Research Article

A Comparative Study of Different Materials for Manufacturing of Miniature Spur Gears by Spark Erosion Wire Cutting Process

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Abstract
Selection of suitable materials plays a key role in machining to produce durable and good quality micro parts and components as well as improve the productivity of machining processes. This paper presents the performance evaluation of Spark Erosion Wire Cutting (SEWC) for the manufacturing of miniature gears from different materials, namely stainless steel SS 304, aluminum 7075, copper, and brass. The major objectives of this performance evaluation of SEWC are to determine the effect of gear materials on the quality of the gears, the economic aspects of miniature gears, and the productivity of SEWC for fabricating miniature spur gears. The optimal range of SEWC parameters from past research works was considered for conducting experiments for this study. Four miniature spur gears were fabricated from each gear material. It was concluded from this study that 1) the use of SS 304 as miniature spur gear material results in a better surface finish than aluminum, copper and brass; 2) use of aluminum as miniature gear material is more productive than SS 304, copper and brass; 3) aluminum is more economical and material-efficient than SS 304, copper and brass to fabricate miniature gears by SEWC; 4) material lost in copper is higher as compared to other selected materials; and 5) cost of SS 304 miniature gear is more as compared to other fabricated gears by SEWC.

Keywords: Fabrication, Microgeometry, Miniature spur gear, Spark erosion wire cutting, Surface roughness

1 Introduction

Nowadays, selections of efficient, cost-effective, and lightweight materials are playing a key role in several industries namely micro-electromechanical systems (MEMS), pharmaceuticals, aircraft, and electrical and telecommunication industries to ensure satisfactory performance and durable life cycles, and minimum energy consumption of manufactured parts during operations. Miniature gears are small-scale-sized gears whose addendum diameter and module are always below 10 and 1 mm, respectively. The major applications of these gears are in microsystems devices, precision instruments, and miniature transmitting and actuating devices. The operating performance of these devices mainly depends on the quality of the gears used [1], [2]. American Gear Manufacturers Association (AGMA), Deutsches Institut für Normung i.e. German Institute for Standardization (DIN), and Japanese Industrial Standards (JIS) are universally adopted international standards to designate the gear quality number. Microgeometry and surface roughness are the two most responsible factors in determining the gear quality and assign them the quality numbers according to the standards followed [3], [4]. The selection of materials for gears mainly depends upon the type of applications, operating environment, type of transmitting load, cost, and manufacturing processes.

Gear materials greatly affect the performance of manufacturing processes and therefore selected based upon the application requirement. Ferrous and non-ferrous materials are commonly used for manufacturing gears by SEWC. Stainless steel, high carbon steel, alloy steel, aluminium, copper, brass, and bronze are the most generally used gear materials. Aluminium, copper, brass, and bronze are nonferrous materials. Whereas, steel is mostly used ferrous material for gears. Ferrous-based gear materials are most suitable to transmit medium to high load at minimum speed while non-ferrous gear materials are mainly adopted for high-speed applications at no to low load [1], [5].

The most commonly used conventional manufacturing processes to produce several categories of miniature gears are hobbing, milling, die-casting, extrusion, forging, and injection molding [5]–[7]. However, they are not capable of manufacturing gears of good quality and require the assistance of finishing operations. This consequently increases the manufacturing cost and time. To overcome such problems, advanced machining like spark erosion wire cutting (SEWC) can be explored as an alternate. SEWC is also referred to as wire-assisted electrical discharge machining (WEDM) or wire-assisted spark erosion machining (WSEM). SEWC can be used to manufacture miniature gears from metallic materials.

SEWC is an advanced machining process where the workpiece and wire are partially or fully submerged in continuously flowing deionized water that acts as a dielectric (i.e. electrical insulator) until the electrical sparks occur when the wire comes to the workpiece and the distance becomes small enough at some portions [8]. The developed electric sparks heat a small portion of the workpiece to thousands of degrees, varying from 8000 oC to 12000 oC. A very fine fresh metallic wire is constantly fed from the feed roll for machining to avoid wire breakage due to its erosion during machining. SEWC is widely used to manufacture micro parts and components from hard-to-difficult materials.

