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Research Article

Effect of Cryogenic Heat-Treated Honing Gears on Surface Quality Improvement of Bevel Gears in P-ECH Process

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ABSTRACT

In this paper, bevel gears made of 20MnCr5 alloy steel are finished using pulse electrochemical honing (P-ECH) process. The honing gears used during finishing process were made of same material, which obtained higher hardness than the workpieces through two distinct heat treatments. The two different heat treatments viz. (i) case hardening through a carburizing process (CP) alone, and (ii) a combination of CP followed by deep cryogenic treatment (DCT), (referred to as CP_DCT) were utilised to improve the surface characteristics of the honing gears. These honing gears were used in P-ECH process for finishing workpiece bevel gears. The experimental results indicates that the hardness of honing gears is crucial factor in improving surface quality of the workpiece bevel gears. Surface quality of workpiece bevel gears was assessed in terms of surface finish. The results show that, honing gears underwent through CP_DCT improves the surface roughness of workpiece gears by over 50% compared to those processed with CP alone. The enhancement will increase the service life and operating performance, reducing noise levels and the chances of premature failures of the finished bevel gears.

Keywords: Surface quality, Hardness, Carburising, Cryogenic treatment, Bevel gear, P-ECH.

INTRODUCTION

Gears are essential components in machinery for transmitting power, altering speed and torque, and change in required direction. Gears are used across various applications, including automotive, marine, aerospace, and industrial sectors. Bevel gears are in high demand across these industries, prompting a focus on producing high-quality, lightweight, cost-effective options. The design of bevel gear is bit complex compare to the other gears like spur and helical, hence it makes finishing challenging, yet crucial for enhancing load capacity and extending service life. The design and finishing of bevel gears greatly influence its performance, noise levels, and wear resistance [1]. Hence, the teeth profile of bevel gears should be smooth and geometrically precise to ensure efficient motion transmission, quiet operation, enhanced performance and extended service life. This can be achieved through a suitable combination of finishing techniques and processes that improve the material properties. Conventional finishing processes like grinding and lapping are particularly suited for bevel gears. Gear grinding improves bevel gear quality but incurs high costs and can cause defects like grind lines and burns, leading to noise, vibration, and potential tooth breakage. In contrast, gear lapping removes material slowly with less precision, resulting in minimal adjustments for the desired tooth profile [2]. These limitations highlight the need for an alternative gear finishing process that is less damaging, more efficient, and independent of the hardness of the workpiece material. This process should be capable of simultaneously enhancing the surface quality of bevel gears. To address these requirements, electrochemical honing (ECH) and its pulsed variant, pulsed electrochemical honing (P-ECH), Abrasive flow finishing (AFF) have been investigated as potential solutions [3]. Figure 1, illustrates the various stages of the gear manufacturing process, covering everything from material turning to the final completion stage, including the quality assessment of the finished gears.

To achieve high-quality gears made from hard materials, hybrid finishing processes are used in the current decades. These techniques combine various conventional finishing methods, such as grinding, honing, and superfinishing, to enhance surface quality and dimensional accuracy. By effectively reducing surface roughness and improving wear resistance, hybrid finishing not only prolongs the lifespan of the gears but also ensures optimal performance under heavy loads and challenging operating conditions. The integration of advanced technologies in hybrid finishing allows for precise control over the finishing parameters, resulting in gears that exhibit superior strength, durability, and reduced noise during operation. The P-ECH process is an innovative approach that combines the strengths of electrochemical finishing (ECF) and mechanical honing, effectively overcoming their individual limitations. One of the key capabilities of P-ECH is its ability to finish workpiece gears made of materials with any hardness, which is a significant advantage over traditional honing techniques. The honing gear (HG) used in P-ECH process removes the passivating metallic oxide layer formed on the flank surface of anodic gear teeth due to oxygen evolution during electrolysis [4].

