Int J Adv Manuf Technol (2015) 80:1863–1877
DOI 10.1007/s00170-015-7130-2

ORIGINAL ARTICLE

Spark erosion machining of miniature gears: a critical review

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Received: 26 February 2015 / Accepted: 6 April 2015 / Published online: 30 April 2015

Abstract This paper presents a review of previous work conducted as regards to the machining of miniature gears by *spark erosion machining* (*SEM*) process and its variants. Miniature gears are key components of various small devices. Their proper function requires the selection of an appropriate manufacturing and/or finishing process that will deliver the required fit for purpose quality. Spark-erosion-based machining processes have a proven track record to impart the relevant quality characteristics and to minimize the number of operations required. This paper commences with an introduction to miniature gears before outlining the spark erosion machining of gears. Details as regards to previous efforts conducted on machining of these gears by SEM-based processes are presented before selected future research trends, directions and avenues for possible future research are offered. This paper focuses exclusively on SEM of miniature gears even though it is noted that similar research work on macrogears is also limited. This review paper aims to facilitate an overall view of all the available literature on spark erosion machining of miniature gears in a single article, to promote the technology and to provide a road map to researchers for making efforts towards exploring these technologies further.

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Keywords Spark erosion machining · Miniaturization · Mesogear · Manufacturing quality · Surface integrity

1 Introduction

Miniaturization is one of the key requirements of the present technological era, significantly influencing engineers and technologists worldwide to explore new techniques of manufacturing miniaturized products and their components. Other important technologies include sustainable machining and advanced and hybrid machining processes. *Miniature gears* are some of the most important miniaturized components and are extensively utilized in microelectromechanical systems (MEMS), scientific instruments, miniature motors, robots, automobiles, medical equipment and various other electronic appliances. The functional characteristics of these devices largely depend on the manufacturing quality of the miniature gears used. Therefore, highly precise and accurate manufacturing processes are required for manufacturing of these gears.

Brass, bronze, stainless steel, aluminium and plastics are common miniature gear materials. Miniature gears of brass and bronze are usually fine-pitched gears, running at high speed and are primarily used for motion transmission, whereas stainless steel miniature gears are generally used in torque transfer applications [1, 2]. Consequently, minimum running noise, accurate motion transfer, sufficient torque transfer capability and longer service life are the key functional performance characteristics for these gears. In order to achieve these characteristics, the gear should have good surface finish (possesses minimum roughness), be geometrically accurate (have low geometric tolerance) and have superior near-surface mechanical integrity (high hardness). These requirements may be achieved by appropriate selection of the material, heat treatment conditions and manufacturing and/or finishing processes.

Inaccuracy in the microgeometry and macrogeometry of a gear causes deviation from the ideal motion transmission conditions. The microgeometry parameters which affect the operating performance of the gears include errors or deviations in the profile, lead, pitch and runout [2, 3]. The profile error affects the noise behaviour; the lead error governs the load carrying capacity, whereas pitch error and runout affect the motion transfer characteristics as depicted in the Fig. 1. Chordal tooth thickness, span and outside diameter of a gear are important macrogeometry parameters that also affect its functional performance to some extent. The most significant surface condition indicators are as follows: gear flank surface topography, surface texture and two important surface integrity parameters namely microhardness and microstructure of the gear tooth flanks. The important surface roughness parameters which govern the tribological behaviour and largely determine the service life of a gear include average surface roughness, maximum surface roughness, bearing area properties, skewness Ssk and kurtosis Sku [4–6] (see Fig. 1).

Miniaturization is a relative concept that implies "making something smaller". The actual concept of what constitutes small or miniature must therefore be defined unambiguously. A miniature engineering system also called microsystem usually contains MEMS components that perform specific engineering functions. A MEMS may contain components of sizes ranging from 1 to 1000 μm (1 mm) with the microsystem itself being of the mesoscale. Mesoscale implies a scale that is between microscales and macroscales; i.e. it is the size range of millimetres to a centimetre [7]. In a keynote paper during a meeting of the Scientific Technical Committee of the Physical and Chemical Machining Processes of *CIRP* in 2000, Masuzawa [8] suggested that the micro in micromachining implies sizes between 1 and 999 μm. In his specific keynote a range of 1 μm to 500 μm was adopted to refer to micro. He noted that the term *micro* may vary according to era, person, machining technique, type of product and material. What this implies is that, currently, there does not exist a consistent international classification on the basis of size or dimensions for miniature components of which gears are a good example. To be consistent, miniature gears are therefore categorized as either microgears (outside diameter less than 1 mm) or mesogears (outside diameter 1–10 mm) [7, 9, 10].

Manufacturing techniques such as lithography (also named as LIGA), microhot embossing and microelectroforming are typically used to manufacture microgears only [7, 9]. Other techniques such as hobbing, die casting, powder metallurgy, extrusion, stamping, etc. may be used to manufacture micro as well as mesogears. All these techniques have inherent strengths and weaknesses. Lithography, embossing and electroforming are complex, expensive and not suitable for all material types [7, 11, 12]. Hobbing, stamping, die casting, extrusion and powder metallurgy produce poor-quality results initially that usually require finishing operations such as grinding, lapping, honing, etc. [2, 3, 10]. This has led to numerous scientists and engineers exploring alternative methods such as spark-erosion-based processes to manufacture miniature gears. A substantial body of work is therefore available in the literature as regards to micro-meso manufacturing using spark erosion machining processes. Unfortunately, this information is scattered and unfocused and therefore not easily accessible. The aim of this paper is therefore to present the current state of technology as regards to micro-meso manufacturing of gears by the non-conventional manufacturing technique of spark erosion.

