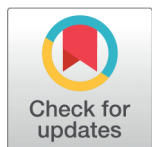


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Cryo-Engineered Alumina-PTFE Composite Venturis for Enhanced Wear Resistance in Powder Coating Systems

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Abstract

Background/Objectives: Venturi components in powder coating systems are high velocity powder – air flow continuously operating wear sensitive parts. Currently, venturis are made of virgin polytetrafluoroethylene (PTFE) suffer progressive wear at the throat, which compromises suction performance, powder flow and uniformity of coating. **Method:** Based on earlier optimization trials involving alumina addition in the range of 0.5–5 wt.%, 1.5 wt.% Al_2O_3 was identified as the optimum composition. Cryogenic treatment (CT) was performed on virgin PTFE and 1.5 wt.% alumina-PTFE composite samples for 8, 12, and 16 h to optimize the soaking duration. The optimum treatment durations were found to be 12 h for virgin PTFE and 16 h for the alumina-PTFE composite. Accordingly, PTFE + 1.5 wt.% alumina composite venturis were fabricated. Both market-available virgin PTFE venturis and developed PTFE-1.5 wt.% Al_2O_3 composite venturis were subjected to CT for these optimized conditions and further evaluated through industrial trials. **Findings:** The optimum PTFE-1.5 wt.% Al_2O_3 composite exhibited a 21.4% lower wear rate than virgin PTFE during laboratory-scale abrasive wear testing. CT further reduced the wear rate by 23.1% for virgin PTFE and 17.3% for the PTFE-1.5 wt.% Al_2O_3 composite under their respective optimum soaking durations. Industrial trials demonstrated that the cryo-treated PTFE-1.5 wt.% Al_2O_3 venturi exhibited the lowest wear rate of 27.6 $\text{mm}^3/\text{N-m}$, corresponding to an overall wear reduction of approximately 22.3% compared with the untreated commercial PTFE venturi. The improvement is attributed to enhanced load-bearing capability provided by nano-alumina reinforcement together with stress relaxation, structural stabilization, and improved resistance to powder-induced erosive-abrasive wear after CT. **Novelty:** Previous studies have primarily focused on laboratory-scale tribological evaluation of PTFE composites or CT of polymeric materials independently. In contrast, the present work integrates alumina-reinforcement optimization, CT optimization and validation under actual industrial powder-coating conditions using fabricated venturi components. The study therefore bridges the gap between laboratory-scale material development and industrial implementation of wear-resistant PTFE venturis. The developed cryo-engineered alumina-PTFE venturi offers a practical solution for improving component service life, reducing replacement costs, reducing the frequency of maintenance and improving the long-term reliability of industrial powder coating systems.

Keywords: PTFE; Alumina; Venturi; Powder coating; Cryogenic treatment; Wear resistance

1 Introduction

Poly tetra fluoro ethylene (PTFE) is widely used for venturi fabrication because of its excellent chemical resistance, low coefficient of friction and self-lubricating characteristics. However, virgin PTFE exhibits relatively low hardness, limited load-bearing capability and poor wear resistance under abrasive and erosive conditions. Burris and Sawyer⁽¹⁾ reported that although PTFE possesses excellent low-friction characteristics, its wear resistance is often insufficient for demanding tribological applications. Similar observations have been reported in subsequent studies, where significant material removal and surface degradation were observed when PTFE was subjected to continuous wear conditions⁽²⁾. Consequently, considerable research efforts have focused on improving the tribological performance of PTFE through the incorporation of suitable reinforcements. Recent developments in PTFE-based composites have demonstrated that ceramic, carbonaceous and hybrid reinforcements can significantly improve wear resistance and mechanical stability. Kamal et al.⁽³⁾ reported that reinforced PTFE composites fabricated from industrial scrap exhibited superior mechanical strength and wear resistance compared with virgin PTFE. Li et al.⁽⁴⁾ demonstrated that nanoparticle addition can improve the wear resistance of PTFE composites by increasing matrix stiffness and reducing deformation during sliding contact. Similarly, Deshpande *et al.*⁽⁵⁾ reported that filler-induced improvements in load-transfer mechanisms contribute significantly to enhanced tribological performance in PTFE-based composites. These studies collectively indicate that reinforcement engineering is an effective approach for extending the service life of PTFE components operating under severe wear conditions.

Alumina (Al_2O_3) has been recorded to have a high hardness, thermal stability and resistance to abrasive wear and is therefore of great interest as a reinforcing material for PTFE. Zhao and Zhu⁽⁶⁾ studied the mechanical and tribological properties of Al_2O_3 /PTFE composites for self-lubricated bearing materials and found that the mechanical and tribological performance of these composites were strongly influenced by the characteristics of the alumina particles. Tian *et al.*⁽⁷⁾ reported that nano alumina reinforcement improves the wear resistance by improving the load-bearing capability and reducing the degradation of the surface. Furthermore, Huang *et al.*⁽⁸⁾ have shown that alumina-containing PTFE coatings have better tribological properties and surface durability, because of their structural stability and resistance to damage caused by wear. The results presented here show that alumina is a suitable reinforcement to enhance the wear resistance of PTFE-based systems. In addition to reinforcement strategies, cryogenic treatment (CT) has proved to be a successful post-processing technique to improve the performance of polymeric materials and composites. Indumathi *et al.*⁽⁹⁾ found that CT was found to enhance wear properties of engineering polymers and composites by altering the structure and increasing resistance to material removal. Pande *et al.*⁽¹⁰⁾ have shown that treatment time can have a significant effect on the thermal, structural and mechanical properties of PTFE, thus, optimizing the cryogenic parameters becomes critical. Other researchers have additionally proposed that CT can be used to relax stress, stabilize dimensions, increase matrix compactness and increase the interaction between matrix and filler in polymer composites, which results in greater resistance to wear and in-service performance^{(11), (12)}.

Although much of this work has been performed on the laboratory scale, most of the reported studies have been on tribological characterisation of PTFE composites and very little information is available about the use of alumina filled PTFE composites in continuous high velocity powder flow condition in powder coating venturi system. Furthermore, reinforcement optimization and cryogenic treatment have generally been investigated independently. Studies examining the combined influence of optimized alumina reinforcement and optimized cryogenic treatment on PTFE venturi performance under actual industrial operating conditions remain scarce.

