Chapter 2
Overview of Wire Spark Erosion Machining (WSEM)

Advanced machining processes (AMPs) are well established in modern manufacturing industries as they are capable of machining most electrically conductive materials irrespective of their hardness and toughness producing complex geometries, shapes and features [1–3]. *Spark-Erosion Machining* (*SEM*) also named as *Electric-Discharge Machining* (*EDM*) is the most widely used thermal type advanced machining process. It is a controlled spark erosion process in which the mechanism of material removal is melting and vaporization by a series of repeated electrical discharges occurring between the tool electrode and the workpiece in the presence of a suitable dielectric fluid [1–3].

Wire Spark-Erosion Machining (*WSEM*) also called *Wire Electric-Discharge Machining* (*WEDM*) is a derived process of *SEM* that utilizes thin wire as the tool electrode unlike *SEM*, where the tool is macro-sized and shaped according to the geometry to be produced in the workpiece.

In spark erosion machining (*SEM*) technology, a pulsed DC power supply is applied between tool electrode and a workpiece for spark generation. In the event of a spark discharge current flow is induced across the gap between the tool electrode and part to be machined. The energy contained in the spark discharge removes a fraction of workpiece material. A large number of these time spaced discharges between the workpiece and tool electrode causes controlled thermo-electric erosion of the workpiece material. Since, erosion is produced by electrical discharges; both tool electrode and workpiece have to be electrically conductive.

Due to the use of a thin wire as a tool, *WSEM* requires low voltage and current, high pulse frequency, longer pulse-off time and shorter pulse-on time when compared to *SEM*. Consequently, it also requires a dielectric having a low dielectric strength. De-ionized water is therefore the most commonly used dielectric due to its low viscosity and rapid cooling rate. To avoid wire breakage, there should not be any contact between the wire and workpiece during the entire process. Reduced electrode wear, lower energy consumption and independency from complicated electrode fabrication are some of the advantages of *WSEM* over *SEM* [1–4].

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In *Micro-SEM* an electrode with micro features is used to produce its mirror image in the workpiece. This requires submicron machine movement resolution to obtain acceptable results. Similarly, in micro-WSEM a thin wire (micro size) is used to cut the workpiece that is also mounted on an accurate submicron resolution movement table. During micro-SEM the pulse generator may be controlled to produce pulses with durations ranging in length between a few nano seconds to a few micro seconds to control the extent of material volume removal [1–4].

2.1 Introduction to WSEM

The phenomenon of material erosion by electric spark was first noticed by *Joseph Priestly* in 1878, but this concept could not use for machining until 1930s. Controlled machining by electric sparks was first done by *Lazarenko* in *Russia* in 1944. In 1969, the SWISS firm '*AGIE*' produced world's first WSEM with simple features and had limitations of wire materials to be copper and brass only. Early WSEM machines were extremely slow with limited machining capabilities but as the technology matured the overall capabilities of WSEM have improved significantly to meet the requirements of various manufacturing needs. Nowadays, most of the WSEM machines are computer numerically controlled (CNC) which helps in improving the efficiency, accuracy and repeatability.

Figure 2.1 illustrates the working principle of WSEM process. A typical WSEM machine tool comprises of a main work table (called as X-Y table), an auxiliary table (U-V) and a wire drive mechanism. The workpiece is mounted and clamped on the main work table with the help of clamps and bolts. The motion along X and Y axes is controlled by means of servo-motors. A very thin wire made of brass or copper or tungsten and having diameter in the range of 0.01–0.3 mm is continuously fed from the wire feed spool and after use is collected in the waste-wire box. The wire is supported under tension, between a pair of wire guides which are disposed on both lower and upper sides of the workpiece. The wire is not reused. The dielectric is supplied through the nozzle coaxial with the wire feed system so as

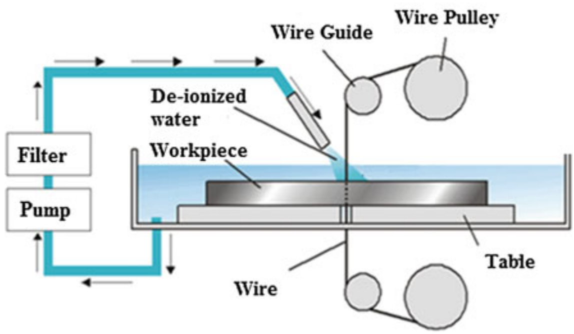

Fig. 2.1 Working principle of WSEM

to continuously flush the machining zone. A resin is used in the dielectric circulating system to maintain the conductivity of the dielectric constant. As the machining proceeds, the work table carrying the workpiece is moved along the path determined according to the geometry of the shape to be machined using the CNC program stored in the machine controller. The controller also maintains machining gap constant at the programmed value. The auxiliary U-V table is used for 3D-profiling applications.

