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Investigations on tip relieving of spur gears by non-contact process

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ABSTRACT

This paper describes tip relieving of spur gears by pulsed electrochemical flank modification (PECFM) process by a novel designed cathodic gear tool and apparatus. This work reports experimental findings on tip relieving and surface finish by varying the concentration, flow rate, and temperature of the electrolyte, modification duration, and cathodic gear rotational speed at four levels each and using predetermined values of voltage, pulse-on time, pulse-off time, and anodic gear reciprocating speed. The amount of tip relief is found to increase considerably with modification duration and electrolyte concentration. Identified optimum values of modification duration, cathode gear rotational speed, concentration, flow rate, and electrolyte temperature are 20 minutes, 45 rpm, 2 Molarity, 30 lpm, and 40°C, respectively. Scanning electron microscopy images of the tip-relieved spur gear revealed that PECFM effectively eliminates the hob cutter marks from its flank surfaces. This work will be helpful to gear manufacturers seeking productive tip relieving.

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Non-contact; flank; modification; spur; cathode; gear; pulsed; electrochemical

1. Introduction

Tip relief is the desired flank modification for gears to reduce transmission error,[1] wear,[2] micro-pitting,[3] contact forces,[4] running noise and vibrations,[5] and to increase transmission efficiency.[6,7] It is achieved by the controlled removal of material from the entire face width of the gear flank surface and along the profile direction from a point above the pitch line and moving toward the tip of a gear tooth as depicted in Fig. 1. It smoothens the engagement and disengagement of gear teeth meshing thus reducing contact forces.[8] Trubswetter et al.[9] compared flank surface topography and vibrations of the gears, which were provided tip and end relief by polish grinding and continuous generating grinding with the gears manufactured by the skiving process without any tip and end relief. They reported that tip and end relieving of gears influence their vibrations more than affecting their surface topography, establishing importance of tip relieving of gears. But very limited work is available on tip relieving of spur gears and the available works have used conventional processes only such as gear shaving, gear skiving, gear hobbing, gear grinding, and gear honing for flank modifications to spur and helical gears. Hsu et al.[10] simulated gear shaving to provide twist-free profile and lead crowning to helical gears by variable pressure angle cutter and an auxiliary crowning mechanism. They reported that their method significantly reduced twist on flank surfaces. Zheng et al.[11] used gear skiving for flank modifications of helical gears by cutter offset correction, cutter tilted correction, and crossed angle correction methods. They found that cutter offset correction method caused slight twist error in the crowned helical gears. Tran et al.[12] simulated gear hobbing process for lead crowning of helical gears without any twist. They used dual-lead hob cutter with pressure angle changing in the longitudinal direction. They found that setting the diagonal feed motion of cutter as second order function of its transverse motion helps to provide twist-free lead crowning to the helical gears. Yang et al.[13] used generating grinding process for flank modification of helical gears and proposed a new method to obtain the required profile of the grinding worm. This process requires dressing the grinding worm according to the desired modification. Yu et al.[14] used a gear honing process for tip relieving, root relieving, and end relieving spur gear by a worm-shaped honing tool. This process requires a two-threaded worm-shaped honing tool when spur gear has an odd number of teeth.

It can be inferred from the review of the relevant past work that the researchers have used contact-type conventional processes to provide different modifications to the flank surfaces of gears. The use of contact-type processes yields the following disadvantages: (i) Flank modification by gear grinding process resulted in fine cracks, thermal distortions, grinding burns, and transverse grind line on the modified flank surfaces which cause untimely failures of the modified gears and increases gear noise and vibrations, (ii) Flank modification by gear shaving process left a step mark at root of the involute profile which causes wear of the modified gear and increases gear noise and vibrations. It also has an upper limit on gear material hardness, (iii) Flank modification by gear honing process deforms its tool, which requires frequent redressing,[15] (iv) Flank modification by gear skiving can deteriorate surface integrity of flank surfaces of the modified gears,[16] (v) These processes adversely affect accuracy, surface quality and surface integrity of the modified gears, and generates some undesired effects in them, (vi) These processes require very costly tools which are either unavailable and/or difficult to manufacture, and (vii) They require highly skilled operators due their complexities.

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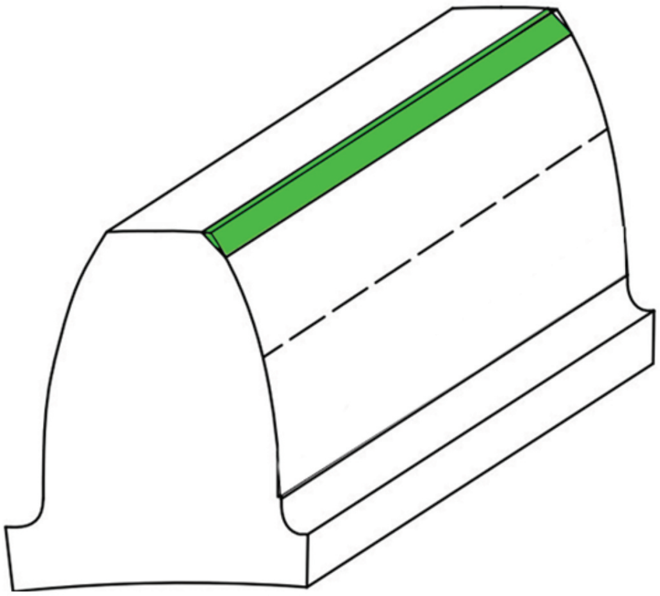


Figure 1. Schematic of tip relieving of a spur gear tooth flank surface.