Therefore, the present study investigates a combined strategy involving nano-alumina reinforcement and cryogenic treatment for improving the wear resistance of PTFE-based venturi components. PTFE composites containing varying nano-alumina contents were initially evaluated to identify the optimum filler concentration. Cryogenic treatment durations were subsequently optimized for both virgin PTFE and the selected alumina-filled PTFE composite. Finally, venturi components fabricated from virgin PTFE and the developed PTFE– Al_2O_3 composite were subjected to optimized cryogenic treatment and evaluated under actual industrial powder coating conditions. The study provides a systematic assessment of reinforcement optimization, cryogenic treatment and industrial validation for the development of longer-life, wear-resistant venturi components.

2 Methodology

Many recent studies report the potential of alumina reinforcement and CT for improving the tribological performance of PTFE, but separately. Zhao and Zhu⁽⁶⁾ explore only the influence of alumina content on wear behavior of PTFE. Similarly, Tian *et al.*⁽⁷⁾ and Huang *et al.*⁽⁸⁾ only reported the improvement in wear resistance and surface durability by optimizing the alumina content in PTFE. On the other hand, Indumathi *et al.*⁽⁹⁾ and Pande *et al.*⁽¹⁰⁾ demonstrated that effectiveness of CT alone on the structural stability and wear performance of virgin PTFE. Additionally, all these studies are restricted to laboratory-scale

tribological testing. The methodology adopted in the present work is developed to address these limitations. Based on the wear-performance improvements reported for alumina-reinforced PTFE composites^{(6), (7), (8)}, nano-alumina was selected as the reinforcement phase, and its optimum content is determined through systematic abrasive wear testing. Later, considering the treatment-duration dependence reported by Pande *et al.*⁽¹⁰⁾, the CT duration is optimized separately for virgin PTFE and the optimized alumina-filled PTFE composite. Unlike earlier studies, the optimized material systems were further fabricated into actual venturi components and validated under industrial powder coating operating conditions. This sequential approach enables evaluation of the combined influence of filler optimization, CT optimization and industrial implementation within a single study, thereby providing a direct link between laboratory-scale material development and practical venturi service performance.

2.1 Materials

Virgin PTFE powder, Inoflon® 610 supplied by Gujarat Fluorochemicals Ltd., India, was used as the matrix material. As per the manufacturer's data, the powder with an average particle size of approximately 200 μm , bulk density of 450 $\text{g}\cdot\text{L}^{-1}$, standard specific gravity of 2.15, and mould shrinkage of about 3.2%. The mineral nanofillers; nano-alumina (Al_2O_3) with an equiaxed/globular morphology was used. This was procured in powder form from Platonic Nanotech Pvt. Ltd., Jharkhand, India, with an average particle size of approximately 50 nm. Alumina-filled PTFE composites were prepared by incorporating alumina particles into the PTFE matrix at different filler loadings ranging from 0.5 to 5 wt.% as mentioned in Table 1 (Part - A). This compositional range was selected to understand the influence of alumina addition on the wear resistance of PTFE. The prepared composites were systematically evaluated to identify the influence of increasing alumina content over the abrasive wear behavior, material loss, and overall durability. The study helped determine the optimum alumina loading that provides improved wear performance without adversely affecting the inherent properties and processability of PTFE.

Table 1. Composition and sample designation of alumina-filled PTFE composites and cryogenically treated PTFE-based samples

Sr. No.	Composition	Sample code
PART – A		
1	Pure PTFE	P0
2	PTFE + 0.5 wt.% nano-alumina	P0.5
3	PTFE + 1 wt.% nano-alumina	P1
4	PTFE + 1.5 wt.% nano-alumina	P1.5
5	PTFE + 2 wt.% nano-alumina	P2
6	PTFE + 2.5 wt.% nano-alumina	P2.5
7	PTFE + 5 wt.% nano-alumina	P5
PART – B		
1	Pure PTFE – untreated	PU
2	Pure PTFE – CT for 8 hrs	P8
3	Pure PTFE – CT for 12 hrs	P12
4	Pure PTFE – CT for 16 hrs	P16
5	PTFE + 1.5 wt.% nano-alumina - untreated	AU
6	PTFE + 1.5 wt.% nano-alumina – untreated – CT for 8 hrs	A8
7	PTFE + 1.5 wt.% nano-alumina – untreated – CT for 12 hrs	A12
8	PTFE + 1.5 wt.% nano-alumina – untreated – CT for 16 hrs	A16

2.2 Composite and Venturi fabrication process

Based on the abrasive-wear study on PTFE nanocomposites, 1.5 wt.% nano-alumina was selected as the optimum filler loadings for venturi fabrication and subsequent cryogenic treatment study. Thus, the virgin PTFE and PTFE reinforced with 1.5 wt.% nano-alumina were selected for the cryogenic treatment study. The composite Venturi manufacturing consisted of compression molding, controlled sintering and precision machining. The provided manufacturing documentation indicates both PTFE powder and nano alumina powder were pre-heated at 100°C for 2 hours to remove moisture and volatiles prior to molding. The powders were then dried and mixed well for uniform distribution of alumina in the PTFE matrix. Green compacts were formed by compacting the mixture at around 2000 psi (13.8 MPa) for 10 minutes. These compacts were then sintered by a controlled

sintering cycle that involved heating to 360–380°C and holding for 2–3 hours to allow the PTFE to fuse and consolidate around the alumina particles. Slow cooling at approximately 0.5–1°C/min was used to minimize warpage, residual stresses, and internal cracking.

After sintering, the consolidated rods were machined through lathe-based facing, turning, and boring operations to obtain the required Venturi geometry. Because alumina was present as a hard ceramic filler, suitable machining conditions such as low cutting speed and carbide tooling were used to maintain dimensional accuracy and tool life. The manufacturing and machining of the PTFE–alumina composite venturis were carried out with industrial support from JV Fluoropolymers, Gujarat. Figure 1 (a and b) shows the fabricated Venturi components manufactured from (a) virgin PTFE and (b) alumina-filled PTFE composite material, whereas, Figure 1 (c and d) shows the actual setup for the powder coating at industry. The manufactured Venturi consisted of a converging and throat section. Among these regions, the throat was considered the most critical from a wear point of view because it experiences maximum flow velocity and highest powder erosion intensity.

