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RESEARCH ARTICLE

Effect of Inclination Angle on the Micro Dimple Machined Using Inclined Milling Method

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ABSTRACT – In micro-dimple fabrication using the inclined milling method, center marks commonly form at the dimple base, resulting in inconsistent dimple depth and a rough surface texture. These defects can lead to uneven lubricant distribution, increased localized friction, and premature surface damage in tribological applications. This study investigates the influence of inclination angle (θ) on milling center mark formation and overall dimple quality during inclined milling. Experimental work was performed using inclination angles ranging from 0° to 45°, and the machined dimples were analyzed using a Laser Confocal Microscope. The results show that at $\theta = 45°$, the milling center mark on the dimple base was eliminated, and the average area surface roughness (R_a) improved by 70% compared to the perpendicular dimple ($\theta = 0°$). These quantitative improvements highlight the significance of tool inclination in minimizing surface defects and enhancing lubrication pathways. The study demonstrates that optimizing the inclination angle not only mitigates center mark formation but also enhances dimple uniformity and surface finish, addressing critical challenges in micro-texture quality and lubrication efficiency for precision engineering applications.

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1. INTRODUCTION

Micro-dimple surface textures have gained significant attention for their ability to improve tribological performance, including friction reduction, enhanced wear resistance and improved lubricant retention[1], [2], [3]. Previous research work on surface modifications demonstrates wide-ranging applications, particularly in mechanical components such as powertrain [4], cylinder liners [5], piston rings [6] and bearing surfaces. Beyond that, micro-dimpled surfaces have shown promising potential in biomedical engineering, especially for orthopaedic implants, artificial joints, and surgical tools, where reducing friction and wear is critical for prolonging implant lifespan and improving patient outcomes [7]. Furthermore, precision engineering and tool manufacturing industries are incorporating micro-dimple technology to extend tool life, optimize lubrication regimes, and enhance cutting or forming performance, particularly in high-speed machining or metal forming applications[8]. Collectively, these advancements highlight the versatility and effectiveness of micro-dimple surface textures across diverse high-performance engineering fields, driving improvements in reliability, energy efficiency, and overall system longevity.

Various fabrication techniques have been developed to fabricate micro-dimples, each offering distinct advantages and limitations. Laser surface texturing, for instance, provides high precision and non-contact processing but often leads to thermal damage, material microstructural changes, and high capital costs [9]. Electrical discharge machining (EDM) is another alternative that enables micro-dimple fabrication on hard materials but is limited to conductive substrates. Like laser ablation, EDM can also induce thermal defects such as recast layers or micro-cracking, negatively affecting surface integrity [10]. Chemical etching allows for mass production of micro-features with minimal mechanical stress on the workpiece[11]. However, it is highly dependent on material chemistry, limiting its applicability to specific alloys or substrates. Furthermore, etching often struggles with achieving precise depth control and consistent dimple geometry, which are critical for tribological performance[12].

In contrast, milling using ball-end tools provides a cost-effective, flexible, and thermally neutral method for micro-dimple fabrication, suitable for a wide range of materials, including metals, polymers, and composites[13]. Milling offers geometric versatility, controllable dimple depth, and easy integration into conventional manufacturing setups. These advantages make milling particularly attractive for industrial applications requiring precise, repeatable micro-textures without introducing thermal damage or material limitations [14], [15].

Within milling-based approaches, two primary techniques exist: perpendicular milling and inclined milling. In perpendicular milling, the ball-end mill is oriented perpendicular to the work surface, with the tool plunging vertically to create the dimple[16], [17]. While widely used due to simplicity, this method often results in rough, uneven dimple interiors due to the rubbing effect at the tool's center tip, where cutting speed is near zero (Figure 1). Beyond that, uncontrolled roughness on the dimpled surface or regularities on the surface texture can degrade performance in a way that disrupts the intended smooth flow of lubricants as well as disrupts the hydrodynamic pressure effect inside the dimple profile, thus reducing the effectiveness of the dimple surface [18]

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According to previous research works [19], [20], the hemispherical ball-end shape produces variable cutting speed from zero at the axis of rotation to maximum at the tool radius. Due to this variation in cutting speed, ball tips have zero cutting velocity (see Figure 2), causing the rubbing effect when the workpiece surface and cutting tool are in perpendicular position to each other. This phenomenon elevates cutting forces, degrades surface finish, and shortens tool life, particularly in shallow cuts. To address these issues, inclined milling has been introduced (Figure 2), where the tool is tilted at a defined angle (θ) relative to the surface. This orientation avoids the low cutting speed region near the ball tip, minimizing rubbing, reducing cutting forces, and improving both surface finish and tool longevity [21].