However, very limited work is available on using any non-contact process for tip relieving of spur gears except experimental study by Yi et al.,[17] who explored an electro-chemical finishing process to modify one tooth of a spiral bevel gear at a time by moving a rectangular block shaped cathode tool over it with the help of the developed apparatus. They used artificial neural network to develop prediction model for amount of gear flank modification. Pang et al.[18] used pulsed electrochemical finishing process on a flat plate to demonstrate that profile crowning and lead crowning can be provided by using non-uniform interelectrode gap (IEG) for profile crowning and varying velocity of cathode tool for lead crowning. Consequently, present work is aimed for non-contact tip relieving of all teeth of spur gears made of commercially used material by pulsed electro-chemical flank modification (PECFM) process without causing any undesired impact on their accuracy, quality, and surface integrity and simultaneously overcome disadvantages of conventional processes of gear flank modifications. It is accomplished through noble design and development of required cathodic gear and PECFM apparatus, and identification of optimum values of concentration, flow rate and temperature of electrolyte, modification duration, and cathodic gear rotational speed to maximize tip relief amount, surface finish, and volumetric material removal rate (MRR) in spur gear tip relieving. Since PECFM process is a non-contact type process, therefore cathodic gear and anodic workpiece gear will not contact each other, thus avoiding mechanical and thermal distortions of the modified gear. It involves removal of material from workpiece gear in a very controlled manner according to Faraday's laws of electrolysis imparting it self-regulating capability.[19] Outcome of the present study will be helpful to the gear manufacturers and end users of spur gears to minimize their running noise, vibrations, and wear, and to maximize their operating performance and service life.

2. Materials and methods

Normalized case-hardened Alloy steel 20MnCr5 was chosen as the material to manufacture workpiece gears due to its commercial use in spur gear manufacturing. The gear hobbing process was manufactured with specifications such as a 3 mm module; 16 teeth; 20 mm face width; and 20° pressure angle. The samples have hardness in the range 170–190 HB, which follows the guidelines as per EN10084:2008 standard.[20]

2.1. Design of cathode gear for tip relief and its mechanism

The designed cathode gear for tip relief is a combination of three parts. The conductive part made of copper is sandwiched between two non-conductive parts made of Metalon. Figure 2a shows the schematic design of a single tooth of cathode gear for tip relieving of spur gear. It is designed in such a way that (i) it removes material only from the tips of teeth of anodic workpiece spur gear by its electrochemical dissolution. It is achieved by truncating gear teeth on conductive part as depicted in Fig. 2a, and (ii) variable interelectrode gap (IEG) is maintained between its conductive part and workpiece gear during their engagement. It is achieved by providing non-uniform circumferential gap between non-conductive and conductive parts of the cathode gear. Its value is minimum (i.e., $\Delta r_2 = 0.5$ mm) at base circle diameter "d_b" and is maximum (i.e., $\Delta r_1 = 1$ mm) at conductive portion diameter "d_{tr}". Variable IEG provides flexibility to limit electrochemical action above pitch circle diameter of cathode gear and helps to remove material only from tip of anodic workpiece gear teeth. This gap also prevents short-circuiting by avoiding contact between workpiece gear and conductive part of cathode gear. A schematic depicting the engagement of the anodic spur gear (workpiece) with the developed cathode gear for tip relieving is presented in Fig. 2b. From Fig. 2b it can be seen that the tip portion of the workpiece gear was in close peripheral of the truncated cathode gear teeth and the inter electrode gap between them was filled with an aqueous solution of sodium chloride (NaCl), this allows anodic dissolution of the workpiece from the tip region. Following are the specifications of cathode gear: 3 mm module; 24 teeth; 20 mm face width (conductive part face width 10 mm + two non-conductive part face width of each 5 mm); 20° pressure angle; 25 mm bore diameter; 10 mm hub height; and 10 mm hub thickness. Non-conductive parts were manufactured on computer numerically controlled (CNC) milling and conductive part was manufactured by wire electric discharge machining process. Figure 2c shows a photograph of the manufactured cathode gear for tip relieving of spur gears. More details about cathode gear and mechanism for removing the material and imparting tip relief were discussed in.[21]

2.2. Development of apparatus for PECFM

Tip relieving of spur gears by the developed cathode gear was performed in an innovatively designed and developed cathode gear and PECFM apparatus (shown in Fig. 3a) developed by integrating the following units or subsystems: (i) Flank