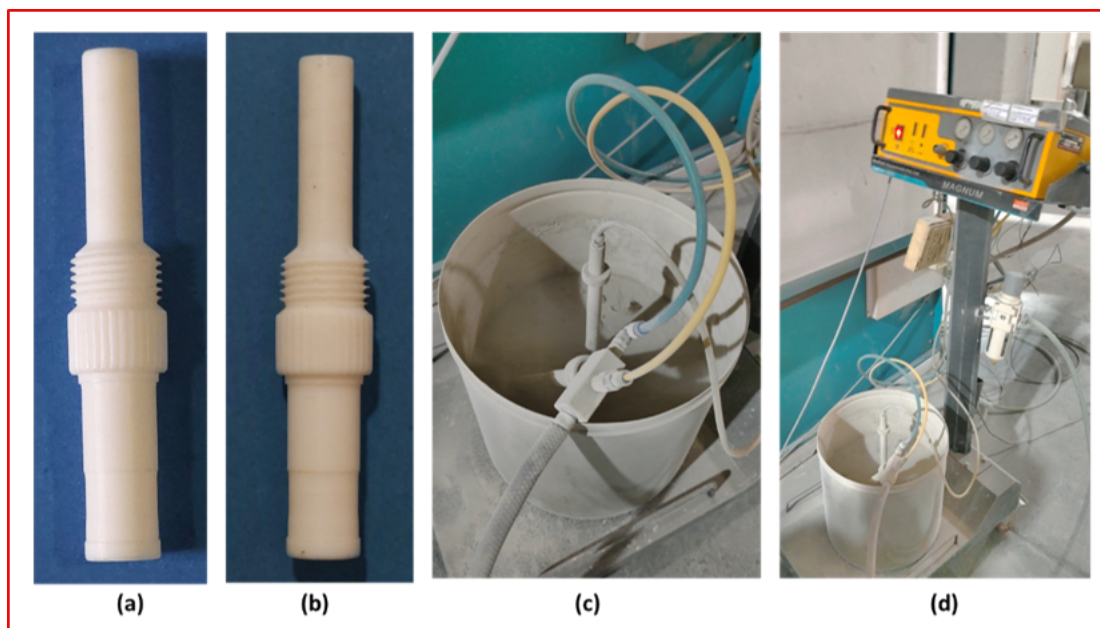


Fig 1. Fabricated Venturi components and industrial powder coating assembly: (a) virgin PTFE Venturi, (b) alumina-filled PTFE composite Venturi, (c) close-up view of Venturi fixing in the actual powder coating assembly, and (d) actual industrial powder coating setup

2.3 Cryogenic Treatment Procedure

Cryogenic treatment (Cryo-treatment) was carried out on both pure PTFE and PTFE + 1.5 wt.% nano-alumina composite samples for different holding durations, namely 8, 12, and 16 h. The untreated samples were also considered as reference materials for comparison. The sample designation used for the study is mentioned in Table 1 (Part -B). Based on the comparative performance evaluation, the cryogenic treatment duration was optimized separately for pure PTFE and PTFE + 1.5 wt.% nano-alumina composite. Subsequently, the market-available PTFE Venturi and the fabricated PTFE + 1.5 wt.% nano-alumina composite Venturi were subjected to their respective optimized cryogenic treatment conditions for further performance assessment.

The cryogenic treatment was conducted in a liquid nitrogen-based cryostat using an in-house fabricated cryostat. The treatment cycle involved controlled cooling from room temperature to approximately $-185 \pm 5^\circ\text{C}$ at a rate of about 1.3–1.5°C/min, soaking at the target temperature, and subsequent controlled warming to room temperature at the same rate. The samples were then stabilized in the laboratory for at least 24 hours prior to industrial testing. Controlled cooling and heating are significant for polymeric materials as sudden cooling and heating can generate internal stresses and/or microcracks in the material. The gradual cooling–soaking–warming process was chosen in the present case to permit the relaxation of stresses and structural stabilization of the PTFE matrix.

2.4 Wear performance testing

The complete test matrix presented in Table 1 was tested for abrasive wear performance on a pin-on-disc type Multi Pass Tribometer from Magnum Engineering, Bangalore, India. To ensure uniformity in specimen shape throughout this study a rectangular pin specimen was used with dimensions of 10 mm × 10 mm × 30 mm. The wear tests were conducted against 220-grade SiC abrasive paper, which was firmly fixed onto a rotating steel disc. A constant normal load of 50 N, sliding speed of 200 rpm, track diameter of 80 mm, and test duration of 3 min were maintained for all experiments at room temperature. Before and after each test, the specimens were cleaned, dried, and weighed using an analytical balance with a precision of 0.1 mg. The mass loss obtained after testing was used to calculate the specific wear rate (SWR) by considering the specimen density, applied normal load, and sliding distance. For each material condition, a minimum of three replicate tests were performed, and the average SWR along with standard deviation was reported.

2.5 Optimized cryo-treatment parameters for Venturi samples

After optimization of the cryogenic treatment parameters for the fabricated composite samples, venturi components were prepared and subjected to cryogenic treatment using the selected soaking durations. As shown in Table 2, the market-available virgin PTFE venturi was treated for 12 h, while the fabricated 1.5 wt.% alumina-filled PTFE composite venturi was treated for 16 h. These optimized cryotreated venturis were then used for further industrial performance evaluation to compare their wear behavior under actual powder-coating operating conditions. For industrial wear evaluation, three venturi components of each material condition were tested independently under identical powder coating operating conditions. The reported wear rate represents the average value obtained from these three industrial trials, thereby ensuring the repeatability and reliability of the experimental observations.

Table 2. Optimized cryogenic soaking times for venturi samples

Sr. No.	Venturi Samples	Optimized Soaking Time
1	Virgin PTFE Venturi (Market available)	12 Hrs
2	1.5 wt.% Alumina-filled PTFE Venturi (Fabricated)	16 Hrs

2.6 Scanning Electron Microscopy (SEM)

The wear tracks formed in the throat region of the industrial trial market available, and the fabricated venturi were examined using SEM to evaluate surface wear behavior under actual powder coating conditions. The throat region was selected as it experiences maximum air–powder velocity and severe abrasive interaction. SEM analysis was performed using a JEOL Scanning Electron Microscope, Model 6380A. Before observation, the worn surfaces were sputter-coated with a thin palladium layer using a JEOL JFC-1600 auto-fine coater. This coating improved surface conductivity and minimized charging during imaging. The SEM observations helped compare wear morphology and damage features of virgin PTFE and alumina-filled PTFE composite venturis.

Generally, the selected methodology enabled the comparison of virgin PTFE, alumina filled PTFE composites and the treated versions of the composites in the cryogenic state. The optimized loading of the filler, the controlled cryogenic treatment and the standardized wear test and industrial validation at Venturi level provides a sound basis for the assessment of the suitability of PTFE–alumina composites for powder coating applications. The discussion of the results of these evaluations is provided in the next sections.

