ESTEEM Academic Journal
e-ISSN: 2689-4934

PENERBIT PRESS
UNIVERSITI TEKNOLOGI MARA

Available online at
http://uppp.uitm.edu.my/online-issues.html

ESTEEM Academic Journal Vol 22, September 2026, 85-97

ESTEEM
Academic Journal
(EAJ)

Effects of boundary lubrication and spindle speed on the surface roughness of UHMWPE in robotic milling

Wan Nor Shela Ezwane Wan Jusoh[1], Mohamad Irwan Yahaya[2*], Mahamad Hisyam Mahamad Basri[3], Shukri Zakaria[4]

[1,2,3,4]*Mechanical Engineering Studies, Universiti Teknologi MARA Cawangan Pulau Pinang, Permatang Pauh Campus, 13500 Permatang Pauh, Pulau Pinang, Malaysia*

ARTICLE INFO

Article history:
Received 1 June 2026
Revised 1 August 2026
Accepted 18 August 2026
Online first
Published 15 September 2026

Keywords:
UHMWPE
Robotic milling
Surface roughness
Palm oil
Mineral oil
Boundary lubrication

DOI:
10.24191/esteem.v22iSeptember.12289

ABSTRACT

Achieving high surface quality in robotic milling of Ultra-High Molecular Weight Polyethylene (UHMWPE) is difficult: the polymer conducts heat poorly and behaves viscoelastically, so the cut readily softens and damages the very surface it is forming. This study examines how boundary lubrication and spindle speed affect the surface roughness of UHMWPE machined on a KUKA KR120 R2700 robotic system. Dry cutting, palm oil, and ISO VG 32 light mineral oil were compared, with both oils pre-applied by hand so that only a static boundary film was available at the cut. Spindle speeds of 6500 and 9500 rpm were used at a fixed feed rate of 1620 mm/min and a depth of cut of 0.3 mm, and Ra, Rq, and Rz were measured using a Mitutoyo SJ-401 profilometer. Palm oil gave the lowest Ra at both speeds, with values of 1.275 µm at 6500 rpm and 1.004 µm at 9500 rpm, corresponding to reductions of approximately 45% and 39% compared with dry cutting and 23% and 21% compared with mineral oil, respectively. The higher spindle speed improved the finish under every lubrication condition. Within the window tested, palm oil therefore earns consideration as a boundary lubricant for robotic UHMWPE milling. However, these data cannot establish how it behaves over a longer cut: friction, wear, cutting temperature, and tool life were not measured, and these parameters would have to be quantified before the oil could be recommended for production use.

[2*]Corresponding author. *E-mail address*: irwan352@uitm.edu.my

1. INTRODUCTION

UHMWPE has served as the bearing material in total joint arthroplasty for more than five decades, and it is used even more widely in sliding bearings and other load-bearing components. Its appeal rests on a combination of impact and wear resistance, a low coefficient of friction, and chemical inertness in physiological environments [1], [2], [5]. The same polymer is awkward to machine. It is viscoelastic, and it conducts heat poorly, so cuts that would be unremarkable in metals tend to leave burrs, dimensional errors, and a degraded finish [3], [4]. Of these defects, surface roughness carries the greatest clinical consequence. A rough articulating surface on a hip or knee component accelerates the generation of abrasive wear particles, and that debris is implicated in osteolysis and implant loosening [1], [2], [5], [6]. Roughness is also the one measure of surface integrity that can be recorded directly and repeatedly on the machined part, which is why it is treated as the primary response throughout this work.

Four influences recur in the UHMWPE milling literature as the principal determinants of surface roughness: the machining platform, the cutting parameters, the tool geometry, and the lubrication strategy [5–9]. On a well-tuned CNC machine, the first three can be pushed far enough to yield low Ra values on UHMWPE components. A robot is a different proposition, because its lower structural rigidity and greater dynamic compliance introduce error sources that a rigid machine tool does not have [10–13]. Parameter effects on UHMWPE surface quality have been mapped reasonably well; however, the effects of lubrication strategy in a robotic cell have not been studied extensively, and direct comparisons between lubricants remain scarce [6–9], [13]. The gap matters because the lubricant governs friction, heat generation, and chip evacuation at the cut, and each of these factors feeds back into the surface that is left behind in polymer machining. For robotic UHMWPE milling, this question has not been sufficiently investigated [14–17].

What the robot gives in return is reach and flexibility. Geometries that would require repeated refixturing on a conventional machine can often be approached in a single setup, and the technique has spread accordingly through metals, composites, and engineering polymers [10–12]. UHMWPE is a conspicuous exception, and work on it remains limited [13]. The lubrication literature shows a similar imbalance. Mineral and synthetic fluids account for most of it, while vegetable-based alternatives such as palm oil have attracted attention more recently for their biodegradability, their comparatively high viscosity, and their capacity to form a stable boundary film [18–22]. In metallic machining and in sliding tribological contacts, palm oil formulations have been reported to lower friction and improve finish relative to some petroleum-based fluids [20–23]. None of that evidence comes from robotic UHMWPE milling, but it is enough to make palm oil worth testing under boundary conditions.

No published study has yet compared palm oil and mineral oil under identical robotic milling conditions on UHMWPE, which leaves the practitioner without a basis for choosing between them. The present work addresses that specific question. Lubricant type (ISO VG 32 mineral oil and palm oil) and spindle speed are varied on a KUKA KR120 R2700 cell, while dry cutting is retained as the baseline, and the response is read from Ra, Rq, and Rz together with SEM examination of the machined surface. The heat and adhesion problems that make UHMWPE difficult to cut [3–5], [7], and the boundary film-forming behaviour reported for palm oil in other contexts [18–23] frame the interpretation offered below. That interpretation is necessarily preliminary, because the machined surface is the only evidence available here.