The review of past research on gear finishing using ECH or P-ECH reveals a common practice of employing either unhardened HGs that possess slightly higher hardness than the workpiece gears or abrasive impregnated HGs. An abrasive impregnated HGs can inflict mechanical damage on the workpiece gears, manifesting as microcracks, scratch marks, and other surface defects. Such damage can lead to a deterioration in surface quality and microgeometry, particularly if the finishing process exceeds the optimal duration or if the HG has a limited lifespan [5]. The surface characteristics of HG are crucial for achieving high-quality finishing outcomes as they directly influence precision, surface quality and overall performance of finished gear. These issues highlight the need for careful selection of HG to ensure high-quality finishing outcomes.

The selection of suitable materials for gears is also crucial, as it ensures excellent hardness and wear resistance while optimizing microstructure through appropriate heat treatment. Most of the automobile industries rely on 20MnCr5 steel for gear manufacturing due to its exceptional toughness and durability [6]. This alloy steel achieves a high surface hardness after undergoing proper heat treatment like carburizing process (CP), while maintaining a tough inner core, enabling it to withstand heavy loads and resist wear effectively. The CP further enhances 20MnCr5 gears surface properties, ensuring long-lasting performance in rigorous applications. As a result, this alloy steel is commonly used in various automotive components, including transmission gears, differential gears, and drive shafts, where precision and reliability are paramount hence preferred as material in many industrial sectors including automotive for high-performance gear applications.

Deep cryogenic treatment (DCT) applied after carburizing offers significant enhancements to the properties of 20MnCr5 gears, making them well-suited for demanding applications [7]. One of the primary benefits of DCT is the substantial improved in gear material properties. The treatment facilitates the transformation of retained austenite into martensite, which is known for its superior hardness. This increase in hardness directly contributes to the gear's ability to withstand wear and deformation during operation. Moreover, retained austenite can convert to martensite when subjected to strain during operation, result in grinding cracks during machining and finishing processes [8]. Another major advantage of DCT is the improvement in wear resistance. The process promotes the formation of ultra-fine carbides within the microstructure, which significantly enhances the gear's durability against abrasive forces. This is particularly important in applications where gears are subject to high friction and wear, as it helps maintain performance over extended periods. In addition to hardness and wear resistance, DCT also plays a critical role in reducing residual stresses that can be introduced during the CP. Reducing these stresses enhances the dimensional stability of the gears through DCT, ensuring they retain precise tolerances and operate reliably across different conditions. Furthermore, the refined microstructure resulting from DCT contributes to improved toughness, reducing the risk of crack propagation and failure under dynamic loads. The application of DCT after carburizing significantly optimizes the mechanical properties of 20MnCr5 gears [7]. The combined benefits of increased hardness, enhanced wear resistance, reduced residual stresses, and improved toughness contribute to a longer service life and more consistent performance.

In light of these challenges, the present work aims to investigate how heat treatment affects the surface quality of the workpiece straight bevel gears made of 20MnCr5, which were heat treated by the CP and subsequently underwent DCT to enhance their properties.

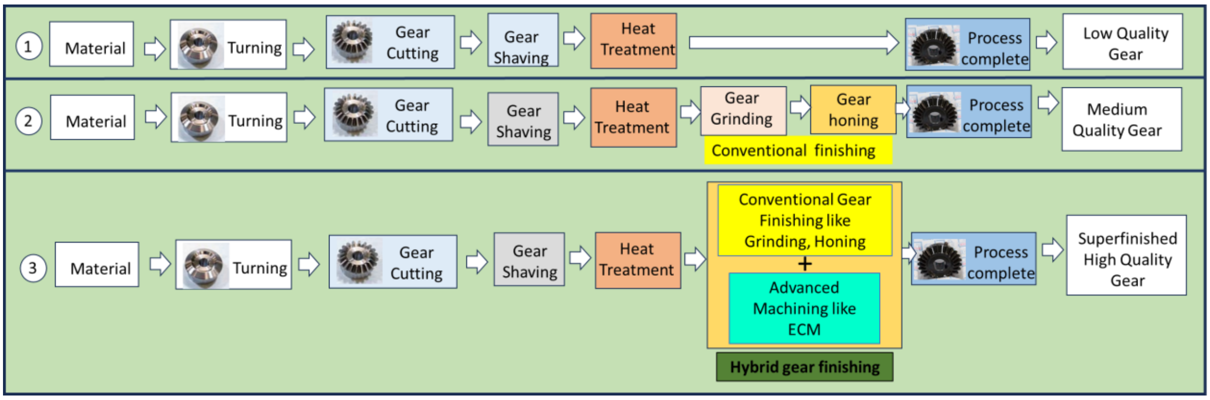


Figure 1. Various stages of gear manufacturing process with corresponding quality