3 Results and Discussion

3.1 Optimization of Nano-alumina content for Wear Performance of PTFE Composites

The effect of nano-alumina addition on the abrasive wear performance of PTFE composites is shown in Figure 2. The average specific wear rate (SWR) of virgin PTFE (P0) is approx. 70.5 mm³/N-m. The addition of nano-alumina results in noticeable reduction in PTFE's wear rate, indicating the benefits of ceramic reinforcement on the tribological behavior of PTFE. As the content increased from 0.5 wt.% to 1.5 wt.%, the SWR progressively decreased from 60.8 mm³/N-m to 55.4 mm³/N-m. The lowest SWR was obtained for the PTFE composite containing 1.5 wt.% nano-alumina (P1.5), corresponding to an improvement of nearly 21% as compared to virgin PTFE.

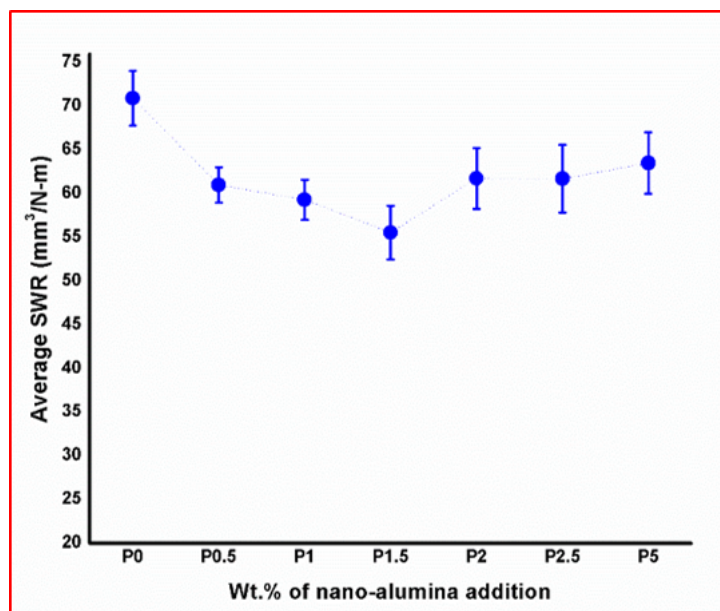


Fig 2. Average specific wear rate (SWR) of PTFE-nano-alumina composites varying with the amount of nano-alumina content exhibits the lowest wear rate at 1.5 wt. % nano-alumina

This decrease in SWR exhibited especially for lower alumina content can be explained by the good reinforcement of the relatively soft PTFE matrix with hard ceramic particles. The nano-alumina particles serve as point load bearing sites, resulting in less deformation of the matrix under abrasive loading, and limiting the formation of deep wear grooves. Moreover, the isolated ceramic particles could be beneficial in stress distribution in the matrix and may help to decrease the stress levels on material removal during sliding and abrasive interactions⁽¹⁾. This is similar behavior reported by Zhao and Zhu⁽⁶⁾. The significant improvement in tribological performance of Al_2O_3 /PTFE composites was attributed to better load transfer and resistance to damage from wear. The alumina-PTFE composites have also been shown to possess a better wear resistance because of the support of applied load by the ceramic particles and their ability to inhibit severe degradation of the matrix in service as demonstrated by Tian *et al.*⁽⁷⁾.

The test results at 1.5 wt.% nano-alumina shows the optimum performance, which indicates that this concentration is capable of giving a favorable balance between reinforcement efficiency and dispersion of the particles. Depending on the filler loading, the volume of reinforcing particles in the contact area might not be enough to ensure abrasive wear resistance throughout the contact area. There may be a beneficial effect of the more uniform distribution of nano-alumina particles in the PTFE matrix at the optimum concentration on the load-bearing ability of the matrix with preserving matrix continuity. Comparable optimum filler amounts have been reported for a number of PTFE composite systems where the optimal particle dispersion led to better tribological behavior and reduced wear^{(4), (6)}.

Beyond 1.5 wt.% nano-alumina, the wear rate increased gradually, reaching approximately $63.4 \text{ mm}^3/\text{N-m}$ at 5 wt.% alumina loading. Although these values remained lower than that of virgin PTFE, the deterioration in performance indicates that excessive filler addition can adversely affect composite structure. At higher filler contents, the possibility of agglomeration increases, leading to non-uniform stress distribution and the formation of localized stress concentration sites. Such agglomerated regions can act as preferential locations for crack initiation, particle pull-out and material removal during abrasive wear. Huang *et al.*⁽⁸⁾ reports that excessive filler loading negatively impacts the tribological behavior by promoting localized defects within the composite structure. Similar observations were reported by Li *et al.*⁽⁴⁾ also who claims that optimum nanoparticle loading is essential for effective load transfer. The trend exhibited by the SWR of nano-alumina reinforced PTFE composites under study are also consistent with the results shown by Kamal *et al.*⁽³⁾. Their study reports that the wear resistance of reinforced PTFE composites is strongly dependent on reinforcement optimization rather than merely increasing filler concentration.

Based on the wear performance results, the PTFE composite containing 1.5 wt.% nano-alumina shows the lowest SWR and was therefore selected as the optimum composition for subsequent CT studies. The identification of an optimum alumina content is particularly significant for industrial venturi applications because it demonstrates that substantial improvements in

wear resistance can be achieved through relatively small additions of ceramic reinforcement, thereby minimizing material cost and processing complexity while enhancing component durability.

3.2 Optimization of Cryogenic Treatment Parameter for virgin PTFE and 1.5 wt.% Nano-Alumina reinforced PTFE Composite

The effect of CT duration on the wear performance of virgin PTFE and the optimized PTFE/1.5 wt.% nano-alumina composite is given in Figure 3. It indicates that CT significantly affects the wear behavior of both the materials, though the magnitude of improvement and optimum treatment duration is different. For virgin PTFE, the treatment of 8 h results in substantial reduction in SWR from 70.5 mm³/N-m to 56.0 mm³/N-m. This SWR further reduced to 54.2 mm³/N-m after 12 h and increasing the soaking period to 16 h did not cause any significant additional improvement. Thus, 12 h was identified as the optimum CT duration for virgin PTFE. This observed improvement can be attributed to structural stabilization within the polymer matrix^{(9), (10)}. Exposure to extremely low temperature can facilitate stress relaxation and reduce localized structural heterogeneity within PTFE, thereby improving resistance to material removal during abrasive interactions. Similar improvements in the tribological behavior of cryogenically treated polymers have been reported by Indumathi *et al.*⁽⁹⁾ who observed enhanced wear resistance following CT due to increased structural stability and reduced wear susceptibility. Similarly, Pande *et al.*⁽¹⁰⁾ also states that CT significantly influences the thermal and structural characteristics of PTFE, leading to measurable improvements in performance.