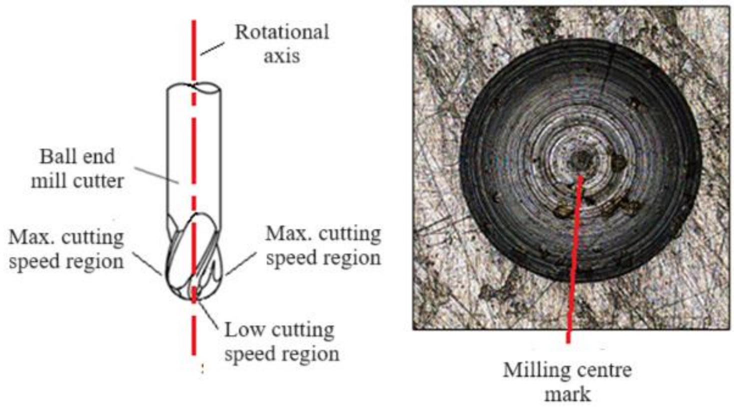


Figure 1. Illustration of cutting speed variation on end mill tool (left) and milling center mark (right) on the micro dimple surface

Despite progress in inclined milling, most studies have focused on process mechanics [22], [23] and force modeling [24], with insufficient emphasis on dimple morphology characterization, particularly regarding center mark formation, optimum inclination angle and surface quality. This gap is critical since irregular dimple profiles compromise lubricant retention, increase friction inconsistencies, and diminish the tribological and functional performance of textured surfaces. Therefore, this research aims to systematically investigate the effect of inclination angle (θ) on milling center mark formation and post-machining dimple morphology in inclined milling processes. By doing so, it addresses the current literature gap and offers valuable insights into optimizing micro-dimple quality, ultimately enhancing the functional performance of textured surfaces for high-demand engineering applications.

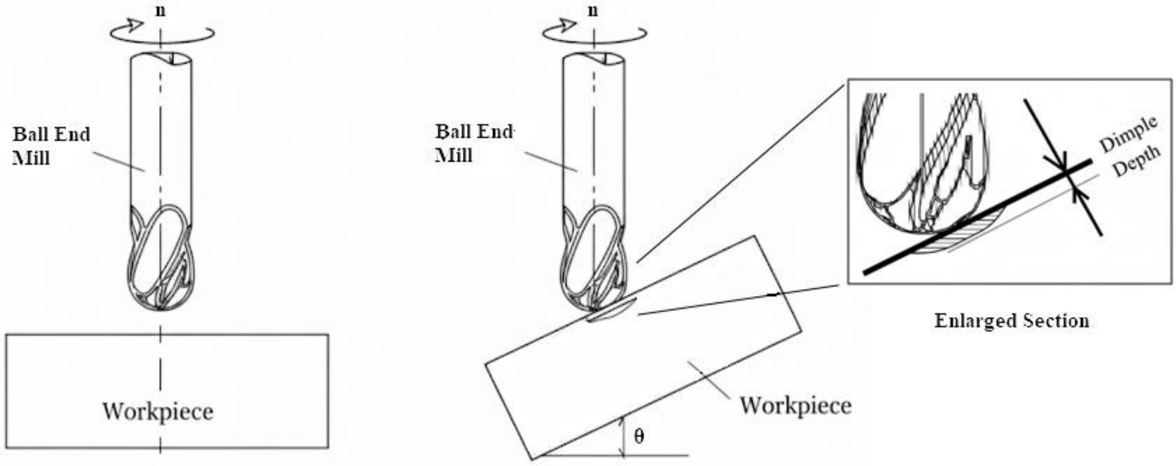


Figure 2. Illustration of perpendicular milling (left) and inclined milling (right) techniques adopted to fabricate the micro dimple profile

2. METHODOLOGY

To investigate the influence of inclination angle (θ) on the micro-dimple profile fabricated through inclined milling operations, a comprehensive set of controlled experiments will be conducted. During these experimental trials, all critical machining parameters, including spindle rotational speed, feed rate, and cutting tool geometry, will be held constant (Table 1) to ensure uniform cutting conditions and to isolate the specific effect of inclination angle on the resulting micro-dimple geometry. Micro-dimple fabrication in this study uses a point-to-point machining approach, in which the cutting tool is precisely positioned at designated locations to generate individual dimples. In such operations, the depth of cut directly determines the final dimple depth, making it a crucial parameter for achieving consistent, repeatable results. Accordingly, the depth of cut is fixed at 70 µm throughout the experiments. This value is selected to maintain the desired dimple aspect ratio (the ratio of dimple depth to dimple diameter) within the range of 0.1 to 0.2, which is considered optimal for tribology applications [7], [25, and to ensure dimensional consistency across the fabricated features.

