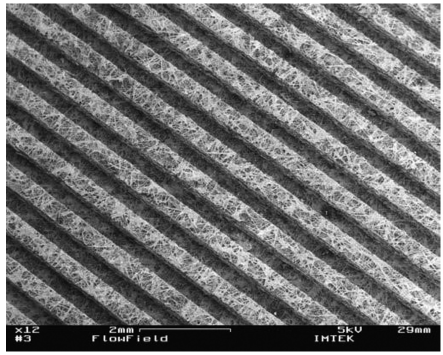

Fig. 8. Flow fields using carbon fiber [56]

Several process performance studies, conducted on WEDM, were employed in silicon wafering and micro-machining of sintered carbide compact dies [57, 58]. The cylindrical WEDM has been used for dressing a metal bonded rotating diamond wheel which is used for accurate grinding of ceramics [59]. The study demonstrated that WEDM can generate precise and intricate profile having minute corner radii, but wear rate is high on the diamond wheel for initial grinding pass. The researchers attributed this to over-projecting diamond grains that are not bonded strongly with the wheel after processing with WEDM [60]. Other exotic materials, NdFeB and MnZn-based intermetallics can also be efficiently processed using WEDM [61].

3. Micro-gear

The use of miniature gears is steeply rising with the large scale use of highly accurate miniaturized equipments like micro motors, pumps, business machines, electronic appliances, home appliances, timing devices, measuring instruments, automotive parts, MEMS and NEMS, etc. Gear with micron-sized feature and small outside diameter (< 10 mm) are regarded as miniature gears. Miniature gears are further subdivided into *micro-gears* with less than 1 mm (< 1 mm) outside diameter and *meso-gears* between the range of 1–10 mm outside diameter [62]. Although, manufacturing of miniature gears, which were traditionally used in products such as watches and precise measuring instruments, etc., was conventionally made by traditional processes such as hobbing, stamping etc. However, modern requirement of these parts have made conventional processes obsolete and they have made way for non-traditional processes because of materials, finish and production volume requirements. A comparative view of miniature gear manufacturing processes is given in Table 1.

Apart from methods mentioned in Table 1, gears are also made by cold working based exclusive gear manufacturing technique known as gear rolling, which can be performed in two ways, i.e., round rolling and flat rolling [63]. In flat rolling, the two rolling tools are flat in shape, move in opposite directions and mesh with gear blank being rolled [64].

Table 1.

Conventional processes for gear manufacturing and their limitations [62]

Methods	Limitations
Gear hobbing	1. Tool marks produce on gear teeth. 2. Requires further polishing operations for the quality improvement. 3. Requires more time for the setup. 4. Tool wear is crucial problem.
Stamping	1. Shaving operation requires for the final finishing operation. 2. Tooth thickness is limited. 3. Wearing and tearing of the die-punch is major issue. 4. Applicable only up to the medium-load duty gears.
Extrusion	1. Secondary operation requires after extrusion for the high accuracy of the gears. 2. Wear of extrusion die is one major problem. 3. Fine-pitched gears cannot be manufactured.
Die casting	1. Extremely accurate gear cannot be manufactured. 2. Trimming operations required after the removal of gear from dies.
Powder metallurgy	1. Finest metal powder is hard to arrange. 2. It is not suitable for all the types of gears. 3. Secondary operations are required for higher accuracy like sizing, burnishing, shaving, grinding, and shaving.

Non-traditional advanced methods such as EDM, WEDM, WED Grinding (WEDG), micro-EDM and micro-WEDM are notable substitutes for conventional processes and ideally preferred mainly because of excellent accuracy, repeatability, shorter set up time, better surface integrity, easiness to cut complex geometries and shapes, lesser residual stresses, ready to use final finish, etc. [65–67]. WEDM is an important variant of EDM suitable for sustainable meso- or micro-gear manufacturing. It eliminates the need of special tool and post machining finish operation, as well. It is able to machine any electrically-conductive material with high hardness and toughness. Moreover, gears manufactured by this process also have good surface finish, good dimensional accuracy, burr free surfaces and cost effective on comparison to other processes [65].

3.1. Materials for miniature gears

Commonly, rolled gears are made of alloy steels with <0.2% carbon, such as 15CrNi6, 16MnCr5, and 20MoCrS5 steels [64]. The miniature parts including gears are manufactured from a wide range of materials including bronze, brass, stainless steel, steels, aluminum, titanium and Ni based alloys, etc. [68]. Large number of materials has been machined and their machining performance has been investigated by WEDM process. Various alloys of titanium, tungsten and nickel including Inconel are used widely and all these alloys typically belong to difficult to machine materials category [69, 70]. Inconel 718, Incoloy 800 superalloy, Inconel 601 and Inconel 825 are used in many researches [71–80]. Nimonic alloys are commonly used for many applications, but the use of this alloy for micro-gear manufacturing has not been investigated much [81–83]. Investigations on micromachining of pure titanium and its alloys have also been performed widely [84–87]. Ti and its alloys have low density and high-temperature strength retention, good creep and oxidation resistance [88]. Nitinol shape memory alloys belong to difficult to machine materials category and find large applications in biomedical and aerospace applications [89]. Aluminum and its alloy like AA6061-T6, Al/SiC metal matrix composite, Al_2O_3 particle reinforced composites (based on 6061 alloy matrix), Al/SiC-MMC, etc., were widely used in machining investigation [90–93]. Steel and its alloy DC-53 die steel, SS-304, AISI-D3, ASTM A572-grade 50 HSLA steel, AISI4140 and rolled armor steel were also studied during micromachining investigations [94–100].

3.2. Major process parameters

3.2.1. Dielectric fluids and electrodes

Apart from traditional dielectrics such as de-mineralized (DM) or de-ionized (DI) water, white spirit, kerosene, etc., several hybrid dielectrics have also been investigated by the researchers. It is reported that kerosene mixed with various particles such as silicon carbide (SiC) or aluminum powder when used in EDM results in increase in material removal rate as well as surface roughness. SiC addition in kerosene increases material removal depth as compared to the mixture of kerosene with aluminum. In fact, an addition of aluminum or SiC in kerosene extends the space between electrode and workpiece and scatters the discharge energy to secure high level surface roughness. Findings of literature reveal that Al powder addition in kerosene is better than SiC additions [101]. Addition of surfactant like graphite reduces the surface tension of dielectric fluid which causes increase in material removal rate. Literature reveals that surface roughness is directly proportional and tool wear rate is inversely proportional to graphite surfactant concentration. Recast layer thickness is directly proportional to the graphite powder concentration. Also, an increase in its concentration results in an initial increase in the recast layer thickness which subsequently starts to decrease [87]. The use of oxygen gas as a medium synergizes sparking with oxidation and results in enhanced metal removal and cutting velocity [92, 102]. Oxygen gas can cause expulsion in the inner electrode gap and impact positively on cutting velocity [92]. Unlike oxygen, air will result in cutting velocity higher than that for nitrogen, because of contribution of O2 gas in the air. Oxygen gas, however, also damages the surface quality and dimensions accuracy. Nitrogen gas has lower cutting velocity than other types of gaseous medium [103].

Various materials are in use for making EDM electrodes, such as tool steels, brass, and materials based on Mo, W, etc. Researchers compared EN19 and EN8 as electrode materials during EDM and reported that EN19 wears less than EN8 [104]. Brass has high specific resistance and consequently results in an increase in efficiency of spark and electrostatic forces. Better surface integrity and accuracy are achieved in brass [105, 106]. As compared to high velocity brass wire, Zn-coated brass wire provides good surface finish and higher cutting speed, but at the same time may cause Zn and Cu contaminations [79]. Undesirable zinc and copper contamination can be reduced using nickel-coated wire. Uncoated wire develops cracks and craters on machined surface [107]. Fine diameter molybdenum wire can be used during precision machining of various materials, such as single-crystal germanium. It achieves the fastest machining time, and since it can be used in fine wire diameter, it produces smallest kerf losses. But, risk of micro cracks is high due to requirement of high discharge energies [108].

3.2.2. Pulse on time

Material removal rate, wire wear ratio, surface roughness and crater formation all increase with the increase in pulse on time (PON) due to transfer of more discharge energy. It produces deep discharge craters on the workpiece surface [78, 82, 93, 95, 96, 99, 103, 105, 108–113]. The effect of PON is most significant on most responses including surface roughness, material removal rate and kerf width, etc. [74, 82, 85, 91, 96–98, 102, 109]. The cutting rate increases with increase in PON [78, 111] mainly because of higher thermal or discharge energy which shifts from wire electrode to workpiece, so that more materials can melt and vaporize from workpiece. Therefore, the crater during process is deeper and produces rougher surface [103, 105, 114]. The gap width is also greatly influenced by PON [108].

3.2.3. Pulse off time

Low pulse off time (POFF) damages the surface integrity and produces large craters [96]. The results presented in the literature indicate that material removal and surface roughness decrease with increment in the pulse-off time due to generation of shallower craters, which are the result of increment in non-cutting time, or low discharges happen for a particular period of time and cause the minor craters and melted droplets on surface that indicate low surface roughness and kerf width [82, 103, 115]. Cutting rate falls with increase of POFF [78]. The POFF is highly significant for MRR and surface roughness [96]. An increase in POFF leads to low cutting velocity because of increment in non-cutting duration [103, 105]. The low POFF during machining of ceramic reinforced composites is the cause of inefficient molten material removal, which is covered by ceramic patches. The outcomes of this molten material are abnormal arcing and therefore wire breakage. The value of POFF should be at relatively higher levels to avoid wire breakage [111]. POFF is the most significant factor for WEDM activity when achieving the targeted value of micro-hardness and the minimization of average roughness are simultaneously considered. POFF in fact pauses the spark and allows time to remove the debris produced during spark on. During this period, quenching of the workpiece also takes place. Hardness decreases with the decrease of POFF because of little time being available for quenching process of the workpiece. Further, when the POFF is low, next spark will take place before the fully cooling and quenching of the work surface. This explains the reduction in hardness with the decrease in pulse off time [99].

3.2.4. Discharge energy or current

Input energy increases the wear rate and wire breakage problem. Crater formation is the major problem at high discharge energy [95]. The material at high discharge energy shows rough surface with lots of built-edge layers, whereas good surface quality is obtained at low-energy input conditions [79, 82, 116]. Higher pulse duration and discharge current is the reason for increment in discharge energy and surface roughness by increasing depth of the craters [74, 98, 99, 105, 113, 115]. Increasing of discharge current indicates higher cutting velocity due to higher heat energy transfer [97, 102]. It also results in coarser surface, kerf width also increases with increment in discharge duration and discharge current [100]. It is observed that higher discharge energy causes higher material removal rates due to high thermal energy transfer [112, 116].

3.2.5. Peak current

Peak current is a highly significant parameter for MRR, kerf width and surface roughness [75, 91, 97, 102]. Too high value of peak current leads to high surface roughness and kerf width [82, 95, 96, 99]. Discharge energy increases with peak current which leads to bigger craters and increases the surface roughness [96]. To obtain good surface finish, peak current should be set at low value, but this will cause lengthy machining time [97]. The metal removal rate and overcut increase with the increase in peak current owing to transfer of more energy to the machining region [71, 75]. It has been reported that increasing peak current over a limit, decreases MRR and efficiency of machining. Tool wear ratio is high at high peak current because of higher material removal [71].

3.2.6. Pulse duration or pulse width

Pulse duration is also significant factor followed by flushing pressure and pulse off time [117]. Craters of greater size form with the increment in pulse duration [95] mainly on account of duration of energy discharge which is increased with pulse duration. This consequently results in increase in cutting speed. If pulse width increases, cutting speed improves, and cutting rate reduces with increment in time between the pulses [106]. The value of surface roughness is observed to increase with pulse duration, because discharge energy also increases which results in larger craters [106, 117]. Pulse width is the crucial parameter that affects wire rupture. Wire rupture increases when pulse width increases, and time between the pulses decreases. Number of discharges improves when time between the pulses is shorter and higher pulse duration leads to more discharge energy, which results in excessive thermal load and breaks the wire [106].

