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On Surface Quality and Wear Resistance of Straight Bevel Gears Finished by Pulsed Electrochemical Honing Process

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Pulsed electrochemical honing (PECH) is a hybrid super finishing process combining the process capabilities and advantages of mechanical honing with pulsed electrochemical machining (PECM) and simultaneously overcoming their individual limitations. This paper reports on influence of pulse parameters (i.e. pulse-on and pulse-off time) and finishing time on surface quality of PECH-finished straight bevel gears made of 20MnCr5 alloy steel. Average surface roughness, maximum surface roughness and surface roughness depth have been used to evaluate the surface finish while, bearing area curve, wear indicators (i.e. coefficient of friction and frictional force), microstructure and micro-hardness has been studied for the best finished gear. A gravimetric aqueous solution of 75% $NaNO_3$ + 25% NaCl with a concentration of 7.5% was used as an electrolyte. It was found that 2 ms pulse-on time, 4.5 ms pulse-off time and finishing the gears for 6 min yielded the best combination of percentage improvements in average surface roughness, maximum surface roughness and roughness depth (i.e. 47.3 %, 46.9 % and 34.2 % respectively). Bearing area curve, wear indicators and micro-structure of the PECH-finished straight bevel gears also improved significantly while, micro-hardness remained unaffected. Such improvements in surface quality will enhance tribological fitness, service life, operating performance, mechanical efficiency and reduce noise and transmission errors in the bevel gears.

Keywords: Gear; Finishing, PECH; Surface Roughness; Wear.

1. INTRODUCTION

Bevel gears are primarily used in automobiles, avionics, machinery used for marine, naval, construction and agricultural applications, machine tools, biomedical applications and in all those machinery where the power and/or motion to be transmitted between the intersecting shafts. The bevel gear teeth profile should be smooth and geometrically accurate for efficient motion transmission, noiseless operation, longer service life and better operating performance. It can be ensured by a using a proper combination of finishing and properties improving processes. Gear grinding and gear lapping are the only two conventional processes which can be used for finishing either hard or hardened conical gears. However, these processes suffer from their inherent limitations. Gear grinding is complicated, capital-intensive and highly-skilled labor requiring process. Karpuschewski et al. [1] highlight that it may also result in some undesirable effects such as transverse grind lines on the finished surface which increases noise and vibrations in the gears and grinding burns, a type of thermal damage, which adversely affects surface integrity of the ground gears and can even lead to gear failure through tooth breakage. Gear lapping is a very slow process which finishes the conical gears in a conjugate pair only. It can correct only minute deviations in the gear geometry while lapping for a longer duration may adversely affect the geometric accuracy of gears. Recently, Heinzel and Wagner [2] used elastic bonded grinding wheels to enhance the subsurface properties of the gears (i.e. compressive residual stress) and to eliminate the grind burns. Some researchers in past [3-8] have tried to overcome the limitations of gear grinding and gear lapping by using electrochemical honing (ECH) for finishing different types of gears fulfilling two basic design requirements of the cathode gear: (i) its conducting portion should not touch the conducting workpiece gear during their meshing at any instant of time to avoid short-circuiting; and (ii) simultaneously ensuring that the required inter-electrode gap (IEG) is maintained between the cathode and workpiece gear for entire duration of ECH in which majority of finishing done by the electrolytic dissolution process. Though, specific geometry of the used cathode gear tool was decided according to the geometry of the gear (i.e. cylindrical or conical; spur or helical; or bevel or hypoid) being finished by the ECH.

ECH is a hybrid super finishing process which combines capabilities and advantages of electrochemical finishing (ECF) with mechanical honing and simultaneously overcoming their individual limitations. Main capabilities of ECF process include: capability to machine/finish material of any hardness, production of stress-free and crack-free surface, higher material removal rate (MRR), and no tool wear. While, main capabilities of honing are: ability to correct the geometric errors and controlled generation of functional surfaces. Main limitation of ECF process is passivation of anodic workpiece surface by the metal oxides formed due to evolution of oxygen gas at anode during its electrolytic dissolution. This anode passivation prohibits further electrolytic dissolution of the workpiece. While, major limitations of honing process includes limited honing tool life, slow process, incapability of finishing a hardened gear, and possibility of mechanical damage (i.e. micro-cracks, hardness alternation and plastic deformation) to the workpiece.

Capello and Bertoglio [3] first time used ECH for finishing the *hardened helical* gear using specially designed cathode in the form of helical gear and $NaNO_3$ as electrolyte. Field-Controlled ECH (FC-ECH) was developed for finishing the *spur* gears by changing electric field intensity to control the electrolytic dissolution continuously [4]. Slow-scanning field controlled ECH (SSFC-ECH) was used as the periodic-control method to correct the *spur* gears tooth profile errors [5]. Altered mixtures of $NaNO_3$ and NaCl were used as electrolyte to finish *spur* gears made of EN8 by ECH and using EN24 as the honing gear material [6]. A gravimetric aqueous solution of NaCl and $NaNO_3$ in a ratio of 3:1 was used to enhance the surface finish of *helical* gears made of EN8 by ECH using EN24 as honing gear material [7]. Twin complementary cathode gears was envisaged by Shaikh et al. [8] for finishing of all the teeth of a bevel gear in a single operation and eliminating need to provide the reciprocating motion to the workpiece gear. Shaikh and Jain [9] developed theoretical models of MRR and surface roughness of the bevel gear finished by ECH and experimentally validated them.

It is well known that use of pulsed current in the ECF-based processes helps to enhance process performance without requiring higher electrolyte flow rate thus minimizing the size and cost of the equipment for the pulsed-ECF (or PECF) based processes. Fang et al. [10] have also reported that the use of pulsed current can improve the MRR and surface profile generated on the workpiece. However, very limited work has been done on using either PECF-based processes or its hybrid process for improving the surface quality of the gears. Ning et al. [11] used pulse electrochemical finishing (PECF) for finishing *spiral bevel* gears. But, they could finish only tooth at a time and used an indexing mechanism to finish all the gear teeth. Pang et al. [12] used PECF process to finish *cylindrical gears* modifying the gear tooth profile using an irregular inter-electrode gap (IEG) and modifying gear profile using a movable cathode tool. They conveyed enhancement in average surface roughness (R_a) value from 3.9 to 0.35 µm. Misra et al. [13] used PECH for finishing the *spur* gears and reported that gravimetric electrolyte composition of 75% NaCl and 25% $NaNO_3$ and electrolyte temperature of 30^{o}C yielded the best results.

From the review of past work it is evident that PECH has not been used to enhance surface quality of the straight bevel gears which can ensure their longer service life, better operating performance and transmission efficiency and noise reduction. Table 1 presents the various surface parameters that affect the service life, operating performance, transmission errors and noise reduction in the gears. The objective of the present work is to bridge the existing research gap by using PECH to finish the straight bevel gears (i) to minimize average surface roughness 'R_a', maximum surface roughness 'R_{max}', depth of surface roughness 'R_z'; (ii) to study the bearing are curve (BAC),wear indicators, microstructure and micro-hardness for the best finished gear.

Table 1 Parameters that affect the various performance aspects of the gears.