In contrast, the inclination angle (θ) of the workpiece surface is the primary manipulated parameter in this investigation. The inclination angle is systematically varied at four levels: 0°, 15°, 30°, and 45°. These specific values were chosen based on a combination of factors, including commonly adopted setups in previous research [26] and practical limitations of the experimental setup. The maximum inclination angle is limited to 45° to avoid potential mechanical interference or collisions between the spindle arbor and the workpiece, ensuring both the safety of the equipment and the integrity of the experimental process.

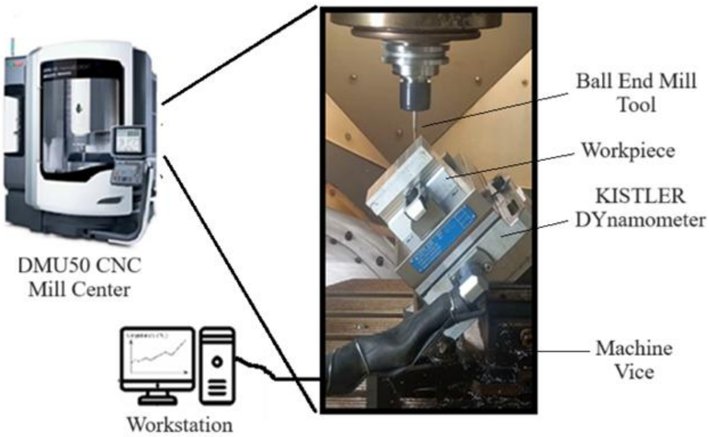


Figure 3. Setup used in the experimental work to determine the effect of inclination angle on the micro-dimple profile in inclined milling operations

In this experimental setup (see Figure 3), a square block of Aluminum alloy (AL6061-T6) with dimensions of 70 mm × 50 mm × 50 mm was selected as the workpiece material. The specimen was securely clamped directly onto a KISTLER Dynamometer, with the required inclination angle (θ) carefully set during the clamping process. The chosen specimen size was based on the physical limitations of the dynamometer's clamping area, ensuring both stability and reliable force measurement throughout the machining process. The KISTLER Dynamometer itself was mounted rigidly onto the machine vice, providing a stable platform to record cutting force data during the milling operation.

During the milling process, a Ø1.0mm HSS TiAl Coated Ball End Mill (BEM) tool was programmed to move from the machine's safety plane to a pre-determined "approach position" using rapid traverse motion and followed by controlled plunge movement toward the inclined surface of the specimen at the specified inclination angle (θ). This plunging movement, executed under precise spindle speed and feed rate conditions, generated the desired micro-dimple feature on the workpiece surface. Once the dimple was formed, the BEM tool retracted to the "approach position," ready to repeat the process for the subsequent dimple location 5 times for each parameter set.

Table 1. Design of experiment to investigate the effect of inclination angle on the micro dimple quality

Run	Variable Factor			
	Spindle Speed (rev.$^{-1}$)	Feed rate (mm/min)	Depth of cut (µm)	Inclination angle (°)
1	1000 (constant)	500 (constant)	70 (constant)	0
2				15°
3				30°
4				45°

Given the microscopic size of the fabricated dimples, detailed characterization of their geometry and surface quality required advanced optical measurement techniques. Therefore, a 3D Laser Confocal Microscope (Olympus LEXT) was employed to capture both two-dimensional (2D) and three-dimensional (3D) images of the micro-dimples. Image acquisition was conducted using a 20× magnification lens, with a laser light source projecting onto the specimen surface. The reflected laser signal was captured and processed by the system to reconstruct high-resolution 2D and 3D models of the machined dimple features.

Based on the image acquisition, two key analyses were performed to evaluate the micro-dimples, which included the dimple morphology and surface area roughness. For the dimple morphology, the analysis focused on investigating the presence and characteristics of the center mark, a common surface feature resulting from the dimple machining process. The study compared the 2D optical images obtained from the confocal microscope across different inclination angle settings (θ) to assess how inclination influences the formation and visibility of the milling center mark at the center of the dimple.