2. METHODOLOGY

2.1 Materials and experimental setup

Milling was carried out on a KUKA KR120 R2700 six-axis industrial robot. Cutting was done with a 10 mm uncoated HSS end mill with a two-flute geometry (ISO HSS-M2, 62 HRC, 100 mm overall length, Miranda Tools). Two flutes rather than four were chosen deliberately, since the wider flute space clears chips more readily and limits heat build-up that viscoelastic polymers tolerate poorly. Workpieces were compression-moulded UHMWPE (Röchling) sectioned into 50 × 50 × 50 mm blocks, with properties as listed in Table 1.

Table 1. Material properties of the UHMWPE workpiece

Property	Value
Density (g/cm^{3})	0.93
Yield Stress (MPa)	20
Tensile Modulus of Elasticity (MPa)	680
Melting Temperature (°C)	135
Heat Deflection Temperature (°C)	79
Coefficient of Thermal Expansion (×10^{-6}/°C)	150–230

Three parallel slots were cut across each specimen face in a single pass, each 50 mm long and 10 mm wide at the full tool diameter, and spaced 5 mm apart. Those three slots are the three repeats for the condition concerned. Fig. 1 shows the layout and the feed direction.

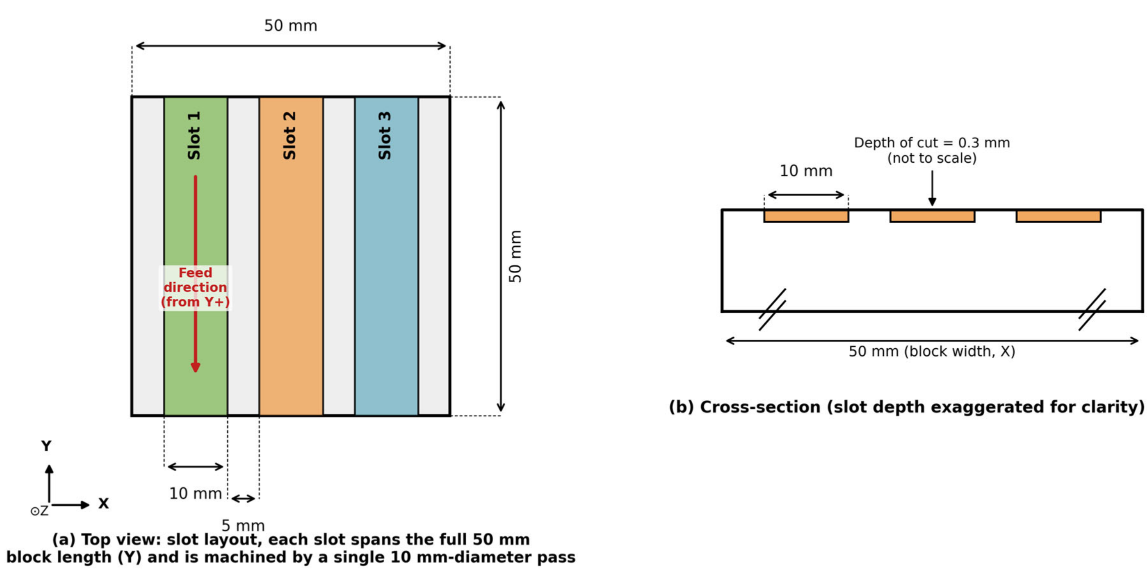

Fig. 1. Schematic of the milled slot geometry on the 50 × 50 mm specimen face: (a) top view of the three parallel slots and feed direction; (b) cross-section showing the slots (depth not to scale)

2.2 Machining parameters

Milling was conducted at spindle speeds of 6500 and 9500 rpm under three lubrication conditions: dry cutting, palm oil, and ISO VG 32 light mineral oil. The feed rate and depth of cut were fixed at 1620 mm/min and 0.3 mm, respectively, as listed in Table 2, and the experimental configuration is shown in Fig. 2. These parameters were selected on the basis of preliminary trials and previous studies on UHMWPE milling, in which higher spindle speeds and shallow depths of cut were reported to reduce thermal accumulation, material adhesion, and tool clogging [24–27]. Both speeds fall within the 6500 to 12500 rpm window used in related robotic milling work on the same UHMWPE dataset [28], [29]. Neither flood nor mist delivery was used. A thin film of lubricant was instead spread over the workpiece surface by hand before each trial and was not replenished, thereby reproducing the static boundary condition in which the cut has only a pre-deposited film to draw on. Withholding a flowing supply also removes convective cooling from the comparison, so that what separates the two oils is their behaviour in the boundary film rather than their capacity to carry heat away. The application procedure was kept consistent throughout. Each condition was repeated three times, and means and standard deviations were computed to gauge repeatability. Table 3 summarises the physical properties of both lubricants.