Despite several advantages of SEWC for the fabrication of micro parts and components, very limited works have been done on the exploration of the performance of SEWC for fabricating miniature gears from different metallic materials. Most of the past works focused on manufacturing miniature gears from stainless steel and brass materials by the SEWC process [9]–[14]. Alhadeff *et al.*, [9] manufactured miniature gears of 10 mm diameter from brass plates (CuZn38) by SEWC and investigated the effect of process parameters on surface roughness, recast layer thickness, and tooth profile. Gupta and Jain [10] used SEWC to manufacture miniature spur gears of 9.8 mm diameter from rectangular brass plates. They successfully manufactured miniature gears of DIN 6 quality standard. In other studies, internal dies and miniature gears were manufactured by Di *et al.*, [11] from stainless steel using micro-SEWC and tungsten wire of 30 µm diameter. They achieved maximum recast layer thickness of 2000 nm, surface roughness of 100 nm, and dimensional accuracy of 200 nm. Wang *et al.*, [12] manufactured miniature gears from X153CrMoV12 steel plates by SEWC. Chaubey and Jain [13] successfully manufactured DIN 6 quality miniature cylindrical and conical gears from stainless steel (SS 304) plates by the SEWC process. Yusron *et al.*, [14] studied the profile error of spur gear made of carbon steel by the SWEC process. They found that the SEWC spur gears' profile error ranged between 79–125 µm. Ali *et al.*, [15] manufactured miniature spur gears of 3.58 mm addendum diameter from 6 mm thick copper plate by SEWC process using ø 0.1 mm brass wire. They obtained average and maximum surface roughness as 1 µm and 7 µm, respectively. Raj *et al.*, [16] manufactured miniature spur gears from Inconel 690 rectangular plates using the SEWC process. They successfully developed RSM and ANN models to predict the surface roughness and material removal rate.

In the past, Chaubey *et al.*, manufactured miniature spur gears with hub and bore from aluminium round bars [4] and miniature spur gears without bore from rectangular brass plates by the SEWC process [17]. They studied the effect of SEWC process parameters on productivity, surface roughness, and gear quality of aluminium and brass miniature spur gears. In the present study, miniature spur gears from aluminium, brass, copper, and stainless steel plates have been manufactured to investigate the effect of gear materials on performance measures such as gear quality, surface roughness, and material removal rate.

The major goal is to determine the impact of gear materials on performance measures, such as gear quality, surface roughness, material removal rate and cost. The overall objectives of the present study are as follows. Investigation of the SEWC's performance in fabricating lightweight miniature gears from different

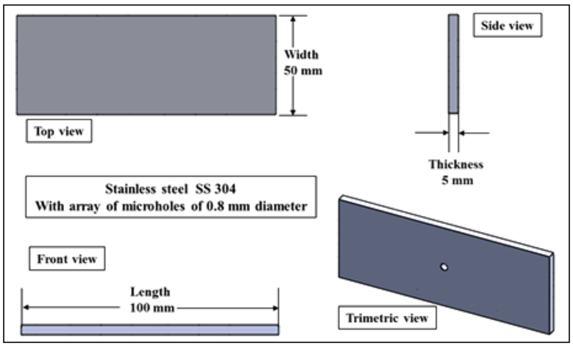


Figure 1: Specifications of selected gear plates for fabrication of miniature gears by SEWC.

metallic materials based on microgeometry, surface roughness, and performance productivity of SEWC. Determination of the influence of gear materials on gear quality and performance productivity of the SEWC. Identification of the superior material for miniature gears concerning quality, productivity, and machining cost in SEWC.