To improve service life and operating performance	To reduce noise and transmission error
• Reduce parameters of surface roughness (i.e. R_a, R_{max} and R_z) on the tooth flank	
• Improve wear indicators by reducing sliding coefficient of friction and friction forces	• Minimize errors in micro-geometry i.e. f_p, f_u, F_p and F_r
• Improve the microstructure	• Remove sharp corners from gear tooth
• Increase the fatigue life	• Increase the wear resistance

2. MATERIAL REMOVAL MECHANISM IN PECH

Material removal in PECH is based on a controlled anodic dissolution of the workpiece reproducing approximately complementary shape and accuracy of the cathodic tool in an electrolyte cell. The voltage in PECH is applied using a pulse generator which supplies short voltage pulses across the two electrodes. The workpiece anodic dissolution occurs during the pulse-on time (T_{on}) ranging from 0.01 to 6 ms. Products of electrochemical reaction are flushed away from the IEG during the pulse-off time (T_{off}) by an aqueous solution of the salt-based electrolyte (such as NaCl, $NaClO_3$, $NaNO_3$ or their combination) supplied through the IEG at a flow rate in the range of 10-50 liter per minute. This helps in maintaining the clean environment in IEG thus helping electrochemical dissolution to continue resulting effective and efficient material removal. Another important function of electrolyte flow is to take away the heat generated due to passage of current and may be due to electrochemical reactions. During the electrolytic dissolution of workpiece gear material, a strong passivation layer of metal oxide is generated on it which limits the further anodic dissolution. A hardened mechanical honing gear is used in PECH to remove this passivating layer thus ensuring continuous anodic dissolution. Use of pulsed power may slow down the overall process in comparison to traditional constant power DC supply but, process becomes more effective.

Mass transport phenomenon plays important role in controlling the anodic dissolution of workpiece and in achieving desired level of surface quality because it affects the current density distribution at macroscopic and microscopic levels. Controlled dissolution by mass transport smoothen the surface because IEG at peaks of a surface is smaller than the IEG at the valleys giving more current density and more material removal at peaks than the valleys (this is referred as *leveling effect*) [14]. The anodic leveling can be achieved by three types of non-uniform current distribution i.e. primary current distribution (Ohmic), secondary current distribution (kinetic), tertiary current distribution due to non-uniform local mass transport [15]. In PECH, effect of secondary current distribution is negligible if sufficient IEG and electrolyte flow velocity are maintained. Therefore, primary and tertiary current distributions mainly contribute towards smoothening of the gear surface. Moreover, the effects of charge transfer kinetics is insignificant and differences due to grain orientation, grain boundaries, dislocations or small inclusions will not play any significant role because of controlled limiting current by mass transport. As a result, material removal at molecular level results in a very smooth surface topography (*brightening effect*) [16].

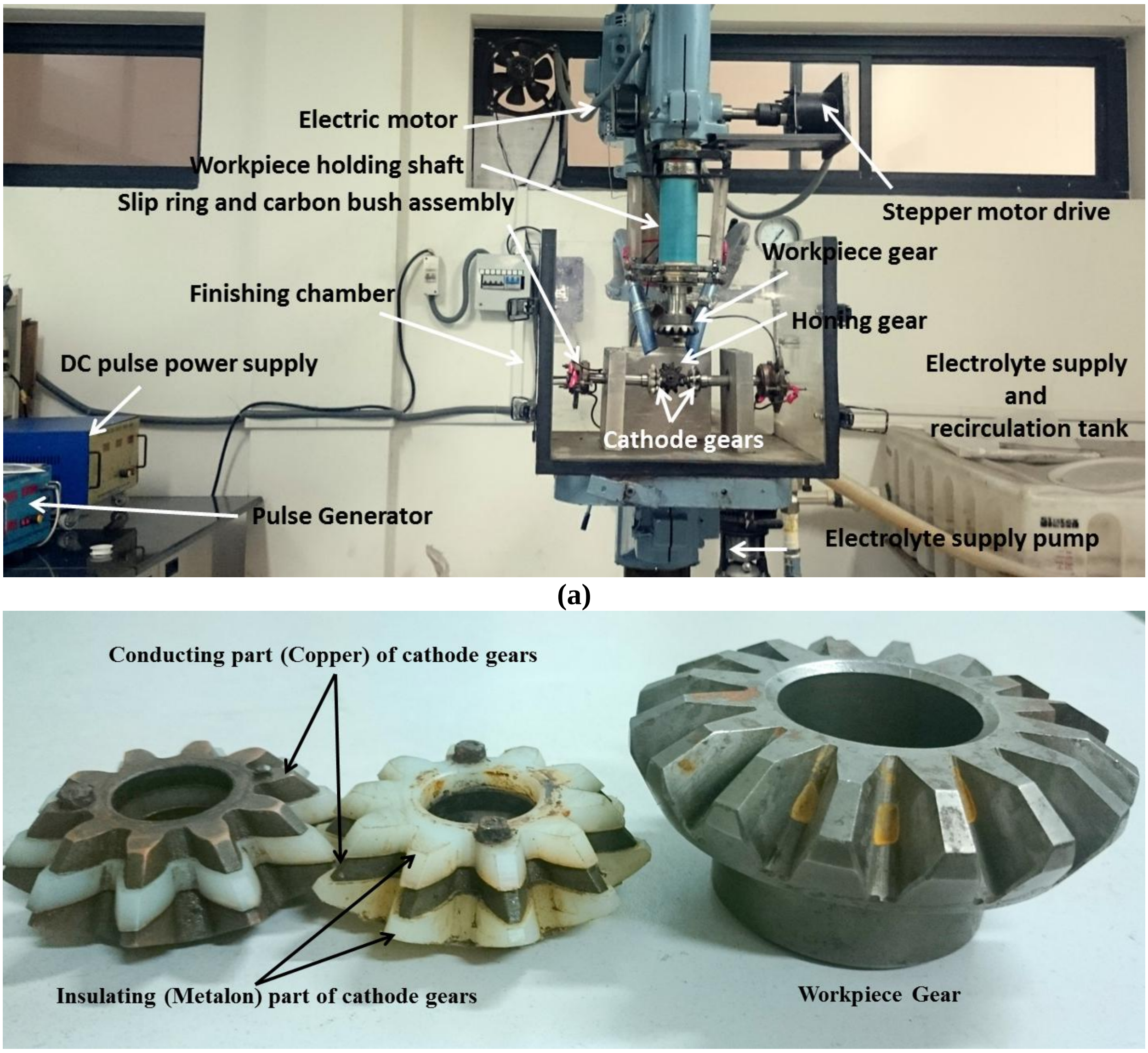
There are four important advantages of PECH which make it superior over the conventional finishing processes:

1. Theoretically, there is no tool wear because there is no physical contact between anode (i.e. workpiece gear) and cathode (cathode gears) tool.
2. The finishing of the workpiece gear is independent of their material mechanical properties i.e. hardness, brittleness, strength, ductility.
3. Uniformity of material removal can be achieved as the material removal is due to its anodic dissolution.
4. Ability of producing the stress-free surfaces and crack-free smooth surfaces.