P-ECH PROCESS IN GEAR FINISHING:

The proposed finishing process for bevel gears using Pulse Electrochemical Machining (P-ECM) and conventional mechanical honing (MH) combined to form Pulse Electrochemical Honing (P-ECH), a hybrid advanced gear finishing technique. A setup with paired matching cathode gears is used to ensure effective finishing while avoiding short-circuiting. In figure 2 (c), The anodic workpiece gear (gear '1') is mounted on a spindle, with two paired matching cathode gears (gear '3' and gear '4') designed to maintain a inter electrode gap (IEG) to prevent short circuits while ensuring contact with the workpiece.

Cathode gears: The cathode gear '3', features an insulating layer of cast Nylon material fixed behind the layers of copper, while cathode gear '4', has a conducting layer of copper placed ahead of cast Nylon material to form a paired matching cathode gears. The conducting layers are undercut by 1 mm to maintain the required insulating gap known as IEG.

A honing gear: The gear '2', with a hardness greater than the workpiece gear is in mesh with workpiece bevel gear. Both working bevel and honing gears possess the same involute profile, and their axes are perpendicular to the axes of the cathode gears.

Electrolyte Supply: A continuous flow of electrolyte ('5') is supplied to the IEG, with a DC current applied across the gap to facilitate the electrochemical process.

Material Removal Process: During the electrochemical material removal process, electrolysis generates a metal oxide passivating layer on the tooth surface of the workpiece gear, which hinders further material removal by P-ECM. The honing gear effectively scrapes off this passivating layer. A tight mesh between the honing and workpiece gears ensures dual flank contact and provides the necessary pressure to remove the layer. As a result, more material is removed from the high spots during the next electrochemical cycle. This continuous dual action of ECM and mechanical honing enhances the surface finish and characteristics of all the teeth on the workpiece gear simultaneously [9]. This dual action ensures that each tooth receives consistent treatment, leading to a uniform improvement in surface quality. Over multiple cycles, the continual refinement enhances the gear's performance, durability, and efficiency, making the gears more suitable for precise applications.

There are limited references available on the finishing of gears, particularly bevel gears, using ECH, and even fewer on the finishing of gears with P-ECH. Chen et al. [10] developed an experimental setup for finishing spur gears with ECH, noted improvements in surface finish, teeth profile accuracy, and reduced noise levels. He et al. [11] employed slow-scanning field controlled (SSFC) ECH as a time-control method to correct profile errors in the spur gears. Yi et al. [12] used ECH for finishing spur gears and observed improvements in surface roughness and tooth profile accuracy compared to unfinished gears. Their work highlighted the stabilization of ECH as a promising method for correcting micro-geometrical errors, noting its superior productivity compared to gear grinding. They noted that modifying the gear tooth profile is one effective approach to enhancing the load-carrying capacity of the gears. Capello and Bertoglio [13] were used ECH for finishing hardened helical gears. They employed a specially designed cathode shaped like a helical gear, while Misra et al. [14] used sandwiched copper cathode gear between two Bakelite gears. They mentioned that, ECH can finish gears of any hardness irrespective of heat treatment. Shaikh et al. [15] finished bevel gears using the ECH process. They introduced the concept of complementary cathode gears to address the challenges of synchronized finishing of all bevel gear teeth ensuring the maintenance of the required inter-electrode gap. In their most recent work, Pathak et al. [16] further advanced P-ECH for straight bevel gears, investigating the effects of various process parameters on the synchronized improvement of surface quality, microgeometry, and surface integrity of the P-ECH finished gears.