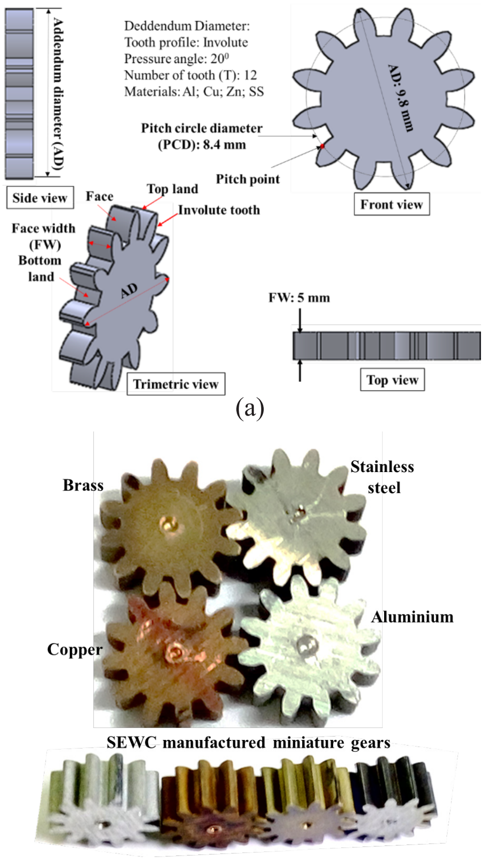
2 Details of Experimentation

2.1 *Materials for lightweight miniature gear and its preparation*

Four rectangular plates made of stainless steel SS 304, aluminium 7075, copper, and brass were used for cutting miniature gears by SEWC. Four miniature spur gears were manufactured from each plate by the SEWC process to determine the influence of gear materials on the gear quality and performance of SEWC. The detailed specifications of the gear plate are shown in Figure 1. Even variation in microns of the plate thickness significantly affects the quality of SEWC-manufactured gears. Therefore, surface preparation becomes a necessary activity to achieve the desired dimension of each plate. The sequence of processes used for surface preparation of rectangular plates is milling, surface grinding, and buffing to obtain the perfectly flat top and bottom faces of each plate of desired dimensions because different sizes of plates are available in the market.

2.2 *Specifications of gear and machine*

In this study, miniature spur gears without center-hole



(b)

Figure 2: (a) Detailed dimensional specifications and different views of the miniature spur gears; and (b) actual SEWC manufactured gears from different materials.

were manufactured from rectangular plates made of SS 304, aluminium 7075, copper, and brass by SEWC process using brass wire of 0.25 mm diameter and deionized water. Commonly, these gears are used for motion transfer at high speed in micro-system devices and precision instruments. Some typical applications of these gears are miniature pumps, miniature gearboxes, miniature actuators, timing mechanisms, and rack and pinion in precision instruments. Detailed specifications of proposed miniature spur gears for this study are presented in Table 1. Three-dimensional schematic views of proposed gears along with specifications and actually manufactured gears from brass, copper, aluminium, and stainless steel plates are shown in Figure 2.

For this study, a non-submerged type four-axis (i.e. two linear movement axes along X and Y directions and two axes for the inclination of wire with respect to X and Y) computer numerical controlled (CNC) Eco-Cut SEWC machine made by Electronica India Limited Pune, India was used to fabricate lightweight miniature spur gears from rectangular plates using soft brass wire 250 µm diameter in the presence of continuous flowing deionized water acts as dielectric. The tensile strength of the chosen wire is varying in the range of 470–510 N/mm^2. This machine can cut inclination angles as ±50 up to the height of 50 mm. The detailed specification of this machine is given in Table 1.

Table 1: Considered SEWC parameters, gear materials, and gear specifications

SEWC Variable Parameters (units)	Levels		
	A	B	C
Servo-voltage 'Sv' (Volts)	10	15	-
Spark-on-time 'Ton' (µs)	0.9	1.3	1.5
Spark-off-time 'Toff' (µs)	54	56	-
Wire rigidity 'WT' (g)	1140	1380	-
Constant parameters: Cutting speed (C_S): 100 %; Wire feed rate: 12 m/min, Electrode material: soft brass wire; Electrode diameter: 0.25 mm; and Flushing pressure (W_P): 7 kg/cm^2			
SEWC specifications: Type: 4-axes CNC, flushing type; Model: Eco-Cut; Make: Electronica Ltd. Pune(India); Electrode: Soft brass wire 250 µm diameter; Machining medium: Deionized water			
Gear materials: Stainless steel (SS 304); Alumunium 7075; Cooper and Brass			
Detailed gear specifications: Gear type: External spur gear; Tooth: Involute; Addendum diameter: 9.8 mm; Pitch circle diameter: 8.4 mm; module: 0.7 mm; Dedendum diameter: 6.65 mm; Gear Thickness: 5.0 mm; Number of teeth: 12; Tooth width: 1.12			

2.3 *Fabrication of miniature spur gears by SEWC*

This section provides detailed information for the fabrication of lightweight miniature spur gears by the SEWC. The part-programming phase, the preparation phase, the machining phase, and the measurement phase are four major activities involved during the fabrication of miniature spur gears by SEWC. Figure 3 shows the activities involved in fabricating miniature spur gears by SEWC.