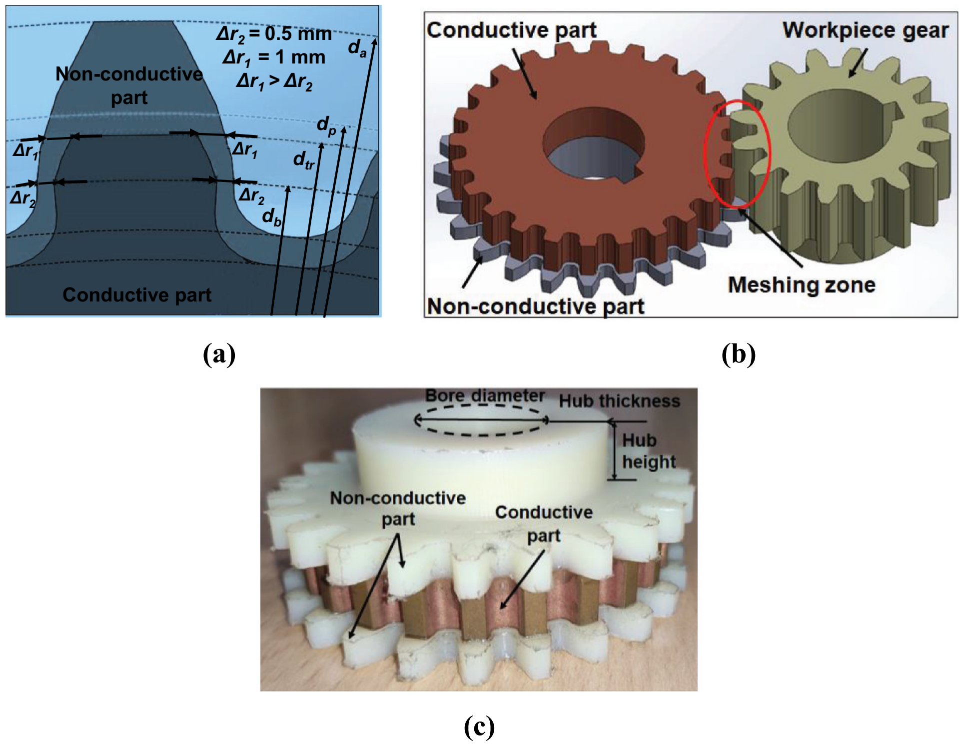
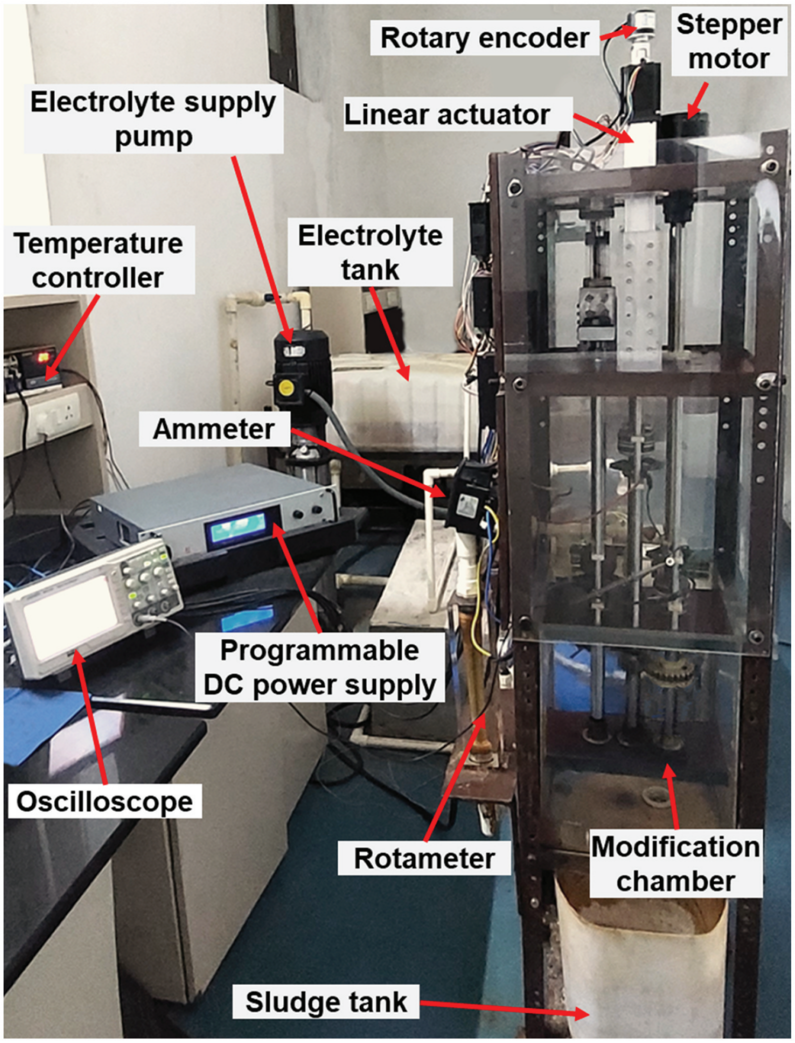


Figure 2. Development of cathode gear for tip relieving of a spur gear: (a) schematic of single tooth design, (b) schematic of engagement of the workpiece spur gear with the developed cathode gear for its tip relieving, and (c) photograph of the manufactured cathode gear.