Meanwhile, the second analysis, which is the surface area roughness analysis, will be carried out to evaluate the machined micro dimple average surface area roughness, S_a with particular attention to evaluate the dimple quality numerically. These analyses provided valuable insights into the influence of inclination angle and machining conditions on the surface integrity, dimensional accuracy, and overall quality of micro-dimple structures produced by inclined milling operations. In the surface area roughness measurements, the region of interest (yellow circle) has been selected based on the 3-point circle method, which is capable of fitting into the micro dimple profile perfectly, as shown in Figure 4.

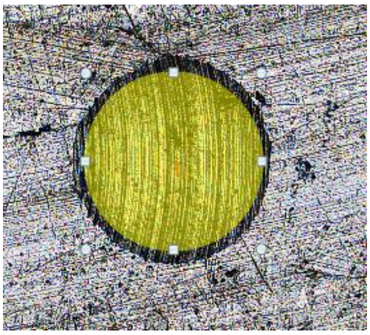
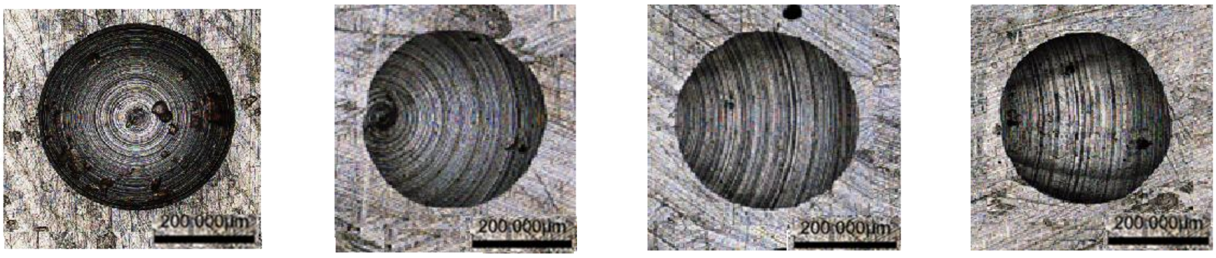


Figure 4. Three-point circle method for roughness measurement on micro-dimple profile

3. RESULTS AND DISCUSSION

Figure 5(a)–(d) presents the two-dimensional images of the machined micro-dimples captured using a 3D Laser Confocal Microscope (Olympus LEXT) at different inclination angles $\theta = 0°$, 15°, 30°, and 45°, respectively. These images clearly demonstrate the influence of inclination angle on the resulting dimple profiles, particularly with respect to the presence of centre marks. Under perpendicular milling ($\theta = 0°$), a pronounced centre mark is visible at the middle of the micro-dimple. As the inclination angle increases to $\theta = 15°$, the centre mark remains evident but is slightly shifted toward the dimple edge. At higher inclination angles ($\theta = 30°$ and $\theta = 45°$), however, the centre mark completely disappears, indicating that the tip of the cutting tool is no longer in contact with the work surface during the micro-dimple cutting operation.

In addition, across all machining conditions, the fabricated micro-dimples exhibit diameters in the range of approximately 500–800 µm and depths of less than 70 µm. Given these microscale feature dimensions, a 20× magnification lens on the Olympus LEXT 3D Laser Confocal Microscope was selected as optimal, providing sufficient clarity and resolution for capturing the detailed dimple profiles.



(a) (b) (c) (d)

Figure 5. 2-D image of micro dimple profile with 20X magnification machined using S1000 R.PM, F500 mm/min, inclination angle of 0, 15°, 30° and 45° respectively

Table 2 presents the area roughness (**S_a**) measurements of machined micro-dimple surfaces obtained using the LASER Confocal analysis software. This data provides a quantitative assessment of the influence of inclination angle on the surface roughness of the micro dimples. For each inclination angle, roughness measurements were taken from five different dimples to account for variability and ensure reliable results. The mean roughness value represents the overall surface quality at each inclination angle, enabling direct comparison between conditions. Generally, lower roughness values indicate a better surface finish, whereas higher values suggest poorer surface quality. A visual comparison of these results is illustrated in the bar chart in Figure 6.