Previous research on gear finishing addresses the limitations of traditional honing gears used in gear finishing by investigating the impact of honing gear hardness on the surface quality of spiral bevel gears. By applying cryogenic treatment post carburising case hardening, the research bridges the gap to ensure the performance and durability of honing gears, reducing the risk of mechanical damage such as microcracks and scratches, which can compromise surface quality. This approach seeks to improve the overall effectiveness of the finishing process, ensuring better surface characteristics and longevity of the workpiece gears.

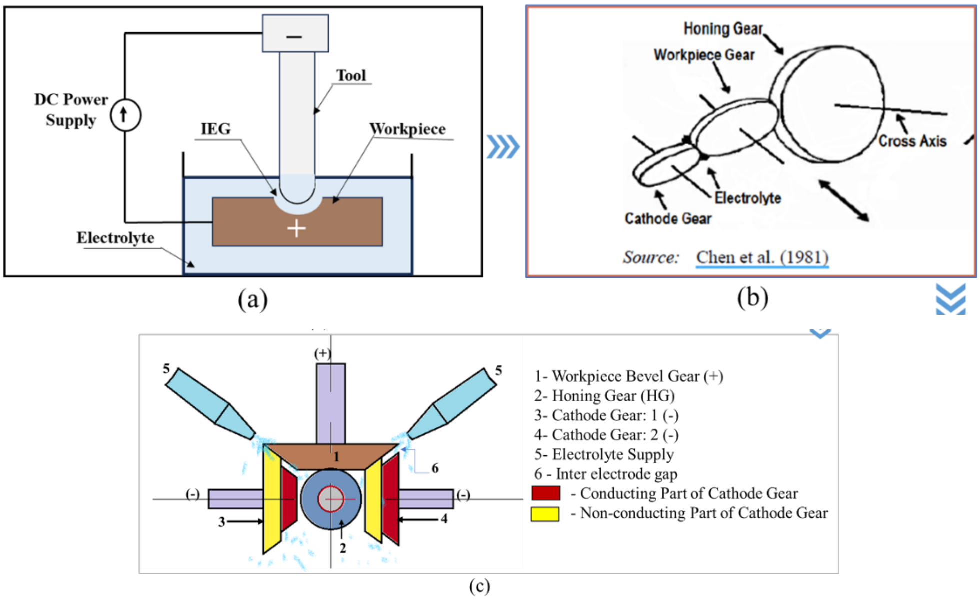


Figure 2. shows (a) the conceptual diagram for ECM process, (b) working principal of ECH explained by Chen et al. and (c) Paired matching cathode gears: concept used in current research for finishing of bevel gear in P-ECH process.

MATERIAL AND METHODS:

Selection of straight bevel gear workpiece and HGs materials: In this research, alloy steel, 20MnCr5 with a hardness of 54 HRC is used as the material for straight bevel gears. Alloy steel is selected due to its excellent mechanical properties, including high tensile strength, high fatigue strength, high hardness, and high Young's modulus, making it ideal for manufacturing bevel gears in various commercial applications [17]. The standard size of the alloy steel bevel gear is sourced from the automobile industry, as shown in Figure 3.

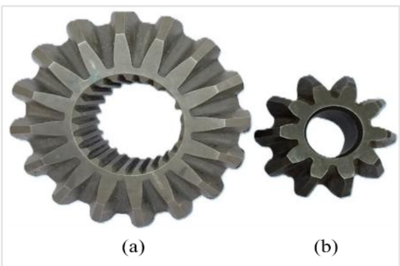


Figure: 3. Photograph of (a) the Workpiece straight bevel gear and (b) honing (pinion) gear.

The dimensional specifications of the straight bevel gear workpiece bevel are provided in Table 1. The chemical composition of the 20MnCr5 alloy steel is detailed in Table 2.

Table1. Specifications of straight bevel gear and honing gear.

Parameter	Gear	Pinion (Honing Gear)
No. of Teeth	16	10
Outside Diameter (mm)	82.23	58.1
Module (mm)	5	

Table 2. Chemical composition of 20MnCr5 alloy steel used for workpiece and honing gears.