3. EXPERIMENTAL SETUP

Fig 1(a) shows the photograph of the developed experimental setup for straight bevel gear finishing by PECH. It comprises of four subassemblies: (i) finishing chamber, (ii) tool and motion unit, (ii) pulse programmable DC power supply unit, and (iv) electrolyte supply and recirculating unit [17]. A *finishing chamber* houses workpiece gear, two complementary cathode gears, honing gear and supporting and mounting elements for these gears. In the PECH process, the material is removed from the workpiece gear due to its controlled anodic dissolution under pulsed current in an electrolytic cell. The workpiece gear meshes with the specially designed cathode gears which avoids short-circuiting and also maintains an IEG. The complex geometry of the conical gears makes their finishing by PECH more difficult and challenging than finishing of the cylindrical gears. This is due to the difficulty faced in the design and fabrication of the cathode gears and in the arrangement of the cathode and honing gears for finishing of bevel gears by PECH process. This challenge was met by using the twin complementary cathode gears envisaged by Shaikh and Jain [9]. In this concept, one of the cathode gears has a conducting layer of copper sandwiched between two insulating layers of metalon while, other complimentary cathode gear has an insulating layer of metalon sandwiched between two conducting layers of copper. In both the complementary cathode gears the conducting layers of copper are undercut by 1 mm as compared to the corresponding insulating layers to avoid direct electrical contact and short-circuiting during meshing of these gears with the workpiece gear in PECH process. This also ensures that IEG required for electrolytic action is maintained between the workpiece and cathode gears. Fig. 1(b) illustrates photograph of the cathode and workpiece gears. A hardened honing gear without any abrasive grains or abrasive coating but having hardness higher than the workpiece gear is used to remove the passivating layers of metal oxides from the workpiece gear which are formed due to evolution of oxygen at anode as a product of electrolysis reactions. A suitable electrolyte, usually an aqueous solution of salt, is pumped under pressure to the IEG to flush away the material dissolved from the workpiece.The workpiece gear is mounted on the spindle of a vertical bench drilling machine. The complementary cathode gears and a honing gear are mounted perpendicular to the workpiece gear in such a way that the axis of rotation of the cathode gears are coincident and axis of rotation of the honing gear is perpendicular to it. The points of contact of the cathode and honing gears with the workpiece gears should lie in the same plane. The workpiece gear is provided rotary motion by means of a DC motor while other gears rotate due to tight meshing with the workpiece gear. Workpiece and honing gears were made of 20MnCr5 alloy steel (chemical composition: Cr: 1-1.3%; Mn: 1.1-1.4%; C: 0.17-0.22%; P: max. 0.025%; Si: max. 0.4%; S: max. 0.035%). Gear hobbing followed by case hardening up to 0.7 mm case depth was used to manufacture the workpiece and honing gears. This material was chosen due to its use in the automotive industries and in other commercial applications of bevel gears. The honing and workpiece gears were found to have Rockwell hardness of 63 and 57 on the C-scale (i.e. HRC) respectively. The structure of the finishing chamber was made of perspex sheets due to its resistance to corrosion and to provide better visibility during the finishing operations.

The *tool and motion unit* consists of a stepper motor, its driver and a controller programmed by software from *Copley Controls Corporation*. It provides reciprocating motion to the spindle of the bench drilling machine on which the workpiece gear is mounted. It makes the workpiece gear to engage with the honing and cathode gears before its finishing by PECH and disengages it after completion of the finishing operation. A high level of accuracy in feed and better control over process can be achieved using this automation in the feed operation [17].



(a)

(b)

Figure 1. (a) Photograph of the developed experimental setup for finishing the straight bevel gears by PECH; and (b) photograph of the complementary cathode gears and workpiece bevel gear.

The *DC pulse power supply unit* used for the experimentation is capable of delivering an output voltage in the range of 0–100 V, current in the range of 10-110 A and it is equipped with the option for setting pulse-on time and pulse-off time. It comprises of three parts: programmable high-power DC supply, pulse generator and pulse controller with the power switch unit. A power switch apparatus is primarily assessed by switch time, control mode. The pulse controller has the facility to modify the voltage, current, pulse-on time (T_{on}), pulse-off time (T_{off}) and consequently the duty cycle (ζ) i.e. ratio of pulse-on time to sum of pulse-on and pulse-off times. Fig. 2 depicts components of the pulsed power supply used for finishing the bevel gears by PECH. The positive terminal of the pulse power supply was coupled to the workpiece gear i.e. anode, while the negative terminal was joined to the cathode gears using carbon brush and slip ring assembly.

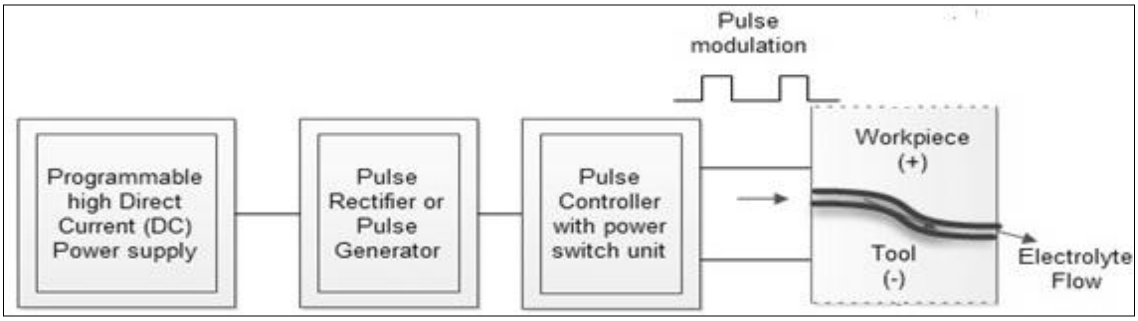


Figure 2. Components of pulsed power supply used for finishing the bevel gears by PECH.

The *electrolyte supply and recirculating unit* comprise of a pump to supply the desired quantity of the electrolyte to the finishing chamber at preset values of temperature and pressure. The system also includes of pressure gauge, flow meter, flow control valves and filters. A heating element was fitted in the storage tank to maintain the electrolyte temperature at a prefixed value and it is controlled using a temperature controller and sensor. An aqueous solution of 75% $NaNO_3$ and 25% NaCl was used as electrolyte for anodic dissolution of workpiece gear material.

4. EXPERIMENTATION

Table 2. Values of the variable and fixed input parameters.

Variable input parameters	Levels					Values of the fixed input parameters
	I	II	III	IV	V	IEG: 1 mm; Voltage:12V
Pulse-on time, T_{on} (ms)	1	2	3	4	5	Electrolyte composition (wt.%): 75% $NaNO_3$ + 25% NaCl
Pulse-off time, T_{off} (ms)	3	4.5	6	7.5	9	Electrolyte concentration: 7.5 wt. %
Finishing time, t (min)	3	6	9	12	15	Electrolyte temperature: 32^oC Electrolyte flow rate: 30lpm Rotary speed of workpiece gear: 40 rpm

Total 17 experiments were conducted using rotatable central composite design technique of the response surface methodology by varying the pulse-on time, pulse-off time and finishing time. Each parameter was having five levels, while the other PECH parameters were kept constant. Table 2 mentions the values of the variable and fixed input parameters.