Table 2. Results of measured area roughness, S_a on the machined micro dimple surface

Inclination angle (°)	Area Roughness (µm)						
	Dimple 1	Dimple 2	Dimple 3	Dimple 4	Dimple 5	Mean	Std. Deviation
0	10.008	11.397	11.437	12.524	11.661	11.4054	0.904
15°	25.782	23.056	25.630	29.183	29.179	26.5660	2.513
30°	3.617	3.074	2.588	2.629	3.443	3.0702	0.480
45°	3.644	3.627	3.256	3.589	3.520	3.5272	0.183

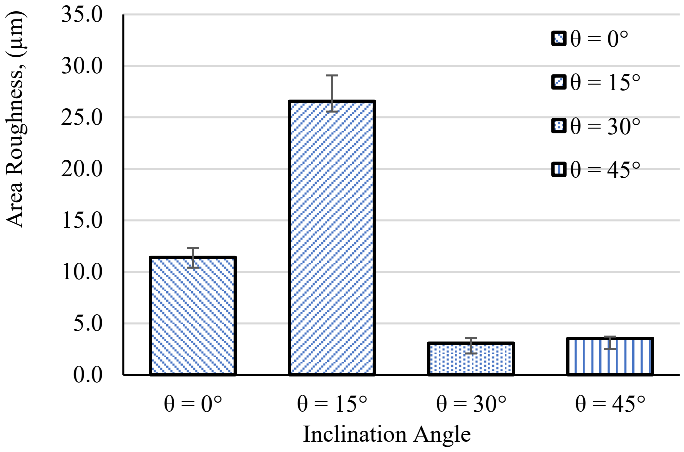
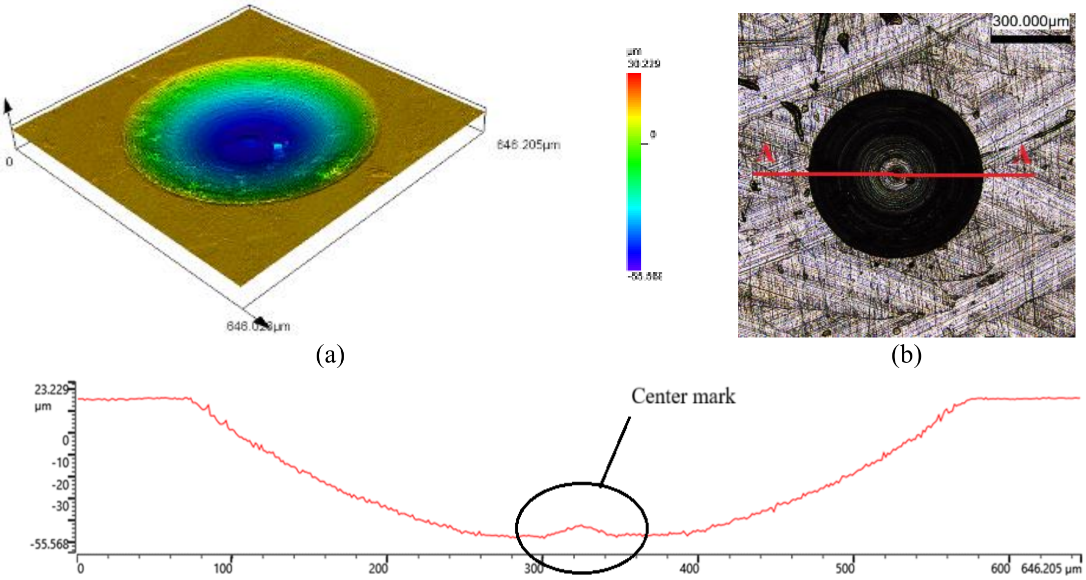


Figure 6. Bar chart comparison of area roughness values at different inclination angles, *θ*

Further analysis of the micro-dimple surface produced using perpendicular milling (inclination angle *θ* = 0°) reveals that the inclination angle, *θ* has a significant influence on the quality of the machined dimples, as illustrated in Figure 7(a)–(c). At *θ* = 0°, the center tip of the ball-end mill makes direct contact with the workpiece, leaving a distinct milling center mark at the center of the dimple surface (Figure 7(a)–(b)). As discussed earlier, this phenomenon is attributed to the rubbing action of the tool's center tip, which occurs due to the near-zero cutting speed at the tool center. Meanwhile, a cross-sectional profile along line A–A, taken precisely through the center mark, shows a raised or protruding feature at the center of the dimple, likely caused by residual uncut material remaining after the milling process (circled in Figure 7(c)). This central mark protrusion contributes to an uneven dimple surface profile, which consequently increases the average area roughness.