Part programming is the initial phase in which part program of proposed gears is prepared with the help of ELCAM software incorporated with the programming station of the used SEWC machine. Next is the preparation phase in which preparation of each rectangular plate uses milling, grinding, and buffing processes to achieve the desired dimensions and perfectly flat surfaces. The next step is mounting prepared plates on the worktable of SEWC with the help of clamps as shown in Figure 4.

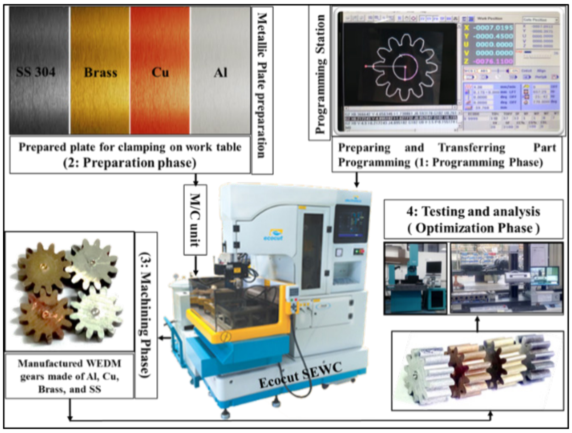
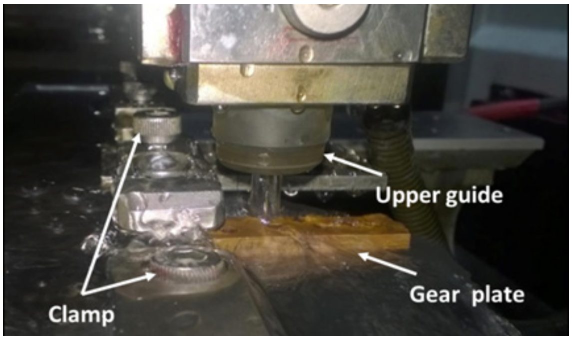
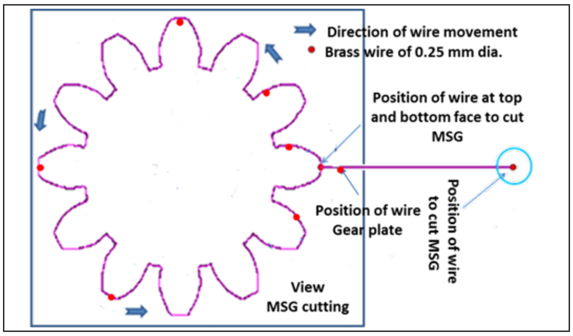


Figure 3: Sequence of phases involved in fabricating miniature spur gears by SEWC.



(a)



(b)

Figure 4: (a) Cutting of miniature spur gear by SEWC; and (b) Layout of miniature spur gear.

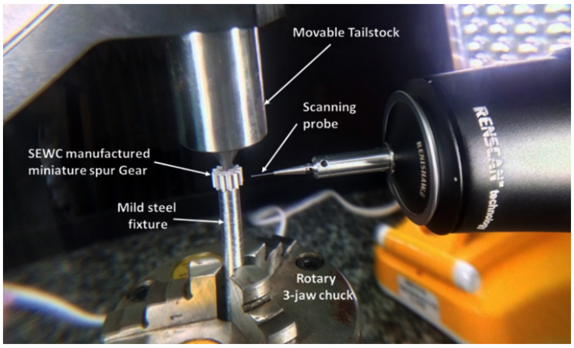


Figure 5: Microgeometry measurement of SEWC fabricated miniature gears by CNC smart gear metrology machine.

The flatness of each rectangular plate on the tabletop of SEWC was confirmed with the help of a dial gauge. It also ensured the firm and accurate positioning of plates with respect to the vertical traveling wire. This phase is idle because no machining actions take place in this phase. In the next phase, machining action takes place. This phase involved several activities namely 1) straight vertical positioning of the wire with the respect to gear plate; 2) next activity is cutting of miniature spur gear, which takes place by the movement of the SEWC worktable, which continuously positions the wire in the designed path as per prepared gear program as shown in Figure 4. No wire plugging is required for the fabrication of another gear. Thus miniature gears can be fabricated without the repetitive machine and workpiece settings. This reduces the total time for fabricating miniature spur gears. Measurement of manufactured gears is the final phase in which inspection of surface roughness and microgeometry of fabricated gears takes place as shown in Figure 5.

