Performance Evaluation of Carbon Nanotube (CNT) Nanofluids in End Milling of Titanium Alloy Ti-6Al-4V Using PCD Inserts

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ABSTRACT

Titanium alloys stand out as advanced metallic materials celebrated for an exceptional strength-to-weight ratio, formidable toughness, robust corrosion resistance, and the capacity to endure extreme temperatures. These traits render them indispensable across aerospace, defense, medical, and high-performance automotive sectors. Their mechanical versatility arises from an allotropic phase transformation: a hexagonal close-packed (HCP) alpha (α) phase shifting to a body-centered cubic (BCC) beta (β) phase near 890°C. Alloying elements such as aluminum (an alpha stabilizer) and vanadium (a beta stabilizer) enable crucial heat-treatment processes, including precipitation hardening. Yet the high cost of raw materials, complex fabrication requirements, and the intrinsically poor machinability of titanium alloys present substantial manufacturing hurdles. To mitigate these challenges, cutting fluids are widely used during machining to reduce friction and wear, cool the cutting zone, cut energy demands, flush away chips, and safeguard finished surfaces from corrosion. The performance of these fluids depends on the machining operation type, the materials of the tool and workpiece, cutting speed, and the chosen application method. Traditional cutting fluids range from water—an excellent coolant but a weak lubricant—and various oils (mineral, animal, vegetable, compounded, and synthetic) for low-speed tasks, to emulsions, semi-synthetics, and synthetics designed for high-speed operations. However, conventional heat-transfer media such as water, oil, and ethylene glycol inherently exhibit low thermal conductivity, which constrains cooling effectiveness. This shortcoming has driven the emergence of nanofluids—fluids embedded with suspended solid nanoparticles—that show markedly enhanced thermal conductivities, thanks to the 1–3 orders of magnitude higher thermal conductivity of crystalline solids relative to conventional fluids. The tiny dimensions and expansive surface areas of nanoparticles not only improve suspension stability but also substantially boost heat-transfer capabilities. Carbon nanotubes (CNTs), whose thermal conductivity exceeds that of water by more than three thousandfold and which possess aspect ratios from 10^3 to 10^5, represent especially attractive candidates for next-generation heat-transfer nanofluids. Theoretical frameworks (such as Maxwell and Hamilton-Crosser models) indicate that effective thermal conductivity climbs with increasing particle volume fraction and surface-area-to-volume ratio, with nanoscale particles delivering roughly a thousandfold advantage over micrometric counterparts. In practice, cutting fluids are applied through four principal mechanisms: flooding (10–225 L/min), mist (70–600 kPa air pressure), high-pressure systems (5.5–35 MPa), and through-the-tool delivery methods (e.g., gun drilling, boring bars). Key considerations for fluid selection include the workpiece and tool materials, environmental and ecological impacts, and operator health concerns related to mist, fumes, smoke, and odors. For example, sulfur-containing fluids are inappropriate for nickel-based alloys, while chlorine-bearing fluids must be avoided with titanium alloys. Additionally, stringent filtration, reuse, and disposal practices are necessary to meet environmental regulations, and post-machining cleaning is required to prevent residues from interfering with subsequent processes such as coating, welding, or brazing. Ultimately, the synergy between cutting-edge titanium alloy development and optimized cutting-fluid technology—especially the advancing field of nanofluids— have sustainabilty to improved machinabilty, reduce cost of production improes tool health and these study helps to elobrate in various industry 4.0.

LITERATURE SURVEY

Nanofluids & CNTs: Nanofluids (nanoparticles suspended in base fluids) enhance heat transfer significantly.

Singh [1] explored their concept and mechanisms, while Wu et al. [3] reviewed preparation and thermal conductivity. CNTs exhibit exceptional properties, with JiaQi et al. [5] addressing mass production challenges and sustainable applications. Assael et al. [2] used transient hot-wire and FEM to study thermal conductivity of CNT nanofluids.

Titanium Alloy Machining: Ti-6Al-4V, widely used in aerospace, exhibits poor machinability due to low thermal conductivity, chemical reactivity, and BUE formation.

Tool Wear Studies: Muthukrishnan & Davim [6] found coolants reduce wear and improve finish. Sales & Maia [11] reported nano-coated tools underperformed due to reactivity; high-pressure coolant enhanced tool life.

Cooling/Lubrication Optimization: Su et al. [4] optimized cooling conditions for coated tools. Setti et al. [13] applied Al_2O_3 nanofluids under MQL in grinding, outperforming conventional coolants. Ramana et al. [16] explored bio-oils (palm oil) as sustainable alternatives.

Surface Roughness Optimization: Pradeepkumar & Thirumurugan [7], Safari et al. [10], and Mohruni et al. [14] used Taguchi, RSM, and GA to optimize milling parameters. Another study [15] developed RSM models for dry milling.

Preheating & Monitoring: Ginta et al. [12] used induction preheating to improve tool life, monitoring forces, torque, and vibration with SEM analysis.

Review Studies: Bharatkumar & Sutaria [8] reviewed turning/milling of titanium alloys. Oosthuizen et al. [9] reviewed machining strategies for aerospace components.

Sustainability: Environmental and health concerns drive research into bio-oils and reduced fluid usage [16].

This short note captures all key studies and findings in a compact, easy-to-reference format.

INTRODUCTION:

Cutting fluids have been used extensively in machining operations to achieve the following applicatios, Reduce friction and wear, thus improving tool life and the surface finish Cool the cutting zone, thus improving tool life and reducing the temperature and thermal distortion of the work piece, Reduce forces and energy consumption, Flush away the chips from the cutting zone Protect the machined surface from environmental corrosion. Cutting fluid could be a coolant, a lubricant or both.

Machining constitutes a fundamental class of manufacturing processes wherein controlled material removal is achieved through the relative motion between a cutting tool and a workpiece. These processes are indispensable across virtually all industrial sectors, enabling the production of components with precise dimensions, complex geometries, and superior surface finishes. The efficacy and economic viability of machining operations are profoundly influenced by the application of cutting fluids, which serve multifaceted roles: reducing friction and wear at the tool-workpiece interface, cooling the cutting zone to mitigate thermal damage, lowering energy consumption, flushing away chips to prevent re-cutting, and protecting finished surfaces from environmental corrosion. Depending on the specific operational requirements, cutting fluids may function as coolants, lubricants, or both, with their effectiveness contingent upon the type of machining operation, tool and workpiece materials, cutting parameters, and method of application.

Machining processes are fundamental to modern manufacturing, enabling the production of precision components across diverse industrial sectors. Among the most widely employed operations are **turning** (performed on lathes for cylindrical components), **milling** (using rotating multi-tooth cutters for flat surfaces and complex contours), **drilling** (for producing cylindrical holes), **grinding** (an abrasive finishing process for tight tolerances and superior surface quality), **shaping and planing** (reciprocating operations for flat surfaces), **broaching** (using multi-tooth linear tools for internal and external profiles), and **sawing** (for stock

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preparation and parting-off). Each of these processes presents unique challenges related to heat generation, friction, chip formation, and tool wear.

To address these challenges, **cutting fluids** are extensively employed to reduce friction and wear at the tool-workpiece interface, cool the cutting zone to prevent thermal damage, lower energy consumption, flush away chips to avoid re-cutting, and protect finished surfaces from corrosion. Cutting fluids may function as coolants, lubricants, or both, with their effectiveness depending on the specific machining operation, tool and workpiece materials, cutting parameters, and application method. Traditional fluids range from water and various oils to emulsions, semi-synthetics, and synthetics, while emerging nanofluids offer enhanced thermal conductivity for superior cooling performance. Application methods include flooding, mist, high-pressure systems, and through-the-tool delivery, each suited to particular operations. Proper fluid selection and application are critical for extending tool life, improving surface finish, reducing production costs, and ensuring operator safety and environmental compliance.

From above study conventional coolent have less to resist to store themal energy leads to decrease tool life becase of high in wear rate and changes its geometrical shape, to avode this prepred nano coolent by CNT nano fluids by varios metalurgical methods, this leads increse tool life.