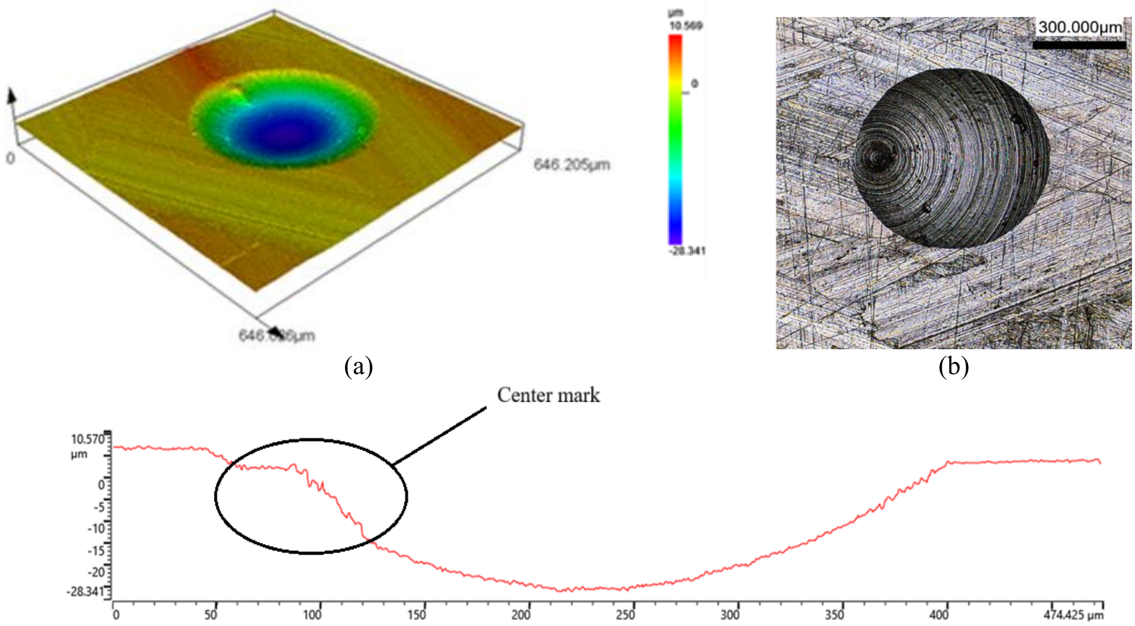


(a) (b)

(c)

Figure 7. Micro dimple profile measurement (a) 3-D view of micro dimple machined with inclination angle, *θ* = 0°, (b) 2-D view of the micro dimple with cross-section profile location, (c) A-A cross-section height graph of micro dimple profile

As the inclination angle increases, particularly at *θ* = 15°, noticeable changes in the surface quality of the machined micro dimples were observed. Specifically, the characteristic of the center mark (circled in Figure 8(c)) caused by the contact of the ball end mill's tool tip, which initially appears at the center of the dimple at *θ* = 0°, is observed to shift toward the edge of the dimple as well as the size of the center mark becomes larger. The 3D image of the machined dimple (Figure 8(a)) shows a clear presence of this shifted center mark, which manifests as a prominent protrusion along the edge region of the dimple.



(a) (b)

(c)

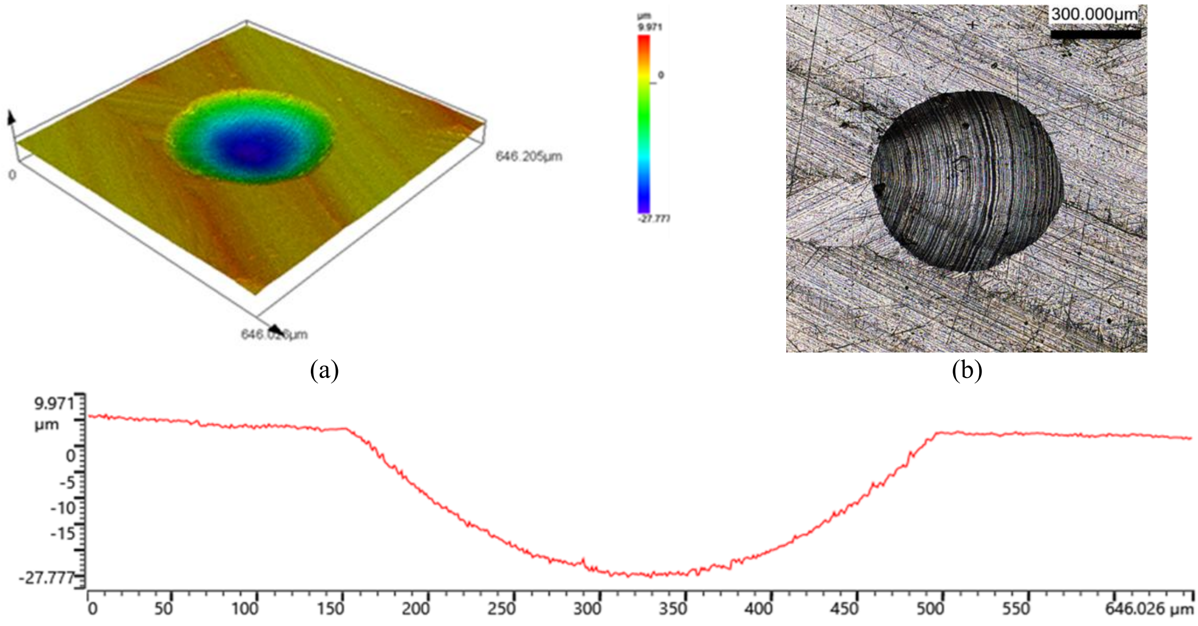
Figure 8. Micro dimple profile measurement (a) 3-D view of micro dimple machined with inclination angle, $\theta = 15°$, (b) 2-D view of the micro dimple with cross-section profile location, (c) X-X cross-section height graph of micro dimple profile