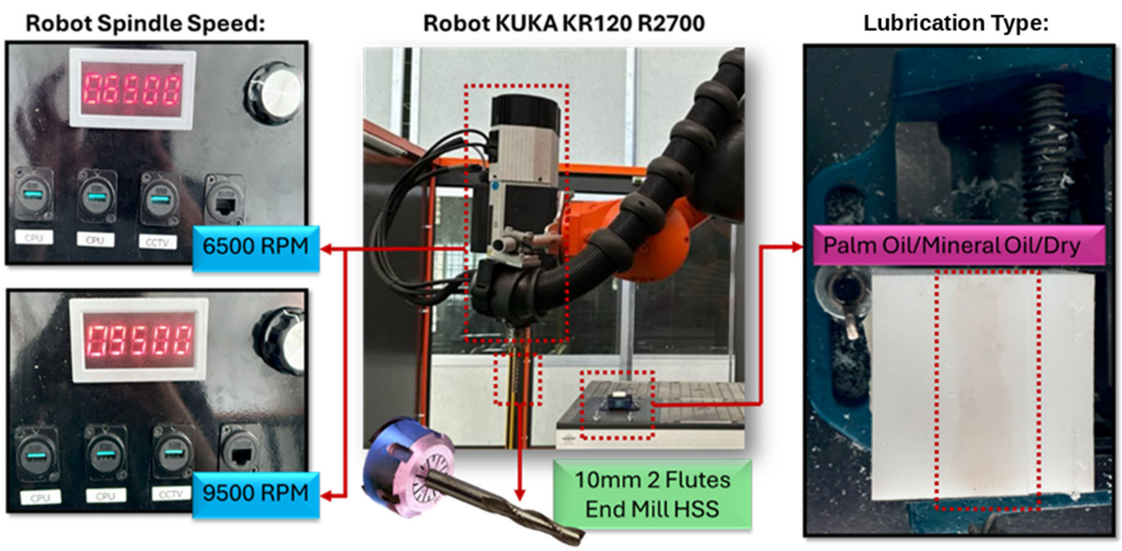

Fig. 2. Experimental setup for robotic milling of UHMWPE using the KUKA KR120 R2700 system, a 10 mm HSS two-flute end mill, and the manual lubricant pre-application method

Table 2. Cutting parameters used in the robotic milling experiments

Parameter	Value
Spindle Speed (rpm)	6500
	9500
Feed Rate (mm/min)	1620
Depth of Cut (mm)	0.3
Lubrication Condition	Dry (without lubrication)
	Palm Oil
	Light Mineral Oil ISO VG 32

Table 3 shows that palm oil exhibited substantially higher kinematic viscosity than the ISO VG 32 mineral oil at both 40 °C and 100 °C, together with a higher flash point. The ISO VG 32 mineral oil is a commonly used industrial lubricant for light machinery and hydraulic applications. The palm oil used in this study was commercially available refined, bleached, and deodorised (RBD) palm olein, a standard commercial grade widely produced in Malaysia and frequently employed in machining and tribological studies [19]. The higher viscosity of palm oil may promote the formation of a more stable boundary film at the tool-workpiece interface, and its influence on machining performance is discussed in Section 3.

Table 3. Physical properties of ISO VG 32 light mineral oil and palm oil

Property	ISO VG 32	Palm Oil
Density at 15 °C (kg/L)	0.86–0.87	0.890
Kinematic viscosity at 40 °C (mm²/s)	32.0	106.8
Kinematic viscosity at 100 °C (mm²/s)	5.5–5.8	12.07
Flash point (°C)	≥ 210	260
Pour point (°C)	−30	−4

2.3 Surface roughness measurement

Ra, Rq, and Rz were recorded using a Mitutoyo SJ-401 profilometer, with the parameters defined according to [30]. Three traces were taken at separate positions along each machined slot and averaged to give the value reported for that surface. The reduction in Ra relative to dry cutting follows Eq. (1):

$$\% \text{ Reduction} = (Ra_{dry} - Ra_{lubricated}) / Ra_{dry} \times 100 \quad (1)$$

where Ra_{dry} is the mean Ra under dry cutting and $Ra_{lubricated}$ is the mean Ra obtained at the same spindle speed with palm oil or mineral oil. Expressing the improvement as a percentage allows the two speeds to be compared despite their different baselines.

2.4 Surface morphology and microstructure analysis

Machined surfaces were imaged using a Hitachi TM3030 tabletop scanning electron microscope (SEM) fitted with a SwiftED3000 detector, after cleaning to remove loose chips and residual oil. One representative area was imaged for every combination of lubrication condition and spindle speed, and the images were examined for the defects that machining can produce in a viscoelastic polymer: tearing marks, fibrillar deformation, burr-like protrusions, micro-grooves, and smeared material. The SEM analysis is qualitative. It is used here to show what the roughness figures look like on the surface itself, not to quantify wear or friction, neither of which can be extracted from these images.

3. RESULTS AND DISCUSSION

The roughness data are presented first, followed by the SEM images that accompany them.

Table 4 lists the means and standard deviations for every parameter. Scatter was modest relative to the corresponding means, particularly for Ra and Rq, so the three repeats can be considered consistent. The exception is Rz under mineral oil at 6500 rpm (7.725 ± 1.643 µm), where the spread is wide enough to suggest that peak-to-valley formation was itself less stable under that condition.

Table 4. Mean ± standard deviation of Ra, Rq, and Rz by spindle speed and lubrication condition

Spindle speed (rpm)	Lubrication condition	Ra (µm)	Rq (µm)	Rz (µm)
6500	Dry cutting	2.331 ± 0.229	3.044 ± 0.251	11.765 ± 0.967
6500	Palm oil	1.275 ± 0.119	1.714 ± 0.077	6.493 ± 0.779
6500	ISO VG 32 mineral oil	1.655 ± 0.331	2.097 ± 0.457	7.725 ± 1.643
9500	Dry cutting	1.656 ± 0.228	2.075 ± 0.307	7.509 ± 0.723
9500	Palm oil	1.004 ± 0.061	1.234 ± 0.113	4.520 ± 0.472
9500	ISO VG 32 mineral oil	1.278 ± 0.077	1.700 ± 0.199	6.414 ± 0.774

Fig. 3 shows the Ra results. Palm oil produced a consistent reduction in Ra across both tested spindle speeds, followed by mineral oil, while dry cutting produced the highest values. At 6500 rpm, palm oil reduced Ra from 2.331 µm under dry cutting to 1.275 µm, a reduction of approximately 45%, and by about 23% compared with mineral oil. At 9500 rpm, the corresponding reductions were approximately 39% against dry cutting and about 21% against mineral oil.