Cr	Mn	C	P	Si	S
1-1.3%	1.1-1.4%	0.17-0.22%	max. 0.025%	max. 0.4%	max. 0.035%

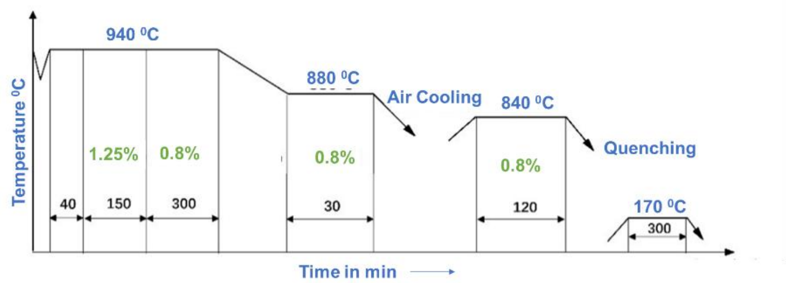
HEAT TREATMENT OF HGS:

The heat treatment of HG is carried in two stages (i) Case hardening of HG through Carburising process and (ii) post carburising deep cryogenic treatment.

(i) Case hardening of the HG through carburising:

Case hardening of the HG made of 20MnCr5 alloy steel was done using carburising process as shown schematically in Figure 4. To achieve a uniform and effective carburizing layer, the HG was initially cleaned using an aqueous cleaning process to eliminate oils, greases, and other contaminants. Following the cleaning, the HG was rinsed with clean water to remove any residual cleaning agents. Finally, it was dried in drying ovens to prevent oxidation before the carburizing process.

For achieving a uniform and effective carburizing layer, before carburising, the HG was cleaned by aqueous cleaning process to remove oils, greases, and other contaminants. After cleaning, the HG rinsed with clean water to remove any residual cleaning agents. The HG dried using drying ovens to prevent oxidation before carburizing.



The comprehensive heat treatment sequence shown in figure 4 ensures that the HG achieves the optimal balance of hardness and wear resistance necessary for its intended application in the P-ECH process. The hardness of HG after carburising was measured using microhardness tester, it found in the range of 59-60 HRC.

Figure 4. Schematic illustration of the carburizing heat treatment processes cycle used for honing gears

(ii) Cryogenic heat treatment on HG after carburising:

Cryogenic treatment, also known as deep cryogenic treatment (DCT), is an advanced process that serves as an enhancement to conventional heat treatment of steel. This technique involves subjecting steel components to extremely low temperatures, typically below -196°C, which significantly alters their microstructure and improves various mechanical properties. Research over the past two decades has shown that significantly enhancing mechanical properties, especially wear resistance, can be achieved by further reducing the temperature of sub-zero treatments. This is accomplished by using liquid nitrogen (LN_2) as a cryogen or cooling agent. This approach not only improves the hardness and durability of materials but also contributes to the transformation of retained austenite into martensite, thereby optimizing the performance of various components.

Three HGs underwent heat treatment using conventional carburizing process, used for deep DCT. Figure 5, shows the DCT applied on the HGs after carburising. DCT was conducted to enhance the mechanical properties of carburized 20MnCr5 HGs. This procedure aimed to improve wear resistance and hardness by transforming retained austenite into martensite and promoting the formation of ultra-fine carbides.

The process began with the preparation of the carburized gears, which involved a thorough visual inspection to identify any surface defects such as cracks or pitting. Dimensional verification was performed using precision measuring instruments to ensure that the gears met specified tolerances. Following inspection, the gears were cleaned to eliminate any oils, greases, or contaminants. This was accomplished through aqueous cleaning, where the gears were immersed in a water-based detergent solution and then rinsed. Alternatively, vapor degreasing was used to effectively remove residual contaminants with solvent vapors.

After cleaning, the gears underwent pre-cooling to prevent thermal shock before the cryogenic treatment. This involved gradually reducing the temperature of the gears by placing them in a cold chamber, with a controlled cooling rate of approximately 1°C to 2°C per minute until they reached -100°C. Thermocouples were attached to monitor the temperature continuously, ensuring uniform cooling throughout the components. Once the gears were adequately pre-cooled, they were submerged in liquid nitrogen at approximately -196°C. This step was crucial for facilitating the transformation of retained austenite into martensite. The gears were held at cryogenic temperatures for a duration ranging from 24, 48, and 72 hrs (named as soaking time CP_DCT-1, CP_DCT-2, and CP_DCT-3 steels, respectively), allowing sufficient time for microstructural changes, including the precipitation of ultra-fine carbides. Finally, the samples were warmed to room temperature and then tempered at 150°C for 1 hour.