Conventional cutting fluids—such as water, oils, emulsions, and synthetics—possess **low thermal conductivity (0.1–0.6 W/m·K)**, which limits their ability to effectively dissipate heat from the cutting zone. This inadequacy leads to: **Accelerated tool wear** due to elevated temperatures, **Geometrical changes** in the tool (flank wear, crater wear, edge rounding) ,**Thermal distortion** affecting dimensional accuracy **Built-up edge (BUE) formation** degrading surface finish **Thermal cracking** in intermittent cutting operations To overcome these limitations, **Carbon Nanotube (CNT) nanofluids** have emerged as a superior alternative. CNTs exhibit exceptional thermal conductivity (3,000–10,000 W/m·K), enabling rapid heat absorption and dissipation. The preparation of stable CNT nanofluids involves: **Functionalization** (acid treatment or surfactant addition) to prevent agglomeration **Dispersion techniques** such as ultrasonication and high-pressure homogenization **Stabilization** through pH control and optimized sonication The application of CNT nanofluids in machining delivers significant benefits: **Extended tool life** (30–100% improvement reported) **Reduced wear rates** and maintained geometric integrity **Lower cutting forces** and energy consumption **Improved surface finish** through superior lubrication **Enhanced sustainability** through reduced tool consumption and fluid waste

This advancement aligns with smart manufacturing and Industry 4.0, enabling real-time monitoring and adaptive control for optimized machining performance.

Preperation of Nanocoolent:

In order to prepare the nano coolant(1 litre) it requires distilled water, cutting oil, carbon nano particles and surfactant with proportions as shown Below

Ingredients of nano coolant

Distilled water	1litre
Cutting oil	50ml
Carbon nano particles (10nm)	3g
Surfactant	10ml

The nano coolant is prepared by adding Carbon Nano Tubes of size 10nm to the emulsion type cutting fluid (Velvex- Cutvel ‘S’). Cutting fluid is a mixture of water and cutting oil in the ratio of 20:1, in the 0.3% weight ratio. The surfactant Triton X-100(polyethylene glycol 4 – tret – octylphenolether) is added to the mixture in the ratio so that they bind up the CNTs with the cutting fluid. For 1liter of nano cutting fluid 3gms of carbon nano tubes are added and 10ml of surfactant is added and the nano coolant is prepared by magnetic stirring and ultra sonification

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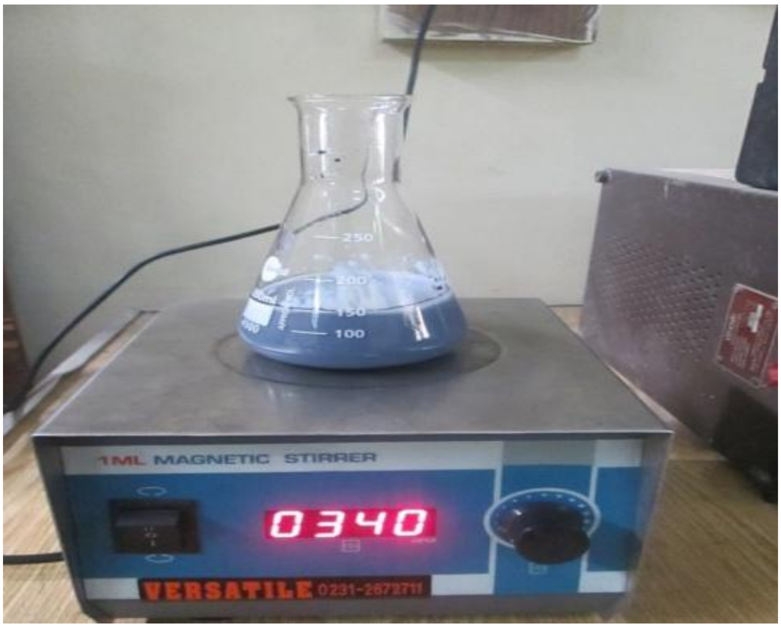
Magnetic stirrer



It employs a rotating magnetic field to cause a stir bar (also called "flea") immersed in the liquid to spin very quickly, thus stirring it. The proportionally mixed solution is placed on the magnetic stirrer and at a frequency between 300 Hz to 350 Hz the stirring is done in clockwise direction and after 1 hr the direction is changed and stirring process is done for another 1hr.

After this the solution is subjected to ultra sonification.

Fig.4.3 Rotating Magnets

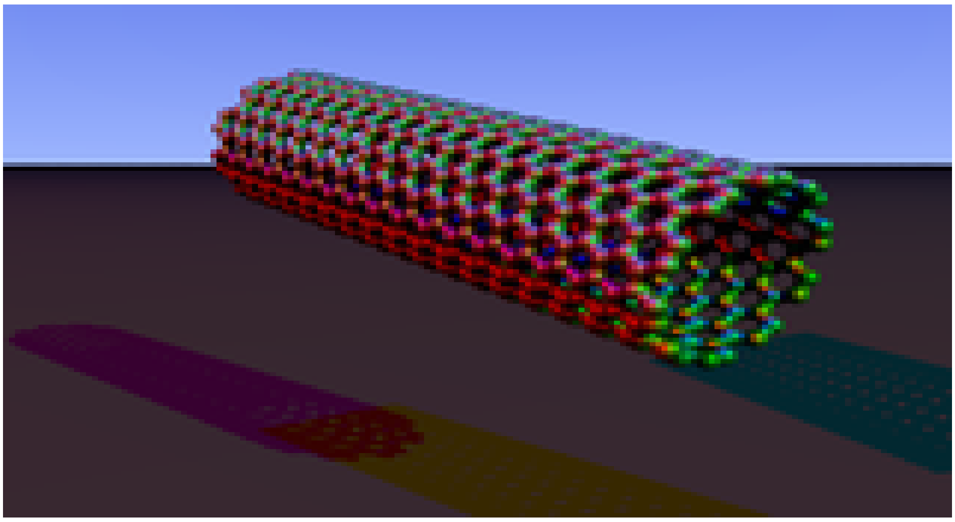
Sonicator

Sonication is the act of applying sound energy to agitate particles for uniform mixing of nano particals. The frequencies induced by the sonicator shown in figure 4.3 are

Ultrasonic having frequencies greater than 60 kHz that are sufficient for effective mixing .

Fig.4.4.Sonicator

The process is carried out for about 3 hours .the outcome of this process is the desired nano coolant .



Carbon Nano tubes

Materials Selection and Equipment

The material selection plays a vital role during any machining process. The several components whose materials are to be selected include work piece, milling cutter, inserts, coolant etc. Table 4.1. depicts the choosen materials for the components in this thesis.

Selection of material for the thesis

Component	**Material**
Work piece	Titanium (Ti-6Al-4V)
Milling cutter	Carbide
Inserts	Polycrystalline diamond (PCD)
Coolants	Nano coolant (MWCNT) Conventional coolant

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The machinery used for the experimental work for this thesis is Vertical milling machine (BFW Agni BMV45 TC20) which is a CNC machining centre.

Selection of Input Parameters

The machining characteristics such as surface finish, tool wear, material removal rate, temperatures mainly depend on the process parameters. The process parameters varied in this thesis are Tool rotational speed, feed and depth of cut. Table 4.2 shows the input parameters choosen in this thesis. These process parameters are arranged in a L27 series for the Design Of Experiments (DOE).

Three different speeds, feeds and depth of cuts are choosen as shown in table 4.2 for performing the milling operation on Titanium work piece using PCD inserts. On varying the process parameters, the tool wear and the surface finish of the work piece varies and are determined in this thesis. A total of 27 experiments are conducted .

Machining parameters

S.No.	**Variable**	**Levels**		
		1	**2**	**3**
1	Depth of cut (mm)	0.4	1	1.6
2	Feed rate (mm/min)	30	45	60
3	Speed (RPM)	1800	2250	2700

Experimental Procedure

Step1: Take the Titanium work piece as per the dimensions

Length of the Work piece: 300 mm

Thickness of the Work piece: 16 mm

Width of the Work piece: 300 mm

Step2: All the surfaces of the work piece are machined to about 2mm by using milling machine so as to make the work piece free from rust and shiny.