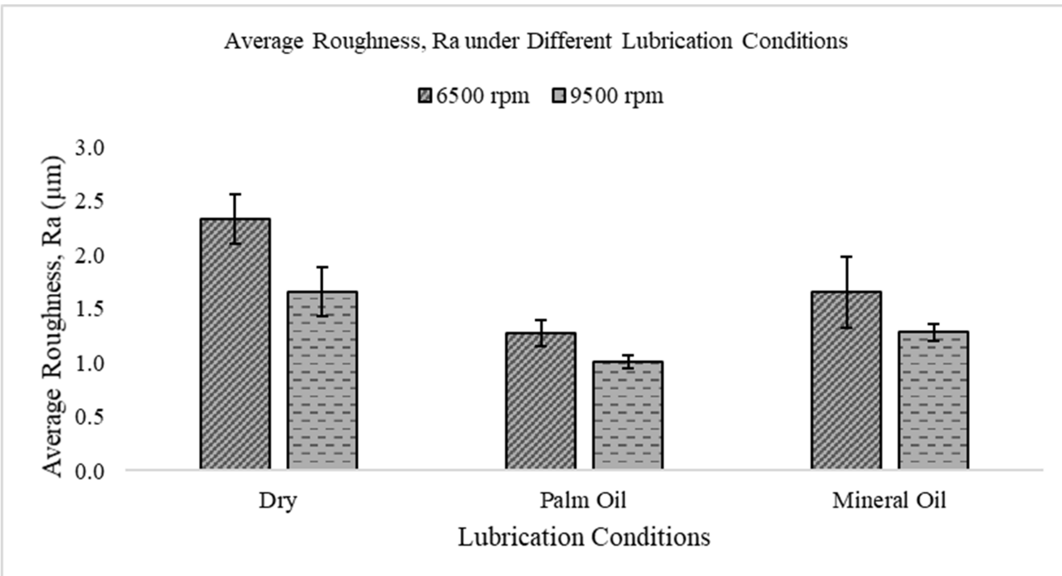

Fig. 3. Average roughness (Ra) of UHMWPE machined under dry cutting, ISO VG 32 mineral oil, and palm oil lubrication at 6500 and 9500 rpm

Rq, in Fig. 4, ranks the three conditions in the same order. Dry cutting gave 3.044 µm at 6500 rpm, mineral oil 2.097 µm, and palm oil 1.714 µm, and the ordering holds at 9500 rpm.

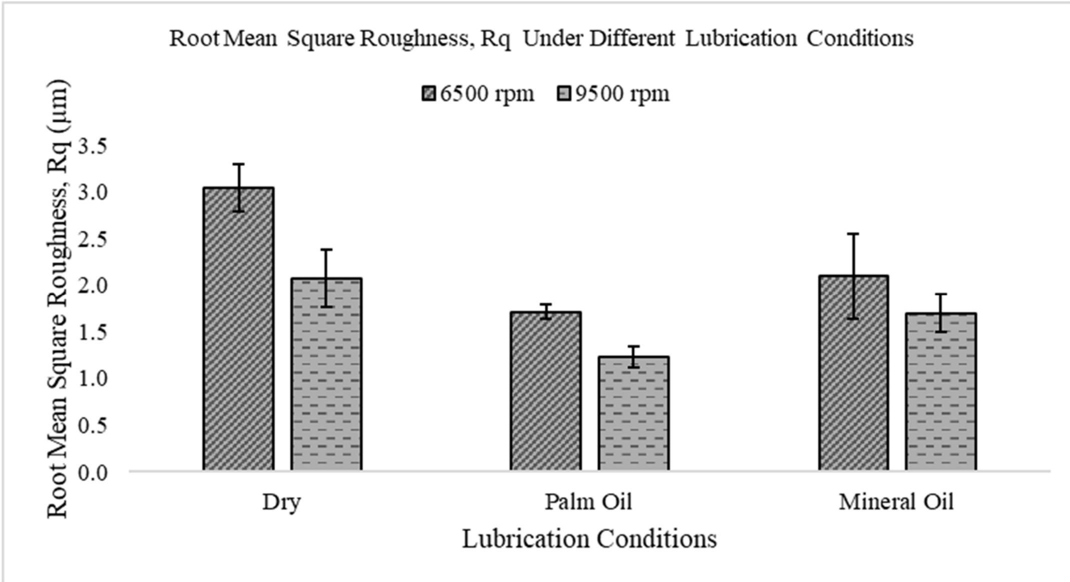

Fig. 4. Root mean square roughness (Rq) of UHMWPE machined under dry cutting, ISO VG 32 mineral oil, and palm oil lubrication at 6500 and 9500 rpm

Fig. 5 shows that peak-to-valley height behaves no differently. At 6500 rpm, Rz fell from 11.765 µm under dry cutting to 7.725 µm with mineral oil and 6.493 µm with palm oil, and the same ranking was preserved at the higher speed. Across all three parameters, then, the two lubricants separate from dry cutting and from each other in a consistent order.