3.2.7. Gap voltage

Gap voltage defines the space between the work-piece and wire electrode. Experimental results demonstrated that kerf width increased with the increment in gap voltage due to the presence of higher discharge energy. It is noticed that gap voltage is more important than pulse duration when it comes to controlling kerf [84]. Gap voltage is a notable factor which significantly affects surface roughness and material removal rate [82, 91, 93]. Surface roughness decreases with the increase in gap voltage [78]. Increment in gap voltage results in larger electrostatic forces and leads to winding the wire during discharging process. That is why SR is lower at higher gap voltage [105]. The surface roughness and oversize decrease by increasing the gap voltage, this is due to the fact that increasing in the gap voltage leads to winding of the spark gap [103]. The consequence of increasing voltage is more discharge energy, therefore it increases cutting speed [93, 111]. Some studies, however, report that enhancement in gap voltage causes low cutting speed but high kerf width under specified range. At a selected value of open circuit voltage, an increase in gap voltage increases the dielectric strength of fluid causing discharge current to decrease during processing, and consequently decreasing the melting and evaporation, and cutting speed [114].

3.2.8. Wire tension

The wire tension, among other factors, controls the vibrations during sparking and wire travel. High tension in wire is useful in overcoming wire rupture and vibrations [96, 109, 118] it also improves the surface finish [71]. Wire tension is a significant parameter for obtaining good surface finish because it diminishes vibration in the wire [84]. Generally, the wire breakage is more frequent when wire tension is high at high discharge energy. At low energy, increasing wire tension reduces wire vibration [109]. Wire tension doesn't affect cutting velocity and surface roughness, but oversize increases at higher tension of wire. The major reason for this inaccuracy are the forces acting on the electrode wire. Higher wire tension leads to rigidity of the wire, so at certain values of discharge energy it does not experience high impact and also does not act in reverse direction [103]. Increment in the wire tension is found to result in low corner deviation. It is demonstrated that stronger forces due to higher tension withstand against force component involved with corner cutting, therefore corner deviation is reduced [110].

3.2.9. Wire feed rate

Surface roughness is found to increase with increase in wire feed rate [96]. When wire feed increases, the wire is quickly renewed and recovered during the process. So non-worn wire increases the spark efficiency and produces the deeper crater. This is the reason that higher wire feed results in rougher surface. It is perceived that wire feed and wire tension both are insignificant factors for cutting velocity [105]. The kerf width is found to reduce with increase of WFR [84].

3.2.10. Flushing pressure

Low flushing pressure is not desirable for dielectric, because it is insufficient to remove the debris and reinforced fibred composites from the machining region. The reinforced composites are settled together in cutting region and may cause wire breakage during machining [93, 111].

3.3. Major response parameters

3.3.1. Cutting speed/velocity

Cutting speed during WEDM is a response which is significantly affected by several process parameters. High values of pulse on time (PON) and current and low values of pulse off time (POFF) gap voltage will result in high cutting velocity. Both wire feed and wire tension doesn't affect cutting velocity [102, 105]. Typically, cutting speeds for composite materials are significantly lower as compared to unreinforced metals/alloys, mainly due to the presence of ceramic reinforcement particles. These ceramic particles are highly non-metallic and steeply lower the thermal and electrical conductivity of the material [111]. The cutting speed also depends on factors such as corner radius, workpiece thickness and number of finished cuts when machining profile includes corners and intricate regions. Error is reduced when the number of finished cuts is increased [118].

3.3.2. Dimensional deviation

Accuracy of machined component and dimensional deviation is mostly affected by pulse on time, peak current, spark gap voltage and wire feed. The deviation is reported to improve by increasing pulse off time and wire tension [74]. Investigations report that dimensional overcut largely depends on peak voltage, peak current and speed of electrode. The overcut, however, initially decreases and then increases with the peak voltage. It also decreases with increasing electrode speed [75].

3.3.3. Material removal rate

For material removal, peak current and pulse on time are more influencing factors than others [81]. MRR closely relates to operating parameters in a way that it increases with increase in pulse on time, input current and wire tension and decreases in pulse off time, wire feed and gap voltage [82]. The MRR also increases with increase in machine feed rate, on the other hand, wire speed and fluid flushing pressure are less effective on MRR [84]. It is reported that material removal rate increases when the dielectric supply rate is reduced. MRR also reported to depend on the melting point. In a typical investigation it is reported that between AA7017 and rolled homogeneous armor steel, the maximum material removal rate was achieved for AA7017 than armor steel due to low melting point [95]. Oxidation and decomposition can also increase the material removal rate. Foamy structure appears due to gas bubbles formation. This is related to oxidation process by thermal energy which leads to higher material removal [96].

3.3.4. Surface roughness

Large number of investigations reported in literature have performed the parametric studies and come out with conclusions based on statistical analysis. In one such investigation, it is reported that PON, servo voltage and peak current, and combined effect of PON and peak current are more significant for SR than other factors [81]. Better surface finish can be secured at higher values of POFF, gap voltage and wire tension and lower values of PON, input current and machine feed rate [74, 82, 84, 102, 105, 111]. Electrode polarity is also an important factor along with current and PON. SR is reported to be low with negative electrode polarity. When electrode is positive, the surface becomes uneven with thick recast layer and marked with the presence of globules. Carbon content on the machined surface is also reported to be more significant with positive polarity tool [83]. Brass wire coated with zinc yields smoother surface and high cutting speed in comparison with high speed brass wire. Also, results show that uncoated wire generates craters, cracks and melted drops on surface [106]. Thermal effect is stronger on the material in the case of aluminum alloy due to its high thermal conductivity and lower melting point. Due to this fact, more material melts and cleaning of debris by dielectric fluid becomes less effective resulting in poor surface finish [91]. During the comparison of Al/SiCp composite and unreinforced alloy, one finds that surface finishing of Al/SiCp composite materials is superior as compared to unreinforced alloy because the solid SiC particles prevent the removal of aluminum matrix. Moreover, these particles don't get melted during machining. Hence, molten material is highly viscous and further decrease the metal removal efficiency [111].

3.3.5. Surface integrity of recast layer

A thin, white and hard layer known as white layer or recast layer is observed on the machined surface. It is formed as a result of phase transformation (i.e., quick re-solidification of melted material) during machining and development of thermal stress on the solidified material [89, 119]. There are two possible ways for recast layer formation, one is thermal-induced phase transformation and the other is severe plastic deformation. Due to the recast layer, the bulk machined material becomes weak due to inducing micro-cracks, tensile stresses and phase transformation [89]. Researchers have identified four characteristic zones in surface affected by the machining process. Outermost zone is called the recast layer or white layer; this is formed as a result of rapid re-solidification of the material due to heat of machining. There is an area below the white layer which, although did not melt, was heated and then cooled slowly. It creates annealed area which is softer and smoother than the parent material. Below this zone, the material properties are not affected by the machining process and all properties of parent substrate are retained [119]. Higher discharge energy is the main reason for a thicker recast layer [116]. Fig. 9 shows the difference between the thickness of recast layer normalized, hardened and tempered AISI4140. Dendritic solidification occurs in the recast layer. This solidification mechanism takes place only if an under-cooled melt exists for example during high cooling rate [116].

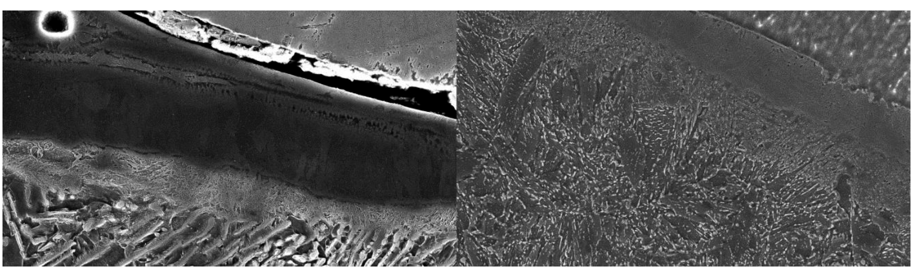

Fig. 9. Recast layer of normalized hardened and tempered AISI4140 [116]

3.3.6. Thickness and composition of white layer

Thickness of white layer is proportional to the magnitude of energy introduced on the surface [119, 120]. It depends on all factors that affect the discharge energy, including polarity of wire electrode. Extensive investigations have been carried out on white layer on variety of materials. In case of steels, it is reported that recast layer is made up of very fine equiaxed martensitic grains (approximately 200 nm) of very high dislocations density. Literature has also demonstrated the presence of spherical deposits in white layer (appearing like bull's eye, as shown in Fig. 10) which were confirmed to be made of electrode material. This surface contamination from the electrode material is due to melting, vaporization and subsequent deposit of electrode material over the machined surface. Some of them get deposited on machined surface and get alloyed with the material to form an amorphous layer [121].

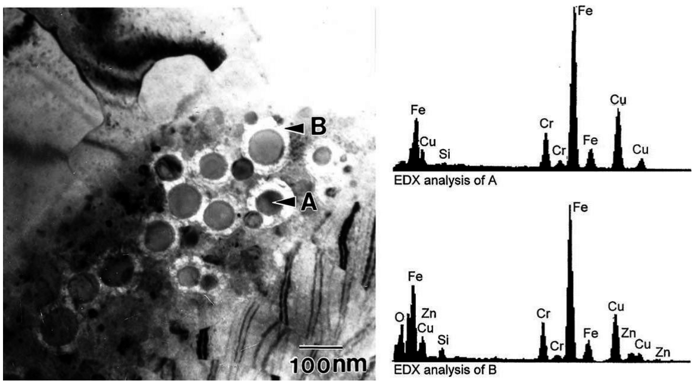

Fig. 10. Bull-eye structure formed due to the spray of molten electrode material during 4th cutting and EDX-analysis of sites: A – spherical deposit; B – the oxide layer [121]

Steels are commonly machined by WEDM using hydrocarbon-based dielectrics. This involves typical chemistry and physics due to which specific elemental make of the white layer is formed. It has been evident from one of such investigations in which nine trim cuts were performed (as shown in Fig. 11). This study reported that the recast layer consisted of Cu and Zn electrode materials and also Mo from the molten material carbides. V and Cr were not identified in white layer/recast layer. The researchers inferred that Fe and Mo need the equal amount of thermal energy for melting while V requires higher amount of thermal energy with a factor of 1.3. That's why Mo was assorted in white layer but V stayed localized [122].

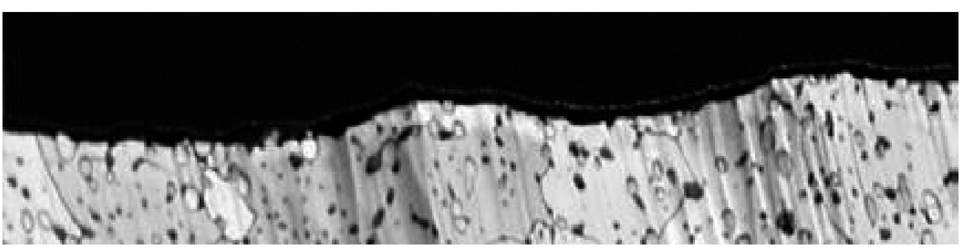

Fig. 11. 9 trim cuts Rim zone pictured with EBSD [122]

When machining is performed in presence of kerosene, water-oil emulsion and DI water, it is noticed that one finds an excessive oxide content on the machined surface during machining under W/O emulsion and DI water. The carbon concentration in recast layer under kerosene was greater than the one formed using water-oil emulsion and DI water because supply of carbon from hydrocarbon oil decomposition; whereas Cu was present in the recast layer when de-ionized water was used [123]. Thus, the composition of white layer in terms of its chemical makeup depends on several factors [123, 124]. Foreign elements, such as Cu and Zn, were detected on main cut that were resettled from the brass wire electrode, but Cu gradually decreased in subsequent trim cut. This was due to poor discharge energy during trim cut causing less abrasion and decomposition of the electrode wire [124, 125]. Due to low evaporation temperature of Ni than Ti, Ni vaporizes and combines with melted electrode material resulting in higher Ni presence in debris than Ti [124]. Further, recast layer's average thickness was found to depend on dielectric in such a way that its average thickness was higher in water-oil emulsion dielectric than in de-ionized (DI) water and kerosene under the same pulse duration because it has higher viscosity than kerosene. Due to this reason, removal of molten material from the sparking zone was inefficient and resulted in deposition on machined surface. The non-unified white layer produced in main cuts was demonstrated to be composed of a thick porous layer at the top, and the other one being a thin hard layer at bottom. The variation in thickness in white layer after roughing trim cut are attributed to high pulse current and pulse on (PON) duration used during trim cut. Under finished trim cuts using both dielectrics, a very thin white layer is observed [126–128].