2.2 Process Parameters of WSEM

The important parameters of WSEM are discussed below:

(a) ***Pulse-on time or Pulse duration***: The work material is eroded in WSEM during the pulse-on time when the spark occurs between wire and the workpiece. During this time, voltage is applied across the electrodes and current starts flowing. Consequently spark occurs and sustain. Longer the pulse-on time, longer the spark sustains and more is the material removal rate. However, the resulting craters are broader and deeper which result in generation of rough surface.

(b) ***Pulse-off time or Pulse interval***: It is the duration between occurrences of two consecutive sparks. The voltage is absent during this part of cycle. It is the time during which there is no power supply to the electrodes and de-ionization of dielectric takes place. Dielectric also flushes out the removed material from the machining gap during this time. Too short pulse-off time may cause wire breakage and increases the surface roughness of the machined surface due to improper removal of material from the gap, whereas too long pulse-off time increases the machining time and the forces generated by the dielectric flushing [5, 6].

Duty cycle (ratio of pulse-on time to sum of pulse-on time and pulse-off time) and *pulse frequency* (reciprocal of sum of pulse-on time and pulse-off time) are other dependent parameters describing the pulse power supply in SEM and WSEM.

(c) ***Spark Gap Voltage***: It is the reference voltage for the actual gap between the workpiece and the wire for the spark to occur between them. The machine senses the actual gap and voltage across it during the machining and tries to maintain them constant or does not allow the gap to increase to such a value that occurrence of the spark is stopped.

(d) ***Peak Current***: Peak current is the maximum value of the current passing through the electrodes for the given pulse. Increase in its value will increase the pulse discharge energy which in turn can improve the cutting rate further. But for higher value of peak current, gap conditions may become unstable.

(e) ***Wire Feed Rate***: It is the rate at which the wire is fed through the wire guides. A lower wire feed rate causes frequent wire breakage which results in poor surface finish and interruptions during the machining (i.e. less productivity) while, very high wire feed rate causes wastage of wire because it is not reused.

(f) ***Wire Tension***: It is a tensile load with which the wire is continuously fed so that it remains straight between the wire guides. Loose wire causes frequent wire breakage, dimensional and geometric inaccuracy and poor machined edge definition. Higher thickness of the workpiece requires more wire tension.

(g) ***Dielectric Pressure***: It is the pressure of the dielectric with which it flows in the machining gap for flushing the removed material. Higher dielectric pressure is required while using higher pulse power and for machining the thicker workpiece. While, low dielectric pressure is used for thin workpiece and for trim cuts.

Wire material, wire diameter, type of dielectric, its conductivity and flow rate are also important parameters which depend on the capabilities and constraints of any individual WSEM machine.

2.3 Advantages and Limitations of WSEM

Advantages

- A thin wire is used as the tool; therefore, the need of fabricating the complex tool of the complementary shape of workpiece shape is eliminated. This is the major limiting factor while using SEM. In fact, WSEM is mostly used to fabricate the complex tools for SEM.
- Any complex shape can be produced.
- No direct contact between the workpiece and the wire eliminates the mechanical stresses during machining.
- Use of significantly lower voltage and pulse-on time, as compared to SEM, also minimizes the thermal damage to the workpiece material.
- Can machine any material irrespective of its hardness, toughness or brittleness, melting points provided it is electrically conducting.
- Most of the WSEM machines are generally CNC therefore unattended machining is possible.
- Produces high quality surface finish and better dimensional accuracy.
- Generates burr-free, corrosion and wear resistant surfaces which generally do not require any post-finishing operation.

Limitations

The deeper and irregular shaped craters produced by violent spark generated at high discharge energy parameters settings and deflection of wire from its intended path known as *wire lag* are the main causes for poor surface finish, surface defects and geometrical inaccuracies in WSEMed products [6–11]. Wire lag is caused due to the impact of the mechanical forces produced by pressure of the gas bubbles, the axial forces applied to straighten the wire, the hydraulic forces induced by the dielectric flushing, the electro-static forces acting on the wire, and the electro-dynamic forces inherent to the spark generation. Nevertheless, these undesirable phenomenon up to a large extent can be controlled by optimized settings of WSEM process parameters. Other limitations of WSEM include:

- High capital cost.
- Problem of formation of recast layer particularly at higher discharge energy parameter settings.
- Not suitable for mass production.
- Not applicable to very large workpieces.

2.4 Applications of WSEM

WSEM process have extensively been using in automotive, aerospace, medical, mould, tool and die making industries. The machine's ability to operate unattended for hours or even days further increases the attractiveness of the process. Machining thick sections of material, with accuracy in dimensions and forms make this process especially valuable for the fabrication of various dies used in extrusion, stamping, powder metallurgy and injection molding. Without WSEM, the fabrication process for dies and punches requires many hours of electrodes fabrication for the conventional SEM technique, as well as many hours of manual grinding and polishing. With WSEM, the overall fabrication time is reduced greatly. Net-shape and near-net shape manufacturing of injection molding and stamping dies for gears, micro components such as micro-shafts and pipes, micro-electrodes, micro-punches, and injection nozzles are some special applications of WSEM. Difficult-to-cut materials such as superalloys, tool steels, titanium alloys, stainless steel, high speed steel (HSS), sintered carbides, metal matrix composites etc. used in automobiles, aerospace, nuclear, cutting tools, dies and moulds, and biomedical applications can be easily machined by WSEM.