2 Spark erosion machining process

2.1 Introduction

Advanced machining processes (AMPs) are well established in modern manufacturing industries, as they are capable of machining most electrically conductive materials irrespective

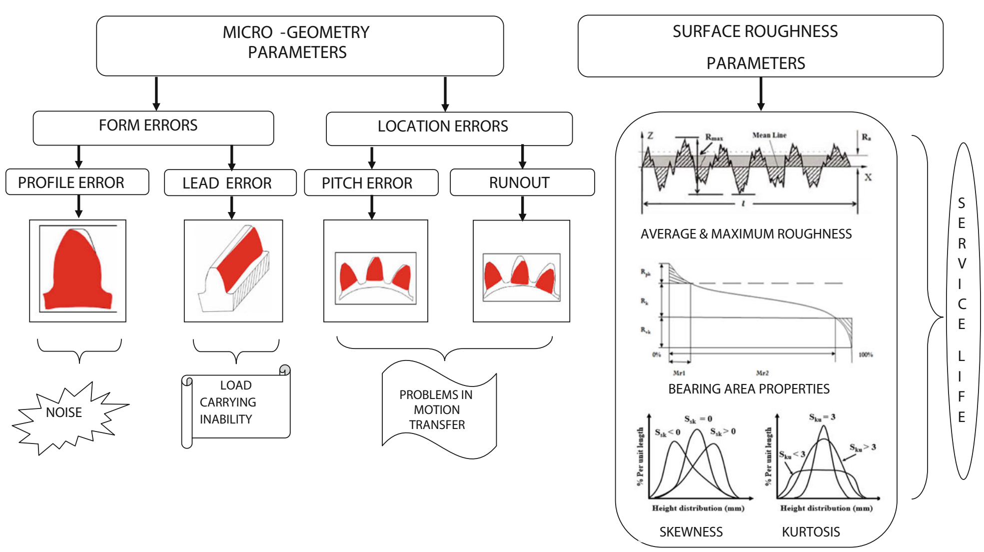

Fig. 1 Details of various parameters affecting functional performance and service life of a gear

of their hardness and toughness producing complex geometries, shapes and features. *Spark erosion machining* (*SEM*) also named as *electric discharge machining* (*EDM*) is the most widely used thermal-type AMP. 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 [13–16].

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 macrosized and shaped according to the geometry to be produced in the workpiece.

In SEM, 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 thermoelectric 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 [13–17].

In *micro-SEM*, an electrode with microfeatures 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 (microsize) 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 nanoseconds to a few microseconds to control the extent of material volume removal [13, 14].

2.2 Machining of miniature 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 [2, 6].

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. Initially, a potential difference (voltage) is applied between the tool electrode/wire electrode and the gear blank (Fig. 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. 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 is transformed into heat). The high energy density erodes a part of the material from both the electrode/wire and gear blank by locally melting and vaporization (Fig. 2c). At the end of the discharge, current and voltage are shut down (Fig. 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 workpiece, 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. The following section details all previously

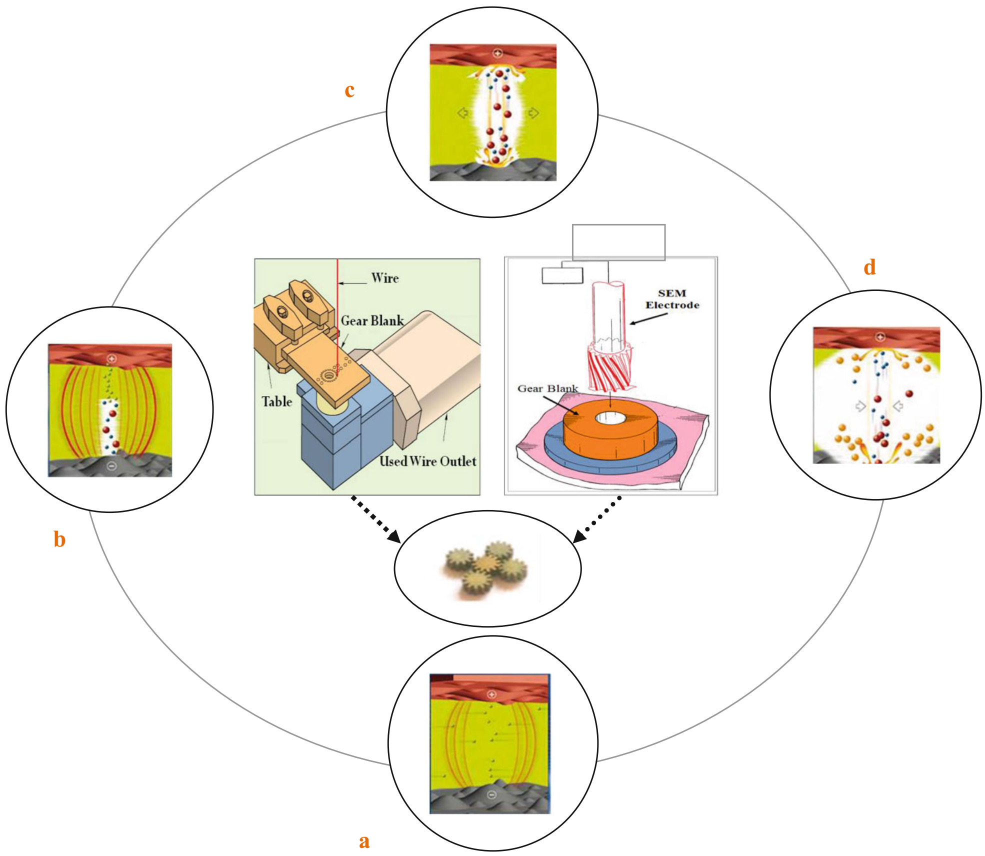

Fig. 2 Mechanism of material removal during gear machining by *SEM* and *WSEM*

published work as regards to machining of gears using spark-erosion-based processes.

3 Previous work on machining of gears by spark-erosion-based processes

The perceived improvement in geometric accuracy, quality finish and good surface integrity of products made by Spark erosion machining (SEM) and its variants has been the driving force for researchers and scientists to use these processes to manufacture parts for MEMS and other miniaturized devices [18–22].

Various investigations have reported on the manufacturing of miniature gears using SEM and WSEM. These are summarized and presented in Table 1.

3.1 SEM 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 microplanetary gear system (0.03 mm) for a chain-type self-propelled micromachine used in power plants was fabricated from SKS3 tool steel and WC–Ni–Cr super-hard alloy by Takeuchi et al. [23] using micro-SEM. This system was used as a micropower reducer and performed satisfactorily for 5×10^{6} total rotations at input torque of 10^{-7} Nm.

Takahata et al. [24] machined a WC–Co microgear 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 micromechanical processing tool. Lithography, electroplating and moulding (LIGA) was used to fabricated negative-type gear electrodes of 200-μm outside diameter in nickel (see Fig. 3a).

The discharge gap produced a reduction of 3 μm in the outside radius of the fabricated gear. This resulted in a microgear of WC–Co with an outside diameter of 194 μm, 1000 μm long and with only a 4-μm variation in outside diameter across the length (Fig. 3b). It was then recommended to use as a processing tool for micromechanical applications.