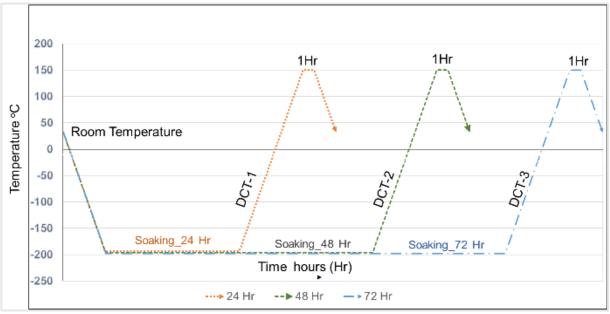


Figure 5. Schematic of Deep cryogenic treatment applied on the HGs after carburising.

HARDNESS TEST ON 20MNCR 5 HGS AFTER DCT:

After the completion of DCT, hardness testing was conducted on the 20MnCr5 gears to evaluate the effectiveness of the treatment and to quantify improvements in mechanical properties. Table 3 Shows the results of Rockwell hardness test performed on honing gear. The results from the hardness tests were compared to pre-treatment values to assess the effectiveness of the DCT. An increase in hardness values after DCT indicated successful transformation of retained austenite into martensite and the formation of ultra-fine carbides, leading to enhanced wear resistance and overall performance of the 20MnCr5 gears.

Table 3. The results of Rockwell hardness test on Honing gears

HG code used for DCT	Soaking Time (hrs)	Before DCT (HRC)	After DCT (HRC)
CP_DCT-1	24	60	61
CP_DCT-2	48	60	62
CP_DCT-3	72	60	62

The results indicate that a soaking time of 48 hours during deep cryogenic treatment (DCT) yields a hardness of 62 HRC (for CP_DCT-2), which is higher than the hardness achieved after soaking for 24 and equal to 72 hours (i.e. CP_DCT-1 and CP_DCT-3). There is no increase in hardness effect observed on HG for CP_DCT-3, having soaking time 72 hours, which is 24 hours more than CP_DCT-2 in the cryogenic treatment cycle. Following this, the workpiece bevel gears made from 20MnCr5, with comparatively less hardness of 50-54 HRC undergo a P-ECH finish. While, the HGs, which has a hardness of 61-62 HRC (CP_DCT-1,2,3), are utilized in the P-ECH process for finishing the workpiece bevel gears. CP_DCT-1

EXPERIMENTATION:

In the experiments, P-ECH process was used to finish the four identical specifications workpiece gears using CP and CP_DCT-1,2,3 heat-treated honing gears, possessing distinct hardness characteristics. The outcomes were assessed through surface roughness measurements.

The experimental setup for finishing bevel gears was designed using the concept of a paired matching cathode gear, design and developed indigenously by the author for the experiments. Figure 6. shows a photograph of the developed finishing chamber, depicting the arrangement of the workpiece bevel gear, two paired matching cathode gears cathode gears, and the HG. The setup comprises four key components: (i) DC pulse power supply unit to delivers precise electrical energy essential for the electrochemical finishing process, enabling fine control over operational parameters. (ii) Electrolyte Supply, cleaning, and recirculation unit to maintains optimal conditions by supplying, cleaning, and recirculating the electrolyte at predetermined temperature, pressure, and flow rate, thereby enhancing surface finishing efficiency. (iii) Finishing chamber to houses the workpiece bevel gear, the cathode gears, and the HG, ensuring a controlled environment that minimizes external contamination during the finishing process. and (iv) Drive unit to provides rotary motion to the workpiece bevel gear and incorporates an automated feed mechanism for the precise engagement and disengagement of the workpiece bevel gear with both the cathodes and HGs.