The investigations were focused on finishing of straight bevel gears by PECH: (i) to improve the surface roughness in terms of average percentage improvement in average surface roughness (PIR_a), in maximum surface roughness (PIR_{max}) and in depth of surface roughness (PIR_z); (ii) to identify the optimum pulse parameters and finishing time for the future experiments; (iii) to analyze the bearing area curve; wear indicators (i.e. coefficient of friction and friction force),microstructure and micro-hardness for the unfinished gear and gear finished by PECH at the identified optimum parameters. Three parameters of surface roughness (namely R_a, R_{max} and R_z) and bearing area curve were evaluated using the contracer-cum-surface roughness analyzer (model SEF 3500) from *Kosaka*

Japan. Two measurements, one on the left-hand profile and other on the right-hand profile, both at the middle of the face width of two consecutive gear teeth were taken before and after finishing the bevel gears by PECH using evaluation length of 1.6 mm; cut-off length of 0.8 mm and Gaussian filter. Arithmetic mean of these four values of a surface roughness parameter was used to compute percentage improvements in it i.e. percentage improvement in average surface roughness ‘PIR_a’ was calculated using eq. 1.

$$Avg.\,PIR_a = \frac{Avg.\ R_a\ value\ before\ PECH - Avg.\,R_a\ value\ after\ PECH}{Avg.\,R_a\ value\ before\ PECH} \qquad (1)$$

Similarly, average values of PIR_{max} and PIR_z were computed using the corresponding average values. A higher value of percentage improvement in a surface roughness parameter indicates smaller value of that parameter after finishing the bevel gear by PECH.

Wear indicators, micro-hardness and microstructure were studied for the unfinished gear and the gear finished by PECH at optimized parametric combination. Wear tests were conducted to evaluate the sliding coefficient of friction and friction force on using fretting wear tribometer (model CM-9104) from *Ducom, India* using load, frequency, time and ball diameter as 50 N, 20 Hz, 20 minutes and 5 mm respectively. Vicker’s micro-hardness was tested using a load of 0.5 kg and dual time 15 seconds using the micro-hardness tester (model VMH-002) from *Walter UHL, Germany*. The changes in the microstructure of the bevel gear tooth flank surface before and after finishing by PECH were studied through scanning electron microscopic (SEM) images obtained by FE-SEM (model *Supra 55*) from *Carl Zeiss Germany*.

5. RESULTS AND DISCUSSION

Table 3 presents the details of all the seventeen experiments along with the averages values of percentage improvements in three parameters used for evaluation of surface roughness. It can be observed from these results that the best combination of responses was achieved for experiment no. 11 having input parameters T_{on} as 2 ms; T_{off} as 4.5 ms and t as 6 minutes. It yielded average values of surface roughness parameters i.e. PIR_a, PIR_{max} and PIR_z equal to 47.3%; 46.2%; and 34.2% respectively. These values are the maximum values for PIR_a, PIR_{max}, and 8th best value for PIR_z. The maximum value of PIR_z was obtained for the experiment no. 15 but it resulted in very low values of other responses. Wear test of unfinished gear and PECH finished gear using the best parametric combination corresponding to experiment number 11 revealed that the coefficient of friction is reduced from 0.157 to 0.046 and friction force from 7.5 to 1.4 N respectively. Micro-hardness test shows no major change before and after finishing by PECH.

Table 3. Surface roughness parameters of bevel gears for different experimental runs.

Input variables				Indicators of surface finish of bevel gears						
				Average surface roughness (R_a)		Maximum surface roughness (R_{max})		Depth of surface roughness (R_z)		
Run	T_{on}	T_{off}	t	Avg.	Avg.	Avg.	Avg.	Avg.	Avg.	*Avg.*

no.	(ms)	(ms)	(min)	value before PECH	value after PECH	*Avg.* PIR_a	value before PECH	value after PECH	*Avg.* PIR_{max}	value before PECH	value after PECH	PIR_z
01	3	6	9	1.43	1.29	10.0	19.12	12.16	36.4	5.6	3.69	34.1
02	3	6	9	1.61	1.33	17.4	13.22	10.95	17.1	5.39	4.22	21.7
03	1	6	9	1.25	1.36	-9.0	18.23	9.93	45.5	4.78	4.44	7.0
04	4	4.5	12	1.44	1.13	21.7	15.57	11.47	26.3	5.44	3.98	26.7
05	2	7.5	12	2.14	1.41	34.1	14.63	13.91	4.9	7.77	4.45	42.7
06	4	4.5	6	1.59	1.19	25.4	13.78	11.27	18.2	8.61	4.47	48.0
07	3	3	9	1.54	1.04	32.6	18.06	16.41	9.1	5.67	3.29	41.9
08	2	7.5	6	1.21	1.33	-10.1	12.48	12.61	-1.0	4.59	4.54	1.2
09	5	6	9	1.69	1.27	24.9	16.72	11.43	31.7	6.18	3.59	41.9
10	2	4.5	12	1.95	1.17	40.1	11.43	12.28	-7.4	6.95	3.9	43.9
11	***2***	***4.5***	***6***	2.52	1.33	***47.3***	16.78	8.91	***46.9***	5.83	3.84	34.2
12	3	6	9	2.11	1.72	18.5	19.00	14.66	22.8	7.58	6.11	19.3
13	4	7.5	6	1.53	1.21	21.2	18.79	18.06	3.9	5.82	4.25	27.0
14	3	9	9	1.91	1.59	16.7	17.45	14.54	16.6	6.67	6.13	8.1
15	***3***	***6***	***3***	2.24	1.35	39.7	19.94	14.95	25.0	8.05	3.58	***55.5***
16	3	6	15	1.21	1.38	-13.4	15.08	11.79	21.8	4.62	4.22	8.7
17	4	7.5	12	1.59	1.13	29.1	17.05	10.99	35.5	6.13	3.6	41.2

5.1 Analysis of surface finish

Response surface models of *avg.* PIR_a and *avg.* PIR_{max} were developed using their experimental values from Table 3 using stepwise regression which eliminates the insignificant terms. Significance of the developed models, their individual terms and lack-of-fit at 95% confidence interval were computed using analysis of variance. It found the quadratic models statistically significant at 95% confidence interval for both the responses. Equations 2-3describe these models.

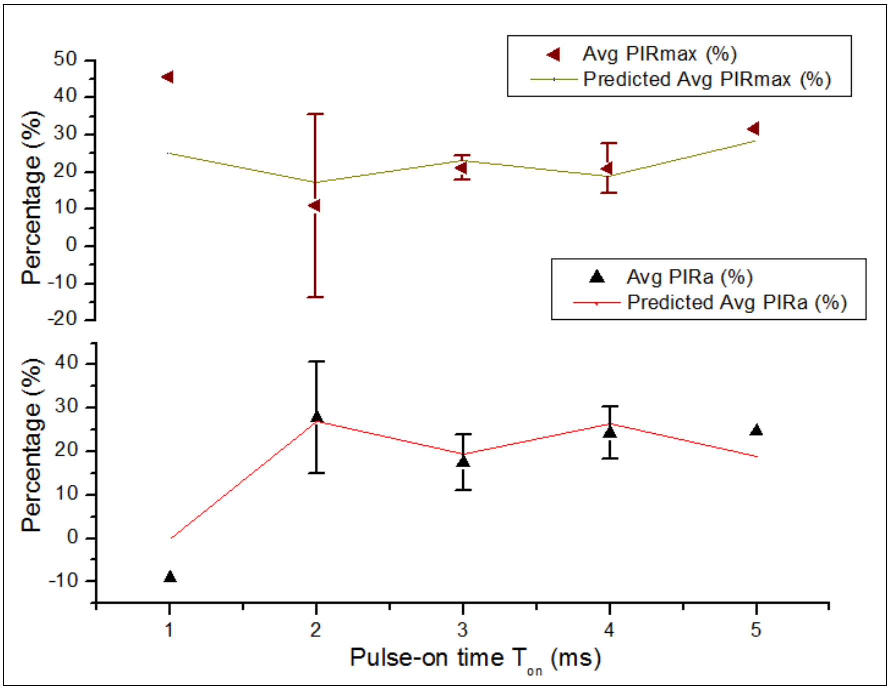
$$Avg.PIR_a = 287.76 - 33.57T_{on} - 36.24T_{off} - 23.23t + 5.55\,T_{on}T_{off} + 1.75T_{off}t + 0.80\,t^2 \quad (2)$$