The response of PTFE/1.5 wt.% nano-alumina composite to CT seems to be different as evident from Figure 3. The untreated composite anyhow exhibited substantially lower SWR of 55.4 mm³/N-m as compared to virgin PTFE. After CT, it was observed that the SWR of the composite continues to decrease progressively with increasing treatment duration. The SWR reduced slightly after 8 h, followed by a further reduction at 12 h and ultimately reaching 45.8 mm³/N-m after 16 h of cryogenic exposure. This is an overall reduction of 17% as compared to untreated composite and 35% as compared to untreated virgin PTFE. This trend of continuous improvement observed in the composite suggests that the presence of nano-alumina particles influences the response of PTFE to CT. In polymer composites, cryogenic exposure may not only stabilize the polymer matrix but may also improve filler-matrix compatibility by reducing interfacial stresses generated during processing and service. Previous studies on cryogenically treated polymer nanocomposites have reported improvements in interfacial bonding and structural uniformity at optimized CT durations^{(11), (12)}. Such effects become increasingly important in reinforced systems where the quality of filler-matrix interaction plays a major role in determining the wear performance. The difference in optimum soaking duration between virgin PTFE and the alumina-reinforced composite further supports this interpretation. While the wear performance of virgin PTFE reached a steady state after 12 h of CT, the composite continued to benefit from longer cryogenic exposure. This behavior suggests that additional time may be required for effective stress redistribution and stabilization around the filler-matrix interface.

It is important to note here that the optimized CT soaking periods identified in the present study are primarily material-specific and cannot be considered universally applicable to all PTFE-based components. The response of polymer composites to CT is strongly influenced by multiple factors such as material composition, filler type and content, crystallinity and the filler-matrix interface. This is claimed and supported by many previous studies^{(10), (11), (12)}. Therefore, although the present study establishes optimum soaking durations of 12 h for virgin PTFE and 16 h for the PTFE–1.5 wt.% nano-alumina composite investigated here, these parameters should be optimized separately for other PTFE formulations and component systems.

Thus, it can be said here that CT is an effective secondary modification strategy for improving the wear resistance of both virgin PTFE and alumina-reinforced PTFE composites. However, the optimum soaking duration depends strongly on material composition. This, for this study, the optimum CT durations of 12 h and 16 h were identified as optimum for virgin PTFE and PTFE/1.5 wt.% nano-alumina composites are considered, respectively. These optimized conditions were therefore selected for the fabrication and evaluation of venturi components under actual industrial operating conditions.

3.3 Industrial Performance of Cryo-treated Venturi Components

The wear performance of untreated and cryo-treated venturis fabricated from virgin PTFE and PTFE/1.5 wt.% nano-alumina composite materials was evaluated under actual industrial powder coating operating conditions and the results are presented in Figure 4. The industrial trials provide a more realistic assessment of material performance as compared to the laboratory-scale wear experiments discussed in the previous sections. In industry setting, the venturi components are exposed to continuous powder flow, repeated particle impact and practical operating conditions encountered in powder coating systems.

The untreated PTFE venturi exhibited the highest wear rate, with an average SWR of 35.5 mm³/N-m. After CT, the SWR of virgin PTFE reduced to 30.3 mm³/N-m, which is approx. 15%. A similar trend was observed for the alumina-reinforced venturi

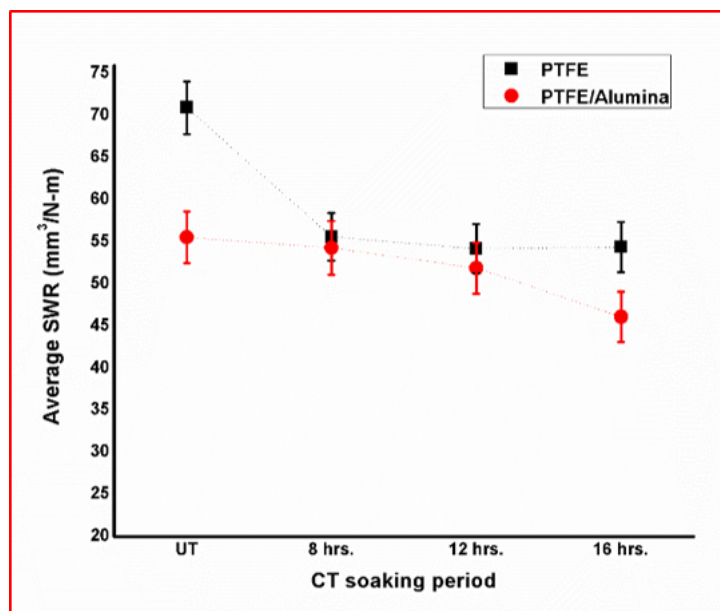


Fig 3. Effect of cryogenic treatment duration on the specific wear rate of virgin PTFE and PTFE + 1.5 wt.% nano-alumina composite samples

components. The untreated PTFE/1.5 wt.% nano-alumina venturi showed wear rate of $31.2 \text{ mm}^3/\text{N-m}$, which was already lower than that of untreated PTFE due to the beneficial effect of ceramic reinforcement. And after CT, the SWR further decreased to $27.6 \text{ mm}^3/\text{N-m}$, which is the lowest wear rate among all the tested conditions. The industrial trial results clearly demonstrate that both alumina reinforcement and CT contribute independently to wear reduction. More importantly, the combined application of these two approaches results in greatest improvement in wear performance. Compared with the untreated PTFE venturi, the cryo-treated PTFE/1.5 wt.% nano-alumina venturi has an overall wear reduction of 22%, indicating a significant enhancement in resistance to erosive-abrasive degradation. This finding confirms that the improvements observed during laboratory wear testing were successfully translated to actual industrial operating conditions.