3.3.7. Heat-Affected Zone

The material adjacent to recast layer, which was not melted but affected by the heat of machining, is regarded as heat-affected zone (HAZ). Depending on the metallurgy and heat treatment condition of the substrate, the material in the HAZ may experience phase change under the effect of high amount of tensile residual stress, porosity, micro-cracks and recrystallization and grain growth [121]. It is observed that HAZ size increases with higher discharge energy. A lot of factors decide about the characteristics of this zone which includes heating and cooling rate, peak temperature and the presence of prior phases. For a typical case (Fig. 12), the

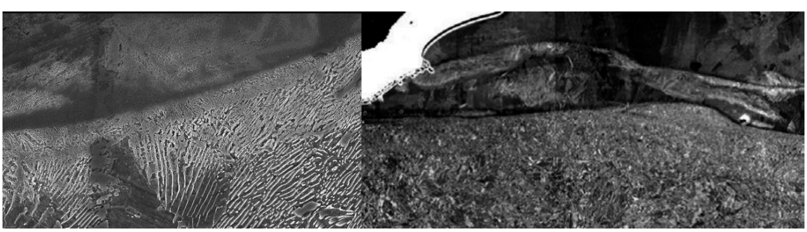

Fig. 12. Rim zone of final normalized material and hardened/tempered material [120]

material was subjected to normalizing and two different phase structures consisting of ferrite and pearlite was observed.

3.3.8. Surface roughness of white layer

EDMed surface has a typical texture built by random arrays of overlapped craters, due to severe heat generation that causes local melting and evaporation of material [119]. The energy dissipated during EDMing is found to be greater than the energy released during laser machining. Due to this fact, the white layer formed during laser machining is uniformly distributed over the surface, whereas the white layer on the EDMed surface is non-uniform and consists of new phases and voids (as shown in Fig. 13).

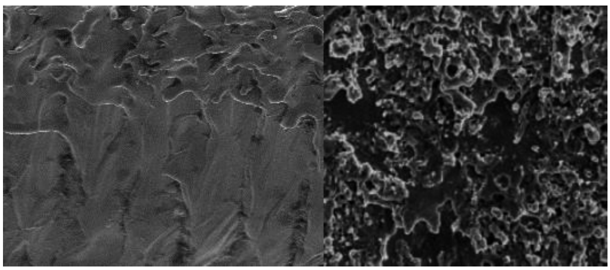

Fig. 13. Laser and EDM white layer topography [119]

The white layer SR of laser machined surface is higher than EDMed surface and a texture consisting of columnar patterns resulting from molten material flow is generated in the laser-machined surface. White layer has a solid structure without any voids or cracks during laser cutting. During EDMing, foreign elements from the dielectric fluid enter into white layer and result in cracks and voids [89]. Even the electrode polarity leaves typical hallmarks on the machined surface and can be characteristically distinguished. In an investigation performed to study the effect of polarity, the electrode negative was applied in initial four cutting passes and later machining was performed with electrode positive in the last cutting pass (i.e. fifth pass). From the results, craters and martensite laths were noticed on finished surface after the fourth pass (Fig. 14). Spherical particles with composition similar to work material were observed on the brim of craters. Whereas, after the fifth pass the surface was found to be partly covered with loose deposit particles. They were comparatively smoother and denser (better surface finish) than the other surfaces cut with negative electrode polarity [121]. Martensitic transformation was not confirmed after the fifth cutting pass because the temperature was not high enough. During multiple trimming, subsequent trim cut one and trim cut two reduce the debris on surface. After the finish trim cut four, an isotropic surface along regular craters was noticed. The debris are observed on surface after the fifth cut but they are very small as compared to the main cut surface due to less thermal impact. Finish trim cut generates highly smooth surface [124, 126].

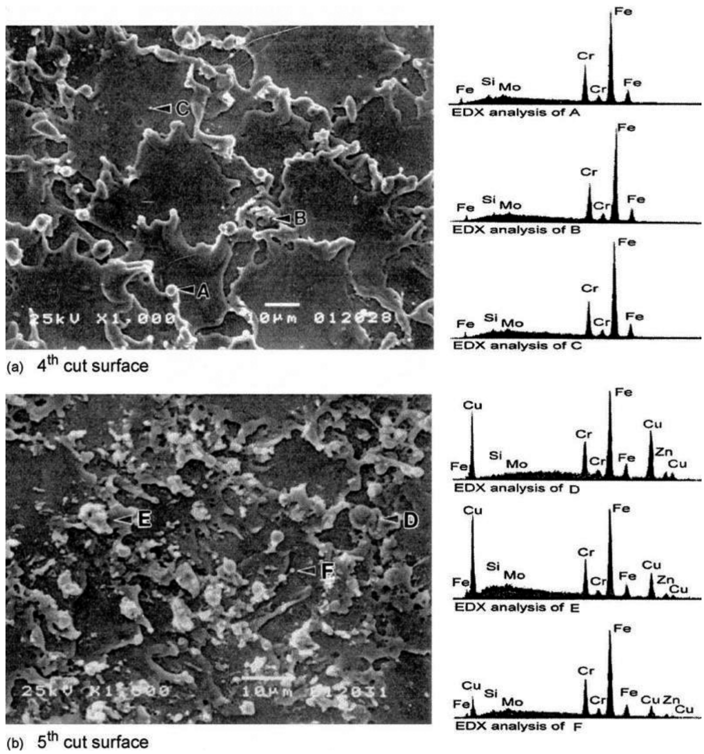

Fig. 14. a) finished surface after 4th cutting pass with NPWE; and b) after 5th cutting pass with PPWE [121]

The surface obtained with W/O emulsion has larger and deeper craters than the one with DI water and kerosene due to high viscosity of W/O emulsion (Fig. 15). Dielectrics with high viscosity obstruct the discharge channel's expansion causing impulsive force accumulation within less area and resulting in large and deep craters [123].

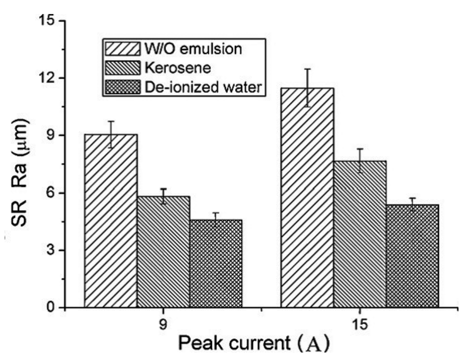

Fig. 15. Comparison of SR under different dielectrics and peak currents

The effect of discharged energy on roughness is more or less similar on different materials with peculiar deviations in texture, which is typically different in different materials. The surface and sub-surface modification of INCONEL 718, for example, were investigated in a study after machining by WEDM using brass wire. Effect of nominal energy per unit length of cut (sum of: 1. Energy required to eliminate material from workpiece, 2. Energy transmitted to the wire electrode and 3. Energy transmitted to machine surface) was examined. In both the roughening and finishing condition, the round shaped re-deposited material was demonstrated to be not equivalently deposited on the surface. Numerous bubbles were seen on the machining surface because of high nominal discharge energy per unit length and duty cycle. Some cracks were visible on the recast layer, as shown in Fig. 16 [129].

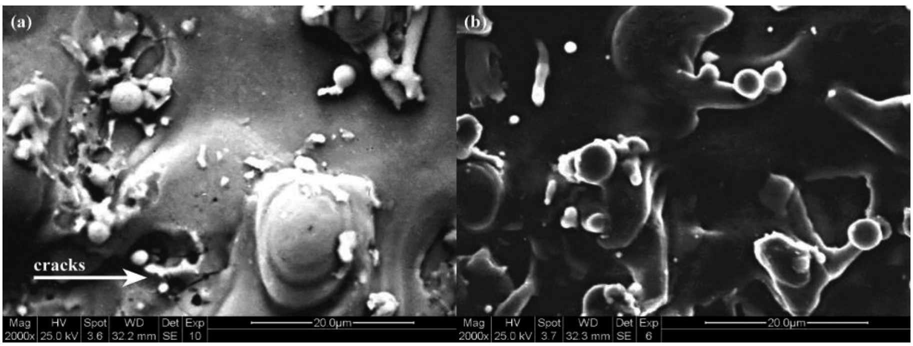

Fig. 16. SEM observation: a) roughing condition b) finishing condition [129]

Likewise, during comparison of trim cut surfaces for S390 and SKD11 after the fourth finish pass, pinholes and craters were observed on SKD11. Whereas, no such globules or cracks were seen on S390 except for a few tiny voids. The surface roughness decreases with the increase of number of cutting passes, since in each successive pass the discharge energy decreases. Thus, high discharge energy is used in the rough cut, and this leads to more resolidified material being accumulated on the surface, resulting in coral reef like microstructure with extremely rough surface. For succeeding trimming passes, very small coral reef, like microstructure and lower roughness, is obtained [120, 125, 127]. Finally, SR of multi-pass machined S390 material is much better than SR of similarly machined SKD11 [127]. The prior heat treatment condition also affect the SR of machined surface, such as in case of an annealed specimen the SR is higher than that of quenched or tempered samples due to higher thermal conductivity of the annealed specimen [119].

3.3.9. Microhardness

The micro/nano hardness of machined surface may remain the same as that of substrate, or may be higher or lower than that. This mainly depends on the material's metallurgy, its initial heat treatment condition, the heating and cooling effects of the heat of machining and the presence of contaminants, if any. The heating and cooling effect, however, directly depends on the machining parameters. In case of Nitinol shape memory alloy, the nano-hardness of white layer is reported lower than the bulk material during laser cutting. In case of laser machining, there are no contaminants, but when the same alloy is machined by EDM there are possibilities of oxidation, and contamination from carbon and other elements, as well as varied quenching rates that may lead to alloy's hardening or white layer hardening [122]. In case of steel, however, the white layer hardness is found to be doubled as compared to the parent material hardness. This could be due to high concentration of carbon and copper below the surface and also due to the presence of high-heat flux and subsequent quenching by the dielectric [120]. Hardness of recast layer is higher in case of W/O emulsion because of the presence of carbon and higher cooling rate [123]. In case of multiple pass machining, there are repeated cycles of heating and cooling that may result in variable surface properties, causing the white layer hardness to vary after ever subsequent pass. In the typical case of nitinol, average microhardness of top layer was reported to first increase up to 50% from the main cut to the 1st trim cut, then moderately increase by the succeeding trim cut 2nd and the 4th trim cut. Discharge energy has a significant role to play in the white layer hardness. The white layer is more uniform and solid at low discharge energy and significant softening occurs in HAZ, attributed to minimization of thermal degradation at low discharge energy [124]. Similarly, the dielectric composition (e.g., W/O and water, etc.) which affect cooling rate has its effect on the surface microhardness, as well. A lower microhardness has been reported for trim cut surface during oil. The reason for lower microhardness is higher residual tensile stress on electric discharge machined surface in water verses oil, causing lower hardness [126]. In case of S390 and INCONEL718, microhardness is increased at the surface in the main cut specimen, because of hardness generated by the metallurgical transformations influenced by extreme temperatures and quenching rate during the WEDMed process. A soft layer of about 10–20 μm thickness is reported just under the surface of each specimen for the first to third trim cut. The thermally influenced zone is decreased significantly from the rough cut mode to the 3rd trim cut mode, therefore, there is no variation of hardness at the last trim cut specimen [125, 127]. In case of tempered and quenched sample, HAZ is smooth because of the over-tempered martensite that develops due to slow heating and cooling. It is observed experimentally that the distribution of microhardness is not changed below the surface by increasing the dielectric fluid pressure, but this increases the hardness of the surface slightly. [119]. Low carbon makes the white layer less hardened [120].

3.3.10. Micro-cracks, micro-voids and burrs

There are many types of burrs, like primary and secondary burr, minor and feathery burr and needle like burr. Burr formation, in conventional machining operations, can be avoided by decreasing the feed rate and axial engagement [90].