The paired matching cathode gears and a HG are positioned perpendicularly to the workpiece bevel gear, with the axes of the cathode gears aligned and the HG's axis perpendicular to them. The point of contact the cathode and HG with the workpiece gear kept perfectly in one plane. The workpiece gear is driven by a DC motor, while the cathode gears and HG rotate due to their close meshing with the workpiece gear. The other parameters employed in the experiments are selected from literature [16] and mentioned in the table 4.

All Workpiece gears were manufactured from 20MnCr5 alloy steel, a widely used material for commercial bevel gears, with an initial hardness of 54-55 HRC. The gears were manufactured on a Gleason-principle-based bevel gear manufacturing machine, in a reputed bevel gear manufacturing industry, ensuring high precision in their geometry.

Table 4. The fixed and variable parameters employed in the experiments.

Variable input			**Fixed input**		
HG parameter			a	**P-ECH parameters**	
Case hardening process		Hardness (HRC)		Pulse time-On (T_{on}) = 2 ms	Pulse time-Off T_{off} = 4.5 ms
i	(CP)	60	b	Finishing Time = 6 min	
ii	(CP_DCT-1) soaking time 24 hours	61	c	IEG = 1mm	
iii	(CP_DCT-2) soaking time 48 hours	62	d	Voltage = 12 V	
iv	(CP_DCT-3) soaking time 72 hours	62	e	Finishing Time = 6 min	
			f	Rotary speed of workpiece bevel gear = 40 rpm	
			g	Electrolyte composition, 75 % NaNO3 + 25 % NaCl	
			h	Electrolyte concentration, 7.5 wt %	
			i	Electrolyte temperature, 32 °C	
			j	Electrolyte flow rate, 30 litter per minute (lpm)	

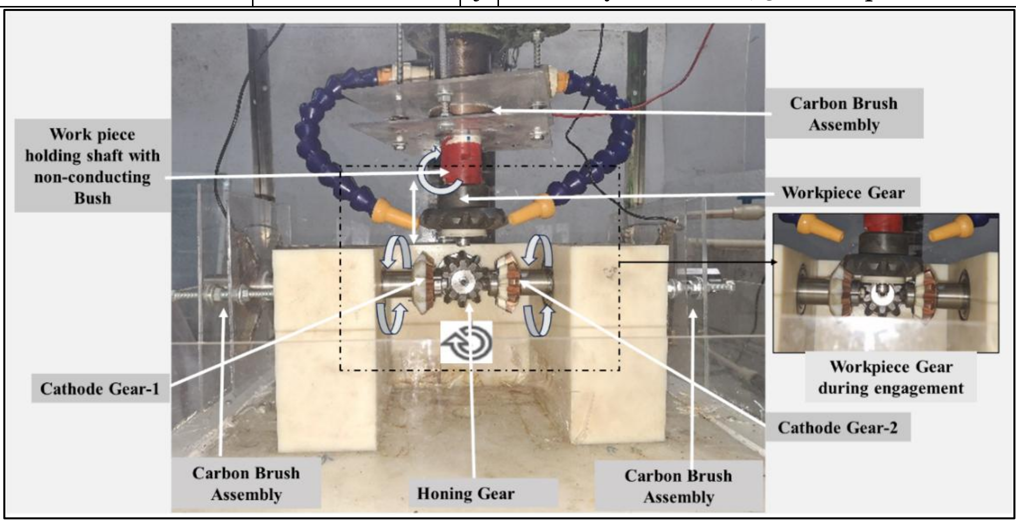


Figure 6. Photograph of the finishing chamber, depicting the arrangement of the workpiece straight bevel gear, two paired matching cathode gears, and the HG

The evaluation of the surface quality of P-ECH finished gears involved a comprehensive analysis of surface finish of workpiece gears. Surface finish improvements were quantified using percentage improvements in average surface roughness ($\%\Delta R_a$) and maximum surface roughness ($\%\Delta R_{max}$). Percentage improvement in average surface roughness '($\%\Delta R_a$)' was calculated using equation (1).

$$\%\Delta R_a = \frac{R_a \text{ value before PECH} - R_a \text{ value after PECH}}{R_a \text{ value before PECH}} \times 100 \quad \ldots (1)$$