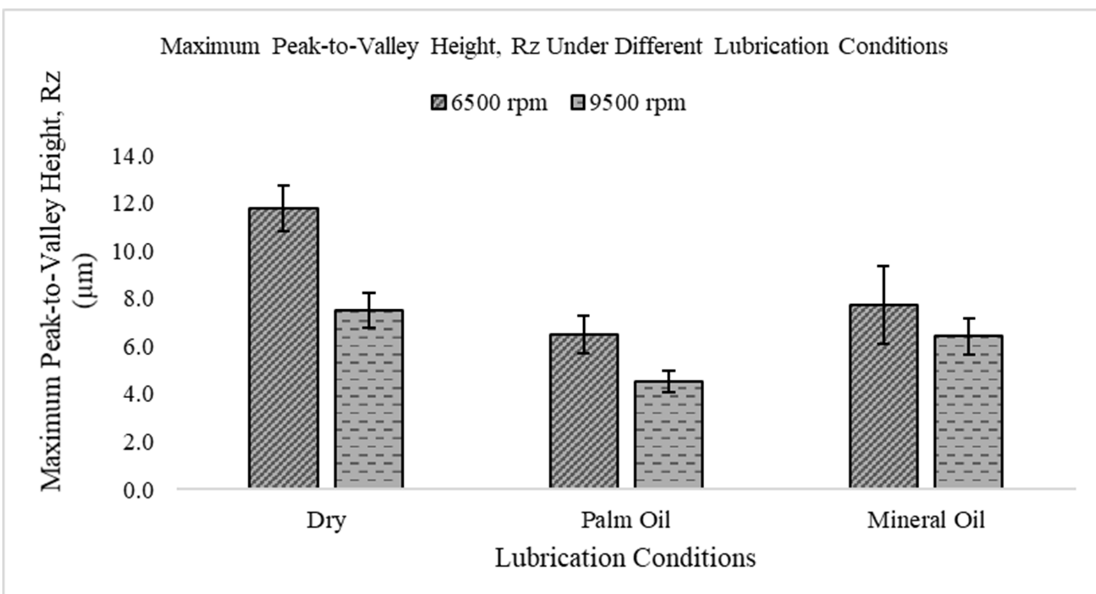

Fig. 5. Maximum peak-to-valley height (Rz) of UHMWPE machined under dry cutting, ISO VG 32 mineral oil, and palm oil lubrication at 6500 and 9500 rpm

Raising the spindle speed from 6500 to 9500 rpm lowered every parameter under every lubrication condition. At the fixed feed rate of 1620 mm/min, the higher speed necessarily reduces the feed per tooth and shortens the period of flute engagement, and chip removal improves accordingly. That is the most plausible reading of the trend, although it was not tested directly here. Comparable behaviour has been reported in polymer machining and in robotic milling more generally [7–13], [24–27].

Fig. 6 compares the three conditions side by side. The dry surfaces are the worst of them: tearing marks run across the machined face, fibrous burrs stand proud of it, and the material is locally distorted, all of which point to the tool sticking to the workpiece and to softening under the heat of the cut, though neither friction nor temperature was measured. Mineral oil takes the severity down without eliminating it. Micro-grooves and fibrillar structure remain plainly visible, so the film reduced adhesion-related damage rather than suppressing it. Under palm oil, the machined face is more uniform and carries fewer of these features than under either of the other conditions, which is what the roughness ranking would predict, and the natural reading is that the palm oil film was retained more effectively at the tool-workpiece interface. Both spindle speeds showed the same trend, so lubrication clearly acts on morphology within the range tested. However, the images cannot separate that effect from cutting temperature, friction coefficient and tool wear, none of which was recorded.

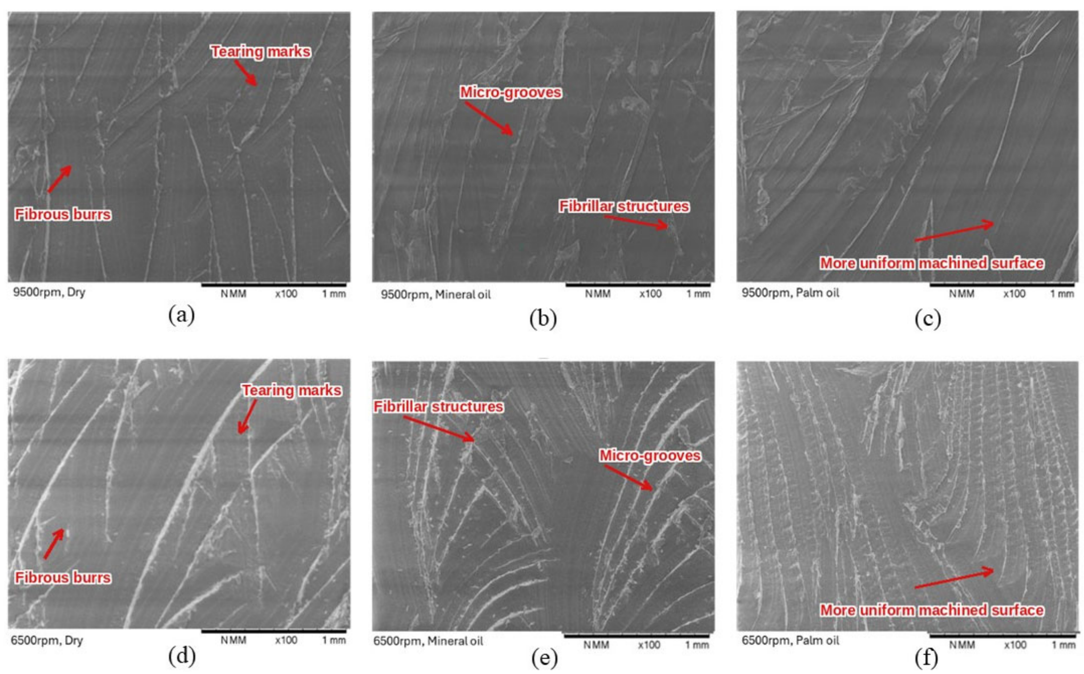

Fig. 6. SEM images of machined UHMWPE surfaces under dry cutting (a) and (d), ISO VG 32 mineral oil (b) and (e), and palm oil lubrication (c) and (f) at spindle speeds of 6500 and 9500 rpm, showing tearing marks, fibrous burrs, fibrillar structures, and micro-grooves as indicated

The improvement under palm oil may be related to its higher viscosity and stronger retention at the cutting interface, which can reduce direct tool-workpiece contact under boundary lubrication conditions. However, this interpretation remains indirect because friction coefficient and cutting temperature were not measured.