Takahata and Gianchandani [25] 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 micro-SEM for simultaneous cutting of a batch of 36 WC–Co super-hard alloy microgears having a

Table 1 Summary of past work on manufacturing of miniature gears by spark-erosion-based processes

Sr. no.	Researcher	Gear type	Specification	Gear material	Process used	Findings
1	Hori and Murata [26]	Microspur 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
2.	Suzumori and Hori [27]	Mesospur 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.
3.	Takeuchi et al. [23]	Microspur gear	Module 30 μm	SKS3 tool steel and WC–Ni–Cr cermets	Micro-SEM	Good in torque transmission performance; Dimensional variation 0.4 %
4.	Takahata et al. [24]	Microspur gear	Outside diameter 200 μm; Face width 1000 μm	WC–Co super-hard alloy	Micro-SEM	Variation in outside diameter 4 μm
5.	Benavides et al. [28]	Mesoratchet 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
6.	Takahata and Gianchandani [25]	Microspur gear	Outside diameter 300 μm; Face width 70 μm	WC–Co super-hard alloy	Micro-SEM	Fabrication time 15 min
7	Schoth et al. [29]	Microspur gear	Outside diameter 1 and 0.5 mm; Number of teeth 8; Face width 6 and 10 mm	X38CrMoVS_1 steel SiSiC	WSEM	Good geometry and surface quality
8.	Di et al. [11]	Microspur 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 [12]	Mesospur 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. [30]	Mesospur 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
11.	Gupta et al. [2, 6, 10, 18, 31–36]	Mesospur gear	Outside diameter 9.8 mm; Number of teeth 12; Module 0.8 mm; Face width 5 mm	Brass (ASTM 858)	WSEM	Profile error 11.9 μm; Pitch error 8.6 μm; Average roughness 1.3 μm; Maximum roughness 6.7 μm; Skewness −0.165; Kurtosis 2.455; Thickness of recast layer 3.5 μm

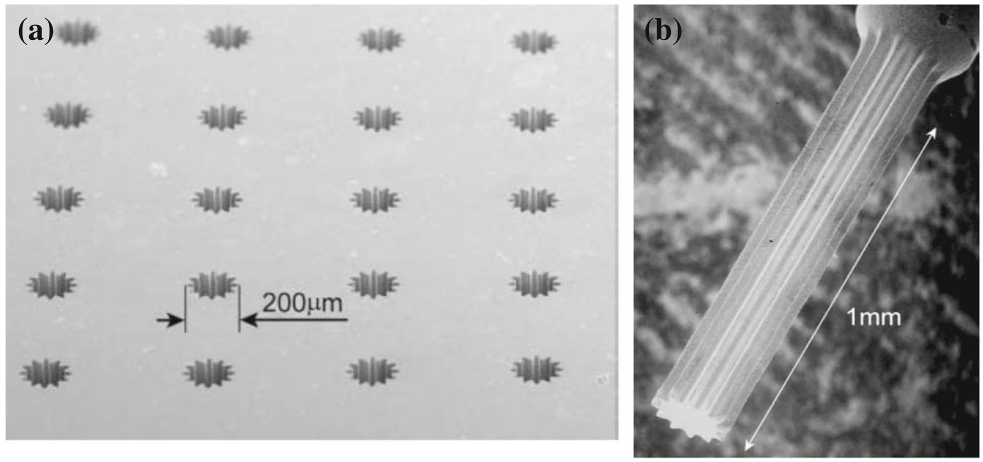

Fig. 3 **a** Array of negative-type nickel electrodes fabricated by LIGA process [24], © 2000, with kind permission from Springer. **b** Microgear manufactured using LIGA-fabricated nickel electrode by micro-SEM [24], © 2000, with kind permission from Springer

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.

3.2 WSEM 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 WSEM 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 microinvolute spur gear of 0.28-mm outside diameter was fabricated by Hori and Murata [26] using microwire spark erosion machining with a tungsten wire of 25-μm diameter. 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 [27]. 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, fabrication and testing of microelectromechanical 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. [28] from the Manufacturing Science and Technology Centre at *Sandia lab* employed micro-WSEM to fabricate a mesosized ratchet wheel of different materials (i.e. 304-L 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 microgeometry 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 approximately 2 h per part. The micro-WSEM machine was equipped with a tungsten wire of 30-μm diameter and deionized water as dielectric. Figure 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. 5a–d). However, Fig. 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) indicate that the ratchet wheels of 304-L stainless steel have the best profile tolerance followed closely by the titanium, thus making them the most favourable materials for fabrication of precision mesoscale parts by micro-WSEM.

Schoth et al. [29] demonstrated the capability of micro-WSEM fabrication of high aspect ratio 3-D 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 eight teeth (Fig. 6a). The same wire was used to fabricate a ceramic (SiSiC) gear wheel (Fig. 6b) of 1-mm outside diameter, 10-mm thickness and eight teeth. Another smaller gear with a 0.5-mm outer diameter, 6-mm height and eight teeth was

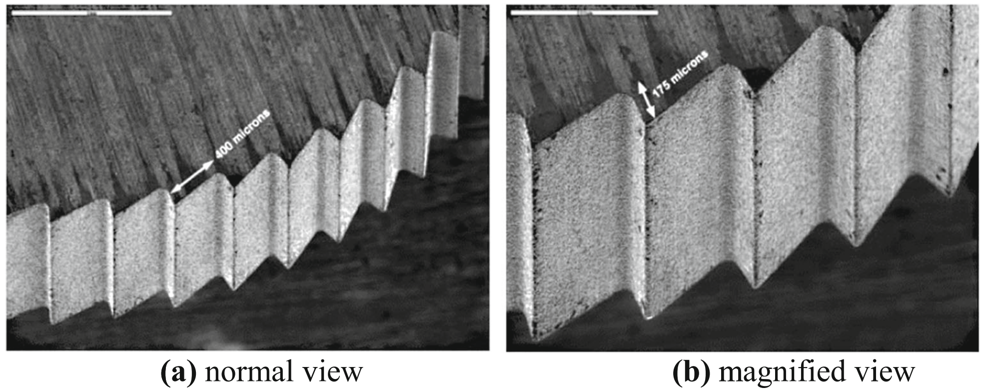

Fig. 4 Scanned electron micrograph of micro-WSEMed ratchet teeth in Nitronic 60 stainless steel. **a** Normal view. **b** Magnified view [28], © 2002, with kind permission from Springer

machined in X38CrMoVS_1 steel by utilizing a 20-μm tungsten wire (Fig. 6c). A gear wheel with integrated shaft, for ease of assembly, was also fabricated by micro-WSEM (Fig. 6d). They concluded that the electrode diameter was the most significant parameter that affected accuracy.

Di et al. [11] manufactured stainless steel microinternal gears of 100-μm module with seven 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. Microforming dies of module 100 μm and 3.5-mm thickness have also been fabricated and have consequently been used successfully to form microgears of aluminium alloys.