Step3: Work piece is clamped firmly in order to make it free from sliding during milling operation .

Step4: Fix the polycrystalline diamond (PCD) inserts to the three flute cutter firmly and insert them into the tool holder which is inserted into the machine spindle.

Step5: Assign the machining parameters say tool rotational speed, feed and depth of cut to the machining centre BFW Agni BMV45 TC20. Using CNC code.

Step6: Now the milling operation is started and it is done in two cases

Case1: using conventional coolant

Case2: using nano coolant.

Step7: In the similar manner repeat the operations for remaining combinations of speed, feed and depth of cut.

Step8: After machining, measure the surface roughness of the work piece of each machining length using " surface roughness tester" and record the values.

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Fig.4.5. Surface Roughness Tester

Step9: Measure the tool wear (flank wear) of the used PCD inserts using "Tool makers microscope"

Fig.4.6. Tool Makers Microscope

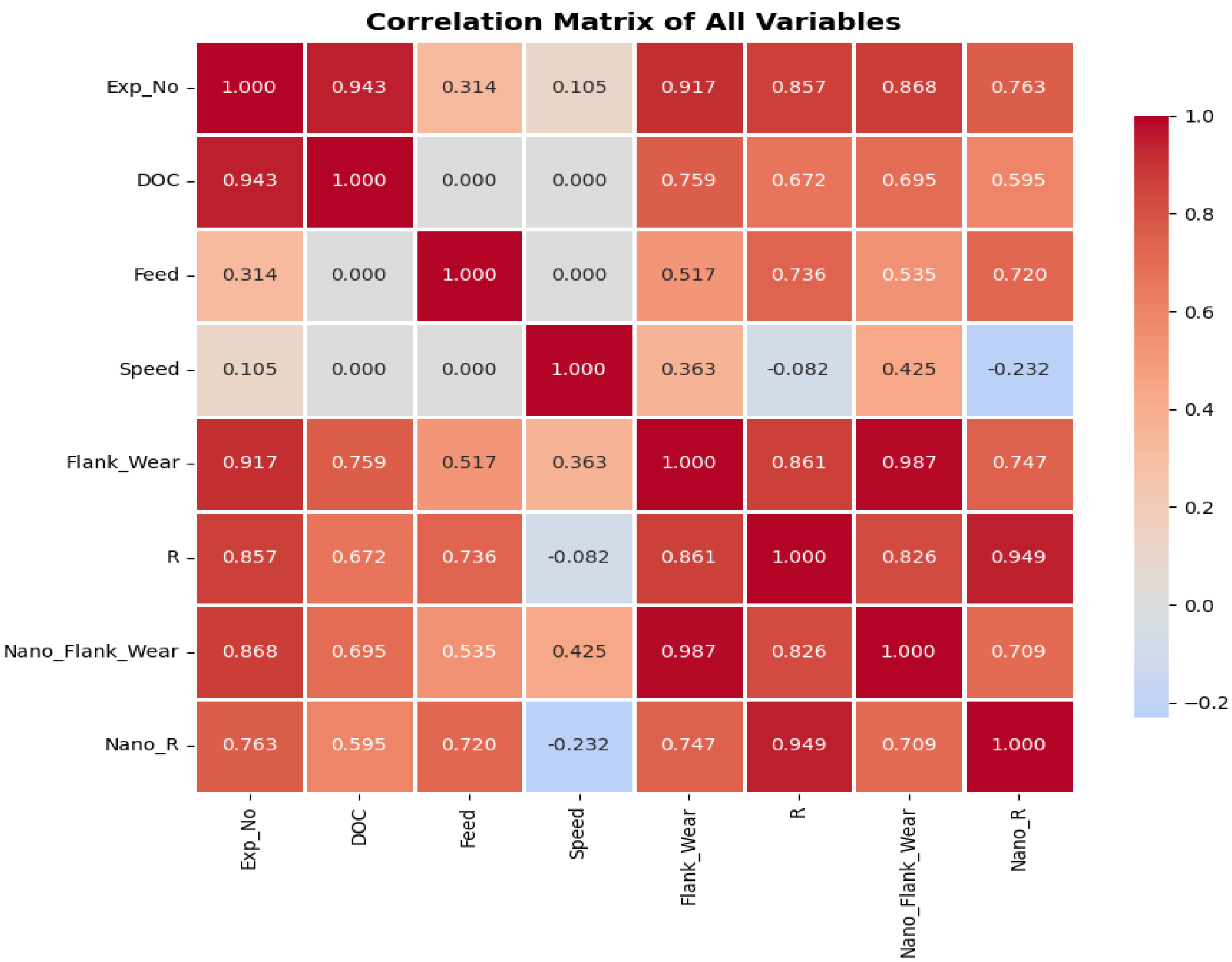
RESULTS AND ANALYSIS

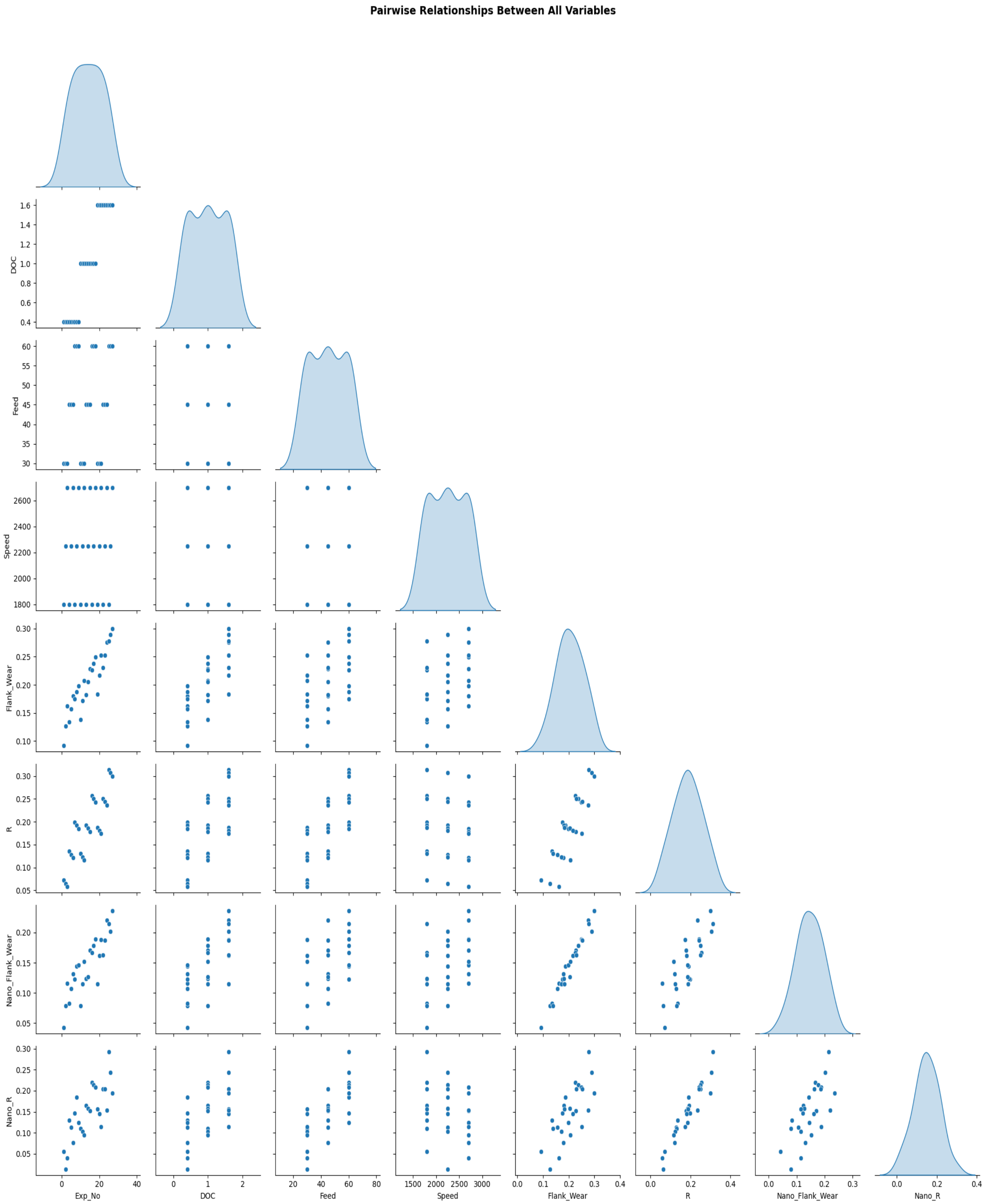
The milling operation is performed on the Titanium work piece using conventional coolant and nano coolant at different speeds, feeds and depth of cuts. A total of 27 experiments are conducted and the tool wear and the surface roughness are measured, as shown in table 5.1.