Palm oil lubrication produced Ra values of 1.275 µm at 6500 rpm and 1.004 µm at 9500 rpm. These values are below the 2.0 µm surface roughness level often reported as desirable for UHMWPE orthopaedic components [5–7], which suggests that palm oil-assisted robotic milling can produce surface finishes within a practically relevant range. The result should nevertheless be read with caution. Meeting a roughness target does not by itself establish clinical suitability; dimensional accuracy, wear debris generation, sterilisation effects, and long-term wear behaviour all bear on that judgement as well [1], [2], [5], [6]. Compared with reported CNC milling studies of UHMWPE, the robotic results remain slightly higher than the lowest surface roughness values achieved on more rigid machining platforms [5–9], which is to be expected given that industrial robots are less stiff than CNC machine tools [10], [11]. Even so, the results demonstrate that suitable boundary lubrication can improve the surface quality of robotic-milled UHMWPE.

The better performance of palm oil compared with mineral oil may be related to both viscosity and molecular structure. Palm oil contains fatty acid ester components that can support boundary lubrication in sliding and cutting contacts [18–23], [31], and these components may improve lubricant retention at the tool-workpiece interface during the short engagement periods associated with milling. That reading is consistent with the lower Ra values obtained under palm oil: at 6500 rpm mineral oil produced Ra values about 23% higher, and at 9500 rpm, about 21% higher. The similar ranking at both speeds suggests that lubricant type had a consistent influence on surface formation. The mechanism itself cannot be confirmed from roughness and SEM data alone, since lubricant film thickness, friction coefficient, cutting temperature, and tool wear were not measured; the explanation offered here is therefore a plausible interpretation rather than direct proof of boundary film behaviour. What the data do establish is that, under identical machining conditions, palm oil produced lower roughness values and fewer visible surface defects than mineral oil, which supports its potential as a boundary lubricant for robotic UHMWPE milling.

Three limitations constrain what can be claimed here. The evidence is confined to roughness and SEM morphology; friction coefficient, cutting force, cutting temperature, tool wear, and wear rate were all outside the measurement set, which is why every statement above about mechanism is offered as an inference rather than a demonstration. The parameter space is also narrow, covering two spindle speeds at a single feed rate and depth of cut, so the results describe that window and should not be generalised to robotic milling; interactions between parameters would need a wider factorial design to resolve. Finally, hand pre-application served the purpose of isolating boundary behaviour under controlled conditions, but it is not how lubricant reaches the cut in a flood or minimum-quantity system, and performance under continuous supply may well differ. Direct tribological measurement, force and temperature monitoring, tool wear analysis, and a statistically designed experiment are the obvious next steps [14–17], [32–34].

4. CONCLUSION

Dry cutting, ISO VG 32 mineral oil, and palm oil were compared as boundary lubricants for UHMWPE milled on a KUKA KR120 R2700 robot, with each oil pre-applied by hand as a static film.

Palm oil gave the lowest Ra at both speeds, 1.275 µm at 6500 rpm and 1.004 µm at 9500 rpm. Compared with dry cutting, these represent reductions of approximately 45% and 39%; compared with mineral oil, approximately 23% and 21%. Rq and Rz ordered the three conditions in the same way, and the SEM images showed correspondingly fewer defects on the palm oil surfaces, indicating that the improvement is visible as well as measurable. Raising the spindle speed from 6500 to 9500 rpm lowered roughness under all three conditions.

Higher viscosity and a more persistent boundary film are the plausible reasons for the advantage of palm oil, but they remain plausible reasons only. Friction coefficient, cutting force, cutting temperature, tool wear, and wear rate were not measured, and the trials covered two spindle speeds at one feed rate and one depth of cut. Confirming the mechanism, and establishing where the optimum lies, will require those measurements together with a broader experimental design.

5. ACKNOWLEDGEMENTS/FUNDING

The authors would like to acknowledge the support of Universiti Teknologi MARA (UiTM), Cawangan Pulau Pinang, Malaysia, and Politeknik Tuanku Sultanah Bahiyah, Malaysia, for providing facility support for this research. No funding was received from any financial organisation to conduct this research.

6. CONFLICT OF INTEREST STATEMENT

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

7. AUTHORS' CONTRIBUTIONS

Wan Nor Shela Ezwane Wan Jusoh: Conceptualisation, methodology, formal analysis, validation, and writing original draft. **Mohamad Irwan Yahaya**: Supervision, data curation, investigation, and writing review and editing. **Mahamad Hisyam Mahamad Basri**: Supervision, data curation, investigation, and writing review and editing. **Shukri Zakaria**: Methodology and software.

8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used Claude to improve language clarity and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The data supporting the findings of this study are available from the corresponding author on reasonable request.

10. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health and Environment (HSE) protocols of Universiti Teknologi MARA.