Similarly average values of % ΔR_{max} was computed using corresponding average values. To measure surface roughness, a surface roughness analyser (Zeiss Accretech) was utilized. Measurements were taken from both the left and right profiles at the midpoint of the face width of two consecutive gear teeth, before and after the P-ECH finishing process. The evaluation lengths set for this analysis were 3.4 mm with a cut-off length of 0.8 mm. The arithmetic mean of the measured values for R_a and R_{max} was calculated to determine the percentage improvements, $\%\Delta R_a$ and $\%\Delta R_{max}$, respectively. This systematic approach ensures a thorough understanding of the surface quality enhancements achieved through the finishing process.

RESULTS AND DISCUSSION

Surface Finish

Table 5. compares the surface finish parameters of four similar straight bevel gears (SB-1 to SB-4), SB-1 finished using HG of case hardened through carburised process and SB-2, 3 and 4 finished using HG, which underwent both the CP for case hardening and additional DCT through the P-ECH process. The results indicate a significant difference in surface finish improvements between these methods. Specifically, the straight bevel gear (SB-3) finished with the HG underwent both the carburizing process for case hardening and additional deep cryogenic heat treatment (CP_DCT-2) achieved a 65.01% improvement in maximum surface roughness ($\%\Delta R_{max}$), which is 55.9 % greater than the 41.7 % improvement observed with the case hardened through carburised process HG. Additionally, the average surface roughness ($\%\Delta R_a$) for the HG underwent both the carburizing process for case hardening and additional deep cryogenic heat treatment (CP_DCT-2) was improved by 50.1 %, compared to 43.3% improvement for the unhardened gear. The other results are presented in the table shows similar improvement in maximum and average surface roughness of straight bevel gear finished with HG in P-ECH using CP_DTC-1,3 compare to straight bevel gear finished with HG through case hardened using carburised process.

Overall, the use of the HG underwent both the carburizing process (CP) for case hardening and additional deep cryogenic heat treatment (CP_DCT-2), demonstrates a clear advantage in enhancing surface quality, highlighting the critical role of material properties in gear finishing processes.

Table 5 Comparison of surface finish parameters of bevel gears finished with CP and CP_DCT honing gears.

Work Piece bevel gear	Type of HG used in P-ECH	Average value of R_a (μm)		(% ΔR_a)	Improvement compares to CP (%)	Average value of R_{max} (μm)		(% ΔR_{max})	Improvement compares to CP (%)
		Before finishing	After finishing			Before finishing	After finishing		
SB-1	CP	2.60	1.47	43.30	-	12.35	7.20	41.7	-
SB-2	CP_DCT-1	2.88	1.43	50.10	11.57 %	13.38	6.13	54.18	29.92
SB-3	CP_DCT-2	2.97	1.31	55.88	12.90 %	16.03	5.61	65.01	55.90
SB-4	CP_DCT-3	2.82	1.33	53.44	12.34 %	13.57	4.98	63.30	51.79

CONCLUSION:

This paper reported on role of honing gear hardness in improving the surface finish, and microhardness parameters of the bevel gear finished by P-ECH. The results have shown significant improvements in the parameters of surface quality of the bevel gears finished using honing gears, which underwent through the carburizing process followed by deep cryogenic heat treatment (CP_DCT-1,2,3).

The following conclusions derived from the current study:

1.The honing gear underwent through the carburizing process followed by additional deep cryogenic heat treatment significantly improves the surface quality of bevel gears, leading to better service life, performance, and corrosion resistance while reducing transmission errors.

2. Bevel gears finished with honing gear underwent through the carburizing process followed by additional deep cryogenic heat treatment exhibit an improvement in maximum surface roughness by over 50% compared to those processed with only carburising process.

3. All three honing gear underwent through carburizing process followed by additional deep cryogenic heat treatment for different soaking time i.e. 24, 48 and 72 hours shows improvement in surface roughness of the workpiece bevel gears.

4. The honing gear underwent through carburizing process followed by additional deep cryogenic heat treatment for 48 hours soaking time exhibits better results for surface finish and of workpiece bevel gears.

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