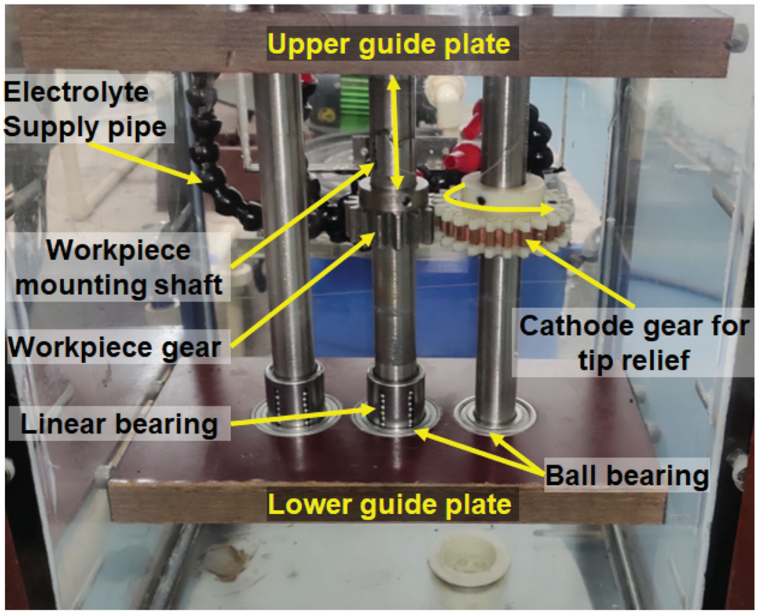
modification chamber; (ii) Motion control unit; (iii) Pulsed power unit; and (iv) Electrolyte supply and recycling system. *Flank modification chamber* (shown in Fig. 3b) has unique arrangement for mounting cathode gear and workpiece gear on their respective shafts between the upper and lower guide plates made of Bakelite. Both the guide plates are supported by the walls of modification chamber made of Perspex sheet because of their non-corrosive nature and good electrical insulation property. Linear bearings are attached to them to facilitate smooth reciprocation of anodic workpiece gear through its mounting shaft. Ball bearings are attached to both guide plates to enable rotary motion of the cathodic gear. *Motion control unit* consists of a linear actuator and a stepper motor controlled by Arduino Uno board programmed using Arduino software. Linear actuator is connected to the workpiece gear shaft to provide reciprocating motion. It is required to impart tip relief to full face width of workpiece gear by conductive portion of the cathode gear whose face width is smaller than workpiece gear face width. The stepper motor is connected to the cathode gear shaft to provide it rotary motion which in turn rotates the workpiece gear through meshing. It is needed to impart tip relieving to the right and left flanks of all teeth of workpiece gear. A rotary encoder is connected to linear actuator to measure reciprocating speed of the workpiece gear and non-contact tachometer is used to measure rotational speed of cathode gear. *Pulsed power unit* SM-100-AR-75 (from Delta Elektronika) having capacity to supply direct current (DC) up to 75A and voltage up to 100 volts, used to provide (DC power to the cathode gear and anodic workpiece gear. It has carbon brushes to connect the rotating shafts of cathode and workpiece gears with negative and positive terminals of the pulsed power supply respectively, due to their ability to slip over the shafts and to provide uninterrupted power supply for PECFM process. An oscilloscope records output of the power supply and pulse form of the supplied voltage. An ammeter is used to measure the supplied current. The prepared electrolyte solution is supplied by a multistage centrifugal pump through flexible pipes to the flank modification chamber from the electrolyte tank as shown in Fig. 3b. Flow rate of electrolyte is regulated by a flow control valve and rotameter is used to measure it. Its pressure and temperature are measured by a pressure gauge and a thermocouple respectively. The used electrolyte is collected in a sludge tank kept below the modification chamber. It is filtered and then sent to the electrolyte tank by a pump for its recirculation.

2.3. Experimentation and measurement of responses

Twenty spur gears were tip relieved using one factor at a time experimental design approach in which modification duration, cathode gear rotational speed, electrolyte concentration, electrolyte temperature, and electrolyte flow rate were varied by four levels each. Following values of other parameters of PECFM process used in the experimentation: reciprocating speed of workpiece gear as 0.96 mm/s; applied voltage as 18 volts; pulse-on time as 3 ms; and pulse-off time as 4 ms (giving duty cycle as 0.43); electrolyte type as an aqueous solution of sodium chloride (NaCl). Amount of tip relief provided by the PECFM process was measured on the 0.1 μm resolution CNC gear metrology machine



(a)



(b)

Figure 3. Photograph of the (a) apparatus developed for imparting tip relief to a workpiece spur gear by pulsed electrochemical flank modification process, and (b) flank modification chamber showing relative positioning of the developed cathode gear and the workpiece spur gear.

(*Smart Gear* 500 from *Wenzel GearTech Germany)* using 1.5 mm radius ruby probe. Measurements were conducted on the tip region of both left and right flank surfaces of four arbitrarily chosen teeth from the unmodified and each tip relieved spur gear i.e., total 8 measurements were carried out for the unmodified gear and each tip relieved gear, and their arithmetic average is used for further study. Values of maximum height “*Ry*” and arithmetical average roughness “*Ra*” (as standard ISO 21,920–1:2021) of a spur gear before and after tip relieving were measured by *MarSurf LD-130* (from *Mahr Metrology, Germany*) tracing 2 μm diameter probe for section length of 2 mm on left and right flank surfaces of its randomly chosen two teeth. Total 4 values of “*Ry*” and 4 values of “*Ra*” were measured, and their arithmetic mean used for further analysis. The following Eq. 1 obtains percentage reduction in arithmetical average roughness “*PRRa*” and similarly “*PRRy*”.