2.5 Machining of Gears by Spark-Erosion Processes

Spark-erosion machining offers unique capabilities for manufacturing miniature gears. The size of the gear manufactured by *SEM* and *WSEM* depends on the size of the electrode and wire used. The path tracing capability, accuracy of the machine and appropriate process parameters affect the quality of the manufactured gear [12].

Any electrically conductive material irrespective of its hardness and melting point can be processed by *SEM/WSEM* to manufacture gears, gear cutting tools, ratchet wheels and splines. The geometric accuracy and surface finish of the gear obtained by *SEM* or *WSEM* may eliminate the need of subsequent finishing operation.

A schematic representation of gear machining by the spark erosion process is presented in Fig. 2.2. Initially a potential difference (voltage) is applied between the tool electrode/wire and the gear blank (Fig. 2.2a). The breakdown of dielectric is initiated at the closest point between the electrode and the gear blank. This increases the electric field in the gap, until it reaches the necessary value for breakdown. When the breakdown occurs the voltage falls and the current rises abruptly. The flow of current at this stage is due to the ionization of the dielectric and formation of a plasma channel between the electrode and the gear blank. The elevated current continues to further ionize the channel and a powerful magnetic field is generated (Fig. 2.2b). This magnetic field compresses the ionized channel and results in localized heating. Even with discharges of short duration, the temperature of the electrodes can rise to such an extent that the gear blank material melts locally (kinetic energy associated with the electrons are transformed into heat). The high energy density erodes a part of the material from both the electrode/wire and gear

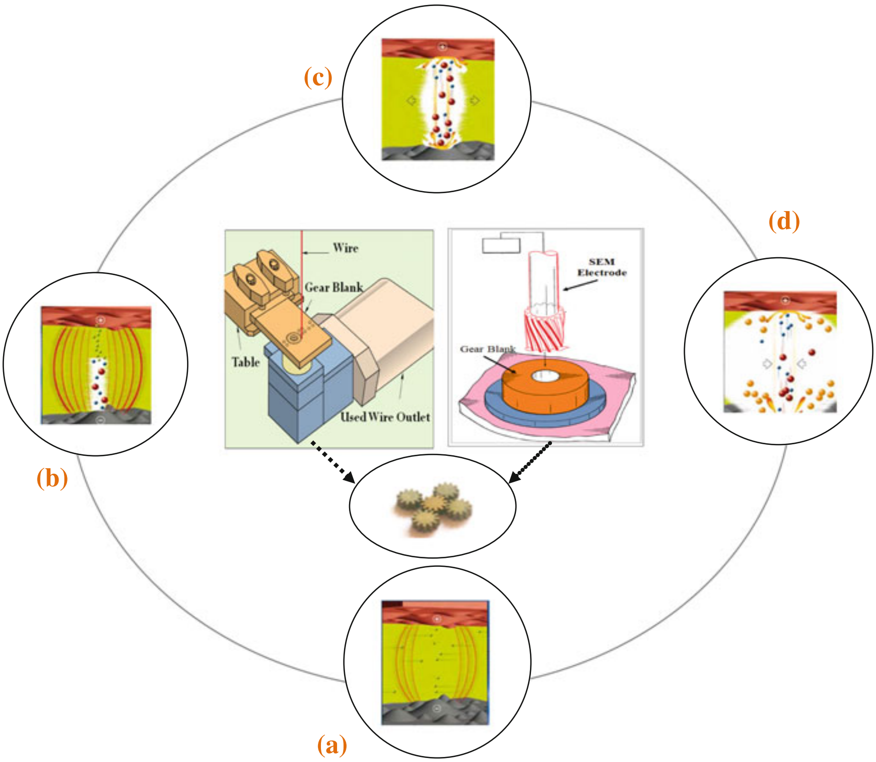

Fig. 2.2 Mechanism of material removal during machining of gears by SEM and WSEM [13]

blank by locally melting and vaporization (Fig. 2.2c). At the end of the discharge, current and voltage are shut down (Fig. 2.2d). The plasma implodes under the pressure imposed by the surrounding dielectric. Consequently, the molten metal pool is taken up into the dielectric, leaving a small crater at the gear tooth surface. This cycle is repeated until the required amount of material to be removed or the prescribed geometry is realized.

CNC programming for manufacturing of miniature gears with *SEM* is usually simply a set of commands to displace (plunge) a gear shaped electrode along the Z-axis displacement into the gear blank, whereas for WSEM, dedicated CAM software is used to define the cutting by defining gear geometry in terms of various parameters in a separate subroutine or by importing a CAD file of the appropriate geometry. Using this information, the software can generate the geometry of the gear profile to be manufactured and displays it graphically in terms of lines and arcs which represent the path of movement of the wire. The compensation for electrode size (i.e. wire diameter) and machining overcuts can also be specified. The post-processor of the software calculates all the numerical information about the movement of the wire and workpiece (gear blank) table in terms of G and M codes. The same basic procedure is followed to machine gears of any size, specification and electrically conductive material either by *SEM* and *WSEM*.