11. REFERENCES

[1] A. Bistolfi, F. Giustra, A. Bosco, A. Sabatini, P. Aprato, P. Bracco, and M. Bellare, "Ultra-high molecular weight polyethylene (UHMWPE) for hip and knee arthroplasty: The present and the future," *Journal of Orthopaedics*, vol. 18, pp. 98–106, 2021. Available: https://doi.org/10.1016/j.jor.2021.04.004

[2] M. Hussain, R. A. Naqvi, N. Abbas, S. M. Khan, S. Nawaz, A. Hussain, N. Zahra, and M. W. Khalid, "Ultra-high-molecular-weight-polyethylene (UHMWPE) as a promising polymer material for biomedical applications: A concise review," *Polymers*, vol. 12, no. 2, article 323, 2020. Available: https://doi.org/10.3390/polym12020323

[3] V. Mishra, R. Sharma, N. Khatri, H. Garg, V. Karar, G. S. Khan, and R. V. Sarepaka, "Processing of polycarbonate by ultra-precision machining for optical applications," *Materials Today: Proceedings*, vol. 5, pp. 25130–25138, 2018, Available: https://doi.org/10.1016/j.matpr.2018.10.314

[4] D. Adeniji, J. Schoop, S. Gunawardena, C. Hanson, and M. Jahan, "Characterization and modeling of surface roughness and burr formation in slot milling of polycarbonate," *Journal of Manufacturing and Materials Processing*, vol. 4, no. 2, article 59, 2020. Available: https://doi.org/10.3390/jmmp4020059

[5] W. D. Lestari, D. K. Nababan, R. Ismail, J. Jamari, and A. P. Bayuseno, "Dimensional accuracy and surface roughness of acetabular liner with UHMWPE: Assessment results between compression molding and CNC milling," *International Review of Mechanical Engineering*, vol. 12, no. 6, pp. 516–521, 2018. Available: https://doi.org/10.15866/ireme.v12i6.15028

[6] Y. A. W. Ninggar, P. W. Anggoro, B. Bawono, D. B. Setyohadi, M. Tauviqirrahman, and J. Jamari, "Optimization of parameter for cutting condition of UHMWPE acetabular cup based on Taguchi and desirability functions," *Cogent Engineering*, vol. 10, no. 1, article 2233247, 2023. Available: https://doi.org/10.1080/23311916.2023.2233247

[7] M. Piska and K. Urbancova, "Advanced machining of joint implant UHMWPE inserts," *Machines*, vol. 10, no. 11, article 1008, 2022. Available: https://doi.org/10.3390/machines10111008

[8] R. A. Santos, J. L. Amaya, C. G. Helguero, and F. A. Maldonado, "Study of machining strategies for CNC milling of cavities on ultra high molecular weight polyethylene," *Procedia CIRP*, vol. 108, pp. 821–826, 2022. Available: https://doi.org/10.1016/j.procir.2022.04.082

[9] W. D. Lestari, R. Ismail, J. Jamari, A. P. Bayuseno, and P. W. Anggoro, "Optimization of CNC milling parameters through the Taguchi and RSM methods for surface roughness of UHMWPE acetabular cup," *International Journal of Mechanical Engineering and Technology*, vol. 10, no. 2, pp. 1762–1775, 2019. Available: https://iaeme.com/Home/article_id/IJMET_10_02_182

[10] Z. Zhu, X. Tang, C. Chen, F. Peng, R. Yan, L. Zhou, Z. Li, and J. Wu, "High precision and efficiency robotic milling of complex parts: Challenges, approaches and trends," *Chinese Journal of Aeronautics*, vol. 35, no. 2, pp. 22–46, 2022. Available: https://doi.org/10.1016/j.cja.2020.12.030

[11] K. Guo, Y. Zhang, and J. Sun, "Towards stable milling: Principle and application of active contact robotic milling," *International Journal of Machine Tools and Manufacture*, vol. 182, article 103952, 2022. Available: https://doi.org/10.1016/j.ijmachtools.2022.103952

[12] S. Wang, J. Zhang, P. Wang, J. Law, R. Calinescu, and L. Mihaylova, "Deep learning-enhanced human-robot collaboration for human-in-the-loop robotic milling," *Robotics and Computer-Integrated Manufacturing*, vol. 83, article 102608, 2023. Available: https://doi.org/10.1016/j.rcim.2023.102608

[13] S. Zakaria, W. N. S. E. Wan Jusoh, M. H. Mahamad Basri, M. I. Yahaya, and M. R. Daud, "Comparative study of

surface quality on flat and curved UHMWPE surfaces using robotic milling," *Journal of Applied Engineering Design and Simulation*, vol. 5, no. 2, pp. 126–138, 2025. Available: https://doi.org/10.24191/jaeds.v5i2.139

[14] L. Peña-Parás, R. López, A. Maldonado-Cortés, A. Rodríguez-Villalobos, J. A. Cortés, and J. González, "Enhancing tool life, and reducing power consumption and surface roughness in milling processes by nanolubricants and laser surface texturing," *Journal of Cleaner Production*, vol. 246, article 119836, 2020. Available: https://doi.org/10.1016/j.jclepro.2019.119836

[15] G. W. A. Kui, S. Islam, M. M. Reddy, N. Khandoker, and V. L. C. Chen, "Recent progress and evolution of coolant usages in conventional machining methods: A comprehensive review," *International Journal of Advanced Manufacturing Technology*, vol. 119, pp. 3–40, 2021. Available: https://doi.org/10.1007/s00170-021-08182-0

[16] A. Salem, C. Hopkins, M. Imad, H. Hegab, B. M. Darras, and H. A. Kishawy, "Environmental analysis of sustainable and traditional cooling and lubrication strategies during machining processes," *Sustainability*, vol. 12, no. 20, article 8462, 2020. Available: https://doi.org/10.3390/su12208462

[17] P. Pranav, E. Sneha, and S. Rani, "Vegetable oil-based cutting fluids and its behavioral characteristics in machining processes: A review," *Industrial Lubrication and Tribology*, vol. 73, no. 5, pp. 771–779, 2021. Available: https://doi.org/10.1108/ILT-12-2020-0482

[18] O. M. Ikumapayi, E. T. Akinlabi, T. C. Jen, and P. M. Mashinini, "Advances in the application of vegetable-oil-based cutting fluids to sustainable machining operations: A review," *Lubricants*, vol. 10, no. 4, article 69, 2022. Available: https://doi.org/10.3390/lubricants10040069