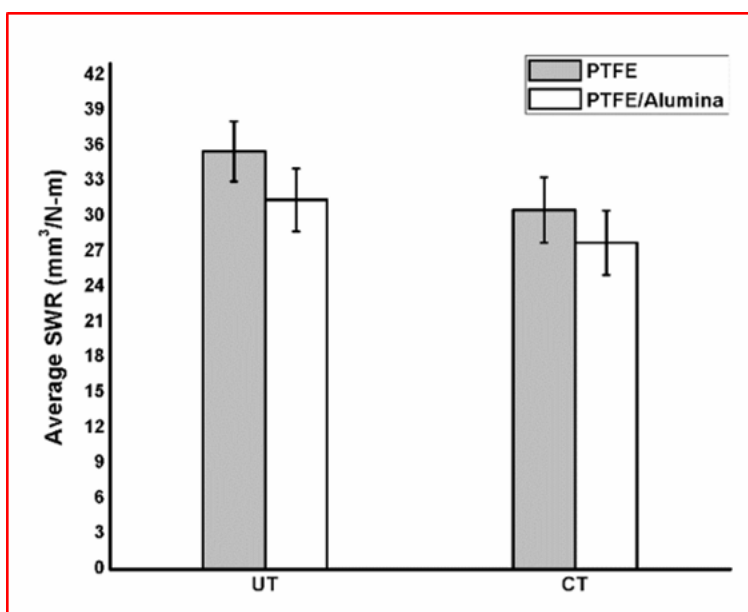


Fig 4. Comparative average specific wear rate (SWR) of untreated (UT) and cryotreated (CT) virgin PTFE and PTFE/1.5 wt.% alumina-filled venturi

This improvement of the alumina-reinforced venturi can be explained by the presence of hard ceramic particles in the PTFE matrix. In coating operation, abrasive powder particles will be continuously colliding with the surface of venturi throat and remove the material. The nano-alumina particles are dispersed on the surface, forming micro-scale reinforcement points, which is able to resist local deformation and decrease the depth of abrasive particles penetrating the material. This means groove formation and removal of material is not as severe. Zhao and Zhu⁽⁶⁾ showed that Al_2O_3 reinforcement greatly enhances the wear resistance of PTFE composites due to increase in the load bearing capacity and surface degradation resistance. The further improvement obtained by CT indicates that the alumina reinforcement is further effective when stabilized in the PTFE matrix. Cryogenic treatment is thought to alleviate residual stresses and to ensure matrix uniformity, which should lead to better stress transfer between the polymer matrix and the reinforcing particles^{(10), (11), (12)}. The synergistic effect of ceramic reinforcement with cryogenic stabilization thus creates a more durable wear-resistant structure that can resist extended exposure to erosive-abrasive conditions.

Current industrial results are also in line with recently published results on advanced PTFE-based protective systems. It is shown by Yuan *et al.*⁽¹³⁾ that Al_2O_3 -PTFE composite coatings have superior wear resistance and surface durability as a result of their synergistic effect, indicating that the alumina-based PTFE systems are suitable for use in severe service conditions. Both the current study and the surface coating study highlight the positive effects of alumina on wear-induced degradation, although the use of bulk composite venturi components is not covered in this study.

From an industrial perspective, the observed reduction in venturi wear is particularly important because venturi deterioration directly affects powder transport efficiency, coating consistency and maintenance frequency. Improved wear resistance can therefore contribute to extended component service life, reduced downtime and lower replacement costs. Antony Jose *et al.*⁽¹⁴⁾ states that the development of wear-resistant engineering materials represents an important strategy for enhancing the reliability and sustainability of industrial systems operating under severe wear conditions. The present results support this perspective and demonstrate that relatively simple material modifications can produce measurable improvements in component durability under actual operating environments. Overall, the industrial trials validate the effectiveness of the proposed material-development approach and confirm that the combined use of nano-alumina reinforcement and optimized cryogenic treatment provides the most favorable wear performance. The cryo-treated PTFE/1.5 wt.% nano-alumina venturi exhibited the lowest wear rate among all tested materials and therefore represents the most promising candidate for long-term powder coating applications.

From a manufacturing perspective, the proposed PTFE/1.5 wt.% nano-alumina composite venturis can be readily integrated into existing industrial production practices since its fabrication involves conventional PTFE processing steps. The procedures like powder blending, compression molding, controlled sintering, and precision machining parameters will not be very different for PTFE/nano-alumina composites as well. No significant modifications will be needed in existing manufacturing route or powder coating equipments. The industries currently producing or using conventional PTFE venturis can adopt the developed composite venturi with minimal changes to established processing practices, enabling improved wear performance while maintaining manufacturing simplicity and cost-effectiveness.

3.4 Wear Morphology and Wear Mechanism

The wear morphology of untreated and cryo-treated PTFE as well as PTFE/1.5 wt.% nano-alumina composite is shown in Figure 5. The worn surface of untreated PTFE exhibits pronounced wear grooves, severe ploughing marks and evidence of extensive material displacement. Deep longitudinal grooves were observed along the sliding direction, indicating significant abrasive interaction between the counter surface and the relatively soft PTFE matrix. Extensive plastic deformation and material tearing suggests that the untreated polymer possesses limited resistance to abrasive particle penetration. Such wear characteristics are typical of unreinforced PTFE and have been widely reported in the literature, where severe matrix deformation and progressive material removal constitute the dominant wear mechanisms^{(1), (2)}. After CT, PTFE surface exhibits noticeably shallower wear grooves and reduced surface damage. Although abrasive wear features were still visible, the severity of ploughing and material displacement was significantly reduced compared with the untreated material. The reduction in groove depth indicates improved resistance to abrasive penetration and material removal.

The untreated PTFE/1.5 wt.% nano-alumina composite shows a comparatively smoother worn surface than untreated PTFE. Although wear tracks remained visible, the extent of plastic deformation and material removal was reduced. This can be credited to the presence of hard nano-alumina particles within the PTFE matrix, which act as localized reinforcement sites and resist abrasive penetration. These particles improve load-bearing capability and distribute applied stresses more uniformly throughout the matrix, thereby reducing the severity of wear-induced deformation. Similar mechanisms have been reported by Zhao and Zhu⁽⁶⁾, who demonstrated that alumina reinforcement improves the tribological performance of PTFE by enhancing resistance to surface damage and reducing wear progression. Huang *et al.*⁽⁸⁾ further reported that alumina-containing PTFE systems

exhibit improved wear resistance owing to enhanced structural stability and suppression of severe surface degradation. Among all the investigated materials, the cryo-treated PTFE/1.5 wt.% nano-alumina composite exhibited the least severe wear damage. The worn surface appeared comparatively smooth and uniform, with significantly reduced groove depth and fewer indications of material tearing or debris formation. The absence of extensive surface damage suggested that the combined influence of ceramic reinforcement and cryogenic stabilization effectively suppressed the dominant abrasive wear mechanisms operating in the untreated materials. These observations correlate well with the lowest wear rates measured during both laboratory and industrial testing and confirm the superior wear resistance of the cryotreated composite system.