2.4 *Experimental details*

Optimized machining combinations for fabricating brass miniature gears were selected for experimentation. Four gears were fabricated from each plate i.e. from SS 304, aluminium 7075, copper, and brass plate. Thus a total of 16 gears was fabricated for comparative evaluation to determine the effect of gear material on the gear quality of SEWC fabricated gears and the productivity of SEWC. Table 1 presents the values of the constant and variable SEWC parameters, which were selected based on past research work on fabricating miniature spur gears from the rectangular brass plates by the SEWC process. Performance productivity of SEWC is the amount (weight) of material lost per minute during the cutting of gear. The total cutting time of miniature gear by SEWC was directly reflected on the monitor of the SEWC machine. The gear quality is commonly indicated by its surface roughness and microgeometry parameters. These parameters significantly affect the overall performance such as service life and functional characteristics of a gear. Form errors (i.e. profile and lead) and in-location errors (i.e. pitch and runout) in a gear are two basic features of the microgeometry. These errors are responsible for noise and premature failure in a gear. A CNC gear metrology machine (i.e. German-made Wenzel SmartGEAR 500) incorporated with Deutsches Institut für Normung 'DIN' 3962 standard was used for microgeometry measurements of SEWC fabricated miniature spur gears. Measurements were performed with the help of a 0.5 mm ruby ball scanning probe. The SEWC fabricated gears were examined using DIN 9 corresponding to the DIN 3961/62 standard. A micro-level variation on top of the tooth surfaces of a gear is indicated by its surface roughness parameters such as average and maximum surface roughness. These parameters considerably influence the performance and durability of a gear. Higher surface roughness values are responsible for the early failure of a gear due to excessive wear and friction. SEF 3500 surface roughness tester cum contour tracer from KOSAKA Japan was used to measure surface roughness parameters.

3 Results and Discussion

Table A1 presents the responses corresponding to the experiments. It is evident that the use of SS 304 as miniature spur gear material results in a better surface finish than aluminium, copper, and brass i.e. avg. surface roughness (Ra) is as SS 304 < Aluminium <Brass< Copper. SS 304 miniature gear has the least value of average surface roughness (0.42 µm). While, the use of aluminium as miniature gear material is more productive than SS 304, copper, and brass. The weight of aluminium miniature gear (0.71g) is very less than brass (2.32g), copper (2.29g), and SS 304 (2.08g). The selected responses (i.e. microgeometry, surface

Table 2: Presents values of the microgeometry parameters of each best quality miniature gear fabricated from selected gear materials.

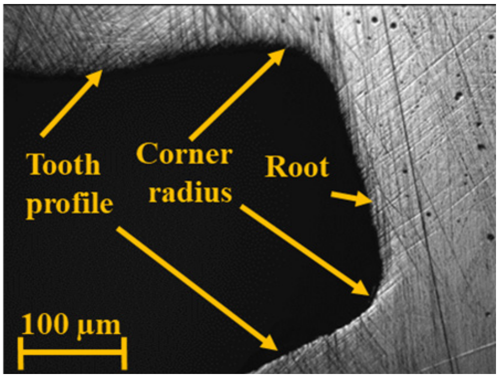
Response (in µm)	Best Quality MSG Manufactured by SEWC			
	SS 304	Al	Copper	Brass
Value of microgeometry and corresponding DIN standard				
Total profile error	14.5 (DIN 9)	11.0 (DIN 7)	10.4 (DIN 7)	11.8 (DIN 7)
Total lead error	6.3 (DIN 6)	7.1 (DIN 7)	8.6 (DIN 8)	7.6 (DIN 7)
Single pitch error	12.2 (DIN 8)	10.8 (DIN 7)	11.2 (DIN 7)	12.2 (DIN 7)
Total pitch error	16.8 (DIN 8)	13.5 (DIN 7)	15.5 (DIN 8)	16.2 (DIN 8)
Radial runout	14.8 (DIN 8)	13.9 (DIN 8)	14.3 (DIN 8)	15.8 (DIN 9)