2.6 Spark Erosion Machining of Miniature Gears State-of-the-Art

The perceived improvement in geometric accuracy, quality finish and good surface integrity of products made by Spark-erosion machining (*SEM*) and its variants i.e. WSEM, micro-SEM and micro-WSEM have been the driving force for researchers and scientists to use these processes to manufacture parts for MEMS and other miniaturized-devices [13–17].

Various investigations have reported on the manufacturing of miniature gears using SEM and WSEM. These are summarized and presented in Table 2.1.

2.6.1 Spark-Erosion Machining of Gears

Meticulously done extensive literature review on miniature gear manufacturing by SEM based processes found few articles on *SEM* (or EDM) of miniature gears and all are based on *micro-SEM* of gears.

A micro-planetary gear system (0.03 mm) for a chain-type self-propelled micro-machine used in power plants was fabricated from SKS3 tool steel and WC–Ni–Cr super hard alloy by Takeuchi et al. [18] using *micro-SEM*. This system

Table 2.1 Summary of past work on manufacturing of miniature gears by spark-erosion-based processes [13]

Sr. No	Researcher	Gear type	Specification	Gear material	Process used	Findings
1.	Takeuchi et al. [18]	Micro spur gear	Module: 30 µm	SKS3 tool steel and WC–Ni–Cr cermets	Micro-SEM	Good in torque transmission performance; Dimensional variation: 0.4 %
2.	Takahata et al. [19]	Micro spur gear	Outside diameter: 200 µm; Face width: 1000 µm	WC–Co super-hard alloy	Micro-SEM	Variation in outside diameter: 4 µm
3.	Takahata and Gianchandani [20]	Micro spur gear	Outside diameter: 300 µm; Face width: 70 µm	WC–Co super-hard alloy	Micro-SEM	Fabrication time: 15 min
4.	Hori and Murata [21]	Micro spur gear	Module: 24 µm; Outside diameter: 0.280 mm; Number of teeth: 9; Face width: 0.3 mm	–	Micro-WSEM	Profile Error: 1 µm; Uniform profile with no undercutting at root area
5.	Suzumori and Hori [22]	Meso spur gear	Module: 63 µm; Outside diameter: 9 mm; Number of teeth: 95–96; Face width: 3 mm	Steel	Micro-WSEM	Satisfactory performance of the motor (equipped with these gears) under high load conditions
6.	Benavides et al. [23]	Meso ratchet wheel	Outside diameter: 6.4 mm; Face width: 0.88 mm	304 SS; austenitic stainless; beryllium copper and titanium	Micro-WSEM	Submicron level surface finish; good profile characteristics; minimum recast layer
7.	Schoth et al. [24]	Micro spur gear	Outside diameter: 1 mm, 0.5 mm;	X38CrMoVS_1 Steel SiSiC	WSEM	Good geometry and surface quality

(continued)

Table 2.1 (continued)

Sr. No	Researcher	Gear type	Specification	Gear material	Process used	Findings
			Number of teeth: 8; Face width: 6 mm, 10 mm			
8.	Di et al. [25]	Micro spur gear	Module: 100 µm; Number of teeth: 7; Face width: 1 mm	Stainless steel	Micro-WSEM	Accuracy: ±0.2 µm; Thickness of recast layer: 2 µm
9.	Ali and Mohammad [26]	Meso spur gear	Outside diameter: 3.58 mm; Number of teeth: 17; Face width: 6 mm	Copper	WSEM	Average roughness: 1 µm; Maximum roughness: 7 µm; Dimensional variation: 1–2 %
10.	Ali et al. [27]	Meso spur gear	Outside diameter: 3.58 mm; Number of teeth: 17; Face width: 6 mm	Beryllium-copper	WSEM	Average roughness: 1.8 µm; Maximum roughness: 7 µm; Dimensional accuracy: 2–3 µm
			Outside diameter: 1.2 mm; Number of teeth: 17; Face width: 6 mm		Micro-WSEM	Average roughness: 50 nm; Dimensional accuracy: 0.1–1 µm

was used as a micro-power reducer and performed satisfactorily for 5×10^6 total rotations at input torque of 10^{-7} Nm.

Takahata et al. [19] machined a WC–Co micro-gear of high aspect ratio (i.e. 5) by *micro-SEM* with only a 4 μm variation in outside diameter which could be adequately used as a micro-mechanical processing tool. Lithography, electroplating and moulding (LIGA) was used to fabricate negative-type gear electrodes of 200 μm outside diameter in nickel (See Fig. 2.3a). The discharge gap produced a reduction of 3 μm in the outside radius of the fabricated gear. This resulted in a micro-gear of WC–Co with an outside diameter of 194 μm, 1000 μm in length and with only a 4 μm variation in outside diameter across the length (Fig. 2.3b). It was then recommended to use as processing tool for micro-mechanical applications.