$$Avg.PIR_{max} = 139.2 - 32.30T_{on} + 20.9T_{off} - 25.32t + 3.67T_{on}t + 2.33T_{off}t - 3.83T_{off}^2 \quad (3)$$

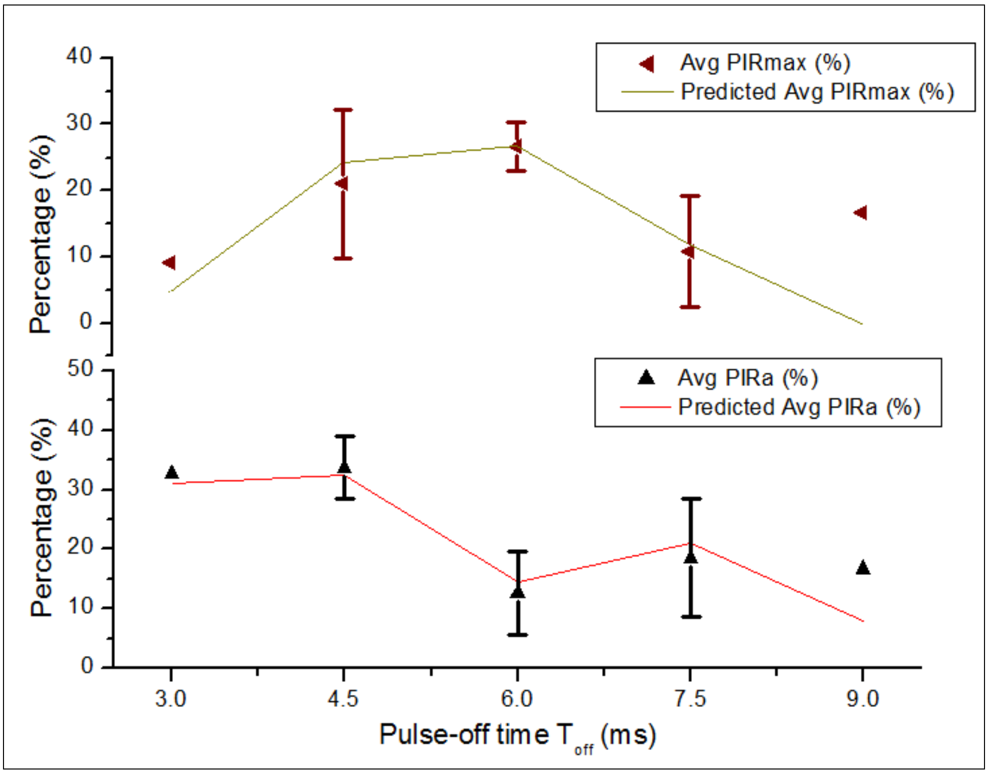
Computation of percentage contribution of significant input variables and their interactions found that T_{off} and its interaction with T_{on} and t, and t^2 are the significant contributors with 19.5%, 20.5% and 18.1% and 20.1% contribution respectively to *avg.* PIR_a. Whereas, interaction of t with T_{on} and T_{off} and T_{off}^2 are the highest contributor with 22.6%, 25% and 22.6% contribution respectively towards *avg.* PIR_{max}. Fig. 3 depicts variation in average values of PIR_a and PIR_{max} with pulse-on time (Fig. 3a), pulse-off time (Fig. 3b) and finishing time (Fig. 3c) showing the range (shown as vertical bars) and average of their experimental values at a particular level of an input parameter. The predicted values of *avg.* PIR_a and *avg.* PIR_{max} (using Eqs. 2 and 3) are shown by the linear graphs. It can be observed from these figures the optimum range of T_{on}, T_{off} and t exist for the maximum values of *avg.* PIR_a, and *avg.* PIR_{max} because the maximum experimental values of *avg.* PIR_a and *avg.* PIR_{max} occurred for T_{on} values in range of 1-2 ms (Fig. 3a); for T_{off} values in the range of 4.5-6 ms (Fig. 3b) and for t values in the range of 3-9 minutes (Fig. 3c). Fig. 4 depicts the variation in the average values of percentage improvement in depth of surface roughness (PIR_z) for the all specimen finished using the parametric combination of all the 17 experiments. It can be seen from this figure that the maximum value of *avg.* PIR_z (equal to 55.5%) achieved in experiment no. 15 having T_{on} as 3 ms; T_{off} as 6 ms and finishing time as *3* minutes. These observations can be explained with the help of following facts:

Use of pulse power in the PECH process helps in reducing the concentration polarization effect (i.e. formation of diffusion layer on the anode surface which acts as barrier), due to high concentration values a higher peak voltage is required to break the barrier of diffusion barrier. Reduced concentration polarization helps in decreasing the dissolution and enhancing the surface finish of the workpiece material. But, a sufficient amount of pulse-on time is needed so that the anodic workpiece gear gets sufficient energy to initiate the dissolution process. Accordingly, it was observed that a higher value of pulse-on time will initiate more electrolytic dissolution of workpiece gear material and also leads to generate higher amount of sludge/electrolyte reaction products. This increase in MRR and high reaction products (i.e. poor flushing) leads to diminish the surface quality of the gears. The obtained trend also obey the Faraday's law of electrolysis, which suggests that the application of high voltage increases the current density which leads to higher dissolution of workpiece material i.e. higher MRR, which adversely affects the surface profile.

Lower value of pulse-off time leads to inefficient flushing of the electrolytic reaction products from the IEG which may clog the IEG. While, a higher value of pulse-off time gives less time for electrolytic finishing of anodic workpiece gear as observed in experiment no. 3. Thus, moderate value of pulse-off time is to be used so that proper flushing and sufficient time for finishing will be available for proper finishing of the bevel gears. Obtained surface profile and finish values reveal the fact that the inclusion of pulse power helps in reducing the difference between the electrolyte conductivity and electrical potential in the IEG which helps in providing more uniform surface profile and better finish [10].