In another study, Ali and Mohammed [12] machined external mesospur 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. [30] compared two variants of SEM namely conventional WSEM and micro-WSEM for manufacturing of microspur gears. In the conventional WSEM process, a best set of parameters was selected during mesofabrication 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 mesogear (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 mesogear (17 teeth and 1.2-mm outside diameter) was machined by micro-WSEM using a wire with diameter of 70 μm, at

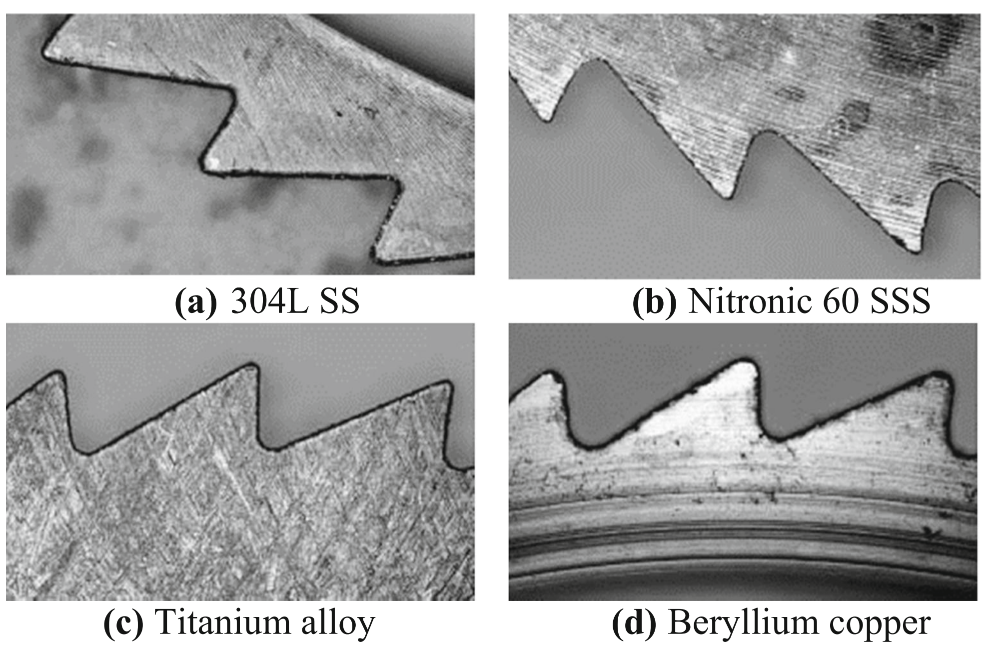

Fig. 5 Profile micrographs of teeth of micro-WSEMed ratchet wheels. **a** 304L SS. **b** Nitronic 60 SS. **c** Titanium alloy. **d** Beryllium copper [28], © 2002, with kind permission from Springer

Table 2 Results of a metrology investigation of fabricated ratchet wheels

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

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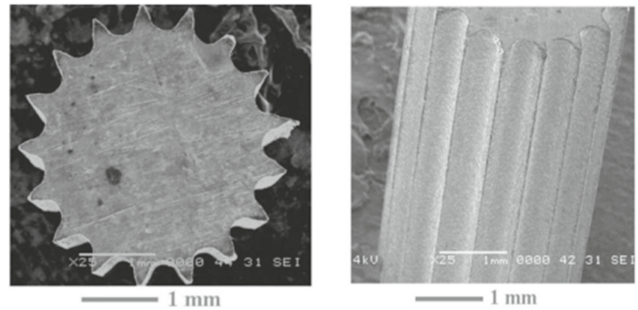
0.1 nF capacitance, 90-V gap voltage and 3.8 μm/s feed rate in a synthetic oil dielectric. The fabricated gear demonstrated a 0.1–1-μm dimensional accuracy and 50-nm average roughness. Figures 7 and 8 depict various micrographic views of both the mesogears.

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 geometric features and surface finish [30].

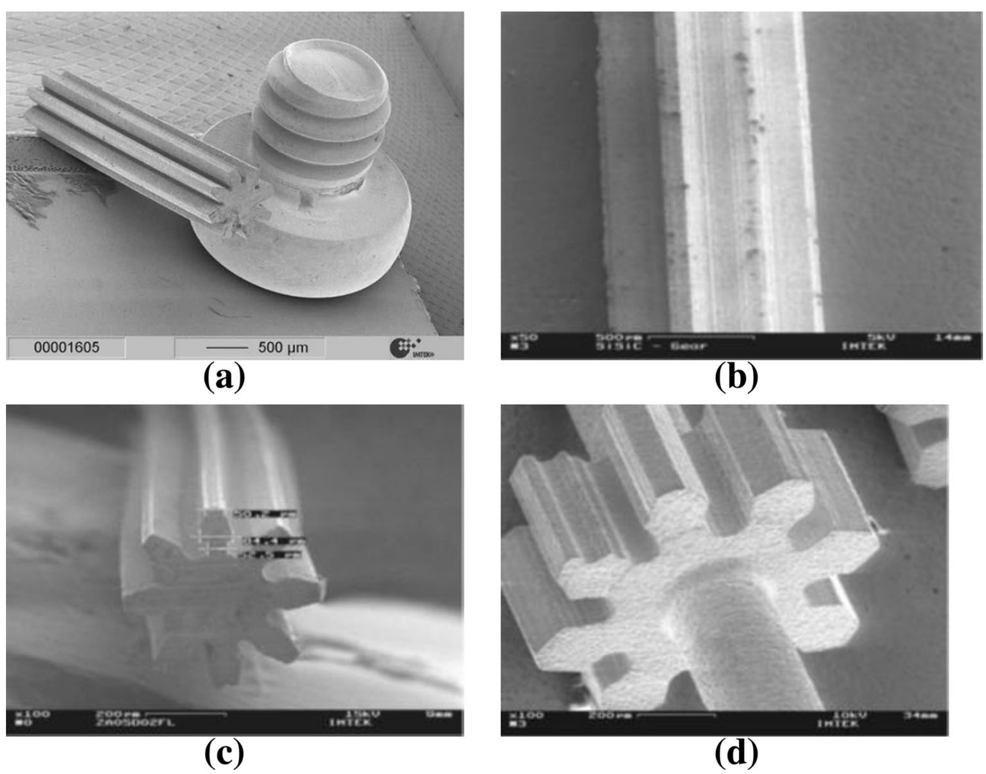
The review as presented above on SEM and WSEM of miniature gears indicates a clear lack of detailed and systematic investigation of how the different process parameters affect the quality aspects (especially microgeometry) of miniature gears. It became abundantly clear that in most cases, only the capability of SEM/WSEM to fabricate the miniature products was of concern and that parameters on quality such as surface integrity and productivity were addressed in passing only. This was the main motivation for the research work conducted by Gupta and Jain [2, 31], published in 2014, to



