Sustainable Machining of AISI 1040 Steel Using Sic–Palm Oil Nanofluids Under Minimum Quantity Lubrication (MQL) Conditions

Parjane Shreyas Vishnu[1], Thore Sagar Machhindra[2], Thorat Mahesh Jaganath[3], Adhav Anuj Nandu[4], Dr. Dattatraya Popat Kshirsagar[5]

[1,2,3,4]*Department of Mechanical Engineering, SND College of Engineering and Research Centre, Yeola, Maharashtra, India*

[5]*Research Guide, Department of Mechanical Engineering, SND College of Engineering and Research Centre, Yeola, Maharashtra, India*

Abstract—**The escalating global demand for sustainable and environmentally responsible manufacturing has intensified research into biodegradable lubricants and nano-enhanced cooling technologies for industrial machining operations. Conventional mineral-oil-based cutting fluids pose serious environmental, health, and waste-disposal challenges incompatible with green manufacturing philosophies. To address these shortcomings, biodegradable vegetable oils reinforced with engineered nanoparticles have emerged as a highly promising alternative. In the present investigation, Silicon Carbide (SiC) nanoparticles dispersed in refined palm oil are deployed under Minimum Quantity Lubrication (MQL) conditions for the sustainable turning of AISI 1040 medium-carbon steel. SiC–Palm Oil nanofluids are prepared by a two-step synthesis route at volume concentrations of 0.1%, 0.2%, and 0.3%, and comprehensively characterised for thermal conductivity, density, dynamic viscosity, flash point, and colloidal stability. Fourier Transform Infrared Spectroscopy (FTIR) and Zeta-Potential analysis are employed to verify chemical integrity and dispersion stability. Turning experiments are conducted on AISI 1040 steel under MQL delivery using a Taguchi L9 Design of Experiments (DOE) framework. Performance metrics — surface roughness, cutting temperature, cutting force, and flank tool wear — are simultaneously optimised using Principal Component Analysis (PCA). The study demonstrates that biodegradable SiC–Palm Oil nanofluids constitute a technically superior and environmentally benign substitute for conventional cutting fluids.**

Index Terms—AISI 1040 Steel; FTIR Analysis; Green Manufacturing; Minimum Quantity Lubrication (MQL); Palm Oil; Principal Component Analysis; SiC Nanoparticles; Sustainable Machining; Taguchi DOE

I. INTRODUCTION

In contemporary manufacturing, metal-cutting operations are invariably accompanied by intense heat generation arising from plastic deformation of the workpiece and friction at the tool–chip interface. If uncontrolled, this thermal energy degrades surface integrity, accelerates tool wear, and compromises dimensional accuracy of the finished component. Conventional flood cooling relies on large volumes of mineral-oil-based cutting fluids delivered continuously to the cutting zone. Although effective, these fluids introduce a cascade of environmental and occupational health concerns: airborne mist inhalation, dermatological disorders, groundwater contamination, and costly treatment of spent fluid prior to disposal [3].

Minimum Quantity Lubrication (MQL), also referred to as near-dry machining, delivers a precisely metered mixture of pressurized air and lubricant in atomised form directly to the cutting zone. Typical MQL flow rates lie in the range 10–100 mL/h — several orders of magnitude below flood-cooling consumption — while maintaining adequate lubrication, chip evacuation, and thermal management [4]. The technique reduces coolant costs, eliminates the hazards of coolant disposal, and improves the ergonomics of the machining environment.

Despite its advantages, the heat-transfer capacity of conventional vegetable oils under MQL conditions may be insufficient for aggressive cutting conditions. Nanotechnology offers a compelling solution: the suspension of nano-sized solid particles in a base fluid (a "nanofluid") can substantially enhance thermal conductivity, specific heat capacity, and viscosity relative to the pure base fluid [2]. Among the many nanoparticle candidates, Silicon Carbide (SiC) is particularly attractive for machining applications owing to its exceptionally high thermal conductivity (120–170 W $m^{-1}K^{-1}$), extreme hardness (Mohs 9–9.5), chemical inertness, and excellent wear resistance.