$$PRR_a = \frac{Avg.Ra\ value\ of\ unmodfied\ gear - Avg.Ra\ value\ of\ tip\ relieved\ gear}{avg.\ Ra\ value\ of\ unmodfied\ gear} \tag{1}$$

Volumetric material removal rate (MRR) was computed by dividing weight difference of spur gear before and after tip relieving by the product of density of spur gear material and modification duration and as mentioned in Eq. 2. Surface morphology of tip region of unmodified and tip relieved flank surfaces of spur gear teeth were studied by using scanning electron microscope (*JEOL JSM-7610F Plus)*.

$$MRR(mm^3/s) = \frac{weight\ of\ unmodified\ gear(g) - \ weight\ of\ tip\ relieved\ gear(g)}{density\ of\ workpiece\ material(g/mm^3) \times modification\ duration(s)} \tag{2}$$

3. RESULTS AND DISCUSSION

The average of measured values of tip relief and the MRR for the 20 experiments, along with the values of variable input parameters and surface roughness parameters before and after tip relieving of the gears, presented in Table 1. Figure 4 shows variation in amount of tip relief and MRR with modification duration (Fig. 4a), rotational speed of cathode gear (Fig. 4b), electrolyte concentration (Fig. 4c), electrolyte temperature (Fig. 4d), and electrolyte flow rate (Fig. 4e). Figure 5 shows the variation in percentage reduction in arithmetical average roughness and maximum height with modification duration (Fig. 5a), the rotational speed of cathode gear (Fig. 5b), electrolyte concentration (Fig. 5c), electrolyte temperature (Fig. 5d), and electrolyte flow rate (Fig. 5e). SEM images showing the surface morphology of the tip region of the flank surface of gear before and after tip relieving are presented in Figs. 6a and 6b, respectively.

Figure 4a shows that amount of tip relief increases with modification duration. The amount of tip relief increased at a higher rate when the modification duration increased from 8 to 16 minutes but increased at a lower rate for 16 to 20 minutes. It is due to an increase in IEG between the conductive part of the cathode gear and workpiece gear, providing tip relief. It decreases the current density and consequently reduces the rate of increase in tip relief. Figure 4b reveals no significant change in the amount of tip relief with the cathode gear rotational speed range from 15 to 35 rpm. But there is a sudden change in tip relief when the rotational speed of the cathode gear shifts to 45 rpm. It is due to rapid engagement and disengagement between the teeth of the cathode and workpiece gears with increased rotational speed,

Table 1. Average value of tip relief, material removal rate, and surface roughness parameters for different parametric combinations of the PECFM process.

Exp. no.	Modification duration (minutes)	Rotational speed of cathode gear (rpm)	Electrolyte concentration (M)	Electrolyte temperature (°C)	Electrolyte flow rate (lpm)	Avg. amount of tip relief (μm)	Material removal rate (mm^3/s)	Arithmetical average roughness “*Ra*” (μm): Before tip relieving	After tip relieving	“*PRRa*” (%)	Maximum height “*Ry*” (μm): Before tip relieving	After tip relieving	“*PRRy*” (%)
1	8					26.6	0.101	2.12	1.71	19.3	20.34	13.49	33.7
2	12					60.4	0.108	2.21	1.23	44.3	19.23	8.51	55.7
3	16	15	0.5	30	20	78.9	0.107	2.42	1.91	21.1	17.98	12.85	28.5
4	20					90.8	0.111	2.38	1.47	38.3	13.79	11.15	19.1
5		15				58.6	0.110	3.76	2.12	43.8	23.44	13.49	42.4
6		25				54.4	0.119	1.45	1.01	30.4	10.18	6.44	36.7
7		35				52.5	0.103	2.36	1.84	21.8	14.09	13.40	4.9
8		45				76.4	0.131	2.12	1.45	31.5	12.78	12.57	1.6
9			0.5			50.5	0.108	1.89	1.34	29.1	11.35	9.45	16.8
10			1.0			58.5	0.242	1.34	1.21	9.7	8.66	8.21	5.1
11			1.5			71.7	0.287	1.34	0.68	49.1	8.82	4.32	51.1
12			2.0			79.5	0.317	1.61	0.80	50.2	14.60	6.86	53.0
13				25		52.9	0.096	2.21	0.97	56.3	13.05	7.41	43.2
14				30		49.4	0.105	1.57	1.20	24.0	11.32	10.93	3.4
16				35		61.1	0.113	2.11	1.51	28.2	13.25	11.02	16.9
16				40		61.6	0.117	2.98	1.44	51.7	18.50	10.39	43.8
17					10	61.6	0.104	2.15	1.45	32.6	13.95	10.22	26.7
18	12	15	0.5	30	20	62.9	0.106	2.67	1.14	57.4	16.88	9.86	41.6
19					30	67.5	0.111	1.45	1.09	25.3	9.64	7.39	23.4
20					40	64.3	0.115	1.67	1.34	19.9	14.07	9.45	32.9

Constant parameters: Applied voltage (V): 18 volts; Pulse-on time (ton): 3 ms; Pulse-off time (toff): 4 ms; Duty cycle (δ): 0.43; Electrolyte type: Aqueous NaCl; Workpiece reciprocating speed: 0.96 mm/s.