Takahata and Gianchandani [20] presented a new method referred to as ‘batch mode micro-SEM’ for precision fabrication of complex patterns of gears simultaneously. A batch of copper electrodes of 10 μm wall thickness and 300 μm height was fabricated through LIGA. These electrodes were then used as tools in

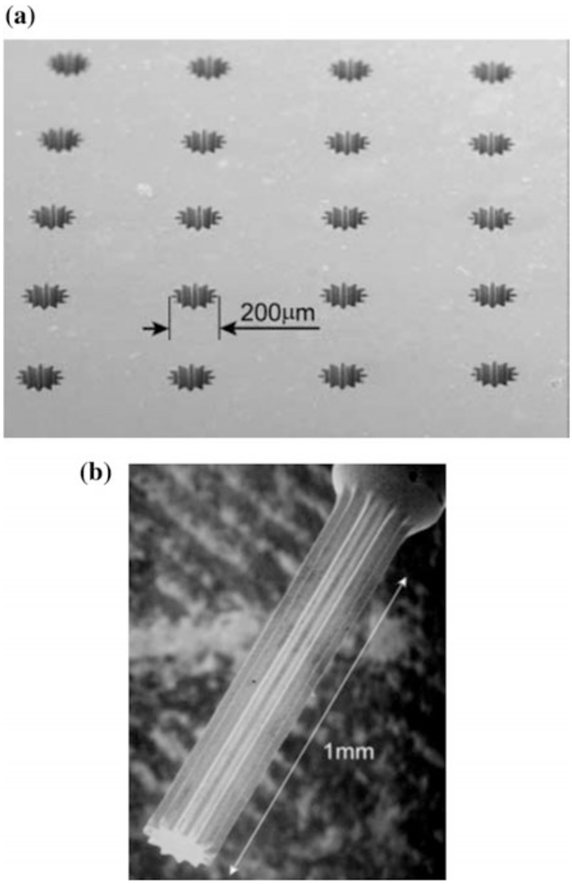

Fig. 2.3 **a** Array of negative-type nickel electrodes fabricated by LIGA process [19]. **b** Micro-gear manufactured using LIGA fabricated nickel electrode by *micro-SEM* [19]

micro-SEM for simultaneous cutting of a batch of 36 WC–Co super-hard alloy micro-gears having a 300 μm outside diameter and 70 μm thickness. The successful production of this batch of gears in 15 min was reported.

Despite the lack of available literature as regards to spark-erosion machining of miniature gears, as demonstrated above, it may be concluded that this is a practical fabrication technique for realizing high-precision mechanical systems with high robustness.

2.6.2 Wire Spark-Erosion Machining of Gears

The amount of literature available on *WSEM* (or WEDM) and *micro-WSEM* of miniature gears indicates the increased interest of researchers to explore this specific process in greater detail. Continued published work dating from the late nineties to the present amply demonstrates the capability and perceived superiority of wire spark-erosion machining for manufacturing of miniature gears. The following paragraphs briefly introduce the available literature on the manufacture of miniature gears by WSEM.

In probably the earliest published study a micro-involute spur gear of 0.28 mm outside diameter was fabricated by Hori and Murata [21] using micro wire spark-erosion machining with a tungsten wire of 25 μm diameters. The machining resulted in a burr-free uniform involute tooth profile with less than 1 μm profile error as demonstrated in the post-fabrication metrological testing and scanned electron micrograph study.

A prototype wobble motor equipped with stator and rotor having composite (involute and arc) teeth profiles for high torque and low load applications was developed by Suzumori and Hori [22]. The rotor and the stator had 95 and 96 teeth respectively. The prototype was 6 mm in pitch diameter, 9 mm in outside diameter, and 3 mm thick. It was fabricated from steel by *micro-WSEM*. The motor maintained almost constant speed and full wobble motion until just stalling during performance testing, unlike a motor equipped with involute tooth profile rotor-stator.

Sandia National Laboratories in the USA has been actively involved in design, development, and fabrication and testing of micro electro mechanical systems (MEMS) for many years resulting in several published and unpublished studies on spark-erosion machining of miniature gears for MEMS and other miniaturized devices. Benavides et al. [23] from the Manufacturing Science and Technology Centre at *Sandia lab* employed *micro-WSEM* to fabricate a meso-sized ratchet wheel of different materials (i.e. 304L stainless steel, nitronic 60, austenitic stainless, beryllium copper, and titanium). A submicron level surface finish, burr-less edges and profiles, minimum recast layer and consistent micro-geometry were achieved. A total of seven test parts were fabricated for their work: two each of 304L SS, nitronic-600 annealed stainless steel and titanium alloy and one of Beryllium Copper. The machining duration on the *micro-WSEM* machine was