(a)



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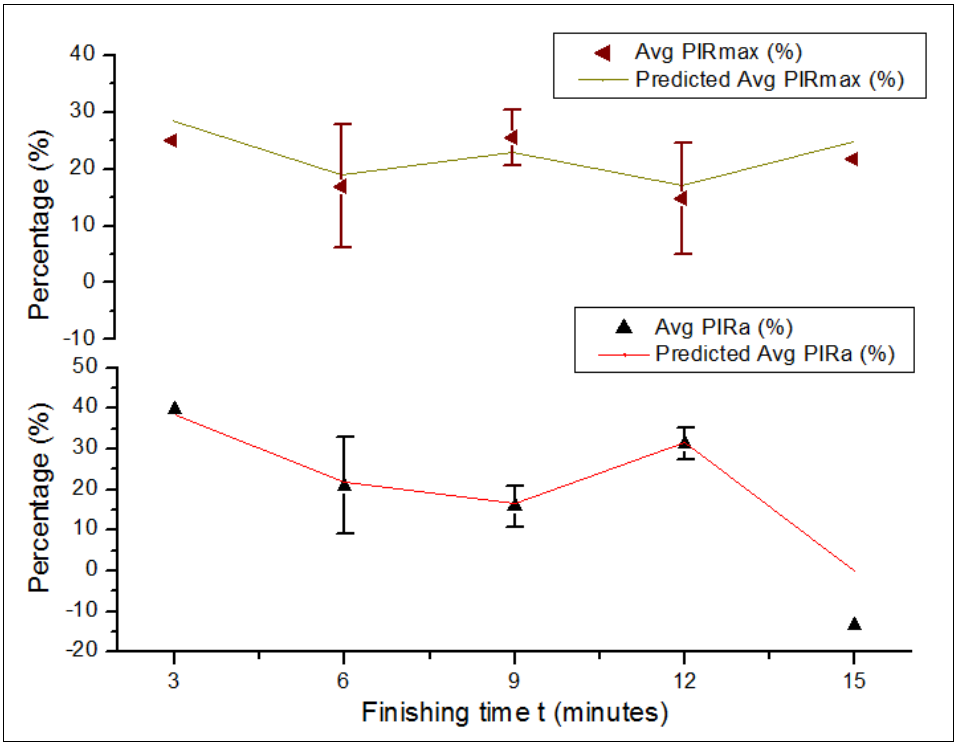


(c)

Figure 3. Variation of PIR_a and PIR_{max} with (a) pulse-on time (T_{on}); (b) pulse-off time (T_{off}); and (c) finishing time (t).

Higher finishing time may provide larger number of cycles for anodic dissolution of the workpiece surface which give higher MRR which may deteriorate the surface finish of the bevel gears.

While, lower values of finishing time helps in better control over the anodic dissolution and give better surface finish values. Obtained results are in good agreement with the previous results on gear finishing by ECH [9, 13] which also mentioned that using higher values of finishing time may lead to higher material removal rate but poor surface finish.

These facts justify the identified optimum input parameters (i.e. T_{on} as 2 ms; T_{off} as 4.5 ms and t as 6 minutes) for maximum improvement in the surface finish of straight bevel gears finished by PECH.

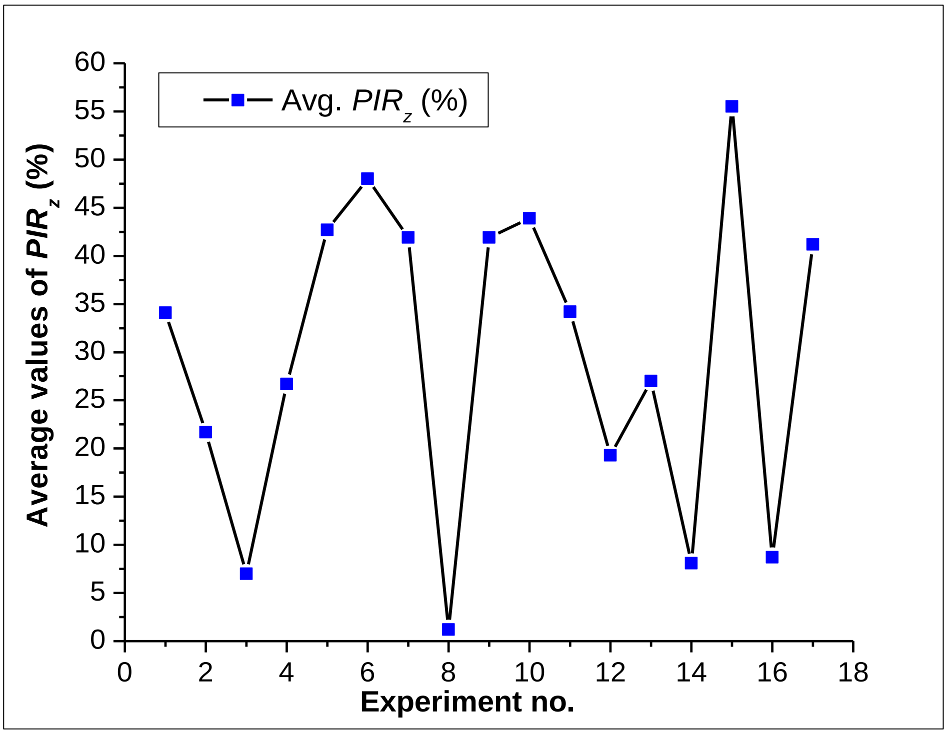
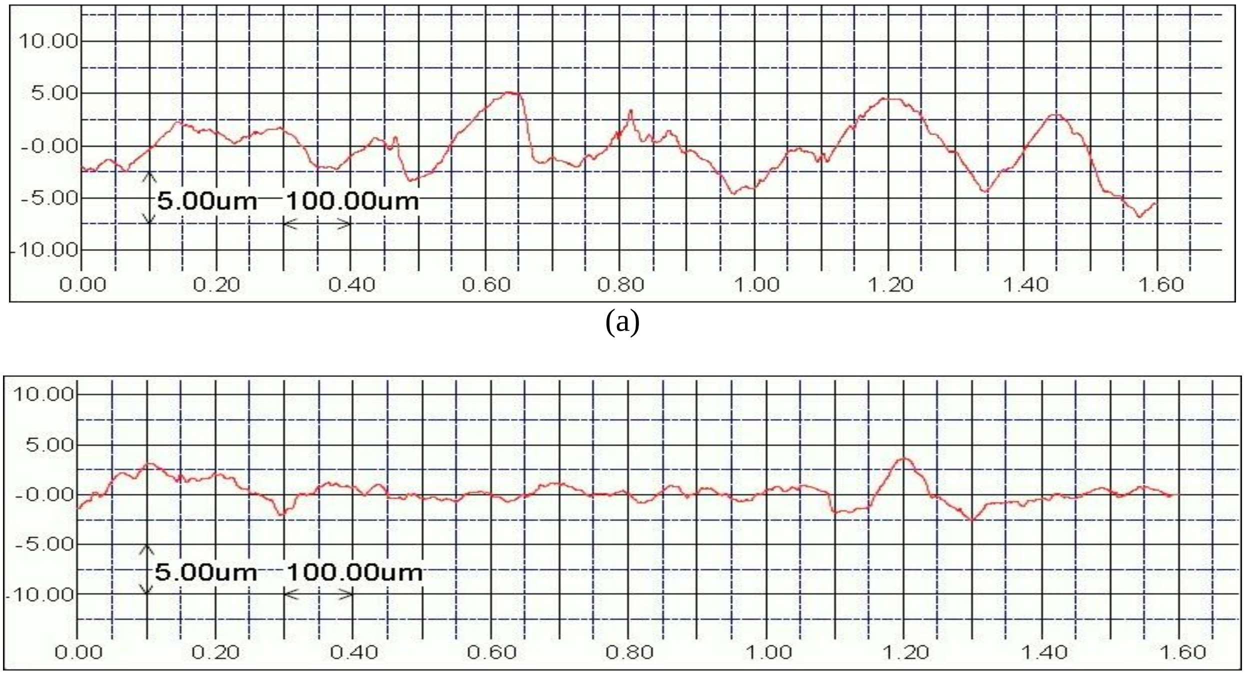


Figure 4. Variation of average value of percentage improvement in depth of surface roughness (PIR_z) for the specimen finished in the different experimental runs.