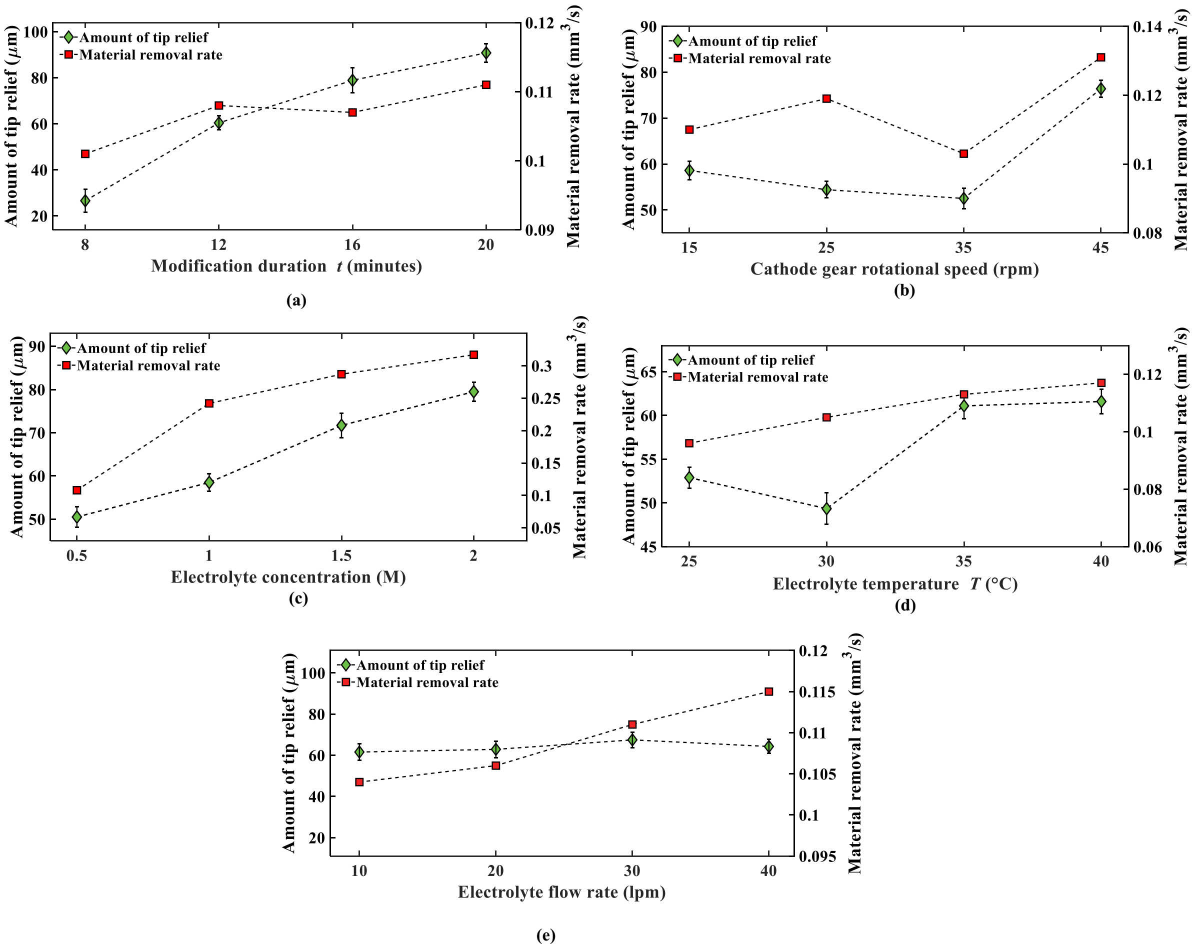


Figure 4. Variation of amount of tip relief provided to spur gear and associated material removal rate with (a) modification duration, (b) cathode gear rotational speed, (c) electrolyte concentration, (d) electrolyte temperature, and (e) electrolyte flow rate.

which helps to fill the IEG with the fresh electrolyte. It facilitates rapid flushing of the removed material and the gases evolved (oxygen at the anodic workpiece gear and hydrogen at the cathode gear) from the modification zone, helping to provide more tip relief. The MRR also follows a trend similar to the tip relief with cathode gear rotational speed. Figure 4c depicts that amount of tip relief and MRR continuously increase with increased electrolyte concentration from 0.5 to 2 Molarity due to increased electrolyte conductivity.[22] Fig. 4d shows that amount of tip relief decreases as electrolyte temperature increase from 25 to 30°C, increases at faster rate up to 35°C, and increases at slower rate for temperature increase from 35 to 40°C. It is due to the electrolyte conductivity increases with temperature. The MRR continuously increase with electrolyte temperature.[23] It implies that 40°C is optimum temperature for electrolyte. Figure 4e depicts that the amount of tip relief does not show any definite pattern of change with electrolyte flow rate and has very minimal effect. The MRR shows increment with an increase in electrolyte flow rate. Increasing electrolyte flow aids in removing the excess heat generated, flushing away the removed material from the modification zone, and filling it with fresh electrolytes. If the electrolyte flow rate is less, then it increases the temperature of the electrolyte along its flow direction and hence its conductivity increases. Also, the removed material will not flush away properly, which will restrict further material removal from the workpiece gear. Complicated interrelation between electrolyte conductivity changes and flushing of removed material decides change in amount of tip relief. It may be the reason for no large variation or trend in amount of tip relief with electrolyte flow rate.