(a) Top view **(b)** Isometric view

Fig. 7 Mesospur gear machined by *conventional WSEM*. **a** Top view. **b** Isometric view [30], © 2010, with kind permission from Springer

Fig. 6 Micrographs of teeth of micro-WSEMed ratchet wheels [29], © 2005, with kind permission from Springer



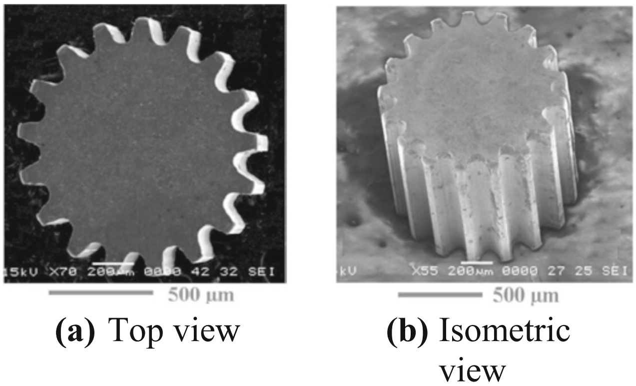


Fig. 8 Mesospur gear machined by *micro-WSEM*. **a** *Top view*. **b** *Isometric view* [30], © 2010, with kind permission from Springer

address some of these highlighted issues. The work is a first attempt to explore in detail the quality aspects and establish wire spark erosion machining (WSEM) as a superior alternative process for the manufacture of miniature spur gears of high quality. An extensive investigation on the effects of WSEM on the quality of the manufactured mesosized spur brass gears (specification given in Table 3) was conducted. Characteristic functional performances deciding parameters such as profile geometry, pitch, etc. along with surface roughness and other surface integrity properties of miniature gears were explored in more detail. The productivity of WSEM in the form of volumetric gear cutting rate was also analyzed and optimized. The research program was subdivided into four distinct stages, namely preliminary [32], pilot [6, 10, 33], main and confirmation experimentation stage [34–36].

In the preliminary experimentation stage, a total of 40 experiments were conducted by cutting simple rectangular-shaped strips from a brass plate of 5-mm thickness by varying the WSEM process parameters such as voltage (v), pulse-on time (Ton), pulse-off time (Toff), and wire feed rate (W) over their entire available range on the particular WSEM machine tool. This was done to obtain the full feasible working range of WSEM parameters which may be suitable for manufacturing mesogears of brass. Wire breakage frequency, roughness of the machine surface and cutting speed were considered as measures of performance [32].

Table 3 Specifications of the mesogear machined and investigated by Gupta and Jain using WSEM

Parameters	Details/value
Type	External spur gear
Material	Brass (ASTM 858[a])
Profile	Involute
Pressure angle	20°
Module	0.7 mm
Outside diameter	9.8 mm
Number of teeth	12
Face width	5 mm

[a] As per optical emission spectrometry

To further narrow down the process parameter variation during WSEM and to obtain a broad understanding of their effects on miniature gear quality, i.e. microgeometry parameters (profile and pitch error) and surface roughness (average and maximum roughness), a total of 23 pilot experiments were designed and conducted using one-factor-at-a-time (OFAT) approach [6, 10, 33]. A CNC gear metrology machine, surface roughness tester, scanned electron microscope and a micro-hardness tester, etc. were used for post-experimental evaluation. The best gear manufactured during pilot experimentation had a 13.2-μm profile error and 11.2-μm pitch error [10] and 1-μm average roughness and 6.4-μm maximum roughness [33] along with a uniform tooth flank topography, good bearing area properties, good microstructural aspects (Fig. 9) and a recast layer not more than 3.5 μm thick [6].

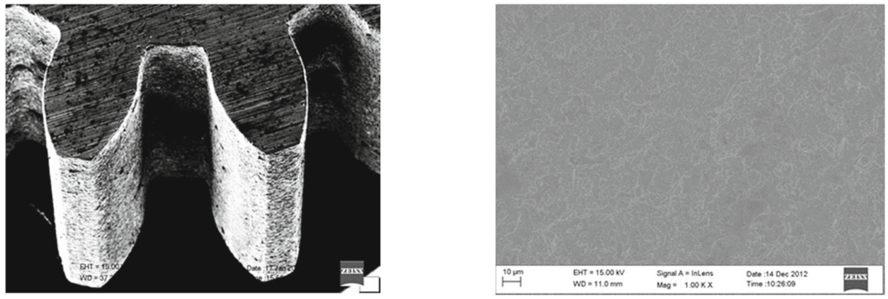
The miniature gear fabricated complied to the German quality standard DIN-8 and DIN-6 for profile and pitch, respectively, and is better than typically obtained by other conventional processes.

Based on the results obtained during the pilot stage of the investigation, an additional set of 29 experiments based on the *Box-Behnken* method of response surface methodology was initiated in main experimentation stage. An analysis of variance (*ANOVA*) was conducted to investigate the relevance of the various parameters.

This was followed by an optimization and confirmation stage consisting of nine experiments [2, 35, 36]. The conflicting objectives considered were minimization of geometric inaccuracy (profile error and pitch error) and surface roughness (average roughness and maximum roughness) and maximization of the WSEM process productivity (in terms of volumetric gear cutting rate). Figure 10 depicts the various tasks performed for mesofabrication of gears by WSEM [31].

A detailed discussion of the effects of WSEM process parameters (voltage, pulse-on time, pulse-off time and wire feed rate) on the microgeometry [36], surface roughness [35] and the process productivity [34] is presented. In essence, the ANOVA study found that all four WSEM process parameters significantly affect the outcome. Figures 11 and 12 depict the effects of the two important energy discharge parameters, namely, pulse-on time and voltage on the microgeometry and surface roughness of WSEMed miniature gears [35, 36].