[19] G. Durango-Giraldo, C. Zapata-Hernandez, J. F. Santa, and R. Buitrago-Sierra, "Palm oil as a biolubricant: Literature review of processing parameters and tribological performance," *Journal of Industrial and Engineering Chemistry*, vol. 107, pp. 31–44, 2022. Available: https://doi.org/10.1016/j.jiec.2021.12.018

[20] K. E. Ojaomo, S. Syahrullail, F. M. Zawawi, and M. Z. M. Yusop, "Potential of palm oil with tert-butylhydroquinone in place of mineral oil lubricant for reducing environmental degradation," *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 237, no. 6, pp. 1342–1352, 2023. Available: https://doi.org/10.1177/13506501221151100

[21] A. Yahaya, S. Samion, U. Abidin, and M. K. A. Hamid, "Different behaviors of friction in open and closed forging test utilizing palm oil-based lubricants," *Lubricants*, vol. 11, no. 3, article 114, 2023. Available: https://doi.org/10.3390/lubricants11030114

[22] P. Zulhanafi, S. Syahrullail, and M. A. Ahmad, "The tribological performance of hydrodynamic journal bearing using bio-based lubricant," *Tribology in Industry*, vol. 42, no. 2, pp. 278–287, 2020. Available: https://doi.org/10.24874/ti.843.02.20.05

[23] A. M. Sabri, N. Talib, A. Azmi, and A. S. A. Sani, "Machinability evaluation of nanoparticle enriched in vegetable-based-nanofluids for machining process," *Journal of Advanced Mechanical Engineering Applications*, vol. 2, no. 2, 2021. Available: https://doi.org/10.30880/jamea.2021.02.02.003

[24] J. Ni, R. Dai, X. Yue, J. Zheng, and K. Feng, "Contribution ratio assessment of process parameters on robotic milling performance," *Materials*, vol. 15, no. 10, article 3566, 2022. Available: https://doi.org/10.3390/ma15103566

[25] A. D. Wambua, J. N. Ikua, G. N. Mwiti, and S. Kamande, "Material removal rate and surface roughness in CNC milling of medical-grade PMMA using uncoated and coated carbide cutting tools," *International Journal of Manufacturing, Materials, and Mechanical Engineering*, vol. 12, no. 1, 2022. Available: https://doi.org/10.4018/IJMMME.293226

[26] W. N. S. E. Wan Jusoh, M. I. Yahaya, S. Zakaria, M. H. Mahamad Basri, M. R. Daud, and N. I. Ismail, "New approach to minimise surface roughness in Polytetrafluoroethylene (PTFE) through robotic spindle speed control," *ESTEEM Academic Journal*, vol. 21, pp. 106–118, 2025. Available: https://doi.org/10.24191/esteem.v21iMarch.4359.g3122

[27] W. N. S. E. Wan Jusoh, M. I. Yahaya, S. Zakaria, M. H. Mahamad Basri, and M. R. Daud, "Directional effects in robotic milling of UHMWPE: An empirical study on surface roughness," *International Journal of Innovation and Industrial Revolution*, vol. 8, no. 24, pp. 357–371, 2026. Available: https://doi.org/10.35631/IJIREV.824022

[28] W. N. S. E. Wan Jusoh, M. I. Yahaya, M. H. Mahamad Basri, and S. Zakaria, "Improving parameter selection reliability in robotic milling of UHMWPE using multi-response RSM optimisation and statistical validation," *The International Journal of Advanced Manufacturing Technology*, Jun. 2026. Available: https://doi.org/10.1007/s00170-026-18584-7

[29] W. N. S. E. Wan Jusoh, M. I. Yahaya, M. H. Mahamad Basri, S. Zakaria, and M. R. Daud, "Parameter optimization for robotic milling of ultra-high molecular weight polyethylene: A digitally prepared central composite design-response surface methodology framework with experimental validation," *Applied Research*, vol. 5, no. 4, article e70126, Aug. 2026. Available: https://doi.org/10.1002/appl.70126

[30] ISO 21920-2:2021, *Geometrical Product Specifications (GPS) — Surface Texture: Profile — Part 2: Terms, Definitions and Surface Texture Parameters*. Geneva, Switzerland: International Organization for Standardization, 2021. Available: https://www.iso.org/standard/72226.html

[31] M. Piska and K. Urbancova, "On the machining of joint implant UHMWPE inserts," *MATEC Web of Conferences*, vol. 378, article 01012, 2023. Available: https://doi.org/10.1051/matecconf/202236801012

[32] A. Siahsarani, S. Fattahi, A. Alinaghizadeh, B. Azarhoushang, R. Bösinger, and S. Amini, "Data-driven optimization of processing parameters and cooling strategies in UHMWPE high speed milling through multi-criteria decision making using PCA and Pareto-based evolutionary algorithms," *International Journal of Precision Engineering and Manufacturing-Green Technology*, 2026. Available: https://doi.org/10.1007/s40684-025-00836-8

[33] M. J. Hisam, M. A. Suhaimi, S. Sharif, et al., "Assessment of novel palm oil modifications performance in high-speed milling of Inconel 718 through minimum quantity lubrication application," *International Journal of Precision Engineering and Manufacturing*, vol. 26, pp. 1549–1565, 2025. Available: https://doi.org/10.1007/s12541-025-01213-w

[34] W. Wang, Q. Guo, and Z. Yang, "A state-of-the-art review on robotic milling of complex parts with high efficiency and precision," *Robotics and Computer-Integrated Manufacturing*, vol. 79, article 102436, 2023. Available: https://doi.org/10.1016/j.rcim.2022.102436