For an EDMed surface, micro cracks are formed because of very fast cooling of melting material, which results in thermal stress [119]. Rapid resolidification of molten metal under flushing of the dielectric may also form micro-void due to entrapment of gases and vapors. During the machining under W/O emulsion, the presence of surface cracks and micro-cracks is more evident as compared to machining under kerosene oil, due to generation of extensive amount of gas, as shown in Fig. 17, which diminishes the recast layer strength. The results indicate that surface micro-crack density decreases with higher peak current, no matter what is the type of dielectric [123].

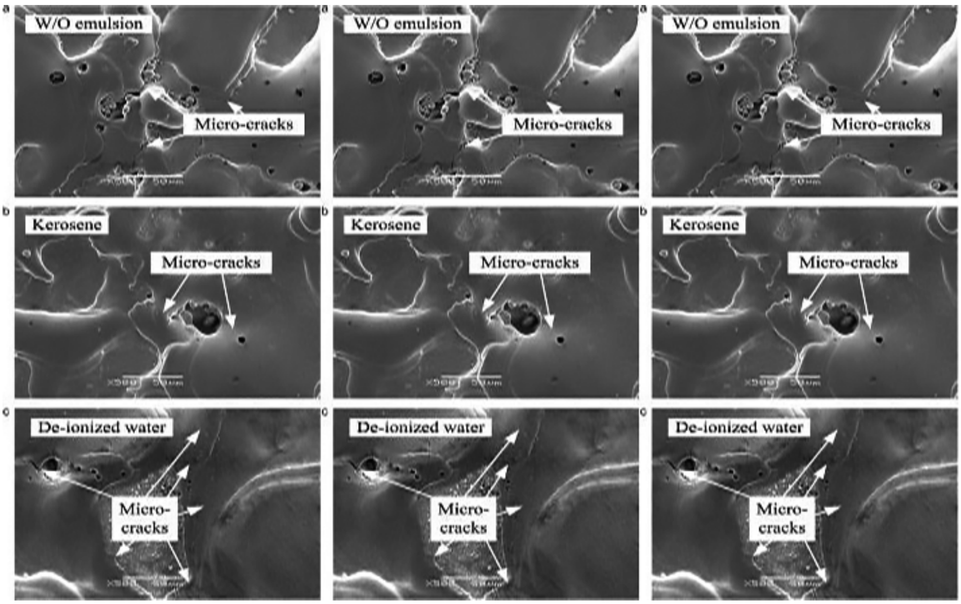

Fig. 17. Micro-cracks on samples surface machining in diverse dielectrics

In case of Inconel 718, multiple cracks are noticed during EDMing due to the fact that the surface produces by Electric Discharge Machining has vast possible sites for initiation of crack, as shown in Fig. 18. There are various causes for the loss in fatigue life in the case of EDMed specimens that exhibit high tendency for recast layer formation, high tendency for recast layer cracking, large surface tensile residual stresses and, finally, surface irregularities [130].

Micro-cracks are formed on white layer of main cut surface due to high tensile residual stress, large heat energy release by discharge and rapid cooling. The subsequent trim cuts don't show any micro-cracks and globules on the surface and produce less coral reef microstructure due to gradually decreasing discharge energy [124, 127]. In case of IN718, the tendency of cracks formation is very low due to high toughness and high thermal conductivity which conducts the heat away from the heating region very quickly [125]. Crack density in the white layer grows with

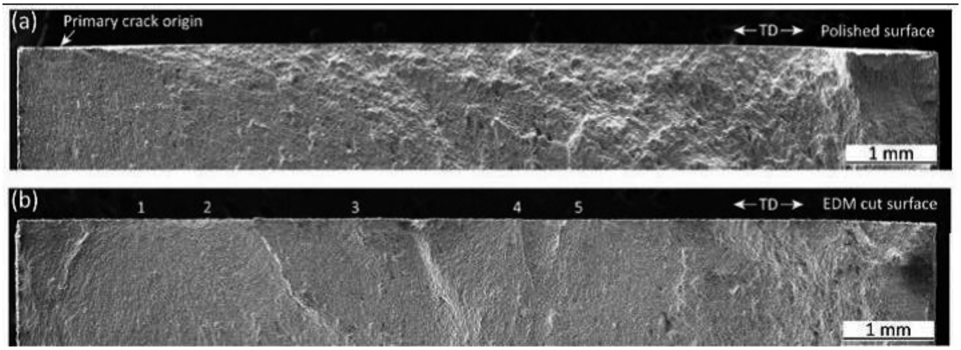

Fig. 18. Comparison of the fracture surface with different surface conditions. Multiple crack origins from the EDM cut surface, these are indicated by numbers in (b) [130]

increasing duration of pulse and open-circuit voltage [119]. Longer crack inside hole can sometimes also be observed when machining is done using EDM, as shown in Fig. 19 [44].

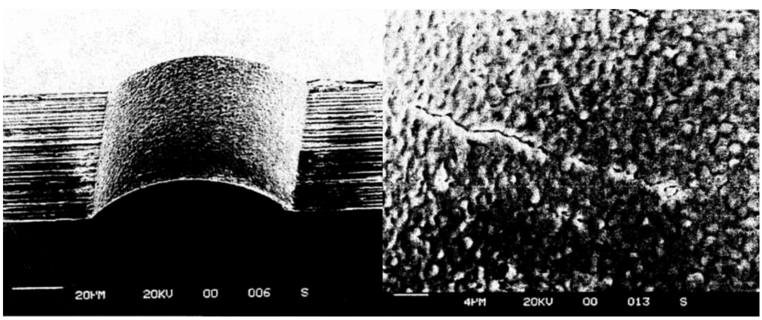

Fig. 19. Internal surface of the micro-hole and defects inside a micro-hole [44]

3.3.11. Residual stress

The reasons behind the residual stress are the strains developed by the metallurgical transformations and non-uniform heat flow during WEDM machining [127]. Despite the high thermal loading, the peak of the residual stress is not located on the metal surface because a stress reduction mechanism is present there, it is located at the interface between white layer and heat affected zone. Peak residual stress increases with spark energy due to higher current [119]. The higher residual stress is reported in HAZ, because the molten material speedily quenches and re-solidifies, and the contact of re-solidified materials on upper surface and bulk material just below restricts the contraction. The high quenched rate of DI water dielectric generates higher residual stresses than those in oil during main cuts and finish trim cuts [126]. A comparison of residual stress between SKD11 and S390 reported that S390 has higher residual stress than that of SKD11 due to the difference in yield strength, and has a better finish, as well [126].

4. Research on micro-gear manufacturing

Although enormous amount of work has been reported on micromachining, yet there is limited literature in the area of micromachining of miniature gears. Machining of miniature gears assumes importance given that products such as instruments, devices that are expected to employ them steeply bound upwards. Literature reporting various aspect of micro-gear manufacturing is very scarce. In a typical investigation, micro wire-EDM was employed for profile roughing and final dressing for miniature gear machining on polycrystalline diamond (PCD) wheel. As conventional WEDM provides higher discharge energy than micro WEDM, it is very likely to cause higher thermal damages, thick edge and craters over the PCD surface, leading in turn to thick damaged layer and rougher surface, as shown in Figs 20–22 [131].

The geometrical deviations in macro- and micro-sized geometry of wire EDMed miniature external spur gear is a major issue. The basic dimensional parameters, such as span, outside diameter and tooth thickness, are macro-geometry

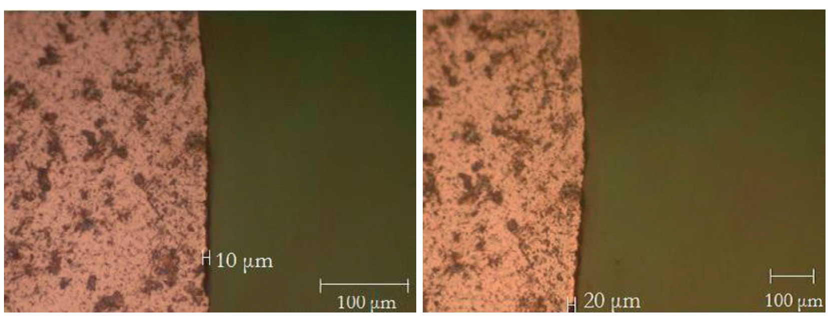

Fig. 20. Edge of PCD surface obtained by Micro WEDM and WEDM

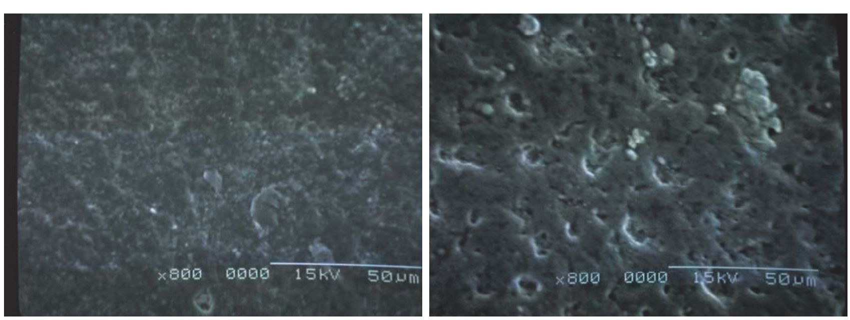

Fig. 21. SEM images of PCD surface by micro WEDM and WEDM [131]

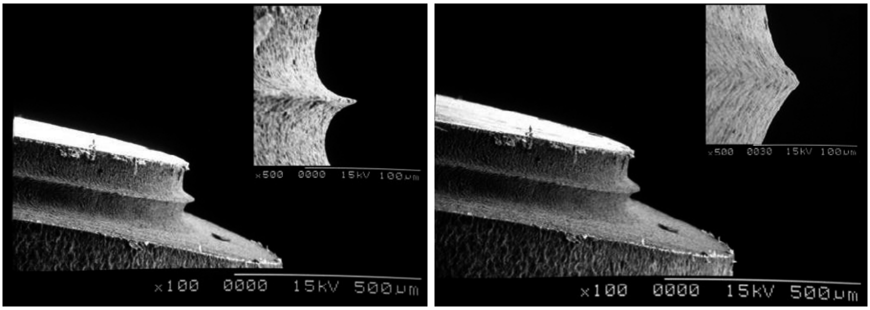

Fig. 22. SEM images of PCD wheels fabricated by micro wire-EDM and wire-EDM [131]

parameters, on the other side, profile, pitch run-out, lead and SR parameters are micro-geometrical parameters [80, 132–134]. The profile error commonly affects the noise behavior and pairing, pitch and run-out error affect the motion transfer characteristics, and the lead error controls the load carrying capacity, as shown in Fig. 23 [80]. The basic reasons for micro-geometrical deviations when using WEDMed are asymmetrically shaped craters generated by the produced intense spark due to excessive discharge energy [134] and the divergence of wire from the planned pathway, noted as wire-lag [135]. There are many reasons for wire lag, such as mechanical forces generated due to pressurized gas bubbles, electrostatic forces acting on electrodes, hydraulic forces produced by flushing dielectric, electro-dynamic forces due to the spark generation and the axial forces that straighten the wire. One of the important factors for macro-geometrical deviations in miniature gears are wire vibration, machine tolerance and gear blank.