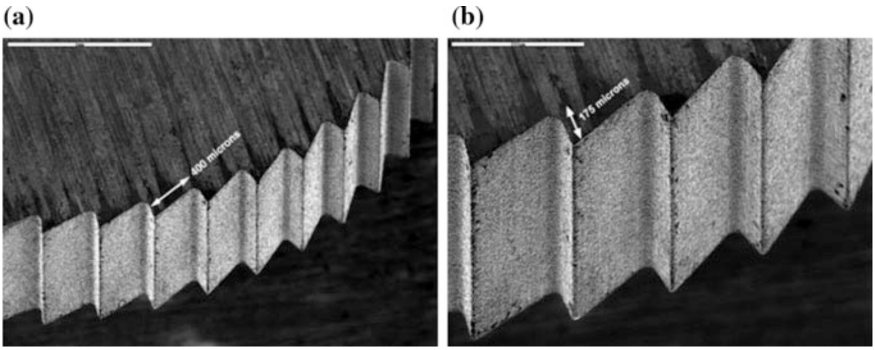

Fig. 2.4 Scanned electron micrograph of micro-WSEMed ratchet teeth in Nitronic 60 stainless steel [23]. **a** Normal view. **b** Magnified view

approximately two hours per part. The *Micro-WSEM* machine was equipped with tungsten wire of 30 µm diameter and de-ionized water as dielectric. Figure 2.4a, b depicts the scanned electron microscopic images of the ratchet teeth cut into a nitronic 60 ratchet wheel test part.

All materials displayed satisfactory edge definition and very thin recast layers (See Fig. 2.5a–d). However, Fig. 2.5c indicates that the titanium alloy ratchet wheel's features are smoothest and have minimum recast layer. Metrology investigations for the fabricated ratchet wheels (details are given in Table 2.2) indicate that the ratchet wheels of 304L stainless steel have the best profile tolerance

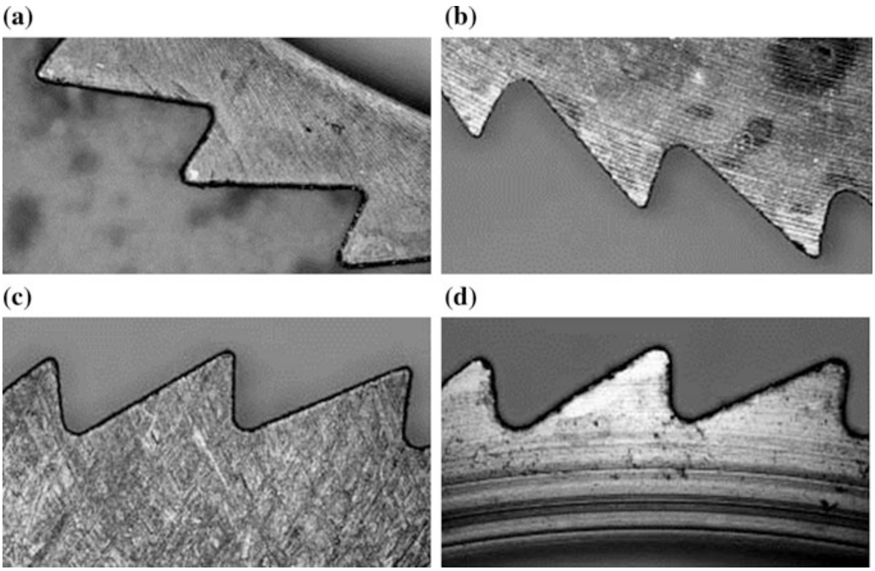

Fig. 2.5 Profile micrographs of teeth of micro-WSEMed ratchet wheels [23]. **a** 304L SS. **b** Nitronic 60 SS. **c** Titanium alloy. **d** Beryllium copper

Table 2.2 Results of a metrology investigation of fabricated ratchet wheels [23]

Material		Profile tolerance (in microns)
304L SS	Part no. 1	1.5
	Part no. 2	1.5
Nitronic 60 SS	Part no. 1	4.1
	Part no. 2	4.1
Titanium alloy	Part no. 1	2.3
	Part no. 2	2.3
Beryllium copper	Part no. 1	3.8

followed closely by the titanium, thus making them the most favorable materials for fabrication of precision meso-scale parts by *micro-WSEM*.

Schoth et al. [24] demonstrated the capability of *Micro-WSEM* fabrication of high aspect ratio 3D microstructures in selected ceramics and metals. A 30 μm tungsten wire was used to fabricate a gear wheel of X38CrMoVS_1 steel with a 1 mm outside diameter, 6 mm thickness and 8 teeth (Fig. 2.6a). The same wire was used to fabricate a ceramic (SiSiC) gear wheel (Fig. 2.6b) of 1 mm outside