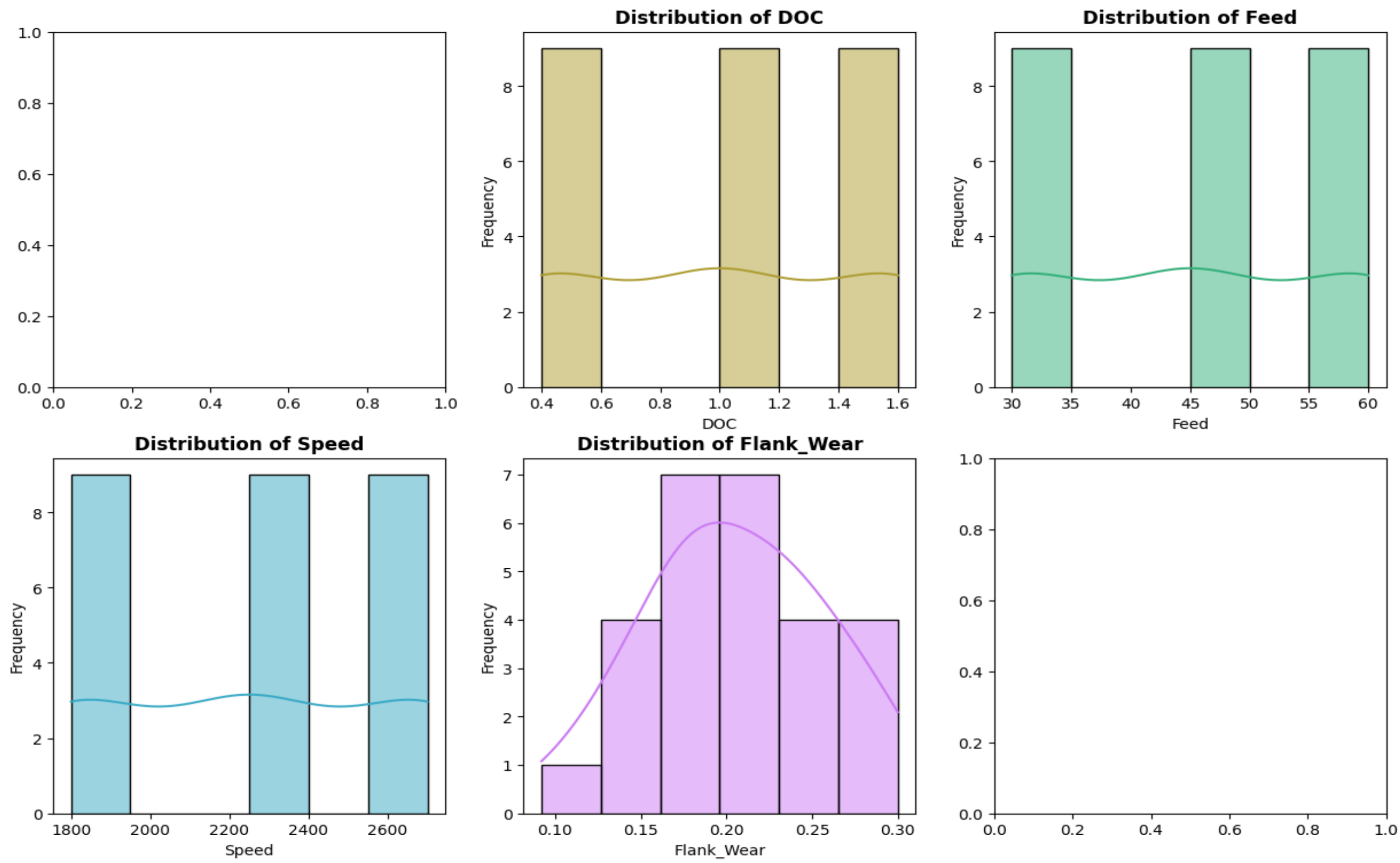
Table 5.1. Experimental observations

Exp. No.	DOC (mm)	Feed (mm/min)	Speed (RPM)	Conventional coolant		Nano- coolant	
				Flank wear (mm)	R_a (µm)	Flank wear (mm)	R_a (µm)
1	0.4	30	1800	0.092	0.072	0.042	0.056
2	0.4	30	2250	0.127	0.065	0.079	0.014
3	0.4	30	2700	0.162	0.058	0.116	0.040
4	0.4	45	1800	0.134	0.136	0.083	0.130
5	0.4	45	2250	0.157	0.128	0.107	0.113
6	0.4	45	2700	0.180	0.121	0.131	0.076
7	0.4	60	1800	0.175	0.199	0.123	0.147

8	0.4	60	2250	0.187	0.192	0.144	0.185
9	0.4	60	2700	0.198	0.185	0.146	0.124
10	1	30	1800	0.138	0.130	0.079	0.110
11	1	30	2250	0.172	0.123	0.115	0.103
12	1	30	2700	0.207	0.116	0.152	0.095
13	1	45	1800	0.182	0.193	0.124	0.165
14	1	45	2250	0.205	0.186	0.127	0.158
15	1	45	2700	0.228	0.179	0.171	0.152
16	1	60	1800	0.226	0.257	0.167	0.219
17	1	60	2250	0.238	0.250	0.178	0.214
18	1	60	2700	0.249	0.243	0.189	0.209
19	1.6	30	1800	0.183	0.188	0.115	0.156
20	1.6	30	2250	0.217	0.181	0.162	0.145
21	1.6	30	2700	0.252	0.174	0.188	0.114
22	1.6	45	1800	0.230	0.251	0.163	0.204
23	1.6	45	2250	0.253	0.244	0.187	0.204
24	1.6	45	2700	0.276	0.237	0.22	0.154
25	1.6	60	1800	0.278	0.314	0.215	0.292
26	1.6	60	2250	0.289	0.307	0.202	0.243
27	1.6	60	2700	0.300	0.300	0.236	0.195




Pairwise Relationships Between All Variables
DOC
Feed
Speed
Flank_Wear
R
Nano_Flank_Wear
Nano_R
Exp_No
DOC
Feed
Speed
Flank_Wear
R
Nano_Flank_Wear
Nano_R



Variation of surface roughness

As the surface roughness of machined Titanium work piece is measured at several combinations of speed, feed and depth of cut using conventional coolant and nano coolant. There surface roughness values are shown graphically in the figure 5.1