Gupta and Jain [36] reported that w*ire lag*, i.e. deflection of wire from its intended path, wire breakage and non-uniform wear of wire (at low wire feed rate) are the main causes of microgeometry errors (profile error and pitch error) of gears machined by WSEM. Wire lag is due to displacement and vibration under the influence of electrostatic force (at low voltage), forces induced by violent spark and pressure of gas bubbles (at high voltage and high pulse-on times) (see Fig. 11), hydraulic forces (at high pulse-off times), short



(a) Burr-free uniform teeth profile (at 40 X) **(b)** crack-free surface and defect-free microstructure of gear tooth (at 1000X)

Fig. 9 Micrographs showing (**a**) burr-free uniform tooth profile (Magnification at 40 X) and (**b**) crack-free surface and defect-free microstructure of gear tooth (Magnification at 1000 X), of the best-quality miniature gear machined during pilot experimentation [6], © 2014 Springer

circuits and vibration caused by residual debris interaction (at low pulse-off times).

The formation of deep and irregular craters as a result of violent spark discharges at high-energy parameter settings (voltage and pulse-on time) (see Fig. 12), improper flushing of the molten material from the machining zone (at lower pulse-off time settings) and adherence of the wire on the gear flank surface (at lower wire feed rates) were the main reasons reported for deterioration in surface finish [35].

Significant interaction among WSEM parameters affecting the responses was also reported [35]. Regression and artificial neural network (ANN) modelling were also conducted and compared for establishing relations in parameters and responses with the ultimate aim to be able to predict and engineer the gear quality and productivity when fabricating miniature gears by WSEM. The ANN models were found to provide superior results when compared with the regression models.

Parameter optimization by the desirability analysis approach was then done in order to minimize wire lag for minimizing microgeometry errors, to pacify the generation of violent sparks and, thereby, the formation of irregular and deeper craters to minimizing the surface roughness and to maximize gear cutting rate [34–36]. The optimized values of profile error, pitch error, surface roughness and gear cutting rate are presented in Table 4. The values of microgeometry errors, i.e. 11.5-μm profile error and 9.1-μm pitch error (optimized values when considering profile and pitch error together), as presented in Table 4 imply compliance to DIN-7 and DIN-5, respectively, which are much better than those typically obtained for gears made by other conventional processes. A best surface finish with an average roughness of 1.1 μm and a maximum roughness 6.39 μm (acceptable for miniaturization) was obtained with a highest gear cutting rate of 42.97 mm^3/min possible.

No single set of parameters could however produce the highest productivity with the best surface finish and least

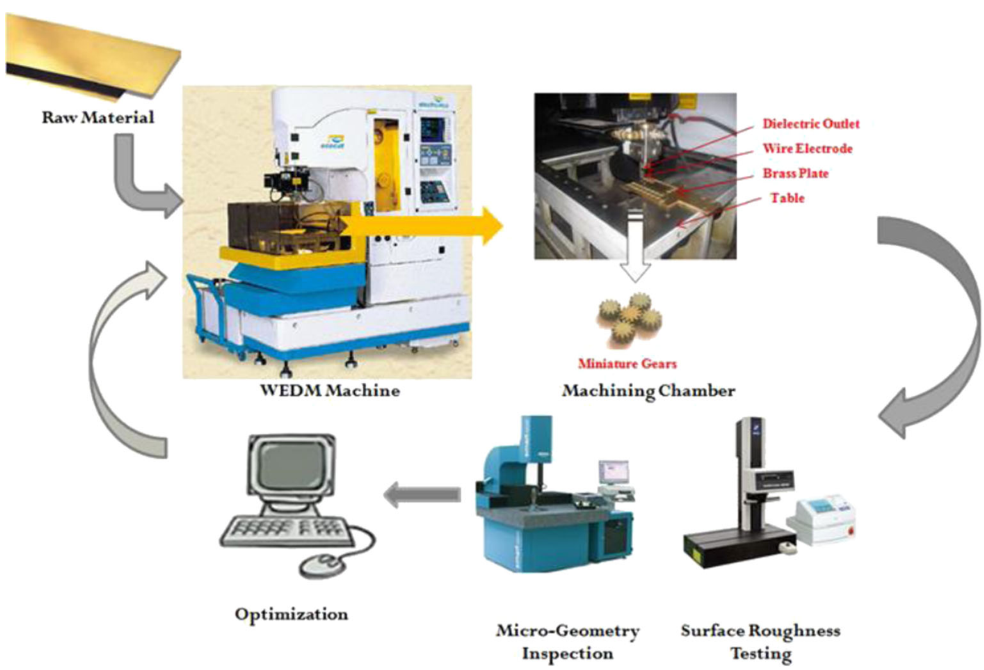


Fig. 10 Tasks performed for mesofabrication of quality gears by *WSEM* [18], ©2014 Taylor and Francis LLC

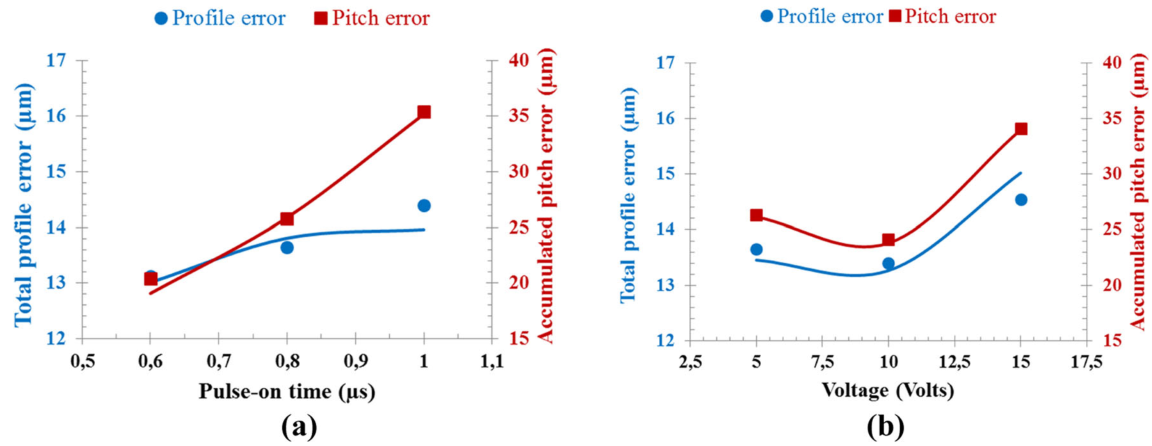


Fig. 11 Effects of **a** pulse-on time and **b** voltage on microgeometry errors of miniature gears [36], © 2014 Elsevier

geometric inaccuracy (microgeometry errors). Consequently, a multi-objective optimization was performed using a RSM-based desirability approach and back propagation neural network (BPNN) integrated genetic algorithm (GA) technique involving all responses [31]. The best values of all the responses obtained together through multi-objective optimization (by BPNN-GA technique) were reported in [18]. Microgeometry, surface roughness and various other surface integrity aspects were evaluated by multi-objective optimization.