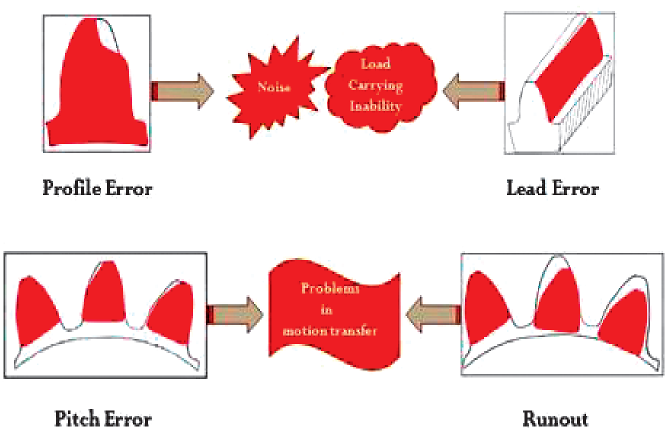

Fig. 23. Effects of micro geometry errors on the performance of miniature gear [80]

Profile-related errors are caused by most of the EDM process parameters. Minimum values of the profile error and pitch error are observed at the low voltage, as high voltage and P_{ON} time develops greater forces owing to intense spark (discharge energy) and gas bubble pressure which causes poor surface finish and high MRR [135–137, 139, 140]. Surface finish becomes poorer if pulse-off time (POFF) is maintained at very low levels, consequently increasing chances for short circuit of wire. There should be an optimum range of the POFF and wire feed for good quality micro-gear because, at lower POFF time and wire feed rate, there will be wire vibrations due to the short circuit, while at higher values, there will be excessive hydrostatic forces which result in wire lag and again increase the profile and pitch errors [136–140]. Higher voltage and PON and shorter POFF increase discharge energy, and availability of time to transfer this energy to the tooth surface of gear and decrease the flushing time. All these factors produce deeper and irregular craters on gear tooth surface and also increase the SR and profile and pitch error [136–138, 141, 142]. At low rate of wire feed, wire can tolerate high discharge energy, which increases the wire-lag, non-uniform wire wear and wire-breakage. All these factors result in high pitch and profile. Higher feed rate of wire decreases duration of spark at a specific place on wire and therefore decreases wire-breakage and wire-lag, and thus, reduces profile and pitch error [137, 138]. In any case, as the discharge energy is significantly low and pulse frequency is very high, in the case of micro-WEDM compared to conventional WEDM, the gears produced by micro-WEDM are better than WEDM in all respects, as it is clear from the photographs of parts produced by the two methods (Fig. 24 and Fig. 25).

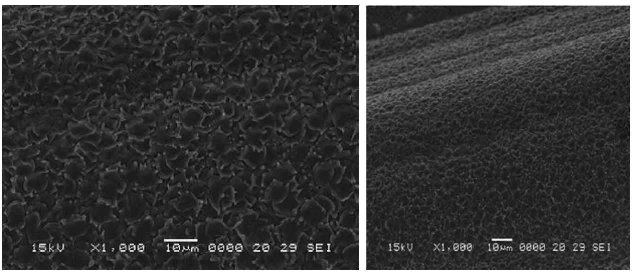

Fig. 24. Comparison of SR of conventional and micro-WEDM [139]

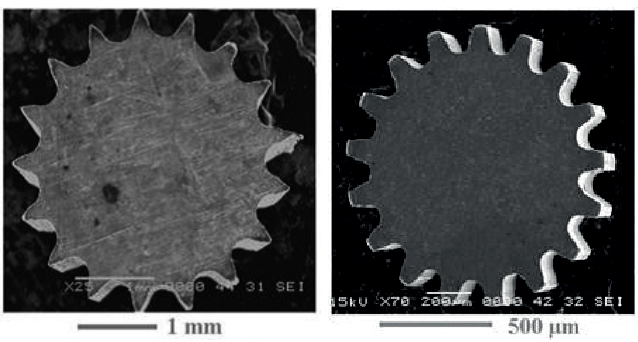

Fig. 25. Micro sized gear by WEDM and Micro WEDM [140]

Most of materials which are used in fabricating miniature gears, such as AISI-304L and other austenitic stainless steels, beryllium copper, Nitronic 60 and titanium and most of these, are difficult to machine, and machining micro-features on them becomes even more difficult. Given this situation, micro-WEDM becomes highly suitable to machine such parts. AISI 304 and titanium alloy offer an excellent profile tolerance. The titanium alloys have minimal re-cast layers and very smooth features. Hence, it is noticed that micro-WEDM can develop high aspect ratio (HAR) and good tolerance in meso/micro scale parts [143]. The re-cast layer hardness is higher under micro-WEDM. This is because of the high quantity of cementites. These cementites result due to carbon absorption from pyrolysis of dielectric. [144]. It is practicable to manufacture miniature gear surface without cracks, protrusion and pits. The surface can be generated with uniformly distributed regular shaped craters using WEDM and Micro-WEDM method, as shown in Fig. 26 [68, 131, 138–144]. The miniature spur gear produced by WEDM shows the defect-free microstructure, good surface finish, very thin recast layer and good gear quality up to DIN 5 for micro-geometry parameters such as profile and pitch, which is much better than the quality of miniature spur gears produced by other conventional processes [68, 136].

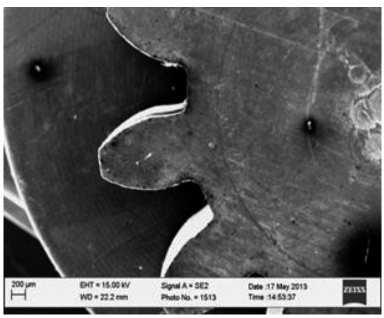

Fig. 26. Miniature gear manufactured by WEDM
at optimal parameter [144]

5. Future directions

Previous sections have unwrapped the performance of micromachining task using various conventional and non-conventional processes. It is pertinent to mention that the desired levels of profile and dimensional accuracy and surface qualities expected from the miniature parts are extremely difficult to obtain through conventional processes. Among non-traditional processes, WEDM and micro-WEDM are the most suitable processes. Hybrid and sequential micro machining process can also improve the machining quality of micro components. Hybrid micromachining such as ECDM milling and laser assisted micro-milling can be effective in fabricating complex shapes from hard and brittle materials with high machining accuracy.

Such type of approaches are specifically beneficial in reducing positioning errors and improving dimensional inaccuracy. The expected level of part accuracy is very high and depends on a complex mix of parameters including, electrical (pulse current, pulse on off time, voltage, overcut voltage (OCV), frequency, etc.) and mechanical (wire feed speed, wire tension, type of dielectric, spark gap, flushing pressure etc.), as well. Most of the reported studies have been performed on some arbitrarily selected materials and reports concentrate on effect of most common parameters on common responses, such as kerf width, surface finish, etc. Actually, producing of miniature parts requires comprehensive regime of investigations involving accuracy of micro profile, and various dimensional features of profile, mechanism of dielectrics in action, effect of tiny process forces on wire vibration and in turn its effect on part accuracy, etc. Unfortunately, most of the research work was related to mere material selection, process parameters, performances, product manufactured, miniature product generation, and micro-tool fabrication. Little work has been performed in the area of manufacturing of proper miniature products, such as micro gear, micro wheel, micro tools, MEMS, etc., using wire EDM, and concerned investigation of machined part's quality through a comprehensive measurement regime. Very few studies have been done on the liquid and powder mixed dielectric fluid, spark energy, dielectric strength, and breakdown mechanism of dielectric fluid. Surface integrity and white layer characterization of miniature products should also be investigated. Wire tension and deflection of the workpiece are some major issues. Different dielectric fluids have different effects on the workpiece. The research work on different dielectric fluids may also be taken up. The effect and action of dielectric fluid on surface integrity, recast layer, HAZ, etc., may also be an area to focus on.

6. Conclusions

In this review, efforts have been made to bring out state of the art on micromachining using non-conventional processes such as Micro-EDM, WEDM, etc. The literature revealed that extensive research has been done in the field of material selection, process parameters, performances, miniature product generation, and micro-tool fabrication. This report presents key discussions with a focus on different parameters (discharge current, pulse on and off time, pulse duration, spark gap voltage, cutting velocity, wire feed rate, and so on) and the response factors (material removal rate, surface roughness, dimensional deviation, cutting speed, surface integrity of recast layer and so on). In the study, the recast layer, heat effected zone, microhardness, micro cracks, residual stress, etc., have been analyzed in the light of effect of important and relevant parameters. The study also has a showcase status report on research done on micro-gear manufacturing till now. Various macro-geometry features (e.g., span, outside diameter and tooth thickness) and micro-geometry (profile, pitch run-out, lead and SR) of the micro-gears have been studied and analyzed by the researchers. A comparative study has been done on other conventional processes for micro-gear manufacturing and WEDM. The study shows that WEDM is a better process for micro-gear manufacturing as compared to other manufacturing processes. There are many reasons behind this fact, such as defect-free microstructure, good surface finish, better surface integrity and good gear quality defined based on (micro-geometry parameters such as profile and pitch). The errors related to macro and micro geometries can also be reduced by machining using WEDM with optimized parameters. This is mainly attributed to the fact that the conventional processes use heat and forces which are applied on bulk of material, whereas during WEDM the energy is supplied in microscopic volume and the affected volume is removed, hence the material bulk remains less affected. Hybrid and sequential processes can also implement to fabricate micro-gears. These methods considerably improve the MRR, SR geometrical accuracy and tool life. These processes are specifically advantageous to develop the complex 3D miniature parts with high accuracy, surface quality and efficiency. Sequential processes reduce repositioning errors and achieve high level of accuracy. It has been noticed that non conducting brittle materials are mostly micro-machined using these processes. Research could also proceed for some other types of materials.

Further, it is also noticed that most research work is focused on the general process parameters and their effects on response factors for the macro-sized product. The effect of these parameters has been less investigated on miniature products such as micro-gear, micro-tools, micro-channels, micro-electric boards, etc. The focus should also be directed, with a special focus, on micromachining, on how these parameters affect spark energy, mechanism of energy dissipation at spark gap, pulse wave form; as these features in turn translate into material removal rate, dimensional accuracy, surface integrity and dimensional accuracy of miniature products. Most of the research is done for some specific types of dielectrics and powder mixed dielectrics. There is very little research report on multiphase systems comprising liquid and powder and gaseous additions. Different dielectrics show different breakdown mechanism and multiphase systems may yield positive effect through synergy of constituents. No research has been observed in the field of mechanism of dielectric breakdown. Future research may be focused on the dielectric breakdown mechanism of liquid, powder, and combination of both liquid and powder dielectric and the effect of the dielectric breakdown mechanism on the response factors. Spark energy plays important role in the field of accuracy of profile and material removal rate in micromachining; and also depends on the breakdown mechanism of dielectric fluids. More research should be focused on that area, as well. The effect of the dielectric constant or dielectric strength of different dielectric fluid should also be observed on the response factors such as MRR, SR. kerf width, etc. The focus should be given to energy consumptions and dissipation at the spark gap and its relevance for the input parameters such as effect of dielectric fluids, wire tension, effect of forces on surface integrity, accuracy of profile and dimension during micro-gear manufacturing using WEDM, etc.

Manuscript received by Editorial Board, June 30, 2017;
final version, February 06, 2018.

References

[1] T. Özel. Editorial: special section on micromanufacturing processes and applications. *Materials and Manufacturing Processes*. 24(12):1235, 2009. doi: 10.1080/10426910903129349.

[2] T. Masuzawa. State of the art of micromachining. *CIRP Annals*, 49(2):473–488, 2000. doi: 10.1016/S0007-8506(07)63451-9.

[3] S.P. Leo Kumar, J. Jerald, S. Kumanan, and R. Prabakaran. A Review on Current Research Aspects in Tool-Based Micromachining Processes. *Materials and Manufacturing Processes*, 29(11-12):1291–1337, 2014. doi: 10.1080/10426914.2014.952037.

[4] P. Piljek, Z. Karen, and M. Math. Micromachining – review of literature from 1980 to 2010. *Interdisciplinary Description of Complex Systems*, 12(1):1–27, 2014. doi: 10.7906/indecs.12.1.1.

[5] V.K. Jain. *Introduction to Micromachining*, 1st ed.; Narosa Publishing House Pvt. Ltd: New Delhi, India, 2011.

[6] S.Z. Chavoshi, S. Goel, and P. Morantz. Current trends and future of sequential micromachining processes on a single machine tool. *Materials & Design*, 127:37–53, 2017. doi: 10.1016/j.matdes.2017.04.057.

[7] T. Masuzawa, C.-L. Kuo, and M. Fujino. A combined electrical machining process for micronozzle fabrication. *CIRP Annals*, 43(1):189–192, 1994. doi: 10.1016/S0007-8506(07)62193-3.

[8] M. Kunieda, M. Yoshida, H. Yoshida, and Y. Akatmatsu. Influence of micro indents formed by electro-chemical jet machining on rolling bearing fatigue life. *ASME, Production Engineering Division (Publication) PED*, 64:693–699, 1993.

[9] A.B.M.A. Asad, T. Masaki, M. Rahman, H.S. Lim, and Y.S. Wong. Tool-based micromachining. *Journal of Material Processing Technology*, 192-193:204–211, 2007. doi: 10.1016/j.jmatprotec.2007.04.038.