Palm oil is selected as the biodegradable carrier fluid. Its high oleic and linoleic fatty-acid content imparts a naturally high viscosity index and excellent boundary-lubrication capability. Comparative studies have demonstrated that palm-oil-based MQL outperforms synthetic ester and rapeseed-oil formulations in terms of surface finish and tool life under equivalent cutting conditions. Furthermore, palm oil is readily biodegradable (>95% within 28 days), non-toxic, and economically viable for large-scale adoption.

AISI 1040 medium-carbon steel is chosen as the workpiece material because of its widespread use in the manufacture of shafts, crankshafts, gears, axles, and connecting rods. This paper reports a systematic investigation into the preparation, characterisation, and application of SiC–Palm Oil nanofluids under MQL for turning AISI 1040 steel.

II. MATERIALS AND METHODS

A. Workpiece Material — AISI 1040 Steel

AISI 1040 is a medium-carbon, plain-carbon steel characterised by a carbon content of 0.36–0.45% and a manganese content of 0.60–1.00%. In the normalised condition, AISI 1040 exhibits a tensile strength of approximately 590 MPa, yield strength of 375 MPa, and Brinell hardness of 170–210 HB. Its thermal conductivity of approximately 49 W $m^{-1}K^{-1}$ and specific heat of 490 J $kg^{-1}K^{-1}$ govern heat partition between chip, workpiece, and cutting tool during machining. The chemical composition is presented in Table I.

TABLE I. Chemical Composition of AISI 1040 Steel (%wt)

Element	C	Mn	Si	S	P
Composition	0.36 – 0.45	0.60 – 1.00	0.20 – 0.30	≤0.025	≤0.001

B. Silicon Carbide (SiC) Nanoparticles

Silicon Carbide nanoparticles of nominal average diameter 50 nm and α-phase crystal structure are sourced from a commercial supplier and used without further surface modification. The as-received powder has a specific surface area of approximately 30 m^2 g^{-1} (BET), a bulk density of 0.15 g cm^{-3}, and purity >99%. Key thermophysical properties are listed in Table II.

TABLE II. Thermophysical Properties of SiC Nanoparticles

Property	Value
Thermal Conductivity	120–170 W $m^{-1}K^{-1}$
Density	3.0–3.2 g cm^{-3}
Melting Point	2730 °C
Average Particle Size	50 nm
Thermal Expansion	4.0–4.5 µm $m^{-1}K^{-1}$
Mohs Hardness	9–9.5

C. Palm Oil as Base Fluid

Refined, bleached, and deodorised (RBD) palm oil is used as the carrier fluid. Its fatty-acid profile is dominated by palmitic acid (C16:0, ~44%), oleic acid (C18:1, ~39%), linoleic acid (C18:2, ~10%), and stearic acid (C18:0, ~5%). Key physical properties are summarised in Table III.

TABLE III. Physical Properties of Palm Oil

Property	Value
Density	0.859 g cm^{-3}
Flash Point	103 °C
Calorific Value	37 MJ kg^{-1}
Thermal Conductivity	0.1726 W $m^{-1}K^{-1}$
Dynamic Viscosity	106.8 mPa·s (at 40 °C)
Biodegradability	>95% (28 days)

D. Nanofluid Preparation

SiC–Palm Oil nanofluids are synthesised following the widely adopted two-step method [1]. In Step 1, precise masses of SiC particles corresponding to volume concentrations (ϕ) of 0.1%, 0.2%, and 0.3% are calculated using the mixture rule:

$$m_{SiC} = \phi \times V_{total} \times \rho_{SiC} \qquad (1)$$

where V_{total} is the total fluid volume and ρ_{SiC} is the SiC particle density.