A comparison of the quality parameters achieved for the miniature gear in question is presented and compared to a hobbed gear in Table 5. The gear complies with DIN-7 for profile and DIN-5 for pitch which also shows an improvement in gear quality from pilot to confirmation experimentation stage.

A detailed study based on a comparison of WSEM and *hobbing* (most extensively used process for mesogear manufacturing) on various aspects of manufacturing of quality miniature gears has been reported in [18]. A selection of mesogears of similar material and specifications and manufactured by hobbing was procured as generally available in industry. The best gear was selected for comparison with the multi-objectively optimized WSEMed miniature gear. The quality (based on the amount of microgeometric errors) of the WSEMed gear (DIN-7 and DIN-5) was shown to be superior of the hobbed gear (DIN-10). The macrogeometric deviations of the WSEMed gear were also low when compared to the hobbed gear. The hobbed gear was however found to have a better surface finish. Although the hobbed gear displayed a good surface finish, distinctive tool marks were observed by visual inspection and topography study on the flank surfaces. On the basis of topography study, it was concluded that despite having a superior surface finish, the hobbed gear cannot guarantee better performance during its service life until the tool marks are removed by a subsequent finishing operation. The WSEMed gear has very little deviation of actual flank surface from the theoretical one; i.e. no marks were observed on flank surfaces. Also, the surface finish is acceptable for miniaturization. It is however recommended that a concerted effort be initiated towards the improvement in surface finish of miniature gears especially when WSEMed.

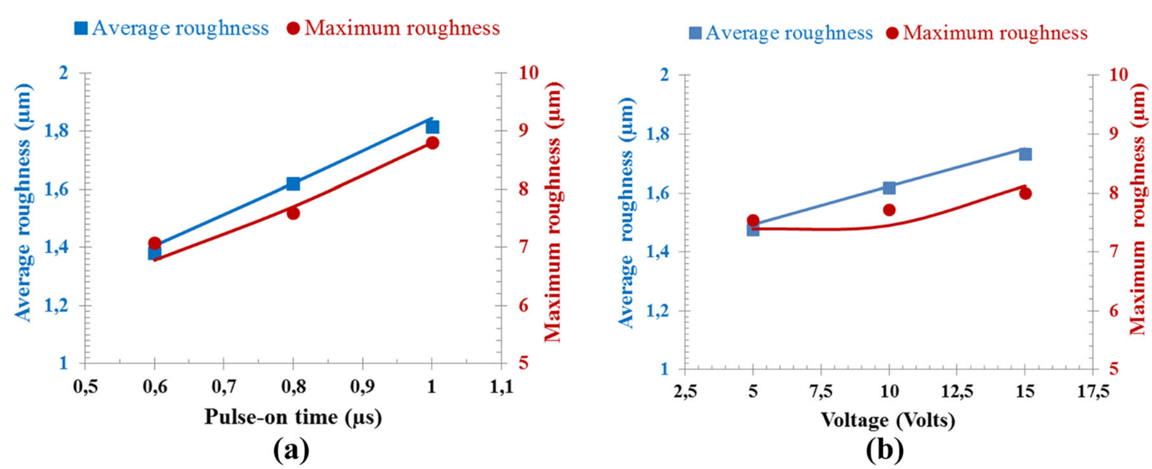


Fig. 12 Effects of **a** pulse-on time and **b** voltage on surface roughness of miniature gears [35], © 2014 Sage Publications

Table 4 Set of optimized WSEM parameters and corresponding optimum responses achieved experimentally from the past work done by Gupta and Jain

Responses			Optimized WEDM parameters			
		Optimum value	V (volts)	T_{on} (µs)	T_{off} (µs)	W (m/min)
Microgeometry errors (µm)	F_a	11.1	8	0.6	165	13
	F_p	8.4	9	0.65	155	13
	F_a-F_p	11.5–9.1	9	0.6	160	13
Surface roughness (µm)	R_a	1.05	6	0.6	165	14
	R_{max}	6.34	8	0.6	150	14
	R_a-R_{max}	1.1–6.39	6	0.6	160	14
Gear cutting rate (mm^3/min)	GCR	42.97	15	0.85	100	9

From [34–36]

Microhardness measurement of the WSEMed miniature gears produced at the multi-objectively optimized parameters displayed the presence of thin, i.e. 3.5-µm, recast layers [18] that seems not to have adverse thermal effects on gear teeth surfaces. This is largely the result of the high thermal conductivity of the gear material (brass) that is conducive to rapid dissipation of heat during machining.

A micrographical study of the miniature gears (Fig. 13) machined for WSEM parameters optimized for surface roughness (Fig. 13a–b), microgeometric accuracy (Fig. 13c–d) and for the multi-objective optimized set (Fig. 13e–f) reveals the formation of burr-free uniform teeth profiles without any undercutting at the root area.

The main conclusions for the work conducted by Gupta and Jain [13, 18, 34–36] may be summarized as follows:

- The four WSEM parameters considered here, i.e. pulse-on time, pulse-off time, voltage and wire feed rate, were all identified as significant and influencing the geometric accuracy and surface finish of miniature gears and also the productivity of the process.
- Formation of irregular-shaped craters due to high discharge energy parameter settings and the existence of wire lag due to excessive wire vibration were reported as the main factors responsible for the deterioration of surface finish and geometric inaccuracy of the miniature gears.
- Reasonable constraint on the discharge energy is the key to machining quality miniature gears by WSEM.
- The higher quality (as far as geometric accuracy is concerned) achieved during the machining of gears by wire spark erosion eliminates the need of secondary finishing operation.
- Wire spark erosion is capable and has the potential to manufacture gears with low microgeometric errors and good surface integrity which may improve the operating performance and service life of miniature gears and therefore makes it a suitable alternative to conventional processes for miniature gear manufacturing.

Table 5 Comparison of WSEMed gear and hobbed gear on the basis of microgeometry, macrogeometry and surface finish

Microgeometry parameter	WSEMed gear		Hobbed gear	
	Value	DIN no.	Value	DIN no.
Profile error (µm)	11.9	7	30.2	10
Pitch error (µm)	8.6	5	48	10
Surface roughness parameter	Value			
Average roughness (µm)	1.26		0.2	
Maximum roughness (µm)	6.67		1	
Skewness	−0.165		−0.360	
Kurtosis	2.455		2.635	
Macrogeometry parameter	Value			
Deviation in span (µm)	4		44	
Deviation in tooth thickness (µm)	5		47	
Deviation in outside diameter (µm)	10		97	

From [18],

The review presented on manufacturing of miniature gears by micro-WSEM and WSEM, has identified these processes as emerging techniques to fabricate quality miniature gears, if properly controlled.