roughness, volumetric gear cutting rate) were measured for all SEWC manufactured gears from different selected materials i.e. 4 SS 304, 4 aluminium 7075, 4 copper, and 4 brass. The best quality miniature gears from each material were selected to evaluate the effect of gear materials on selected responses and performance of SEWC. The values of the microgeometry parameters of each best-quality miniature gear fabricated from chosen gear materials are presented in Table 2. It can be observed from Table 2 that the SEWC fabricated aluminium miniature gears have better microgeometry as compared to SS 304, copper, and brass miniature gears. The best quality aluminum miniature gear has an 11.0 µm (DIN 7) total profile error; 7.1 µm (DIN 7) total lead error; 10.8 µm (DIN 7) error in single pitch; 13.5 µm (DIN 7) error in total pitch; and 13.9 µm (DIN 8) radial runout. The corresponding values of considered microgeometry parameters for SS 304 miniature gears are 14.5 µm (DIN 9); 6.3 µm (DIN 6); 12.2 µm (DIN 8); 16.8 µm (DIN 8); and 16.8 µm (DIN 8), respectively. For copper miniature gears corresponding values of considered microgeometry parameters are: 10.4 µm (DIN 7); 8.6 µm (DIN 8); 11.2 µm (DIN 7); 15.5 µm (DIN 8); and 14.3 µm (DIN 8), respectively. While for brass miniature gears these values are: 11.8 µm (DIN 7); 7.6 µm (DIN 7); 12.2 µm (DIN 7); 16.2 µm (DIN 8); and 15.8 µm (DIN 9), respectively. The major cause for poor microgeometry of fabricated miniature gears is the slipping of gears during measurements as shown in Figure 5. Gear is held between a mild steel bar and movable tailstock from top to bottom. Tailstock helps to hold firmly the SEWC fabricated gear on the mild steel bar as shown in Figure 5. The mild steel bar is held by a rotary three-jaw chuck. Rotation of the chuck is necessary for microgeometry measurements, which leads to micron-level slipping during measurements. To avoid this problem gears should be manufactured with centre-hole. Other reasons for poor microgeometry are 1) indexing error; 2) alignment of gear with scanning probe; 3) inaccurate positioning of wire with gear plate; and 4) inclination of the wire during fabrication of miniature gears by SEWC.

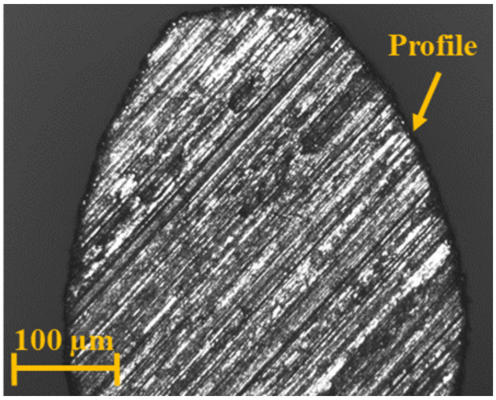
As a summary of results, Table 3 presents economic aspects namely machining time; setting time; total machining time; cost of machining and consumables; total cost; and material loss during gear fabrication. It can be concluded from Table 3 that the total machining time and total cost of aluminum gear are very low as compared to SS 304, copper, and brass gears. The amount of wire consumption and material loss during the cutting of miniature gears are high for SS 304 and copper miniature gears, respectively. Miniature gears manufactured by selected gear materials have the same machine idle time. It can be proven from the above results that aluminum material is more economical and material-efficient than SS 304, copper, and brass to fabricate miniature gears by SEWC gears. The cost of the same miniature gears from hobbing process is approximately 100 € [18]. Thus, it was concluded that aluminium gears have the best gear quality DIN 7 and are manufactured in less machining time with the lowest cost compared to gears manufactured from other materials.

Table 3: Comparison of economic aspects of miniature spur gears fabrication by SEWC

Economic Aspect	SEWC Fabricated Best-quality Miniature Gear			
	Al	Cu	Brass	SS 304
Machining time (min)	10	25	31	35
Setup time (min.)	10	10	10	10
Total machining time	20	35	41	45
Material loss (g)	0.22	0.79	0.78	0.66
Wire consumption (g)	45	116	130	161
Machining cost (€)	1	2	2.5	3
Material loss (g)	0.22	0.78	0.8	0.61



(a)



(b)

Figure 6: Optical microscopic images of SEWC manufactured best quality aluminum gear: (a) profile of gear tooth at the bottom; and (b) tooth involute profile.