Table 1 also presents the variation in the values of considered surface roughness parameters such as arithmetical average roughness "*Ra*" and maximum height "*Ry*" of the tip relieved gears. The results were presented in terms of percentage reduction in roughness i.e., *PRRa* and *PRRy*. Figure 5a shows that the maximum percentage reduction in arithmetical average roughness and maximum height is achieved at 12 minutes of modification duration. In PECFM, faster material removal occurs at lowest IEG (shortest path for electric current passing) between cathode and anodic workpiece gear. As time increases, more peaks are removed, and surface is smoothened, but further IEG between cathode and anodic workpiece gear increases, reducing the current density and material removal, which may affect the surface roughness. From Fig. 5b, it can be seen that at higher rotational speed (i.e. more than 25 rpm) the time span available at a particular instant for flank surface of the gear to be tip relieved is reduced, hence the peaks of the surface roughness profile are removed abruptly and resulting in lower values of *PRRa* and *PRRy*. Figure 5c shows that the highest improvement in *PRRa* and *PRRy* was achieved using

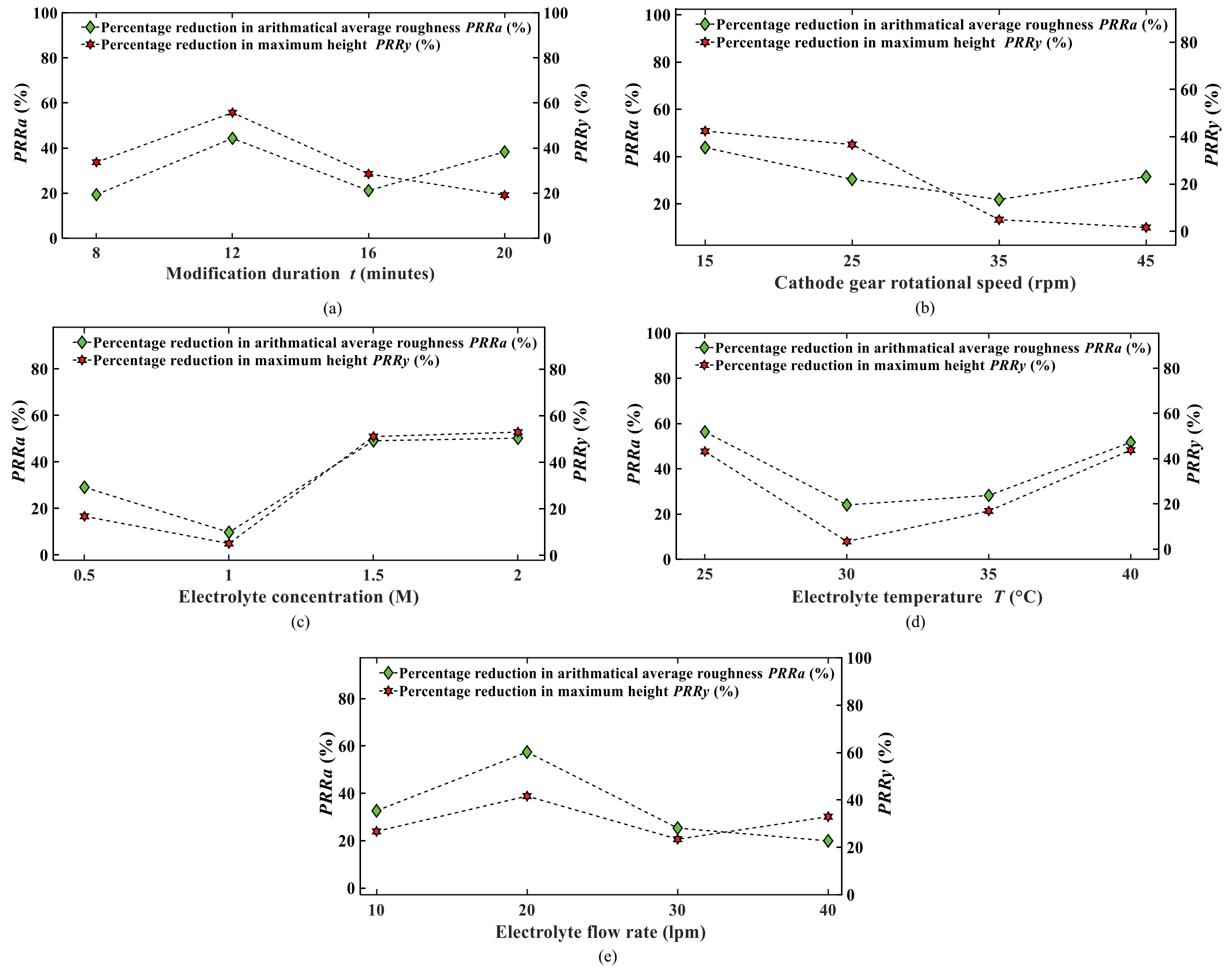


Figure 5. Change in percentage reduction in surface roughness parameters with (a) modification duration, (b) cathode gear rotational speed, (c) electrolyte concentration, (d) electrolyte temperature, and (e) electrolyte flow rate.