To gain a deeper understanding of this surface irregularity, a cross-sectional profile along line A–A was extracted, passing directly through the center mark (Figure 8(b)). The resulting cross-section profile, shown in Figure 8(c), highlights the uneven protruding feature at the dimple edge, which is likely the result of uncut material accumulation caused by ineffective cutting action at the tool center tip region during inclined milling. Here, the size of the center marks clearly indicates a significant change in size where the size of the center marks increases almost double compared to the center mark produced at $\theta = 0°$. This phenomenon could be due to the imbalance of the cutting force that led to tool deflection and vibration during the cutting.

This surface defect contributes significantly to the deterioration of the overall surface quality, as indicated by increased area roughness (S_a) values. A direct comparison with perpendicular milling ($\theta = 0°$) demonstrates the severity of this issue. At $\theta = 0°$, the remaining uncut material at the dimple center produced an area roughness of 11.405 µm. However, at an inclination angle of $\theta = 15°$, the severity of uncut material accumulation is significantly higher, resulting in an area roughness of 26.566 µm — an increase of approximately 130% (Table 2). This substantial rise in roughness underscores the pronounced influence of inclination angle on dimple surface integrity, particularly due to the shifting and enlargement of the center mark defect.

At an increased inclination angle of $\theta = 30°$, a marked improvement in the quality of the machined micro-dimple profile is observed compared with lower inclination angles. Detailed surface analysis using the 3D Laser Confocal Microscope shows that the center mark, which is clearly visible at inclination angle $\theta = 0°$ and $\theta = 15°$ due to contact between the ball-end mill's tip center and the workpiece, is eliminated at this inclination angle. Instead, the resulting micro-dimple exhibits a smooth, symmetrical, and well-defined geometry with a clean-cut surface, as illustrated in Figure 9(a)–(c). This qualitative improvement is strongly supported by quantitative measurements of surface roughness. The average area roughness (S_a) decreases sharply to 3.0702 µm, representing nearly a 90% reduction compared with the roughness recorded at $\theta = 15°$ (26.566 µm). The simultaneous disappearance of the center mark and reduction in surface roughness confirm that, at $\theta = 30°$, the tip center of the ball-end mill no longer contacts the workpiece during cutting.

These results align with the kinematics of inclined milling, where increasing the inclination angle shifts the tool–workpiece engagement away from the tool tip center region associated with near-zero cutting speed towards more active cutting edges that operate at higher effective cutting speeds. This shift enhances material removal efficiency while minimizing rubbing and ploughing at the tool center, ultimately producing cleaner surfaces and significantly improved dimple quality.



(a) (b)

(c)

Figure 9. (a) 3-D view of micro dimple machined with inclination angle, $\theta = 30°$. (b) 2-D view of the micro dimple with cross-section profile location. (c) X-X cross-section height graph of micro dimple profile

Finally, at an inclination angle of $\theta = 45°$, microscope observations (Figure 10(a)–(c)) reveal results comparable to those obtained at θ = 30°, in which the center mark is no longer visible on the machined micro-dimple surface. This confirms that the ball-end mill tip does not engage with the workpiece, thereby preventing uncut material accumulation at the dimple center mark and producing a clean, symmetrical profile. However, while the overall morphology is improved, the average surface roughness at $\theta = 45°$ was measured at 3.527 µm, showing a slight increase compared with θ = 30°. This indicates a trade-off: increasing the inclination angle further enhances dimple symmetry and eliminates center defects, but it may introduce marginally higher surface roughness.