Based on the experimental observations and supporting literature, a schematic representation of the proposed wear-improvement mechanism is shown in Figure 6. The mechanism consists of two complementary components, namely nano-alumina reinforcement and cryogenic stabilization, which collectively contribute to the enhanced wear resistance of the developed composite venturi material. The first component of the wear-improvement mechanism arises from the incorporation of nano-alumina particles into the PTFE matrix. During powder coating operations, the venturi throat is continuously exposed to high-velocity powder particles that repeatedly impact and slide against the internal surface. In untreated PTFE, the relatively soft polymer matrix offers limited resistance to particle penetration. Consequently, abrasive particles readily create deep grooves and initiate localized plastic deformation. Repeated particle impacts promote material tearing, crack initiation, debris formation, and progressive material removal, ultimately resulting in accelerated wear. These features are evident in the SEM micrograph of untreated PTFE (Figure 5), which exhibits severe groove formation and extensive surface damage.

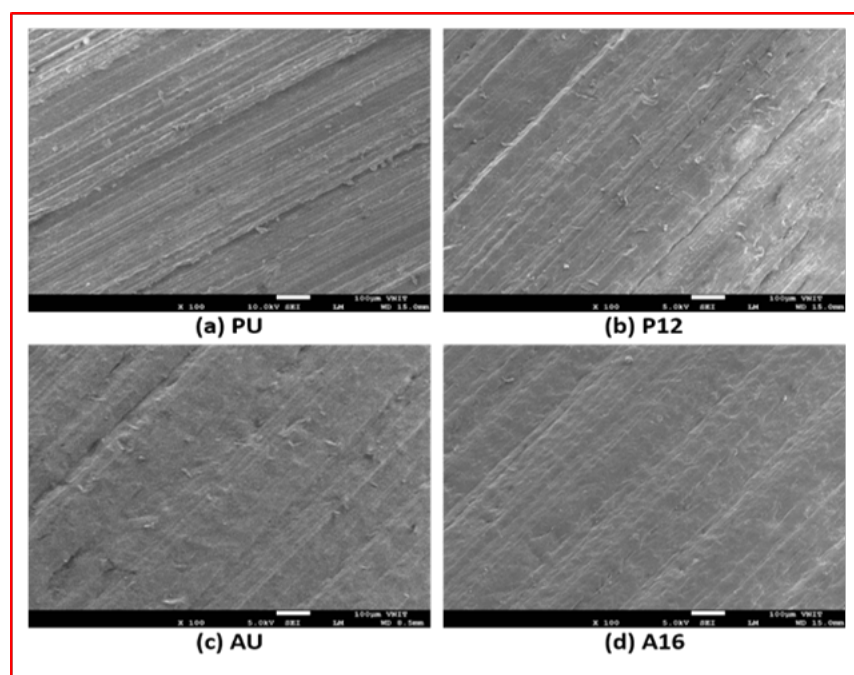


Fig 5. SEM micrographs of worn out venturi surfaces with the comparative wear morphology of untreated and cryo-treated PTFE and PTFE-1.5 wt.% alumina composite

The addition of nano-alumina fundamentally alters this wear process. Owing to their high hardness and stiffness, alumina particles function as localized load-bearing sites within the PTFE matrix. When abrasive particles interact with the composite surface, a portion of the applied load is transferred from the polymer matrix to the embedded ceramic particles. This reduces localized stress concentrations within the PTFE matrix and limits plastic deformation. Simultaneously, the hard alumina particles act as barriers that restrict the propagation of wear grooves and inhibit deep penetration of abrasive particles. As a result, the composite surface experiences lower material displacement, reduced crack formation, and decreased debris generation. The improved load-sharing capability also promotes more uniform stress distribution throughout the composite, thereby enhancing resistance to wear-induced surface degradation^{(14), (15)}. Similar reinforcement-induced wear suppression mechanisms have been reported for alumina-filled PTFE composites and other nanoparticle-reinforced PTFE systems, where ceramic particles effectively improve load transfer and reduce matrix damage under tribological loading conditions⁽⁴⁾.

The second component of the wear-improvement mechanism is associated with CT. Exposure of PTFE and PTFE/alumina composites to cryogenic temperatures promotes structural stabilization of the polymer matrix. At extremely low temperatures, residual stresses generated during processing and cooling can be relieved, resulting in a more stable and uniform microstructure. CT may also reduce free-volume irregularities within the polymer network, improve molecular packing, and enhance resistance to deformation under applied loads^{(10), (11), (12)}. Consequently, the cryo-treated matrix becomes less susceptible to groove formation, material tearing, and progressive wear. CT is believed to facilitate stress redistribution at the filler-matrix interface, resulting in improved interfacial stability and more effective load transfer between the polymer and ceramic phases^{(16), (17)}. The significance of interfacial stability in reinforced PTFE systems has also been emphasized in recent investigations on particulate-filled PTFE materials. Wang et al.⁽¹⁸⁾ reports that the effectiveness of stress transfer mechanisms strongly depends on the integrity of the reinforcement-matrix interface, while Miao et al.⁽¹⁹⁾ states how the improved particle-matrix interaction contributes to enhanced structural performance in PTFE-based composite architectures. Such observations are consistent with the present hypothesis that stabilizing the filler-matrix interface improves the effectiveness of load transfer, but in this study this stabilization is achieved through CT. Therefore, enhanced interfacial integrity reduces the likelihood of particle debonding and pull-out during abrasive wear⁽⁸⁾. Since particle pull-out often creates additional voids and stress concentration sites that accelerate wear progression, suppressing this phenomenon contributes significantly to improved wear resistance.