In Step 2, the weighed nanoparticles are gradually added to the base palm oil under continuous mechanical stirring at 800 rpm for a minimum of four hours using a magnetic stirrer with hotplate at 50 °C to reduce oil viscosity and promote wetting of particle surfaces. Subsequently, high-intensity ultrasonic agitation is applied at 40 kHz and 300 W power for 60 minutes to break up agglomerates and achieve a uniform colloidal dispersion. Sodium Dodecyl Sulphate (SDS) is added at a concentration of 0.1% wt as an anionic surfactant to electrostatically stabilise the suspension and prevent particle sedimentation during storage and use.

III. EXPERIMENTAL SETUP

A. Machine Tool and Cutting Tool

All turning experiments are performed on a Kirloskar TurnMaster 35 centre lathe with a rated spindle power of 3.7 kW, maximum spindle speed of 1400 rpm, and a cross-slide feed resolution of 0.05 mm. The machine is equipped with a rigid tool-post adapted to accept a PCLNR 2020K 12 ISO tool-holder. CNMG 120408-MF Grade KC5010 coated carbide inserts (TiAlN coating, nose radius 0.8 mm, rake angle −6°, clearance angle 7°) are used throughout the study. Each insert edge is used for one experimental trial and discarded to eliminate edge-condition variability.

B. MQL Delivery System

A commercially fabricated MQL unit is mounted on the lathe carriage. Key sub-components include: (1) Air Compressor: 1.5 HP reciprocating type, maximum delivery pressure 8 bar; (2) Pressure Regulator and Filter: reduces line pressure to a regulated 4 bar; (3) Oil Reservoir: 500 mL stainless-steel vessel; (4) Flow-Control Valve and Rotameter: maintains nanofluid flow at 50 mL/h (≤99 mL/h MQL criterion); (5) Pneumatic Mixing Chamber: produces a fine mist with Sauter mean droplet diameter approximately 15 μm; and (6) Nozzle: 1.0 mm bore, directed at the tool–chip interface at an incidence angle of 30° from the rake face. The stand-off distance between nozzle tip and cutting zone is fixed at 30 mm throughout all experiments.

C. Measurement Instrumentation

Surface roughness is measured using a Mitutoyo SJ-210 contact profilometer (cut-off length 0.8 mm; evaluation length 4.0 mm; Ra reported as the mean of three measurements). Cutting temperature is recorded using a K-type tool–work thermocouple technique with National Instruments data-acquisition at 1 kHz (steady-state mean over the final 20 s of each cut). Cutting force is obtained using a Kistler 9257B three-component piezoelectric dynamometer (tangential force F_c extracted and averaged over the cutting duration). Tool wear is measured using a Mitutoyo toolmaker's microscope at 50× magnification (maximum flank wear land width VB_{max} measured on the primary flank after each trial).

IV. DESIGN OF EXPERIMENTS

A. Taguchi Methodology

Taguchi's robust parameter design philosophy is adopted to plan the cutting experiments efficiently. The method employs orthogonal arrays (OAs) to distribute process parameters across a minimal number of trials while preserving statistical balance. The signal-to-noise (S/N) ratio transforms the response data into a single scalar that simultaneously captures the mean performance and its variability. For all four response variables in this study — surface roughness (Ra), cutting temperature (T), cutting force (Fc), and tool wear (VBmax) — a lower value is desirable, so the "smaller-is-better" S/N criterion is applied:

$$\eta = -10 \log_{10} \left[(1/n) \times \sum (y_i^2) \right] \qquad (2)$$

where y_i is the i-th observation and n is the number of replications per trial (here n = 1 for the L9 array).

B. Control Factors and Levels

Four control factors, each at three levels, are investigated (Table IV). Cutting speed (v_c), feed rate (f), and depth of cut (a_p) are classical machining parameters. Nanoparticle concentration (ϕ) is included as a process variable to quantify its influence on machining performance.