Figure 6(a) and (b) show the optical images of the best quality gear of aluminum captured at 5x magnification. These images revealed a burr-free uniform and accurate tooth profile without undercut.

4 Conclusions

A comprehensive comparative evaluation of the material's effect on gear quality, surface roughness, material removal rate, manufacturing cost, and productivity of SEWC for fabricating miniature spur gears is reported in this paper. This work also investigated the capability of SEWC to manufacture miniature gears from different metallic materials. The conclusions drawn from this study are as follows. A comparative evaluation for fabricating miniature gears from different materials by the SEWC process was successfully conducted. Lightweight (ranging between 2.81 to 0.71g) miniature spur gears from SS 304, aluminium 7075, copper, and brass by SEWC process was achieved. While, miniature gears made from aluminium are much lighter than other selected materials. Miniature gears from SS 304, aluminium 7075, copper, and brass plates were fabricated without wire plugging and changing machine and workpiece settings. The volumetric gear cutting rate of aluminium miniature gears is much higher than SS 304, copper, and brass miniature gears. While the volumetric gear cutting rate of SS 304 miniature gears is lower than copper and brass. The total cutting time of SS 304 miniature gears is higher than copper, brass, and aluminium gears. Material loss during the fabrication of miniature gears by SEWC is higher in copper as compared to other selected materials. The use of SS 304 as a miniature spur gear material results in a better surface finish than aluminium, copper, and brass. Good surface finish with 0.42 µm average surface roughness of SS 304 miniature gears was achieved, which is lower than copper, brass, and aluminium miniature gears. Gear quality of aluminium gears up to DIN standard number 7 was achieved, indicating their suitability in precision applications. SEWC of aluminium is more economical and material efficient than SS 304, copper, and brass. It was concluded that the absence of center-hole and wire alignment is responsible for poor microgeometry in the SEWC fabricated gears. The outcomes of this study will be very useful for industrial applications in the field of miniature gear fabrication by spark erosion-based processes such as SEC, SEWC, and hybrid machining processes.

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Author Contributions

S.K.C.: conceptualization, methodology, research design, investigation, data analysis, validation, data curation, formal analysis, and writing an original draft; K.G.: conceptualization, methodology, formal analysis, writing-reviewing and editing, funding acquisition, project administration; N.K.J.: conceptualization, methodology, formal analysis, writing-reviewing and editing, funding acquisition, project administration. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

DIN	Deutsches Institut für Normung
SEWC	Spark-erosion wire cutting
CNC	Computer Numerical Control
T_{on}	Spark-on-time
T_{off}	Spark-off-time
S_V	Servo voltage
W_T	Wire rigidity

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Appendix

Table A1: Experimental runs and corresponding values of responses

Ex. No.	Variable Parameters				Gear cutting time (Minutes)				Responses															
	S_V (V)	T_{on} (µs)	T_{Off} (µs)	W_T (g)					Gear weight (g)				Material Loss 'M' (g)				Volumetric gear cutting rate (mm^3/min)				Average surface roughness 'R_a' (µm)			
					SS	Cu	Al	Brass	SS	Cu	Al	Brass	SS	Cu	Al	Brass	SS	Cu	Al	Brass	SS	Cu	Al	Brass
1	15	1.3	56	1140	35:18	32:07	10:29	35:07	2.09	2.29	0.71	2.32	0.66	0.78	0.23	0.81	2.35	2.72	8.11	2.81	0.44	1.12	0.50	1.23
2	10	1.5	54	1380	37:03	25:05	09:58	31:05	2.08	2.44	0.72	2.45	0.65	0.79	0.22	0.78	2.19	3.52	8.15	3.65	0.42	1.26	0.99	1.29
3	10	0. 9	56	1140	52:31	32:21	09:27	37:21	2.10	2.81	0.71	2.65	0.61	0.77	0.22	0.82	1.46	2.67	8.58	2.88	0.66	1.25	0.58	1.28
4	15	0. 9	56	1140	36:38	37:40	12:50	41:40	2.11	2.40	0.71	2.75	0.65	0.81	0.23	0.77	2.23	2.78	6.60	2.81	0.48	0.72	0.65	0.99