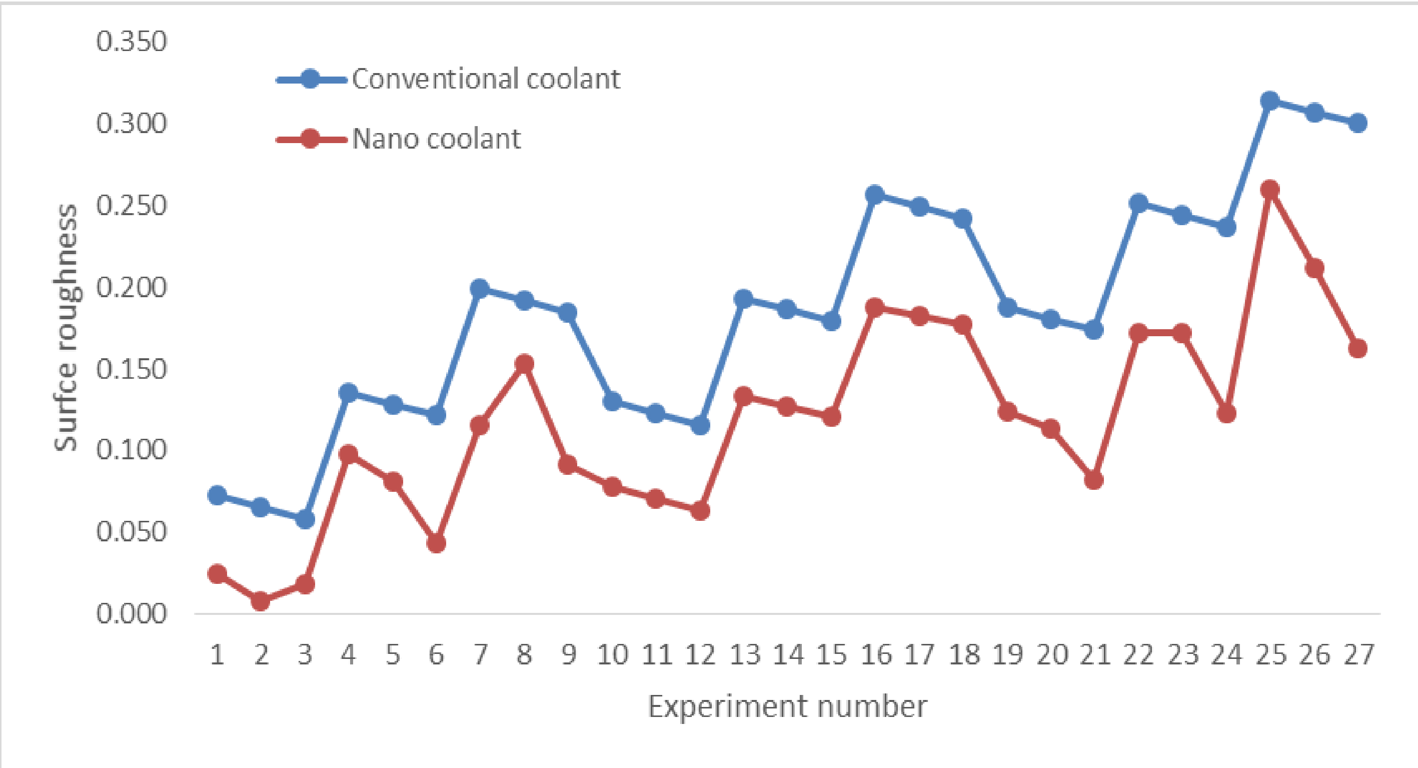


Fig.5.1 Variation Of Surface Roughness

It is observed from the graph that the surface roughness of the Titanium work piece is lower in the case of nano coolant. Where as we get higher surface roughness values while using conventional coolants during milling operation. While using conventional coolants, the minimum surface roughness is obtained during the 3rd experiment. At the speed 2700 rpm, feed 30 mm/min and depth of cut 0.4 mm the minimum surface roughness of 0.058 µm is obtained. While using conventional coolants, the maximum surface roughness is obtained during the 25th experiment. At the speed 1800 rpm, feed 60 mm/min and depth of cut 1.6 mm the maximum surface roughness of 0.314 µm is obtained. While using nano coolants, the minimum surface roughness is obtained during the 2nd experiment. At the speed 2250 rpm, feed 30 mm/min and depth of cut 0.4 mm the minimum surface roughness of 0.0140 µm is obtained. While using nano coolants, the maximum surface roughness is obtained during the 25th experiment. At the speed 1800 rpm, feed 60 mm/min and depth of cut 1.6 mm the maximum surface roughness of 0.292 µm is obtained.

Variation of Tool wear

As the tool wear of machined polycrystalline diamond (PCD) inserts are measured at several combinations of speed, feed and depth of cut using conventional coolant and nano coolant. There tool wear values are shown graphically in the figure 5.2

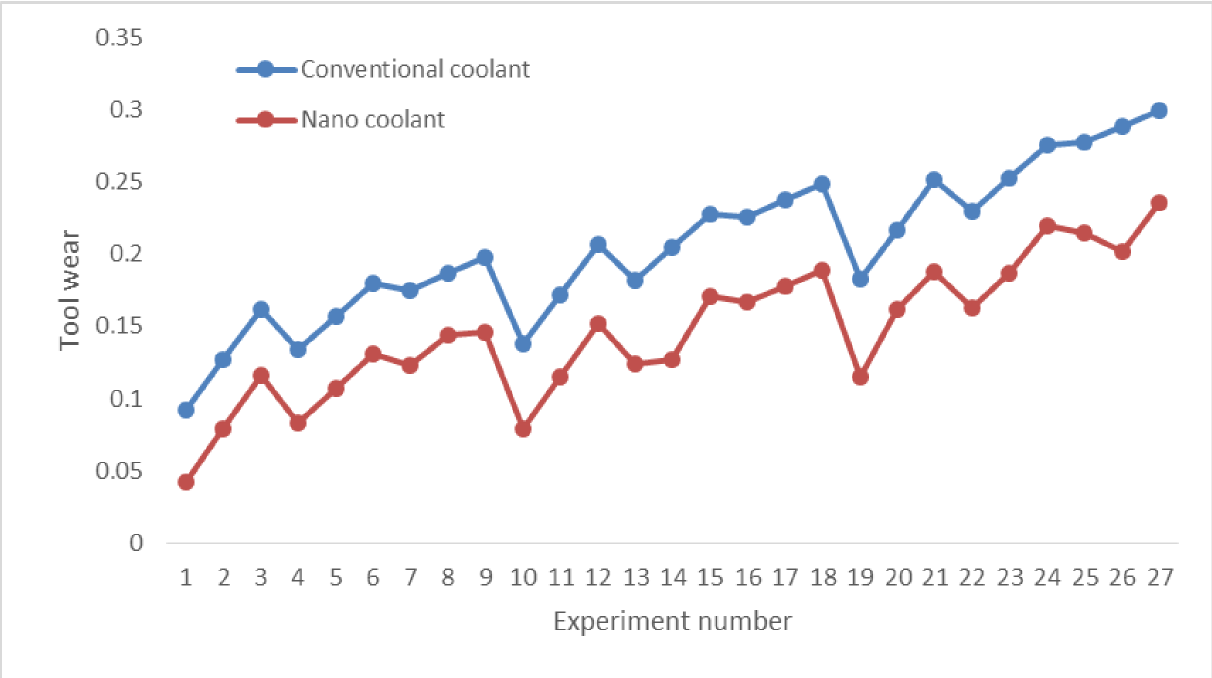


Fig 5.2 Variation Of Tool Wear

It is observed from the graph that the tool wear of the polycrystalline diamond (PCD) inserts are lower in the case of nano coolant. Where as we get higher tool wear values while using conventional coolants during milling operation. While using conventional coolants, the minimum tool wear is obtained during the 1st experiment. At the speed 1800 rpm, feed 30 mm/min and depth of cut 0.4 mm the minimum tool wear of 0.092 µm is obtained. While using conventional coolants, the maximum tool wear is obtained during the 27th experiment. At the speed 2700 rpm, feed 60 mm/min and depth of cut 1.6 mm the maximum tool wear of 0.300 µm is obtained. While using nano coolants, the minimum tool wear is obtained during the 1st experiment. At the speed 1800 rpm, feed 30 mm/min and depth of cut 0.4 mm the minimum tool wear of 0.042 µm is obtained. While using nano coolants, the maximum tool wear is obtained during the 27th experiment. At the speed 2700 rpm, feed 60 mm/min and depth of cut 1.6 mm the maximum tool wear of 0.236 µm is obtained.