[10] S.Z. Chavoshi and X. Luo. Hybrid micro-machining processes: A review. *Precision Engineering*, 41:1–23, 2015. doi: 10.1016/j.precisioneng.2015.03.001.

[11] W. Lang. Silicon microstructuring technology. *Materials Science and Engineering*, 17(1):1–55, 1996. doi: 10.1016/0927-796X(96)00190-8.

[12] M. Mehregany and A.S. Dewa. *MCNC Short Course Handbook*. Case Western Reserve University, Cleveland, USA, 1993.

[13] *A beginner's guide to MEMS processes*. www.memsnet.org

[14] S.S. Choi, M.Y. Jung, D.W. Kim, M.A. Yakshin, J.Y. Park, and Y. Kulk. Fabrication of microelectron gun array using laser micromachining. *Microelectronic Engineering*, 41/42:167–170, 1998. doi: 10.1016/S0167-9317(98)00037-9.

[15] A. Semerok, C. Chaléard, V. Detalle, J.-L. Lacour, P. Mauchien, P. Meynadier, C. Nouvellon, B. Sallé, P. Palianov, M. Perdrix, and G. Petite. Experimental investigations of laser ablation efficiency of pure metals with femto, pico and nanosecond pulses. *Applied Surface Science*, 138-139:311–314, 1999. doi: 10.1016/S0169-4332(98)00411-5.

[16] N.H. Rizvi. Femtosecond laser micromachining: Current status and applications. *RIKEN Review*, 50:107–112, 2003.

[17] X.-Q.Sun, T. Masuzawa, and M. Fujino. Micro ultrasonic machining and its applications in MEMS. *Sensors and Actuators A: Physical*, 57(2):159–164, 1996. doi: 10.1016/S0924-4247(97)80107-0.

[18] B.H. Yan, A.C. Wang, C.Y. Huang, and F.Y. Huang. Study of precision micro-holes in borosilicate glass using micro EDM combined with micro ultrasonic vibration machining. *International Journal of Machine Tools and Manufacture*, 42(10):1105–1112, 2002. doi: 10.1016/S0890-6955(02)00061-5.

[19] A.C. Wang, B.H. Yan, X.T. Li, and F.Y. Huang. Use of micro ultrasonic vibration lapping to enhance the precision of microholes drilled by micro electro-discharge machining. *International Journal of Machine Tools and Manufacture*, 42(8):915–923, 2002. doi: 10.1016/S0890-6955(02)00025-1.

[20] D. Reynaerts, P.H. Heeren, and H. Van Brussel. Microstructuring of silicon by electro-discharge machining (EDM) – part I: theory. *Sensors and Actuators A: Physical*, 60(1-3):212–218, 1997. doi: 10.1016/S0924-4247(97)01359-9.

[21] R.K. Garg, K.K. Singh, and A. Sachdeva. Review of research work in sinking EDM and WEDM on metal matrix composite materials. *The International Journal of Advanced Manufacturing Technology*, 50(5-8):611–624, 2010. doi: 10.1007/s00170-010-2534-5.

[22] A.N. Siddiquee, Z.A. Khan, and J.S. Tomar. Investigation and optimisation of machining parameters for micro-countersinking of AISI 420 stainless steel. *International Journal of Machining and Machinability of Materials*, 14(3):230–256, 2013. doi: 10.1504/IJMMM.2013.056364.

[23] C. Friedrich. *Precision Micromanufacturing Processes Applied to Miniaturization Technologies*, 1998. http://www.me.mtu.edu/~microweb.

[24] D.P. Adams, M.J. Vasile, and A.S.M. Krishnan. Microgrooving and microthreading tools for fabricating curvilinear features. *Precision Engineering*, 24(4):347–356, 2000. doi: 10.1016/S0141-6359(00)00045-3.

[25] Y.N. Picard, D.P. Adams, M.J. Vasile, and M.B. Ritchey. Focused ion beam-shaped microtools for ultra-precision machining of cylindrical components. *Precision Engineering*, 27(1):59–69, 2003. doi: 10.1016/S0141-6359(02)00188-5.

[26] C. Van Osenbruggen, G. Luimes, A. van Dijk, J.G. Siekman, and N.V. Philips. Micro-spark erosion as a technique in micro-miniaturization. *IFAC Proceeding Volumes*, 2(3):485–493, 1965. doi: 10.1016/S1474-6670(17)68988-2.

[27] A. Wenda, M. Beck, V. Huntrup, M. Meisel, M. Rothenburg, O. Rubenach, J. Schmutz, C. Schwietering, and J. Gabler. Possibilities and limits of micro-machining. *F und M. Feinwerktechnik, Mikrotechnik, Mikroelektronik*, 107(11):64–67, 1999. (in German).

[28] T. Schaller, W. Bier, G. Linder, and K. Schubert. Mechanical microstructuring of metallic surfaces. *F und M. Feinwerktechnik, Mikrotechnik, Mikroelektronik*, 102(5-6):274–278, 1994. (in German).

[29] K. Weinert, G. Guntermann, and Ch. Schwietering. Microfabration of difficult to process materials. *Werkstattstechnik*, 88(11/12):503–506, 1998. (in German).

[30] K. Weinert, M. Buschka, and Ch. Schwietering. Processing strategies for microsystems technology – microframe processing NiTiNb shape memory alloy. *Technica*, 48(8):36–40, 1999. (in German).

[31] E. Brinksmeier, W. Preuss, and J. Schmutz. Manufacture of microstructures by diamond machining. In *Proceedings of 9th IPES/UME 4 International Conference*, pages 503–507, Braunschweig, Germany, 1997.

[32] E. Brinksmeier, W. Preuss, O. Riemer, and R. Sigel. Manufacture of shock-wave target-foils for nuclear fusion research. In *Proceedings of UME 3*, pages 401–404, Aachen, Germany, 1994.

[33] Shichun Di, Ruining Huang, and Guanxin Chi. Study on micro-machining by micro-WEDM. In *Proceedings of the 1st IEEE International Conference on Nano/Micro Engineered and Molecular Systems*. Zhuhai, China, 18–21 Jan. 2006. doi: 10.1109/NEMS.2006.334857.

[34] N. Nebashi, K. Wakabayashi, M. Yamada, and T. Masuzawa. In-process truing dressing of grinding wheels by WEDG and ELID. *International Journal of Electrical Machining*, 3:59–64, 1998.

[35] E. Westkamper, H.-W. Hoffmeister, and J. Gäbler. Manufacturing concepts for the production of micromechanical metallic components. In *Proceeding of Micro Engineering 96*, Stuttgart, Germany, 1996.

[36] V. Piotter, T. Benzler, T. Hanemann, R. Ruprecht, and J. Hausselt. Manufacturing of microstructures by micro injection molding. In *Proceedings of Micro System Technologies*, pages 343–348, Potsdam, Germany, 1998.

[37] V. Piotter, T. Benzler, R. Ruprecht, and J. Hausselt. Manufacturing of micro sized structures by MIM and CIM. In *Proceedings of the International Conference on Powder Metallurgy and Particulate Materials*, pages 1–9, Las Vegas, USA, 31 May–4 June, 1998.

[38] H. Von Wollmer, R. Ruprecht R., and J. Hausselt. Precision casting of micro parts made of metal. *Galvanotechnik*, 90(6):1692–1696, 1999.

[39] T. Masuzawa, M. Yamamoto, and M. Fujino. A micro-punching system using wire-EDG and EDM. In *Proceedings of the 9th International Symposium for Electro-Machining*, pages 86–89, Nagoya, Japan, 1989.

[40] K.Wakabayashi, A. Onishi, and T. Masuzawa. Micropiercing on stainless steel. *Bulletin of Japan Society of Precision Engineering*, 24(4):277–278, 1990.

[41] H.K. Tonshoff, F. Von Atvendeben, A. Ostendorf, G. Kamlage, G., and S. Notte. Micromachining of metals using ultrashort laser pulses. *International Journal of Electrical Machining*, 4:1–6, 1999.

[42] T. Masaki, K. Kawata, T. Sato, T. Mizutani, K. Yonemoti, A. Shibuya, and T. Masuzawa. Micro electro discharge machining. In *Proc. of International Symposium for Electro-Machining, ISEM–9*, pages 28–29, Nagoya, Japan, 1989.

[43] T. Masuzawa, M. Fujino, K. Kobayashi, T. Suzuki, and N. Kinoshita. Wire electro-discharge grinding for Micro-machining. *CIRP Annals*, 34(1):431–434, 1985. doi: 10.1016/S0007-8506(07)61805-8.

[44] D.M. Allen, H.J.A. Almond, J.S. Bhogal, A.E. Green, P.M. Logan, and X.X. Huang. Typical metrology of micro-hole arrays made in stainless steel foils by two-stage micro-EDM. *CIRP Annals – Manufacturing Technology*, 48(1):127–130, 1999. doi: 10.1016/S0007-8506(07)63147-3.

[45] D. Reynaerts, X. Song, W. Meeusen, and H. Van Brussel. Silicon bulk micromachining by micro-EDM milling with electrode compensation. In *Proceedings of the 9th International Fair and Congress for Sensors, Transducers and Systems*, pages 249–254, Nurnberg, Germany 18–20 May, 1999.

[46] X. Song, D. Reynaert W. Meeusen, and H. Van Brussel. Investigation of micro-EDM for silicon microstructure fabrication. In *Proceedings of SPIE Sympium on Micromachining and Microfabrication*, pages 792–799, 1999.

[47] K.-P. Kamper, W. Ehrfeld, J. Dopper, V. Hessel, H. Lehr, H. Lowe, and Th. Richter. Microfluidic components for biological and chemical microreactors. In *Proceeding of 10th Annual International Workshop on Micro Electro Mechanical Systems*, IEEE MEMS'97, Nagoya, Japan, 26–30 Jan, 1997. doi: 10.1109/MEMSYS.1997.581849.

[48] W. Ehrfeld, H. Lehr, F. Michel, A. Wolf, H.-P. Gruber, and A. Bertholds. Micro electro-discharge machining as a technology in micromachining. *Proceedings of SPIE, 2879, Micromachining and Microfabrication Process Technology II*, pages 332–337, Austin, USA, 23 Sept. 1996. doi: 10.1117/12.251221.

[49] A. Twt. Microtube lithography with dynamically changeable reflection mask. *Proceedings of 44th International Sci. Colloquium*, Technical University Ilmenau, 1999. (in German).

[50] K. Kawata, T. Masaki, T. Sato, and T. Masuzawa. Accuracy of micro-electrodischarge machining. *Proceedings of International Conference on Precision Engineering '97*, Taipei, Taiwan, 1997.

[51] H. Li and T. Masaki. Micro-EDM. *SME Technical Paper*, MS91–485, 1991.

[52] G. Spur, E. Uhlmann, U. Doll, and N.-A. Daus. WEDM of microstructured component parts – heat conduction model. *International Journal of Electrical Machining*, 4:41–46, 1999.

[53] E. Uhlmann, G. Spur, N.-A. Daus, and U. Doll. Application of p-EDM in the Machining of Micro Structured Forming Tools. *Proceedings of 3rd International Machining and Grinding Conferen*ce, Cincinnati, USA, 1999.

[54] A.E. Guber, N. Giordano, M. Loser, and P. Wieneke. Mikroinstrumente aus Nickel Titan. *F&M Feinwerktechnik, Mikrotechnik, Mikroelektronik*, 105(4):247–251, 1997.

[55] D.T. Pham, S.S. Dimov, S. Bigot, A. Ivanov, and K. Popov. Micro-EDM – recent developments and research issues, *Journal of Materials Processing Technology*, 149(1-3):50–57, 2004. doi: 10.1016/j.jmatprotec.2004.02.008.

[56] A. Schoth, R. Förster, and W. Menz. Micro wire EDM for high aspect ratio 3D microstructuring of ceramics and metals, *Microsystem Technologies*, 11(4-5):250–253, 2005. doi: 10.1007/s00542-004-0399-y.

[57] Y.F. Luo, C.G. Chen, and Z.F. Tong. Investigation of silicon wafering by wire EDM. *Journal of Materials Science*, 27(21): 5805–5810, 1992. doi: 10.1007/BF01119742.