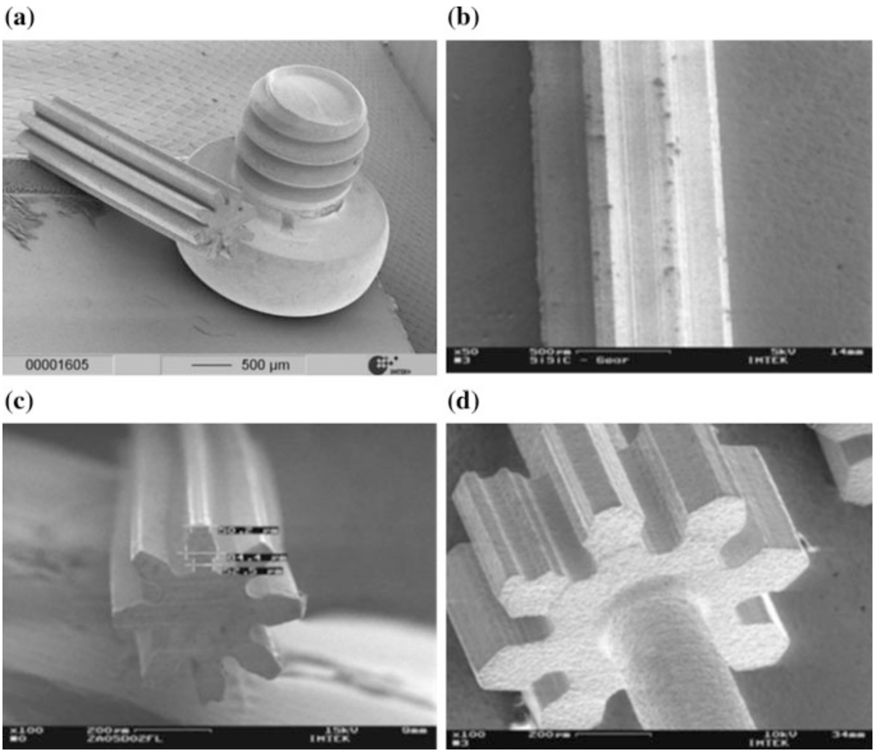

Fig. 2.6 Micrographs of teeth of micro-WSEMed gear wheels [24]

diameter, 10 mm thickness and 8 teeth. Another smaller gear with a 0.5 mm outer diameter, 6 mm height and 8 teeth was machined in X38CrMoVS_1 steel by utilizing a 20 μm tungsten wire (Fig. 2.6c). A gear wheel with integrated shaft, for ease of assembly, was also fabricated by *micro-WSEM* (Fig. 2.6d). They concluded that the electrode diameter was the most significant parameter that affected accuracy.

Di et al. [25] manufactured stainless steel micro-internal gears of 100 μm module with 7 teeth and 1 mm thickness by *micro-WSEM* using a tungsten wire of 30 μm diameter and at a speed of 20 mm/min. The best fabricated gear achieved ±0.2 μm accuracy, 0.1 μm surface roughness and 2 μm thick recast layer. Micro-forming dies of module 100 μm and 3.5 mm thickness have also been fabricated and have consequently been used successfully to form micro-gears of aluminium alloys.

In another study, Ali and Mohammed [26] machined external meso-spur gears with 3.58 mm outside diameter and 17 teeth from a 6 mm thick copper blank with *WSEM* utilizing brass wire of 100 μm diameter. They obtained a 1.4 μm average roughness, 7 μm maximum roughness and only 1–2 % average dimensional variation. Subsequent microstructural investigation and analysis showed the existence of shallow craters and other irregularities on the gear teeth surfaces. Consequently, lower discharge energy parameter settings were recommended for better surface integrity.

Thereafter, Ali et al. [27] compared two variants of SEM namely conventional *WSEM* and *micro-WSEM* for manufacturing of micro-spur gears. In the conventional *WSEM* process, a best set of parameters was selected during meso-fabrication of rectangular plate of Be–Cu alloy. Using this parameter settings (1 A current, 5 V gap voltage, 6 μs pulse-on time, and 5 μs pulse-off time) a meso-gear (17 teeth, 3.5 mm outside diameter and 6 mm thickness) in beryllium-copper alloy was fabricated utilizing brass wire of 100 μm diameter with de-ionized water as dielectric. This gear had 2–3 μm dimensional accuracy, 1.8 μm average roughness and 7 μm maximum roughness. Subsequently a meso-gear (17 teeth and 1.2 mm outside diameter) was machined by *micro-WSEM* using a wire with diameter of 70 μm, at 0.1 n F capacitance; 90 V gap voltage and 3.8 μm/s feed rate in a synthetic oil dielectric. The fabricated gear demonstrated a 0.1–1 μm dimensional accuracy and 50 nm average roughness. Figures 2.7 and 2.8 depict various micrographic views of both the meso-gears.

A micrograph surface study of both gears indicated a crack-free surface structure. A comparison of the dimensional variation and surface roughness revealed *Micro-WSEM* as the superior technique albeit with the disadvantage of being slower than conventional *WSEM*. During experimentation they also observed the increased material removal rate and subsequent deterioration in surface quality with increased discharge current, gap voltage (in conventional WSEM) and capacitance (in *micro-WSEM*). It was therefore unsurprisingly concluded that low discharge energy parameters have to be used in *WSEM* for superior geometrical features and surface finish [27].