Scanning Electron Microscope (Sem) Images

From the table 5.1 the tool wear during milling in the presence of nano coolant at speed1800 rpm, depth of cut 0.4 mm, feed rate 30 mm/min is obtained from the SEM images shown in the figure 5.3. The tool wear during milling in the presence of conventional coolant at speed 1800 rpm, depth of cut 0.4 mm, feed rate 30mm/min is obtained from the SEM images shown in the figure 5.4.

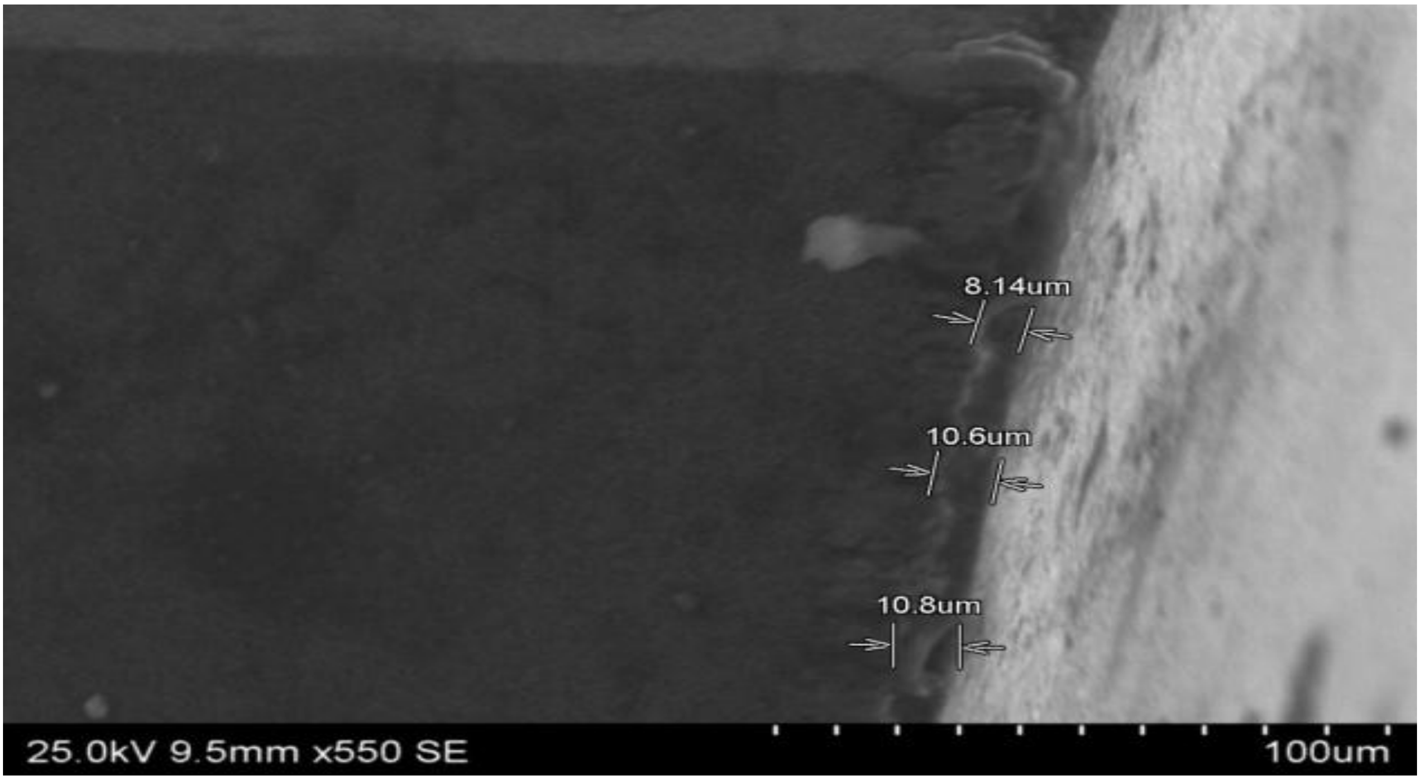


Fig 5.3. SEM image of tool wear using nano coolant for Exp. 1.

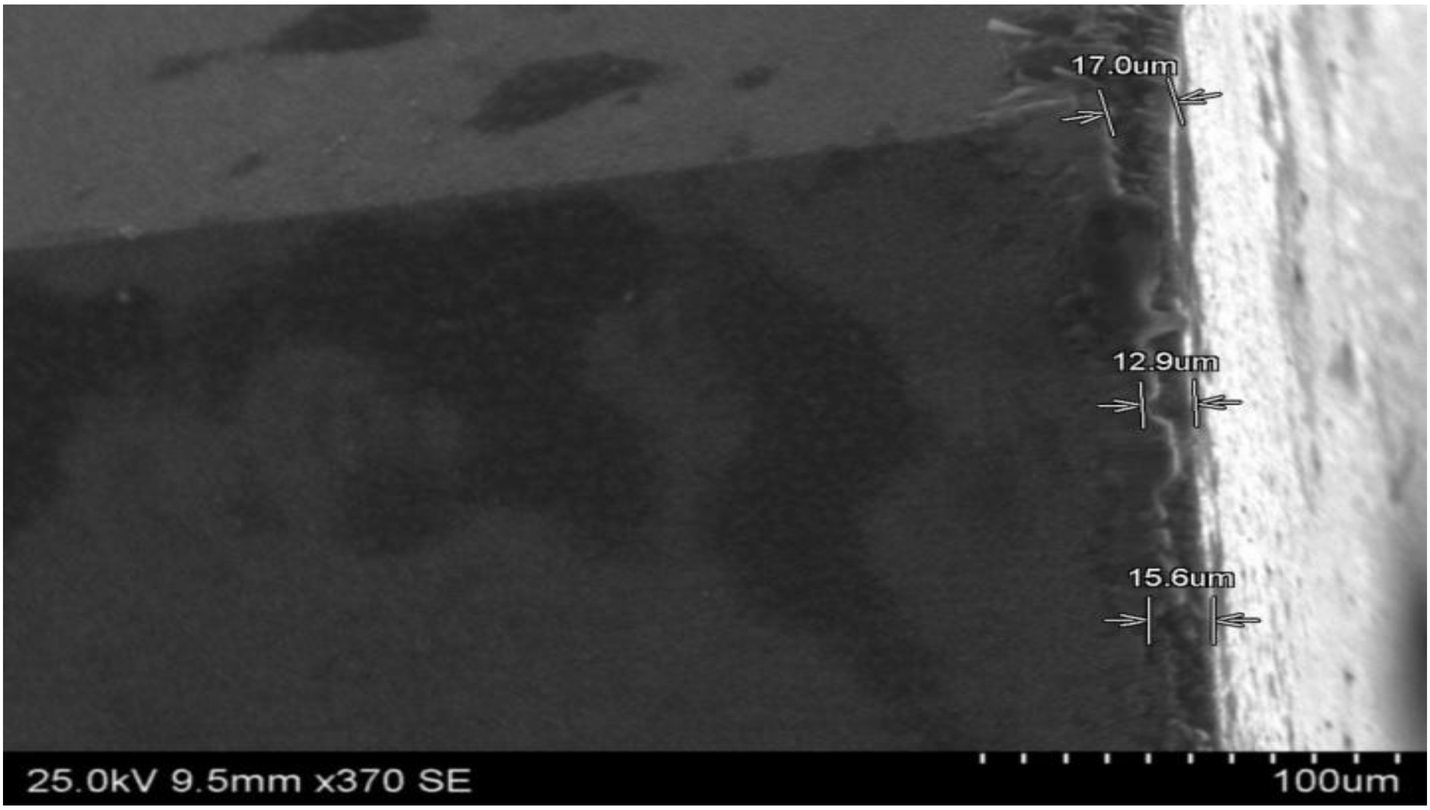


Fig 5.4. SEM image of tool wear using conventional coolant for Exp. 1.