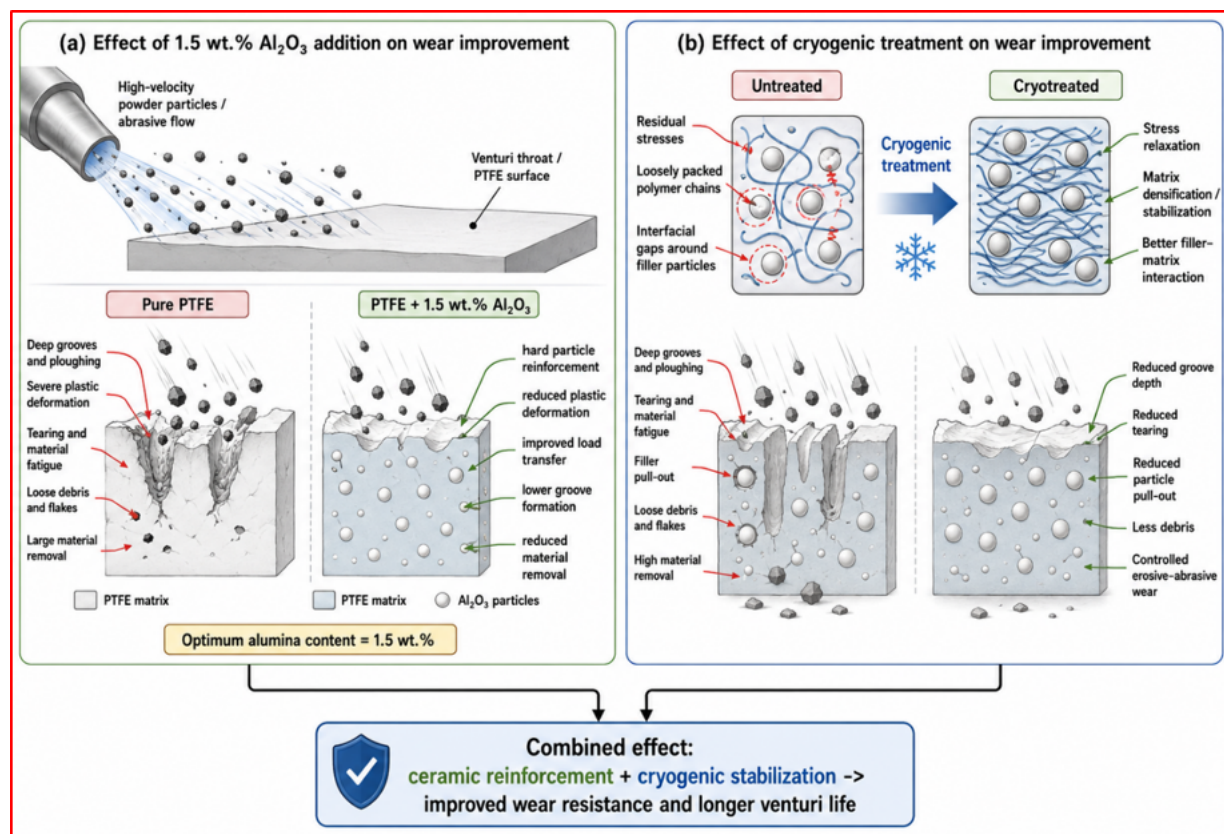


Fig 6. Schematic representation of the wear-improvement mechanisms in PTFE-based venturi materials: (a) effect of 1.5 wt.% Al_2O_3 addition in reducing plastic deformation, groove formation, and material removal, and (b) effect of cryogenic treatment in improving matrix stability, filler-matrix interaction, and resistance to erosive-abrasive wear

Overall, the SEM observations and mechanistic analysis strongly support the wear results presented at laboratory-scale and in industry trials. The progressive reduction in groove formation, material tearing, particle pull-out, and debris generation observed in the cryotreated PTFE/1.5 wt.% nano-alumina composite confirms that the combined modification strategy effectively suppresses the primary wear mechanisms responsible for venturi degradation. Consequently, the simultaneous application of nano-alumina reinforcement and CT provides a practical and effective approach for extending the service life and operational reliability of PTFE-based venturi components operating under erosive-abrasive powder coating conditions.

4 Conclusion

This study demonstrated that the wear performance of PTFE-based venturi materials used in powder coating systems can be significantly enhanced through a combined strategy involving nano-alumina reinforcement and CT. Among the investigated compositions, the PTFE composite containing 1.5 wt.% nano-alumina exhibited the lowest wear rate, indicating that an optimum filler concentration is essential for maximizing reinforcement efficiency. CT further improved wear resistance, with optimum soaking durations of 12 h for virgin PTFE and 16 h for the PTFE/1.5 wt.% nano-alumina composite. The results of industrial trial evaluation further verified the effectiveness of the proposed modification strategy under the actual powder coating operating conditions and the wear rate of the cryo-treated PTFE/1.5 wt.% nano-alumina venturi showed to be the lowest among all tested venturis.

The novelty value of the present work is that it is a systematic integrated study for optimizing the filler, optimizing the CT and validation of the venturi at an industrial scale. Although prior studies have investigated the effect of PTFE reinforcement or the effect of CT, there is limited data on their synergistic effect on venturi performance under actual operating conditions. The results show that the combination of nano-alumina reinforcement and cryogenic treatment is more effective than either reinforcement or treatment alone to reduce groove formation, suppress material removal and provide resistance to erosive-abrasive wear. The developed cryo-treated PTFE/1.5 wt.% nano-alumina composite is a practical solution for increasing the venturi service life, increasing the powder flow stability, reducing the powder coating equipment maintenance cycle and reducing the replacement cost of the parts. The results show that the relatively small changes in material composition and post-processing treatment can result in measurable improvements in operational durability.

The present investigation was conducted using the optimum PTFE composite containing 1.5 wt.% nano-alumina identified through laboratory optimization and was validated under a representative industrial powder coating operating condition. Although the obtained results clearly demonstrate the effectiveness of the combined nano-alumina filler reinforcement and CT, the optimum filler content and CT parameters may vary for different PTFE formulations, component geometries, manufacturing histories and service environments. Therefore, the present findings should be considered specific to the investigated material system and operating conditions, while providing a practical framework for the development and optimization of other wear-resistant PTFE-based engineering components.

Further research could involve testing the service behavior of the cryo-treated PTFE composites over extended operating times within industrial conditions and the possibility of using other ceramic and hybrid reinforcements, as well as the effect of CT on other wear-critical parts of powder coatings. More microstructural and interfacial characterization can also help to better understand the mechanisms behind the synergic effect of ceramic reinforcement and cryogenic stabilization.

Based on the experimental and industrial results, it is recommended that, in order to develop the effective wear resistant and reliable venturi component for powder coating industries, 1.5 wt.% nano-alumina reinforcement with optimized CT should be used together.

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