[58] G.N. Levy and R. Wertheim. EDM-machining of sintered carbide compacting dies. *CIRP Annals*, 37(1):175–178, 1988. doi: 10.1016/S0007-8506(07)61612-6.

[59] B.K. Rhoney, A.J. Shih, R.O. Scattergood, J.L. Akemon, D.J. Gust, and M.B. Grant. Wire electrical discharge machining of metal bond diamond wheels for ceramic grinding. *International Journal of Machine Tools and Manufacture*, 42(12):1355–1362, 2002. doi: 10.1016/S0890-6955(02)00056-1.

[60] B.K. Rhoney, A.J. Shih, R.O. Scattergood, R. Ott, and S.B. McSpadden. Wear mechanism of metal bond diamond wheels trued by wire electrical discharge machining. *Wear*, 252(7-8):644–653, 2002. doi: 10.1016/S0043-1648(02)00019-4.

[61] A. Kruusing, S. Leppävuori, A. Uusimäki, B. Petrêtis, and O. Makarova. Micromachining of magnetic materials. *Sensors Actuators A: Physical*, 74(1–):45–51, 1999. doi: 10.1016/S0924-4247(98)00343-4.

[62] K. Gupta, R.F. Laubscher, J.P. Davim, and N.K. Jain. Recent developments in sustainable manufacturing of gears: a review. *Journal of Cleaner Production*, 112(4):3320–3330, 2016. doi: 10.1016/j.jclepro.2015.09.133.

[63] R. Neugebauer, U. Hellfritzsch, M. Lahl, M. Milbrandt, S. Schiller, and T. Druwe. Gear rolling process. In: Denkena B., Hollmann F., editors, *Process machine interactions*. Lecture Notes in Production Engineering, pages 475–490, Springer, Berlin Heidelberg, 2013. doi: 10.1007/978-3-642-32448-2_22.

[64] R. Neugebauer, M. Putz, and U. Hellfritzsch. Improved process design and quality for gear manufacturing with flat and round rolling. *CIRP Annals*, 56(1):307–312, 2007. doi: 10.1016/j.cirp.2007.05.071.

[65] K. Gupta and N.K. Jain. Comparative study of wire-EDM and hobbing for manufacturing high quality miniature gears. *Materials and Manufacturing Processes*, 29(11-12): 1470–1476, 2014. doi: 10.1080/10426914.2014.941865.

[66] J.P. Davim. *Nontraditional Machining Processes: Research Advances*. Springer, London, 2013.

[67] M. Rahman, A.B.M.A. Asad, and Y.S. Wong. Introduction to advanced machining technologies. In Hashmi, S. (Ed.), *Comprehensive Materials Processing*, pages 1–13, Elsevier, Amsterdam, 2014.

[68] J.R. Davis (Ed.). *Gear Materials, Properties, and Manufacture*. ASM International, 2005.

[69] S. Kuriakose, M.S. Shunmugam. Multi-objective optimization of wire-electro discharge machining process by Non-Dominated Sorting Genetic Algorithm. *Journal of Materials Processing Technology*, 170(1-2):133–141, 2005. doi: 10.1016/j.jmatprotec.2005.04.105.

[70] H.-Ch. Chen, J.-Ch. Lin, Y.-K. Yang, and Ch.H. Tsai. Optimization of wire electrical discharge machining for pure tungsten using a neural network integrated simulated annealing approach. *Expert Systems with Applications*, 37(10):7147–7153, 2010. doi: 10.1016/j.eswa.2010.04.020.

[71] M.S. Hewidy, T.A. El-Taweel, and M.F. El-Safty. Modelling the machining parameters of wire electrical discharge machining of Inconel 601 using RSM. *Journal of Materials Processing Technology*, 169(2):328–336, 2005. doi: 10.1016/j.jmatprotec.2005.04.078.

[72] P. Sengottuvel, S. Satishkumar, and D. Dinakaran. Optimization of multiple characteristics of EDM parameters based on desirability approach and fuzzy modeling. *Procedia Engineering*, 64:1069–1078, 2013. doi: 10.1016/j.proeng.2013.09.185.

[73] V. Muthukumar, N. Rajesh, R. Venkatasamy, A. Sureshbabu, and N. Senthilkumar. Mathematical modeling for radial overcut on electrical discharge machining of Incoloy 800 by response surface methodology. *Procedia Materials Science*, 6:1674–1682, 2014. doi: 10.1016/j.mspro.2014.07.153.

[74] U.A. Dabadea, S.S. Karidkar. Analysis of response variables in WEDM of Inconel 718 using Taguchi technique. *Procedia CIRP*, 41:886–891, 2016. doi: 10.1016/j.procir.2016.01.026.

[75] H. Dong, Y. Liu, Y. Shen, and X. Wang. Optimizing machining parameters of compound machining of Inconel718. *Procedia CIRP*, 42:51–56, 2016. doi: 10.1016/j.procir.2016.02.185.

[76] B.B. Nayak and S.S. Mahapatra. Optimization of WEDM process parameters using deep cryo-treated Inconel 718 as work material. *Engineering Science and Technology, an International Journal*, 19(1):161–170, 2016. doi: 10.1016/j.jestch.2015.06.009.

[77] G. Rajyalakshmi and P. Venkata Ramaiah. Multiple process parameter optimization of wire electrical discharge machining on Inconel 825 using Taguchi grey relational analysis. *The International Journal of Advanced Manufacturing Technology*, 69(5-8):1249–1262, 2013. doi: 10.1007/s00170-013-5081-z.

[78] V. Aggarwal, S.S. Khangura, and R.K. Garg. Parametric modeling and optimization for wire electrical discharge machining of Inconel 718 using response surface methodology. *The International Journal of Advanced Manufacturing Technology*, 79(1-4):31–47, 2015. doi: 10.1007/s00170-015-6797-8.

[79] F. Klocke, D. Welling, A. Klink, D. Veselovac, T. Nöthe, and R. Perez. Evaluation of advanced wire-EDM capabilities for the manufacture of fir tree slots in Inconel 718. *Procedia CIRP*, 14:430–435, 2014. doi: 10.1016/j.procir.2014.03.039.

[80] D.P. Townsend. *Dudley's Gear Handbook: The Design, Manufacture and Application of Gears*. 2nd edition, Tata McGraw-Hill Publishing Company, New Delhi, 2011.

[81] M. Sreenivasa Rao and N. Venkaiah. Parametric optimization in machining of Nimonic-263 alloy using RSM and particle swarm optimization. *Procedia Materials Science*, 10:70–79, 2015. doi: 10.1016/j.mspro.2015.06.027.

[82] A. Goswami and J. Kumar. Optimization in wire-cut EDM of Nimonic-80A using Taguchi's approach and utility concept. *Engineering Science and Technology, an International Journal*, 17(4):236–246, 2014. doi: 10.1016/j.jestch.2014.07.001.

[83] R. Choudhary, V.K. Gupta, Y. Batra, and A. Singh. Performance and surface integrity of Nimonic75 alloy machined by electrical discharge machining. *Materials Today: Proceedings*, 2(4-5):3481–3490, 2015. doi: 10.1016/j.matpr.2015.07.324.

[84] A. Alias, B. Abdullah, and N.M. Abbas. Influence of machine feed rate in WEDM of titanium Ti-6Al-4V with constant current (6A) using brass wire. *Procedia Engineering*, 41:1806–1811, 2012. doi: 10.1016/j.proeng.2012.07.387.

[85] R. Chalisgaonkar and J. Kumar. Multi-response optimization and modeling of trim cut WEDM operation of commercially pure titanium (CPTi) considering multiple user's preferences. *Engineering Science and Technology, an International Journal*, 18(2):125–134, 2015. doi: 10.1016/j.jestch.2014.10.006.

[86] D. Amrish Raj and T. Senthilvelan. Empirical modelling and optimization of process parameters of machining titanium alloy by wire-EDM using RSM. *Materials Today: Proceedings*, 2(4-5):1682–1690, 2015. doi: 10.1016/j.matpr.2015.07.096.

[87] M. Kolli and A. Kumar. Effect of dielectric fluid with surfactant and graphite powder on Electrical Discharge Machining of titanium alloy using Taguchi method. *Engineering Science and Technology, an International Journal*, 18(4):524–535, 2015. doi: 10.1016/j.jestch.2015.03.009.

[88] S. Sarkar, S. Mitra, and B. Bhattacharyya. Parametric optimisation of wire electrical discharge machining of γ titanium aluminide alloy through an artificial neural network model. *The International Journal of Advanced Manufacturing Technology*, 27(5-6):501–508, 2006. doi: 10.1007/s00170-004-2203-7.

[89] C.H. Fu, J.F. Liu, Y.B. Guo, and Q.Z. Zhao. A comparative study on white layer properties by laser cutting vs. electrical discharge machining of Nitinol shape memory alloy. *Procedia CIRP*, 42:246–251, 2016. doi: 10.1016/j.procir.2016.02.280.

[90] G.L. Chern, Y.-J. Engin Wu, J.-C. Cheng, J.-C. Yao. Study on burr formation in micro-machining using micro-tools fabricated by micro-EDM. *Precision Engineering*, 31(1):122–129, 2007. doi: 10.1016/j.precisioneng.2006.04.001.

[91] P.S Rao, K. Ramji, B. Stayanarayana. Experimental investigation and optimization of Wire EDM parameter for surface roughness, MRR and white layer in machining of aluminum alloy. *Procedia Materials Science*, 5:2197–2206, 2014. doi: 10.1016/j.mspro.2014.07.426.

[92] K.T. Chiang, F.P. Chang. Optimization of the WEDM process of particle-reinforced material with multiple performance characteristics using grey relational analysis. *Journal of Materials Processing Technology*, 180(1-3):96–101, 2006. doi: 10.1016/j.jmatprotec.2006.05.008.

[93] A. Manna and B. Bhattacharyya. Taguchi and Gauss elimination method: A dual response approach for parametric optimization of CNC wire cut EDM of PRAlSiCMMC. *The International Journal of Advanced Manufacturing Technology*, 28(1-2):67–75, 2006. doi: 10.1007/s00170-004-2331-0.

[94] R. Paetzel. Comparison Excimer Laser – Solid State Laser. In *Proceedings of 21st International Congress on Applications of Lasers & Electro-Optics*, ICALEO 2002, Scotsdale, Arizona, USA, 14–17 Oct. 2002.

[95] R. Bobbili, V. Madhu, and A.K. Gogia. Modelling and analysis of material removal rate and surface roughness in wire-cut EDM of armour materials. *Engineering Science and Technology, an International Journal*, 18(4):664–668, 2015. doi: 10.1016/j.jestch.2015.03.014.

[96] B.K. Lodhi and S. Agarwal. Optimization of machining parameters in WEDM of AISI D3 steel using Taguchi technique. *Procedia CIRP*, 14:194–199, 2014. doi: 10.1016/j.procir.2014.03.080.

[97] K. Kanlayasiri and S. Boonmung. Effects of wire-EDM machining variables on surface roughness of newly developed DC 53 die steel: Design of experiments and regression model. *Journal of Materials Processing Technology*, 192-193:459–464, 2007. doi: 10.1016/j.jmatprotec.2007.04.085.

[98] Z.A. Khan, A.N. Siddiquee, N.Z. Khan, U. Khan, and G.A. Quadir. Multi response optimization of wire electrical discharge machining process parameters using Taguchi based grey relational analysis. *Procedia Materials Science*, 6:1683–1695, 2014. doi: 10.1016/j.mspro.2014.07.154.

[99] N.Z. Khan, Z.A. Khan, A.N. Siddiquee, and A.K. Chanda. Investigations on the effect of wire EDM process parameters on surface integrity of HSLA: a multi-performance characteristics optimization. *Production & Manufacturing Research*, 2(1):501–518, 2014. doi: 10.1080/21693277.2014.931261.

[100] S. Lal, S. Kumar, Z.A. Khan, and A.N. Siddiquee. Wire electrical discharge machining of AA7075/SiC/Al_2O_3 hybrid composite fabricated by inert gas-assisted electromagnetic stir-casting process. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 36(2):335–346, 2014. doi: 10.1007/s40430-013-0087-x.

[101] H.-M. Chow, B.-H. Yan, F.-Y. Huang, and J.-C. Hung. Study of added powder in kerosene for the micro-slit machining of titanium alloy using electro-discharge machining. Journal of Materials Processing Technology, 101(1-3):95–103, 2000. doi: 10.1016/S0924-0136(99)00458-6.