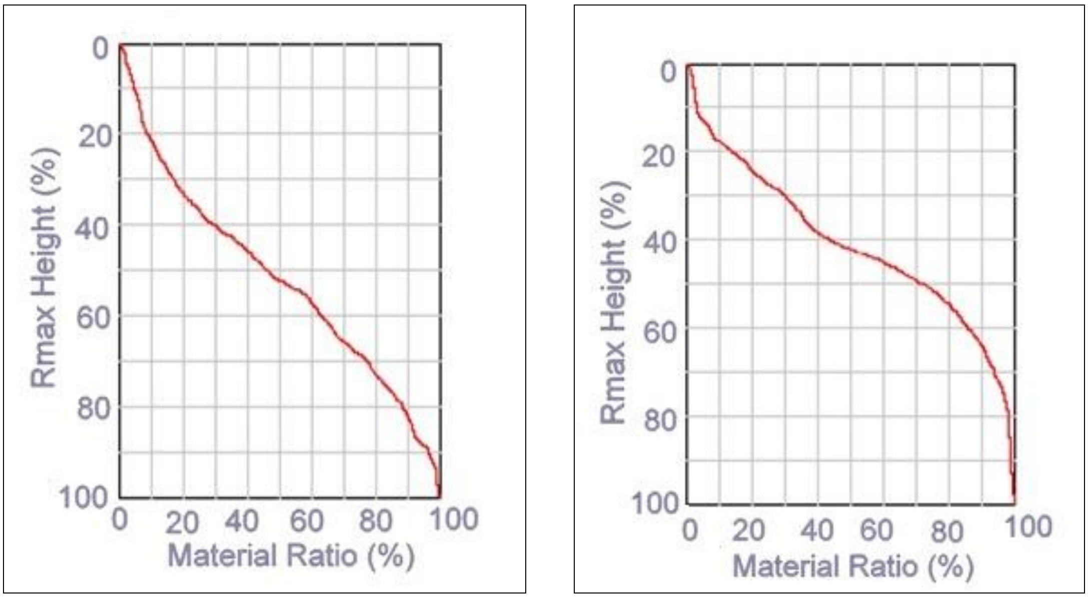
Fig. 5 depicts the surface roughness profile of a particular tooth flank of an unfinished gear (Fig. 5a) and of the same gear tooth flank finished by PECH (Fig. 5b) using the identified optimum input parameters (i.e. exp. No. 11). These profiles show the variation of surface roughness along the evaluation length of 1.6 mm. It can be seen from these figures that finishing a bevel gear for an optimized duration of 6 minutes by PECH significantly reduces its maximum surface roughness (R_{max}) value from 16.78 to 8.91 µm; average surface roughness (R_a) value from 1.93 to 1.02 µm; and depth of surface roughness (R_z) 5.8 to 3.8 µm. Reduced value of R_{max} of the gear tooth flank surfaces gives better operating performance while reduced value of R_a and R_z gives longer service life and reduced noise.



(a)

(b)

Figure 5. Roughness profile of bevel gear along the evaluation length (a) unfinished gear; and (b) same gear finished using the identified optimum PECH parameters (Experiment no. 11).



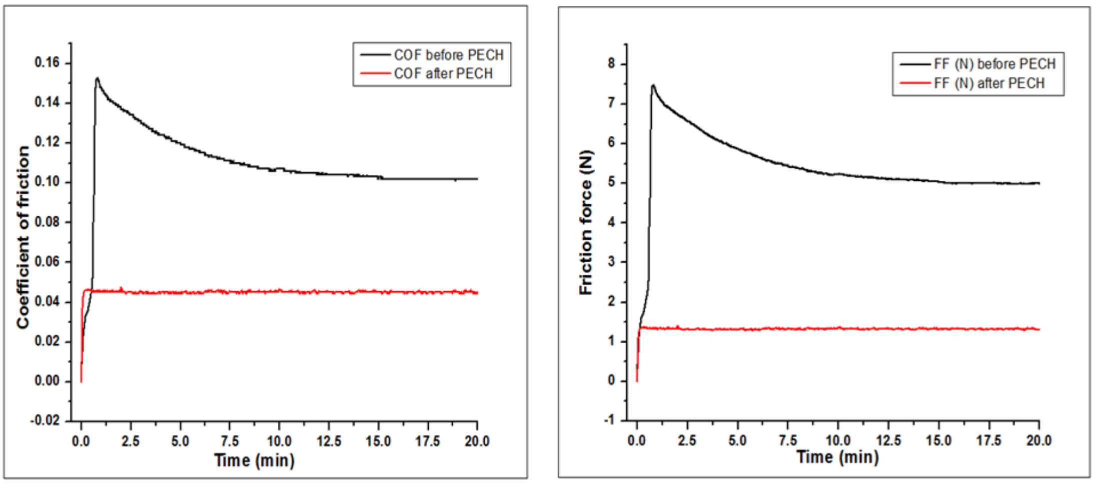
(a) (b)

Figure 6. Bearing area curve on the gear surface (a) before PECH; (b) after PECH

Bearing area curve also called as Abbott firestone curve depicts the graph between maximum surface roughness R_{max} and material ratio also known as bearing length t_p. The uppermost section of the BAC corresponds to the portion of the gear tooth surface which may quickly wear out during the operation. The lower section of the BAC shows the volume of the valley depth. The section covered in the centre portion of the BAC shows the service life of the gear during the operation. Fig. 6a and 6b depicts the variations in the bearing area curve (BAC) before and after finishing the bevel gears by PECH. The improvement in BAC after PECH results in larger contact area which results in better contact ratio, providing enhanced transmission accuracy and hence less wear rate which gives better service life to the bevel gear during the operation.

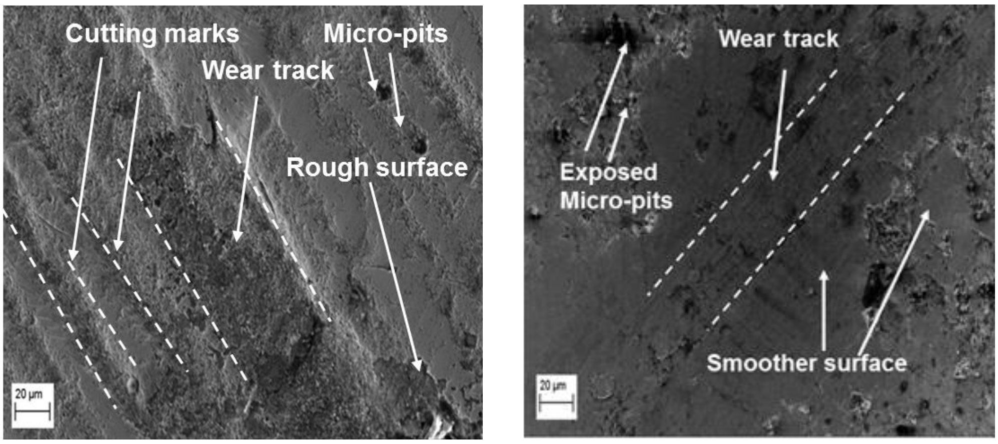
5.2 Analysis of wear indicating parameters

Frictional power losses in the gear drives occur during the meshing process. Moldovean et al. [18] measured mechanical efficiency and service life of the bevel gear and reported their values increases with decrease in the sliding friction coefficient 'μ'. For $\mu < 0.05$, the mechanical efficiency of gears is about 99.5 %.