The review has also shown that there is also hardly any literature available on machining of macrogears by spark-erosion-based machining processes except for the attempt made by Talon et al. [37], in which a macrosize 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.

The following section presents a final conclusion and suggestions for possible future work as regards to the machining of miniature gears by spark-erosion-based processes.

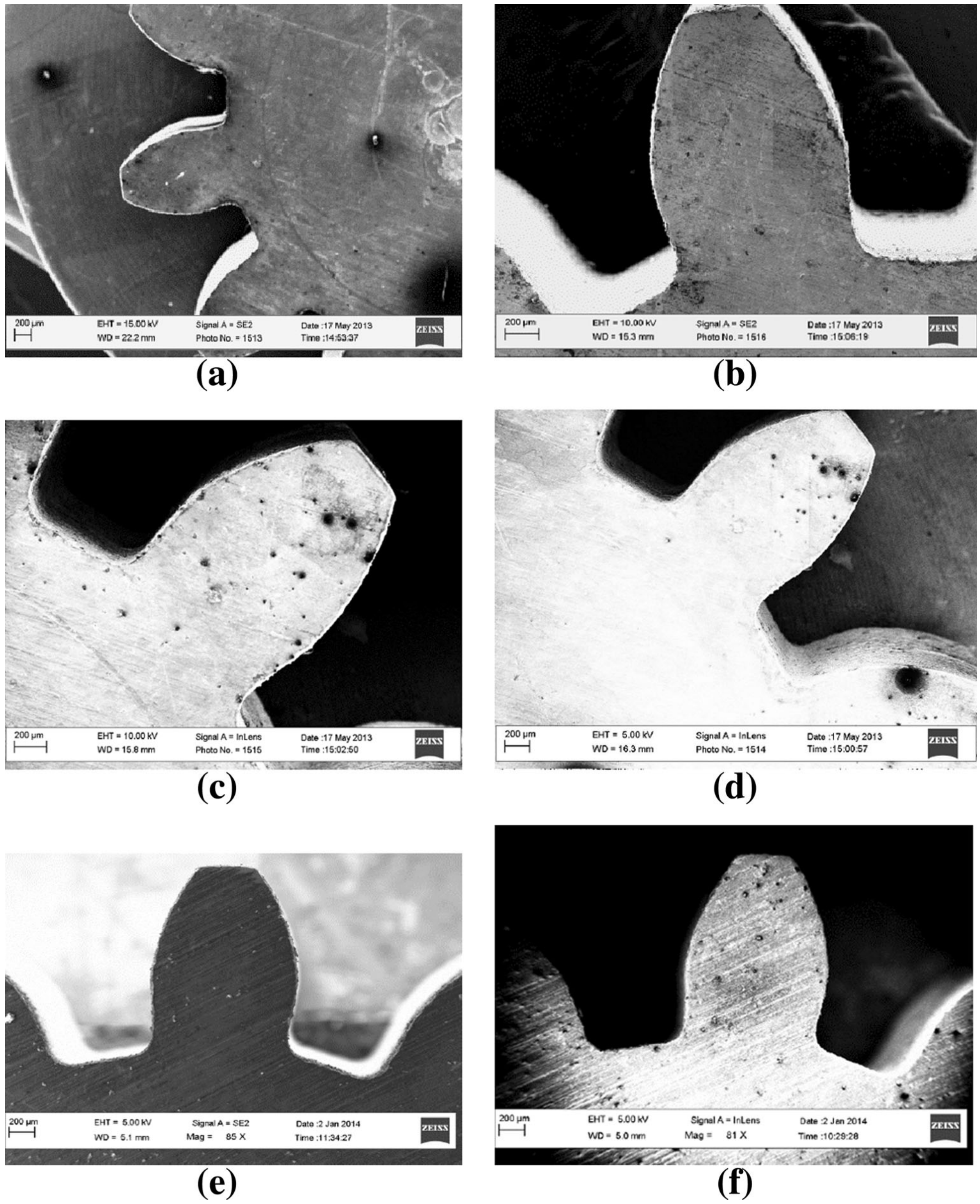


Fig. 13 Micrographs of WSEMed miniature gears [35], **a**–**b** ©Sage Publications [36], **c**–**d** ©2014 Elsevier [18] and **e**–**f** ©2014 Taylor & Francis LLC

4 Conclusion and future direction

A critical review on spark erosion machining of miniature gears is presented in the present paper. The review ultimately concludes that spark-erosion-based machining processes are able to manufacture high-quality miniature gears provided that the machining is conducted with adequately accurate machine tools and appropriate parameter settings. The review has also shown that the results achievable are much less workpiece material specific than the conventional processes. In other words, WSEM conducted on an appropriate machine tool coupled with optimized process parameter settings can be used to manufacture miniature gears of excellent quality and good surface integrity aspects at par with those produced by grinding, honing, lapping and other finishing processes with minimum wastage and at comparatively lower cost. The machining accuracy, i.e. dimensional and/or geometric variation, and the surface quality of miniature gears are strongly affected by the wire vibration and discharge energy.

Almost no work on spark erosion machining of macrogears and very little work, especially on spark erosion machining of miniature gears, have been reported and made available. Nonetheless, some work has recently been reported mainly by Gupta and Jain (2014) that points the way forward, for the resource-efficient and economic manufacturing of quality miniature gears. Major improvements of especially spark erosion machining for manufacturing of miniature gears may still be possible and require further investigation. Gear tooth modifications, i.e. tip correction, root alteration and finishing of gear teeth, by WSEM are some other interesting topics that require additional exploration.

The following points highlight some important future directions for spark-erosion-based machining of gears:

1. Investigations on the effects of other SEM and WSEM parameters such as electrode material, type of dielectric, flushing pressure and discharge current, etc. on the quality of gears and attempts towards their optimization to further improve the quality
2. Investigations on the quality of spark-eroded and/or wire-spark-eroded miniature gears made of other gear materials such as alloy steel, bronze, aluminium, etc.
3. Investigations on the effects of SEM parameters on other quality parameters of gears such as lead error, runout, residual stresses, etc.
4. Perform functional testing of the spark-eroded miniature gears for noise, vibration, fatigue and wear rate
5. Investigations on the SEM/WSEM of other gear shapes such as bevel, worm, non-circular, internal, splines, etc.
6. Improving the productivity of spark erosion processes during manufacturing of miniature gears

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