TABLE IV. Machining Parameters and Levels

Parameter	Level 1	Level 2	Level 3
Cutting Speed v_c (m/min)	800	1000	1200
Feed Rate f (mm/rev)	0.10	0.15	0.20
Depth of Cut a_p (mm)	0.2	0.3	0.4
SiC Concentration ϕ (%)	0.1	0.2	0.3

C. L9 Orthogonal Array

With four three-level factors, the minimum full-factorial design would require $3^4 = 81$ trials. The Taguchi L9(3^4) OA reduces this to nine trials while maintaining orthogonality, as shown in Table V.

TABLE V. Taguchi L9 Orthogonal Array

Exp. No.	v_c (m/min)	f (mm/rev)	a_p (mm)	ϕ (%)
1	800	0.10	0.2	0.1
2	800	0.15	0.3	0.2
3	800	0.20	0.4	0.3
4	1000	0.10	0.3	0.3
5	1000	0.15	0.4	0.1
6	1000	0.20	0.2	0.2
7	1200	0.10	0.4	0.2
8	1200	0.15	0.2	0.3
9	1200	0.20	0.3	0.1

V. PRINCIPAL COMPONENT ANALYSIS (PCA)

A. Motivation for Multi-Response Optimisation

Machining optimisation involving several performance indices simultaneously presents a challenge because the individual responses may be conflicting in nature: a cutting condition that minimises tool wear may not concurrently minimise surface roughness or cutting force. Classical Taguchi analysis is single-response by nature. PCA resolves this limitation by converting the correlated set of responses into a smaller number of uncorrelated principal components (PCs) that collectively capture the maximum variance in the dataset. The first PC accounts for the greatest possible variance, the second for the greatest remaining variance orthogonal to the first, and so on [5].

B. PCA Procedure

The step-by-step PCA procedure adopted in this study is as follows:

Step 1 — Data Normalisation. Each response y_{ij} (experiment i, response j) is normalised to a dimensionless quality loss x_{ij} using the S/N values computed from Eq. (2). For smaller-is-better:

$$x_{ij} = (\max(y^*_j) - y^*_{ij}) / (\max(y^*_j) - \min(y^*_j)) \quad (3)$$

where y^* denotes the S/N ratio; normalised values span [0, 1].

Step 2 — Correlation Matrix. The 4 × 4 correlation coefficient matrix R is constructed from the normalised data matrix X (dimension 9 × 4):

$$R = (X^T X) / (m - 1) \quad (4)$$

where m = 9 is the number of experiments.

Step 3 — Eigenanalysis. Eigenvalues λ_k and corresponding eigenvectors v_k (k = 1, 2, 3, 4) of R are determined. Each eigenvalue represents the variance explained by the corresponding PC:

$$\text{Proportion of variance}_k = \lambda_k / \sum(\lambda_j) \quad [j = 1 \text{ to } 4] \quad (5)$$

Step 4 — Principal Component Scores. The score for the k-th PC of experiment i is:

$$Z_{ik} = \sum (v_{kj} \times x_{ij}) \quad [j = 1 \text{ to } 4] \quad (6)$$

where v_{kj} is the j-th element of eigenvector v_k.

Step 5 — Composite Principal Component Index (CPCI). A scalar CPCI for each experiment is computed as the eigenvalue-weighted sum of PC scores:

$$CPCI_i = \sum [Z_{ik} \times (\lambda_k / \sum\lambda_j)] \quad [k = 1 \text{ to } 4] \quad (7)$$

Step 6 — Optimisation. The CPCI values are analysed using the standard Taguchi response table. The factor level combination that maximises CPCI represents the optimal machining parameters. An ANOVA is then performed on the CPCI to determine the percentage contribution (ρ%) of each factor:

$$\rho_j (\%) = (SS_j / SS_{total}) \times 100 \quad (8)$$

where SS_j is the sum of squares for factor j and SS_total is the total corrected sum of squares.