(a) (b)

Figure 7. Wear indicating parameters of unfinished bevel gear and the gear finished by PECH using optimum input parameters (a) sliding coefficient of friction; and (b) friction force.



(a) (b)

Figure 8. SEM images of wear test on gear tooth at 500X magnification (a) unfinished (b) finished by PECH using optimum input parameters.

Fig. 7 shows wear characteristics of an unfinished gear and a gear finished by PECH using the identified optimum PECH parameters. It is evident from Fig. 7a that the value of sliding coefficient of friction is reduced from 0.157 to 0.046 and from Fig. 7b that the friction force reduces from 7.5 to 1.4N after finishing the bevel gear by PECH for 6 minutes. This is due to the reduction in the surface roughness parameters of the gear tooth flank after finishing by PECH. Fig. 8 shows the SEM images taken after the wear tests on the unfinished gear (Fig. 8a) and the gear finished by PECH (Fig. 8b) using the identified optimum input parameters. It can be seen from these SEM images that the less material is wear out from the surface of tooth flank and the surface layer of tooth flank has become smoother after finishing by PECH. It can be observed from these SEM images that roughness and tooth cutting marks are smoothened; micro-pits are exposed and become visible after finishing by PECH. This smoothing is due to proper flushing of sludge products during the pulse-off time and also, due to restricted re-deposition of the reactants. The reduction in wear properties will enhance the efficiency and service life of the straight bevel gears during the operation.

5.3 Study of micro-hardness

Vicker's hardness testing was done on a tooth flank surface of unfinished gear and of a gear finished by PECH at the optimum input parameters. Five indentations were done along the face width of the gear tooth and average hardness value of the five indentations was used to analyze the effect of PECH on micro-hardness of the workpiece gear material. Fig. 9 compares the hardness values before (i.e. unfinished) and after finishing the gear by the PECH for an optimum duration of 6 minutes. It can be seen from these results that at any particular location Vicker's hardness values of the unfinished and PECH finished gear are almost same.

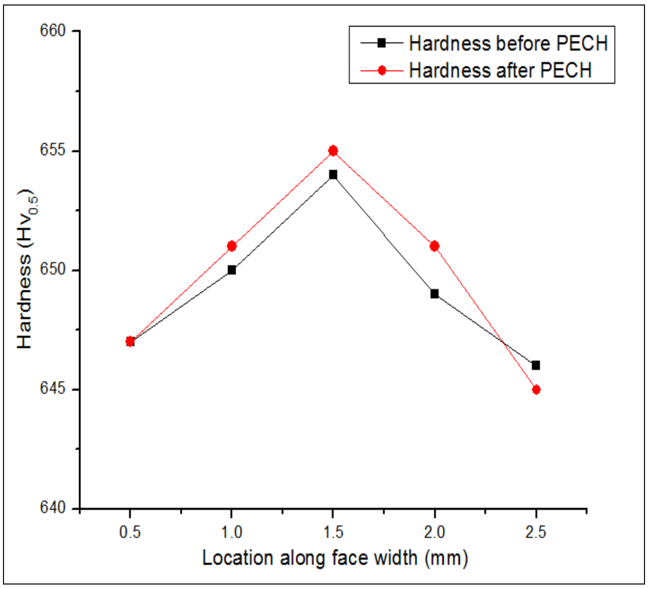


Figure 9. Micro-hardness profile of the bevel gear tooth flank before and after finishing by PECH.

This may be due to the fact that PECH process is non-contact process and only physical contact of workpiece gear is with honing gear which is used to remove the passivating layers only. Also, there is very less or almost negligible heat generated in the IEG which is insufficient to change hardness of the workpiece gear. Obtained results can be justified with the previously reported work in which the authors [8] claimed that ECH process does not affect hardness of the workpiece gear material. Therefore, it can be concluded that finishing of bevel gears by PECH does not alter its surface integrity.

6. CONCLUSIONS

This work involved investigations on the influence of pulse parameters and finishing time on the surface finish of the straight bevel gears in the PECH process along with analysis of bearing area curve, wear indicating parameters, microstructure and micro-hardness of the best finished gear. The objective was to identify the optimum pulse parameters and finishing time for the future research. Following conclusions can be drawn from this work:

1. Pulse-on time, pulse-off time, and finishing time are found to be the most important parameter in enhancing the surface quality of the straight bevel gears finished by PECH process. The optimum values of theses parameters identified are: 2ms as pulse-on time; 4.5 ms as pulse-off time and 6 minutes as finishing time.
2. Pulse-on time should be less than the pulse-off time so as to enable removal of the electrolytic reaction products formed during the pulse-on time and keep the IEG clean for the next cycle of anodic dissolution of the workpiece.
3. Use of the identified optimum PECH parameters yielded the average improvements in average surface roughness as 47.3%; in maximum surface roughness as 46.9%; and in roughness depth as 34.2 %. Improvements in surface roughness parameters helps in better service life, improved operating performance, reduced noise and transmission error of the straight bevel gears.
4. Bevel gear finishing by PECH reduced the sliding coefficient of friction and friction force thus improving their wear characteristics. Lower values of friction force and coefficient of friction also provide lesser noise and enhanced service life during the operation.
5. PECH improves the bearing area curve and micro-structure of the finished gear while it does not affect the micro-hardness of the finished gear. This helps in getting better service life and lesser noise creation during the operation.
6. The SEM images of the gear flank surface finished by PECH revealed that it is free from both mechanical and thermal and related distortions unlike the gears finished by the gear grinding. This is due to fact that in PECH, majority of finishing is done by PECM process while role of mechanical honing is just to remove the passivating layer of the metal oxide.
7. Improvement in surface quality of straight bevel gears by PECH is highly dependent on the accuracy of the cathode gears used and on precision of completing the finishing operation by proper meshing of workpiece gear with the cathode gears and honing gear.

NOMENCLATURE

R_a	Average surface roughness
R_{max}	Maximum surface roughness
R_z	Depth of surface roughness
t	Finishing time
T_{off}	Pulse-off time
T_{on}	Pulse-on time
V	Voltage
μ	Coefficient of friction

ABBREVIATIONS

BAC	Bearing Area Curve
DC	Direct Current
ECM	Electrochemical Machining
ECH	Electrochemical Honing
MRR	Material Removal Rate
IEG	Inter Electrode Gap
PECM	Pulsed Electrochemical Machining
PECH	Pulsed Electrochemical Honing
PECF	Pulsed Electrochemical Finishing

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