The tool wear during milling in the presence of nano coolant at speed 2250 rpm, depth of cut 1 mm, feed rate 45mm/min is obtained from the SEM images shown in the figure 5.5. whereas figure 5.6 depicts the tool wear while conventional coolant is used during milling.

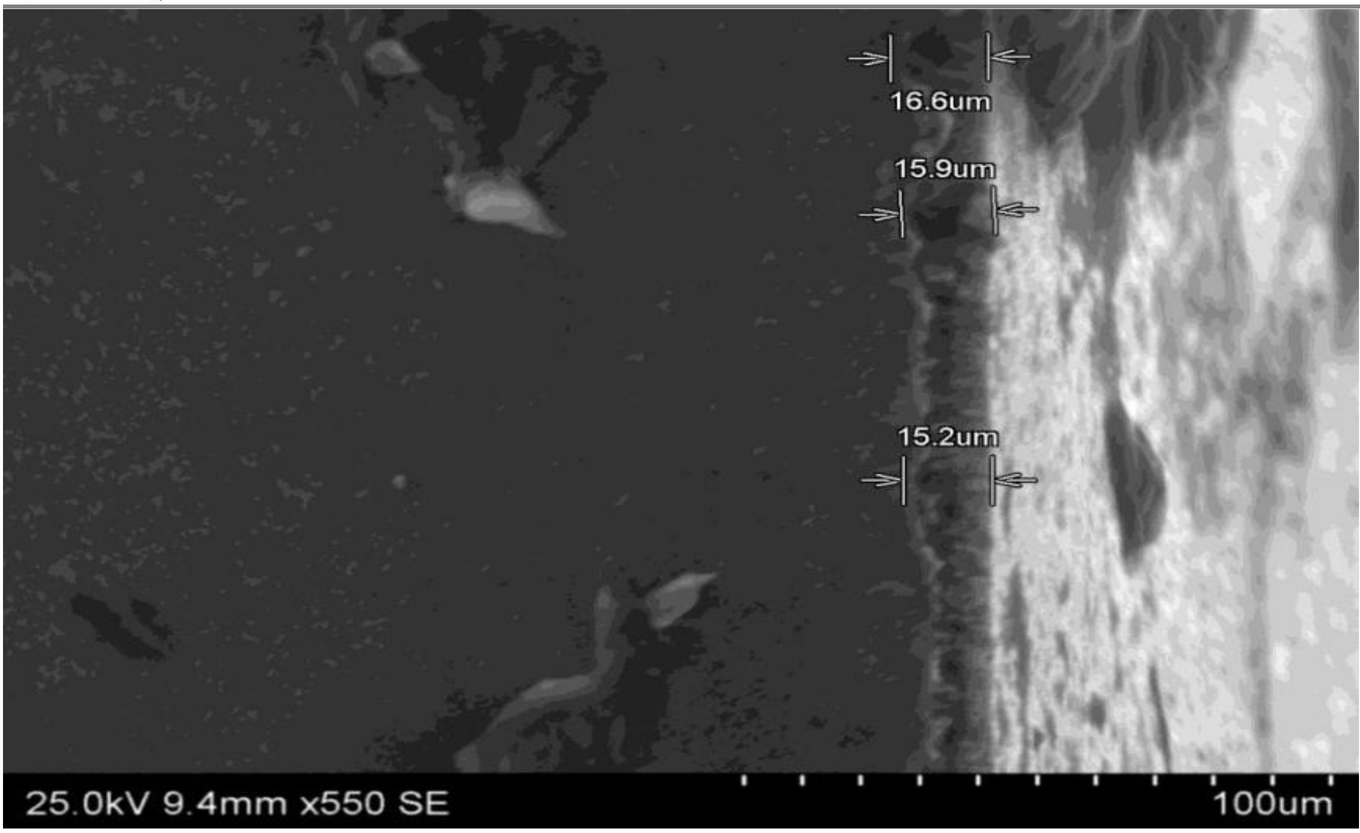


Fig 5.5. SEM image of tool wear using nano coolant for Exp. 14.

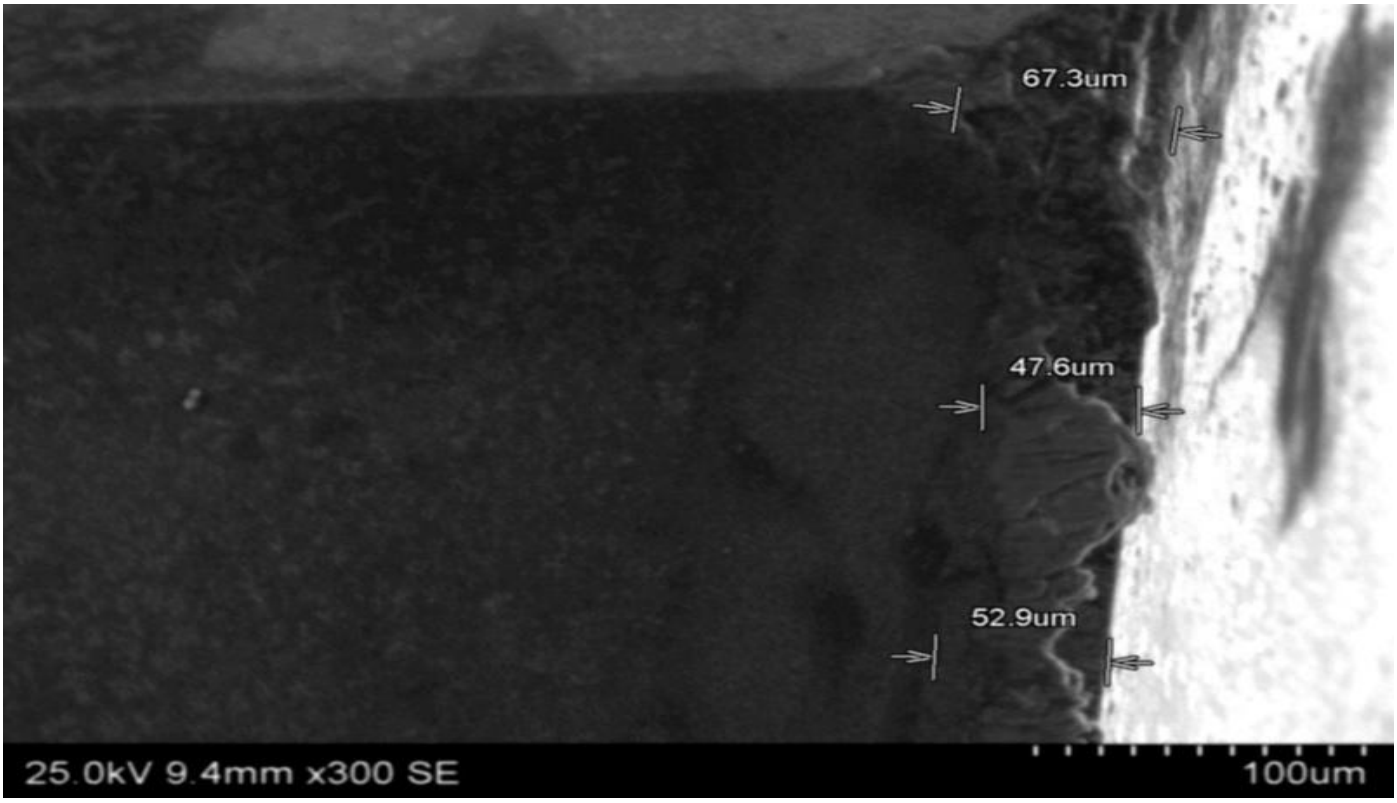


Fig 5.6. SEM image of tool wear using conventional coolant for Exp. 14.

The tool wear during milling in the presence of nano coolant at speed 2700 rpm, depth of cut 1.6 mm, feed rate 60 mm/min is obtained from the SEM images shown in the figure 5.7 whereas figure 5.8 depicts the tool wear while conventional coolant is used during milling.