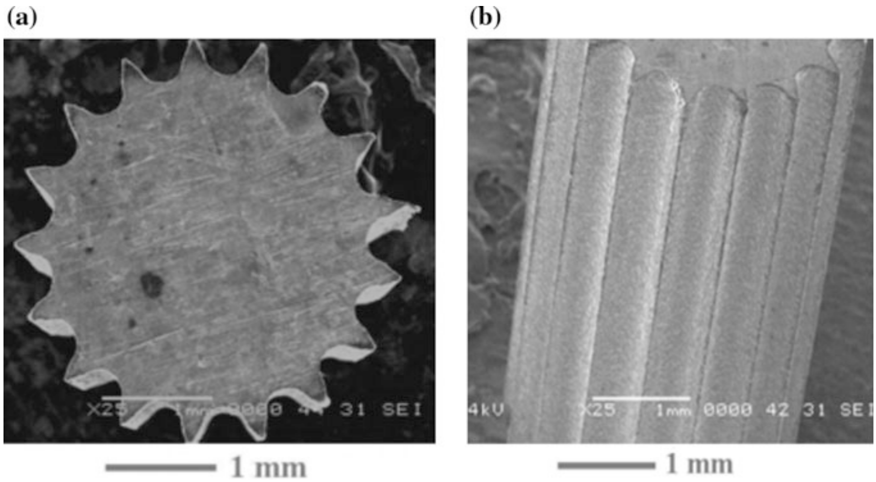

Fig. 2.7 Meso-spur gear machined by conventional *WSEM* [27]. **a** Top view. **b** Isometric view

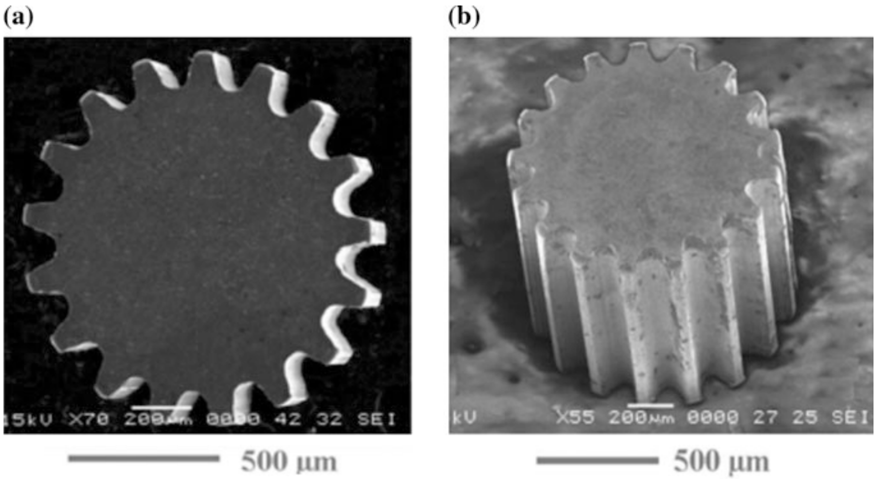

Fig. 2.8 Meso-spur gear machined by *micro-WSEM* [27]. **a** Top view. **b** Isometric view

Critical review based on spark-erosion machining of gears has shown that there is hardly any literature available on machining of macro-gears by spark erosion based machining processes except for the attempt made by Talon et al. [28], in which a macro size spur gear (outside diameter 28 mm; module 2 mm; 12 tooth; 5 mm face width) of important aerospace titanium alloy i.e. Ti–6Al–4V was precisely fabricated in 50 min using WSEM. Post fabrication metrological inspection of this gear by gear tooth Vernier calliper and coordinate measuring machine

(CMM) concluded that a lower dimensional variation and good manufacturing quality (i.e. ISO-7) were obtained.

It became abundantly clear that in most cases only the capability of *SEM/WSEM* to fabricate the miniature gears was of concern and the parameters on quality such as micro-geometry, surface finish and integrity; and productivity were addressed in passing only.

2.7 Conclusions and Scope of Spark Erosion Machining of Miniature Gears

The review of past work as presented in the forgoing sections on *SEM* and *WSEM* of miniature gears indicates a clear lack of detailed and systematic investigation of how the different process parameters affects the quality aspects (especially micro-geometry) of miniature gears. Some major conclusions in terms of research gaps include lack of work on WSEM of meso-sized gears; lack of investigation on the effect of spark erosion process on micro-geometry of gears; and lack of focus on optimizing spark erosion machining process for high quality miniature gear manufacturing.

Based on the limitations of past work, the following points define the scope of research work discussed in the subsequent chapters of this book:

- Exploring the capability of WSEM for manufacturing high quality miniature gears.
- Investigating and analysing the effects of WSEM parameters on micro-geometry, surface roughness and surface integrity of miniature gears.
- Improving the productivity of WSEM while manufacturing high quality miniature gears.
- Modelling and optimization of WSEM process for high quality and productivity.
- Comparative study of gear hobbing and WSEM to manufacture high quality miniature gears.
- Establishing WSEM as a superior alternative to conventional methods for near-net shape manufacturing of miniature gears.

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