[102] R. Bagherian Azhiri, R. Teimouri, M. Ghasemi Baboly, and Z. Leseman. Application of Taguchi, ANFIS and grey relational analysis for studying, modeling and optimization of wire EDM process while using gaseous media. *The International Journal of Advanced Manufacturing Technology*, 71(1-4):279–295, 2014. doi: 10.1007/s00170-013-5467-y.

[103] A.V. Shayan, R.A. Afza, and R. Teimouri. Parametric study along with selection of optimal solutions in dry wirecut machining of cemented tungsten carbide (WC-Co). *Journal of Manufacturing Processes*, 15(4):644–658, 2013. doi: 10.1016/j.jmapro.2013.05.001.

[104] G. Ugrasen, H.V. Ravindra, G.V. Naveen Prakash, and D.L. Vinay. Comparative study of electrode wear estimation in wire EDM using multiple regression analysis and group method data handling technique for EN-8 and EN-19. *Bonfring International Journal of Industrial Engineering and Management Science*, 4(2):108–114, 2014. doi: 10.9756/BIJIEMS.6022.

[105] R.K. Fard, R.A. Afza, and R. Teimouri. Experimental investigation, intelligent modeling and multi-characteristics optimization of dry WEDM process of Al–SiC metal matrix composite. *Journal of Manufacturing Processes*, 15(4):483–494, 2013. doi: 10.1016/j.jmapro.2013.09.002.

[106] F. Nourbakhsh, K.P. Rajurkar, A.P. Malshe, and J. Cao. Wire electro-discharge machining of titanium alloy. *Procedia CIRP*, 5:13–18, 2013. doi: 10.1016/j.procir.2013.01.003.

[107] E. Bamberg and D. Rakwal. Experimental investigation of wire electrical discharge machining of gallium-doped germanium. *Journal of Materials Processing Technology*, 197(1-3):419–427, 2008. doi: 10.1016/j.jmatprotec.2007.06.038.

[108] J.T. Huang, and Y.S. Liao. Optimization of machining parameters of Wire-EDM based on grey relational and statistical analyses. *International Journal of Production Research*, 41(8):1707–1720, 2003. doi: 10.1080/1352816031000074973.

[109] R. Ramakrishnan and L. Karunamoorthy. Multi response optimization of wire EDM operations, using robust design of experiments. *The International Journal of Advanced Manufacturing Technology*, 29(1-2):105–112, 2006. doi: 10.1007/s00170-004-2496-6.

[110] R.T. Yang, C.J. Tzeng, Y.K. Yang, and M.H. Hsieh. Optimization of wire electrical discharge machining process parameters for cutting tungsten. *The International Journal of Advanced Manufacturing Technology*, 60(1-4):135–147, 2012. doi: 10.1007/s00170-011-3576-z.

[111] N.G. Patil and P.K. Brahmankar. Some investigationns into wire electro-discharge machining performance of Al/SiCp composites. *International Journal of Machining and Machinability of Materials*, 1(4):412–431, 2006. doi: 10.1504/IJMMM.2006.012350.

[112] R. Teimouri and H. Baser. Improvement of dry EDM process characteristics using artificial soft computing methodologies. *Production Engineering*, 6(4-5):493–504, 2012. doi: 10.1007/s11740-012-0398-2.

[113] V.K. Saini, Z.A. Khan, and A.N. Siddiquee. Optimization of wire electric discharge machining of composite material (Al6061/SiCP) using Taguchi method. *International Journal of Mechanical and Production Engineering*, 2(1):61–64, 2013.

[114] P. Saha, D. Trafdar, S.K. Pal, P. Saha, A.K. Srivastava, and K. Das. Modeling of wire electro-discharge machining of TiC/Fe in situ metal matrix composite using normalized RBFN with enhanced k-means clustering technique. *The International Journal of Advanced Manufacturing Technology*, 43(1-2):107–116, 2009. doi: 10.1007/s00170-008-1679-y.

[115] S. Lal, S. Kumar, Z.A. Khan, and A.N. Siddiquee. Multi-response optimization of wire electrical discharge machining process parameters for Al7075/Al2O3/SiC hybrid composite using Taguchi-based grey relational analysis. *Journal of Engineering Manufacture*, 229(2):229–237, 2015. doi: 10.1177/0954405414526382.

[116] F. Klocke, S. Schneider, L. Ehle, H. Meyer, L. Hensgen, and A. Klink. Investigations on surface integrity of heat treated 42CrMo4 (AISI 4140) processed by sinking EDM. *Procedia CIRP*, 42:580–585, 2016. doi: 10.1016/j.procir.2016.02.263.

[117] M. Manjaiah, S. Narendranath, S. Basavarajappa, and V.N Gaitonde. Wire electric discharge machining characteristics of titanium nickel shape memory alloy. *Transactions of Nonferrous Metals Society of China*, 24(10):3201–3209, 2014. doi: 10.1016/S1003-6326(14)63461-0.

[118] J.A. Sanchez, J.L. Rodil, A. Herrero, L.N. Lopez de Lacalle, and A. Lamikiz. On the influence of cutting speed limitation on the accuracy of wire-EDM corner-cutting. *Journal of Materials Processing Technology*, 182(1-3):574–579, 2007. doi: 10.1016/j.jmatprotec.2006.09.030.

[119] A. Hasçalýk and U. Çaydas. Experimental study of wire electrical discharge machining of AISI D5 tool steel. *Journal of Materials Processing Technology*, 148(3):362–367, 2004. doi: 10.1016/j.jmatprotec.2004.02.048.

[120] L. Li, Y.B. Guo, X.T. Wei, and W. Li. Surface integrity characteristics in wire-EDM of Inconel 718 at different discharge energy. *Procedia CIRP*, 6:220–225, 2013. doi: 10.1016/j.procir.2013.03.046.

[121] C.A. Huang, F.Y. Hsu, and S.J. Yao. Microstructure analysis of the martensitic stainless steel surface fine-cut by the wire electrode discharge machining (WEDM). *Materials Science and Engineering: A*, 371(1-2):119–126, 2004. doi: 10.1016/j.msea.2003.10.277.

[122] F. Klocke, L. Hensgen, A. Klink, L. Ehle, and A. Schwedt. Structure and composition of the white layer in the wire-EDM process. *Procedia CIRP*, 42:673–678, 2016. doi: 10.1016/j.procir.2016.02.300.

[123] Y. Zhang, Y. Liu, R. Ji, and B. Cai. Study of the recast layer of a surface machined by sinking electrical discharge machining using water-in-oil emulsion as dielectric. *Applied Surface Science*, 257(14):5989–5997, 2011. doi: 10.1016/j.apsusc.2011.01.083.

[124] E. Atzeni, E. Basooli, A. Gatto, L. Luliano, P. Minetola, and A. Salmi. Surface and subsurface evaluation in coated wire-electric discharge machining (WEDM) of INCONEL alloy 718. *Procedia CIRP*, 33:388–393, 2015. doi: 10.1016/j.procir.2015.06.089.

[125] L. Li, X.T. Wei, and Z.Y. Li. Surface integrity evolution and machining efficiency analysis of W-EDM of nickel-based alloy. *Applied Surface Science*, 313:138–143, 2014. doi: 10.1016/j.apsusc.2014.05.165.

[126] A. Klink, Y.B. Guo, and F. Klocke. Surface integrity evolution of powder metallurgical tool steel by main cut and finishing trim cuts in wire-EDM. *Procedia Engineering*, 19:178–183, 2011. doi: 10.1016/j.proeng.2011.11.098.

[127] C. Cao, X. Zhang, X. Zha, and C. Dong. Surface integrity of tool steels multi-cut by wire electrical discharge machining. *Procedia Engineering*, 81:1945–1951, 2014. doi: 10.1016/j.proeng.2014.10.262.

[128] E. Uhlmann, M. Reohner, and M. Langmack. Application of micro-EDM in the machining of micro structured forming tools. In *Proceedings of 3rd International Machining and Grinding Conference*, Cincinnati,1999.

[129] J.F. Liu, L. Li, and Y.B. Guo. Surface integrity evolution from main cut to finish trim cut in W-EDM of shape memory alloy. *Procedia CIRP*, 13:137–142, 2014. doi: 10.1016/j.procir.2014.04.024.

[130] Z. Chen, J. Moverare, R.L. Peng, and S. Johansson. Surface integrity and fatigue performance of Inconel 718 in wire electrical discharge machining. *Procedia CIRP*, 45:307–310, 2016. doi: 10.1016/j.procir.2016.02.053.

[131] M-T. Yan, G-R. Fang, Y-T. Liu, and J-R. Li. Fabrication of polycrystalline diamond wheels by micro wire-EDM using a novel pulse generator. *Procedia CIRP*, 6:203–208, 2013. doi: 10.1016/j.procir.2013.03.013.

[132] V.P. Astakhov. Surface integrity – definition and importance in functional performance. In J.P. Davim, editor, *Surface Integrity in Machining*, pages 1–35, Springer, London, 2010. doi: 10.1007/978-1-84882-874-2.

[133] G.P. Petropoulos, C.N. Pandazaras, and J.P.Davim. Surface texture characterization and evaluation related to machining. In J.P. Davim, editor, *Surface Integrity in Machining*, pages 37–66, Springer, London, 2010. doi: 10.1007/978-1-84882-874-2.

[134] G.F. Benedict. *Nontraditional Manufacturing Processes*, pages 207–254, Marcel Dekker, Inc., New York, 1987.

[135] A.B. Puri and B. Bhattacharyya. An analysis and optimization of the geometrical inaccuracy due to wire lag phenomenon in WEDM. *International Journal of Machine Tools and Manufacture*, 43(2):151–159, 2003. doi: 10.1016/S0890-6955(02)00158-X.

[136] K. Gupta and N.K. Jain. Manufacturing of high quality miniature gears by wire electric discharge machining. In B. Katalinic and Z. Tekic, editors: *DAAAM International Scientific Book 2013*, pages 679–696, DAAAM International, Vienna, Austria, 2013. doi: 10.2507/daaam.scibook.2013.40.

[137] K. Gupta and N.K. Jain. Analysis and optimization of micro-geometry of miniature spur gear manufactured by wire electric discharge machining. *Precision Engineering*, 38(4):728–737, 2014. doi: 10.1016/j.precisioneng.2014.03.009.

[138] K. Gupta, S.K. Chaube, and N.K. Jain. Exploring Wire-EDM for manufacturing high quality meso-gear. *Procedia Materials Science*, 5:1755–1760, 2014. doi: 10.1016/j.mspro.2014.07.365.

[139] M.Y. Ali, A.N. Mustafizul Karim, E.Y.T. Adesta, A.F. Ismail, A.A. Abdullah, and M.N. Idris. Comparative study of conventional and micro WEDM based on machining of meso/micro sized spur gear. *International Journal Of Precision Engineering And Manufacturing*, 11(5):779–784, 2010. doi: 10.1007/s12541-010-0092-2.

[140] M.Y. Ali and A.S. Mohammad. Experimental study of conventional wire electrical discharge machining for microfabrication. *Materials and Manufacturing Processes*, 23(7):641–645, 2008. doi: 10.1080/10426910802316492.

[141] K. Gupta and N.K. Jain. Deviations in geometry of miniature gears fabricated by wire electrical discharge machining. In *Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition*, San Diego, California, USA, 15–21 Nov. 2013. doi: 10.1115/IMECE2013-66560.

[142] K. Gupta and N.K. Jain. On micro-geometry of miniature gears manufactured by wire electrical discharge machining. *Materials and Manufacturing Processes*, 28(10):1153–1159, 2013. doi: 10.1080/10426914.2013.792422.

[143] G.L. Benavides, L.F. Bieg, M.P. Saavedra, and E.A. Bryce. High aspect ratio mesoscale parts enabled by wire micro-EDM. *Microsystem Technologies*, 8(6):395–401, 2002. doi: 10.1007/s00542-002-0190-x.

[144] S. Di, R. Huang, and G. Chi. Study on micro-machining by micro-WEDM. In *Proceedings of the 1st IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, Zhuhai, China, 18–21 Jan. 2006. doi: 10.1109/NEMS.2006.334857.