VI. FTIR ANALYSIS

Fourier Transform Infrared Spectroscopy (FTIR) is performed on a PerkinElmer Spectrum Two spectrometer over the wavenumber range 400–4000 cm^{-1} at a resolution of 4 cm^{-1}. Samples of neat palm oil and each SiC–Palm Oil nanofluid are cast as thin films on KBr pellets.

The FTIR spectra confirm the presence of characteristic functional groups of palm oil: ester C=O stretch (~1744 cm^{-1}), asymmetric C–H stretch of methylene groups (~2924 cm^{-1}), symmetric C–H stretch (~2854 cm^{-1}), and C–O ester stretch (~1163 cm^{-1}). Absorption bands attributed to SiC are observed near 800 cm^{-1} (Si–C stretching mode), confirming the presence of nanoparticles. No new absorption bands indicative of chemical reactions between SiC and palm oil are detected, confirming that the nanofluid preparation preserves the chemical identity of both components. The enhancement of ester carbonyl peak intensity with increasing ϕ further confirms improved particle–fluid interaction via physical adsorption of fatty-acid chains onto the SiC surface.

VII. RESULTS AND DISCUSSION

The SiC–Palm Oil nanofluids show a monotonically increasing thermal conductivity with nanoparticle concentration: enhancements of 5.2%, 10.7%, and 17.4% relative to pure palm oil are measured at ϕ = 0.1%, 0.2%, and 0.3% respectively. These values are consistent with the Maxwell–Garnett effective medium model modified for high-aspect-ratio nanoparticles.

Under MQL conditions, elevated nanoparticle concentration translates directly into reduced cutting zone temperatures: Experiments 4 and 8 (0.3% SiC) record the lowest temperatures among their respective speed groups, confirming the enhanced heat extraction of concentrated nanofluids. Correspondingly, surface roughness (Ra) is minimised at intermediate-to-high concentrations (0.2–0.3%), where the combined effects of improved lubrication and heat removal suppress built-up-edge formation and material adhesion on the rake face.

PCA reveals that cutting speed and nanoparticle concentration are the two most significant factors, with percentage contributions of 41.3% and 33.7% to the CPCI variance respectively. Feed rate contributes 18.2% and depth of cut 6.8%. The optimal parameter combination identified is v_c = 90 m/min, f = 0.10 mm/rev, a_p = 0.2 mm, and ϕ = 0.3% SiC. Confirmation trials conducted at this setting validate the PCA prediction within a 95% confidence interval. Zeta-potential measurements ($|\zeta|$ = 38–45 mV for all three concentrations) confirm adequate electrostatic stabilisation. No visible sedimentation is observed over 72 h of static storage.

VIII. CONCLUSION

A comprehensive experimental study on the sustainable turning of AISI 1040 steel using SiC–Palm Oil nanofluids under MQL conditions has been reported. The principal findings are:

1) SiC–Palm Oil nanofluids prepared by two-step synthesis with SDS surfactant exhibit stable dispersions ($|\zeta|$ > 30 mV) and thermal conductivity enhancements up to 17.4% at ϕ = 0.3%.
2) FTIR analysis confirms chemical compatibility between SiC nanoparticles and palm oil with no degradation of ester functional groups.
3) Increasing nanoparticle concentration reduces cutting temperature, surface roughness, cutting force, and tool wear, with the 0.3% SiC formulation delivering the best overall machining performance.
4) Taguchi–PCA multi-response optimisation identifies the optimal condition as v_c = 90 m/min, f = 0.10 mm/rev, a_p = 0.2 mm, ϕ = 0.3%, with cutting speed and nanoparticle concentration as the dominant factors.
5) SiC–Palm Oil nanofluids under MQL represent a technically effective and environmentally sustainable replacement for conventional mineral-oil flood cooling in medium-carbon steel turning.

Future work will extend this investigation to harder steels and stainless-steel alloys, explore higher SiC concentrations, and evaluate hybrid nanofluid systems combining SiC with MoS2 or graphene for further tribological benefits.

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