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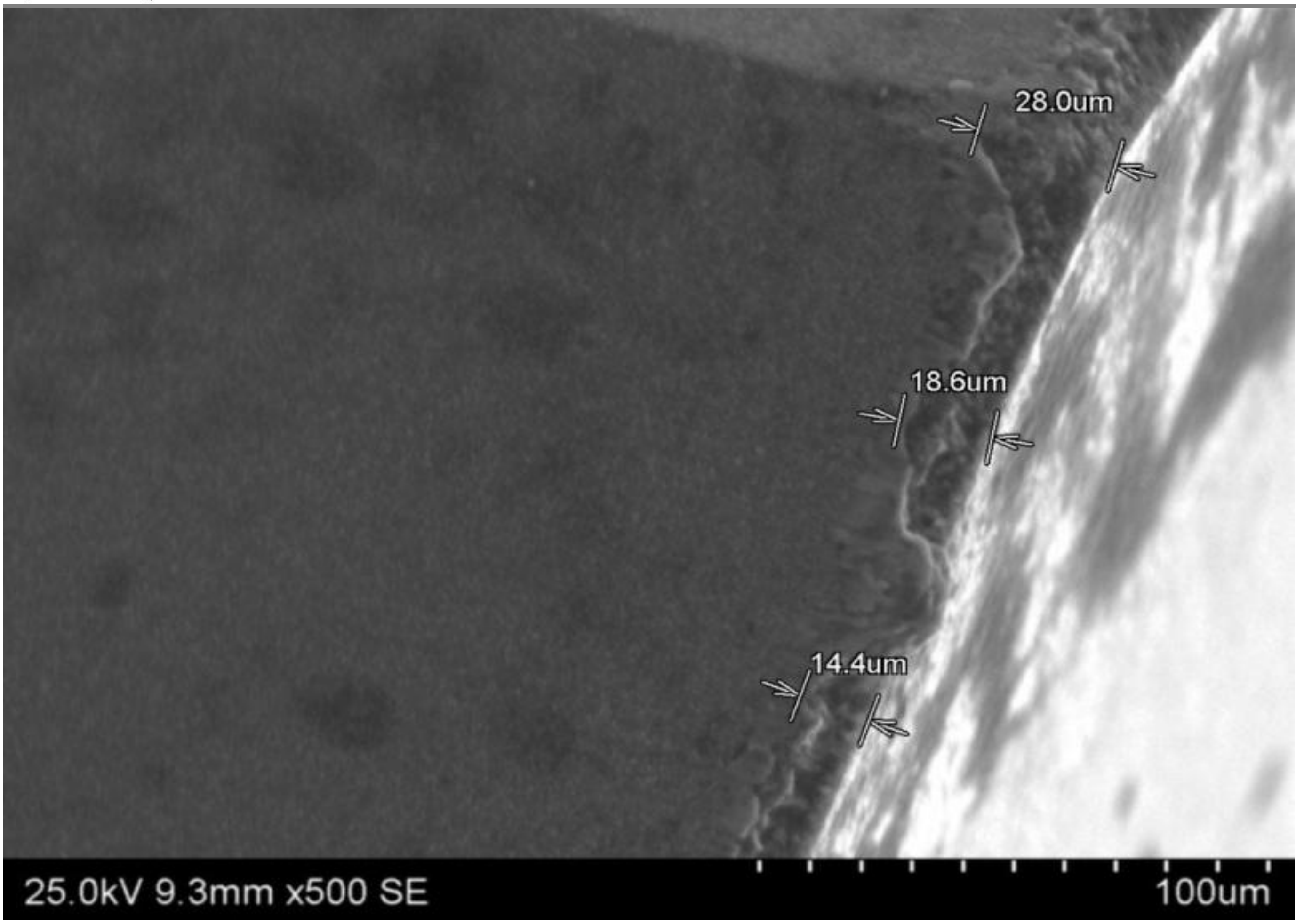

Fig 5.7. SEM image of tool wear using nano coolant for Exp. 27.

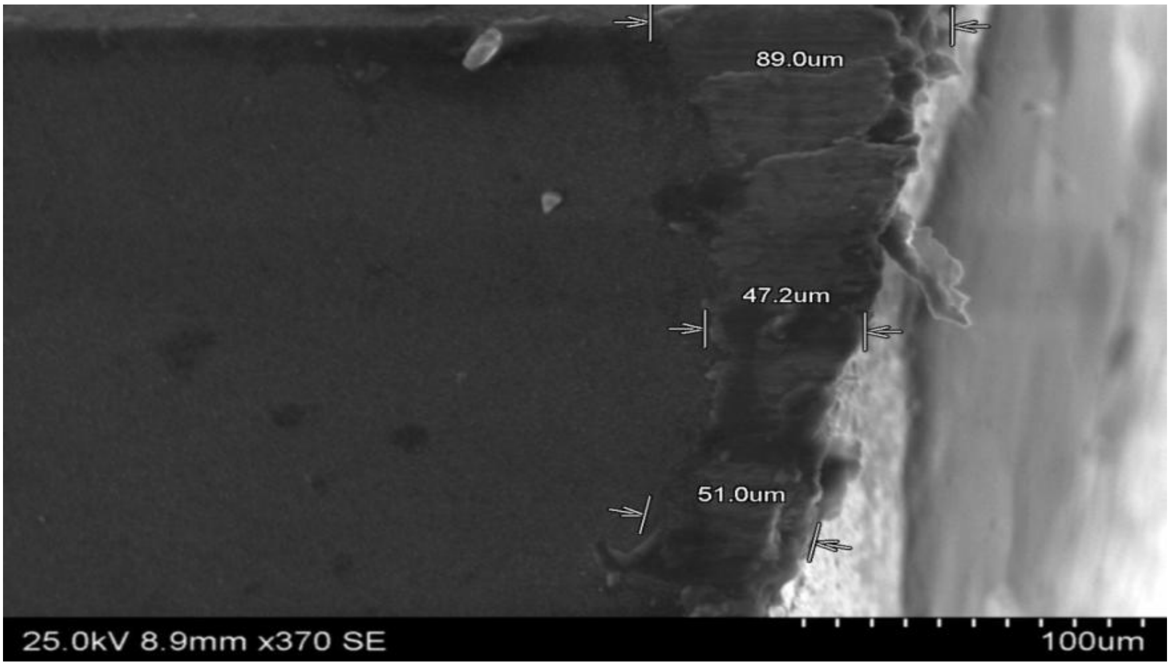

Fig 5.8. SEM image of tool wear using conventional coolant for Exp. 27.

The tool is broken with conventional coolant at the speed 2700 rpm, depth of cut 1.6 mm, feed rate 60 mm/min as shown in the figure 5.9.

Fig. 5.9. Broken PCD Insert Tip

CONCLUSION

The milling operation is performed on the Titanium work piece using conventional coolant and nano coolant at different speeds, feeds and depth of cuts using PCD inserts. Experimental analysis shows that these three controllable machining parameters (feed, cutting depth and cutting speed) have a significant influence on the tool life and surface finish. The tool wear of the Poly Crystalline Diamond (PCD) inserts is lower in the case of nano coolant when compared to conventional coolants during milling operation.While using conventional coolants, the minimum tool wear of 0.092 µm is obtained during the 1st experiment where as the maximum tool wear of 0.300µm is obtained during the 27th experiment. While using nano coolants, the minimum tool wear of 0.042 µm is obtained during the 1st experiment and the maximum tool wear of 0.0236 µm is obtained during the 27th experiment The surface roughness of the Titanium work piece is lower in the case of nano coolant. Where as we get higher surface roughness values while using conventional coolants during milling operation.

While using conventional coolants, the minimum surface roughness of 0.058 µm is obtained during the 3rd experiment and the maximum surface roughness of 0.314 µm is obtained during the 25th experiment. While using nano coolants, the minimum surface roughness of 0.0140 µm is obtained during the 2nd experiment and the maximum surface roughness of 0.292 µm is obtained during the 25th experiment. There is a tremendous improvement in surface finish and tool life in nanocoolant condition.

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