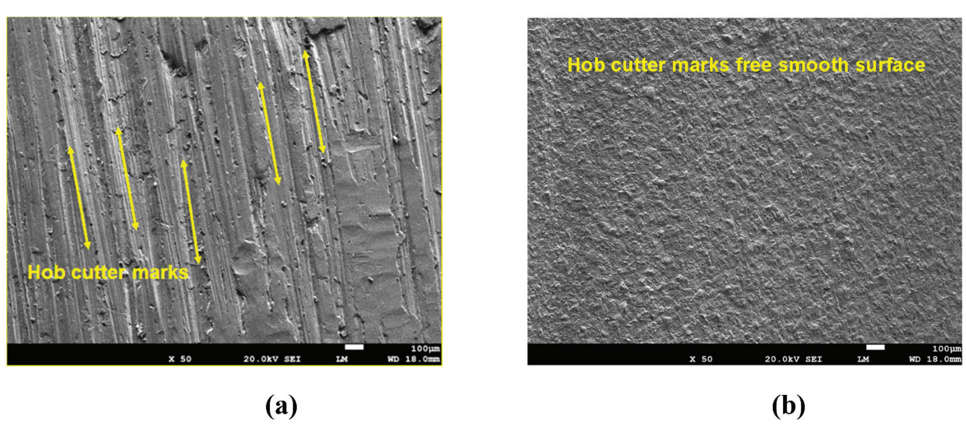


Figure 6. SEM images showing surface morphology of a spur gear tooth tip (a) before tip relieving, and (b) after tip relieving by the PECFM process.

the electrolyte concentration with molarity of 1 and 2. It is because at higher concentrations, the conductivity of the electrolyte increases and hence the current density increases, leading to more material removal and smoothening the surface. From Fig. 5d, it can be observed that the *PRRa* and *PRRy* was better at the use of lower (20°C) and higher temperatures (40°C) whereas at other values it does not show much variation. This may be because as temperature increases, the electric conductivity of the electrolyte increases due to ion mobility improvement, and it helps to remove more material from surface roughness peaks of the workpiece gear flank surface which leads to smoothening the surface more. While at lower temperatures the material removal rate is slower and helps in uniform material removal instead of faster and thus shows better values of *PRRa* and *PRRy*. Figure 5e depicts the variation in *PRRa* and *PRRy* with a change in electrolyte flow rate. It can be seen that the best values of *PRRa* and *PRRy* were attained at moderate

Table 2. Comparison of optimum parameters of PECFM process identified using criteria of tip relief, MRR, and surface roughness parameters.

	Criteria for identifying optimum parameters of PECFM process			
Parameter name	Tip relief (μm)	Volumetric Material removal rate (mm^3/s)	Percentage reduction in arithmetical average surface roughness (%)	Percentage reduction in maximum height (%)
Modification duration (minutes)	20	20	12	12
Cathode gear rotational speed (rpm)	45	45	15	15
Electrolyte concentration (Molarity)	2	2	2	2
Electrolyte temperature (°C)	40	40	25	40
Electrolyte flow rate (lpm)	30	40	20	20

electrolyte flow rate, i.e. 20 lpm. This is due to the fact that it provides sufficient amount of electrolyte to be filled in the modification zone and provides enough fresh electrolyte for continuing electrolytic action. A summary of identified parameters for the improvement in tip relief, *PRRa*, *PRRy* and MRR is presented in Table 2. The PECFM processed gears having surface roughness *"Ra" (0.68 μm to 2 μm)* and "*Ry*" *(4 μm to 12 μm)* were in the range of medium to medium high accuracy and can be used in various applications such as automobile gearboxes, conveyor systems, machine tools, gear pumps and motors etc. Figure 6 presents the scanning electron microscope image of the tip region of workpiece gear before (Fig. 6a) and after PECFM (Fig. 6b). Hob cutter marks are visible in surface morphology of tip region of workpiece gear tooth before tip relieving. They are completely removed from the tip region as shown in Fig. 6b after tip relieving by the developed cathode gear using the non-contact PECFM process and its developed apparatus. Moreover, the PECFM process did not leave any marks on the tip relieved gear flank surfaces.

4. Conclusions

This paper presented effectively imparting tip relief to spur gear by developed cathode gear using the non-contact PECFM process and its developed apparatus and study of influences of modification duration, cathode gear rotational speed, electrolyte concentration, electrolyte temperature, and electrolyte flow rate on the amount of tip relief, MRR, and surface roughness. Following conclusions can be made from this work.

- Spur gears are successfully tip relieved by the developed cathode gear and apparatus of non-contact PECFM process without any undesirable side effects.
- The amount of tip relief significantly increases with modification duration and electrolyte concentration and slightly increases with electrolyte temperature, but no definite trends are found with electrolyte flow rate and cathode gear rotational speed.
- SEM images revealed removal of hob cutter marks from flank surfaces of tip relieved spur gear by the developed cathode gear using non-contact PECFM process.
- Experimental investigation identified 20 minutes, 45 rpm, 2 Molarity, 40°C, and 30 lpm as optimum values for modification duration, cathode gear rotational speed, electrolyte concentration, electrolyte temperature, and electrolyte flow rate, respectively, to achieve higher values of tip relief.
- Considerable improvements in surface roughness parameters have been achieved after tip relieving by PECFM.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Patent

A patent has been filed based on the present research work at Indian Patent Office with application no 202221016570. Response to its first examination report has also been filed which is under examination.

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