The significance of inclination angle extends beyond surface finish improvement to directly influencing the functional role of micro-dimples as lubricant reservoirs. At θ ≥ 30°, the elimination of centre marks and improvement in profile symmetry ensure that dimples maintain consistent depth and geometry, which are essential for predictable lubricant entrapment and distribution across the contact interface. Symmetrical dimples promote uniform hydrodynamic pressure build-up, thereby enhancing load-bearing capacity and reducing localized wear[27] as shown in Figure 10 below. By contrast, asymmetrical dimples with centre defects can interrupt lubrication pathways, leading to uneven fluid retention and premature surface failure. This highlights that inclination angle control is not only a machining parameter but also a design strategy that links manufacturing precision with tribological performance.”

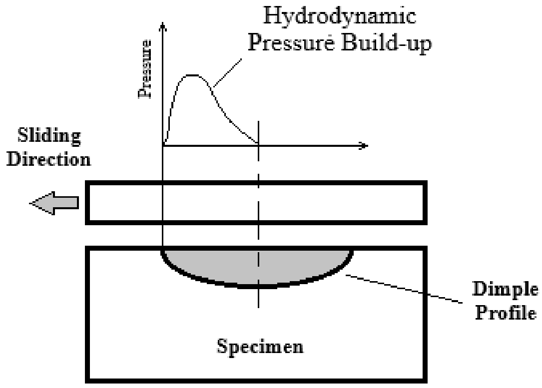
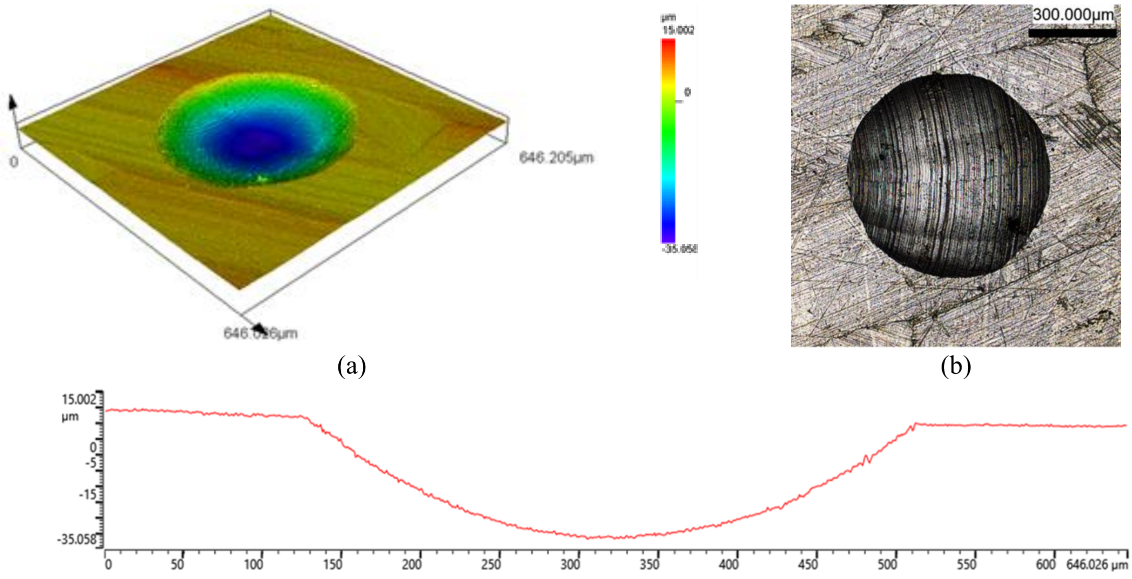


Figure 10. Schematic representation of hydrodynamic pressure generation in a lubricated contact with a spherical segment cavity, showing lubricant flow, velocity field, and pressure distribution [27]

Taken together, these results suggest that the optimum inclination angle for micro-dimple fabrication using a ball-end mill lies within the range of $30° < \theta \leq 45°$. At $\theta = 30°$, the process achieves lower surface roughness, while at θ = 45°, it ensures defect-free and highly symmetrical dimple geometry. This highlights the importance of selecting an inclination angle that balances surface finish with geometrical accuracy, reinforcing the critical role of tool inclination in governing tool–workpiece interaction, surface quality, and overall feature precision.



(a) (b)

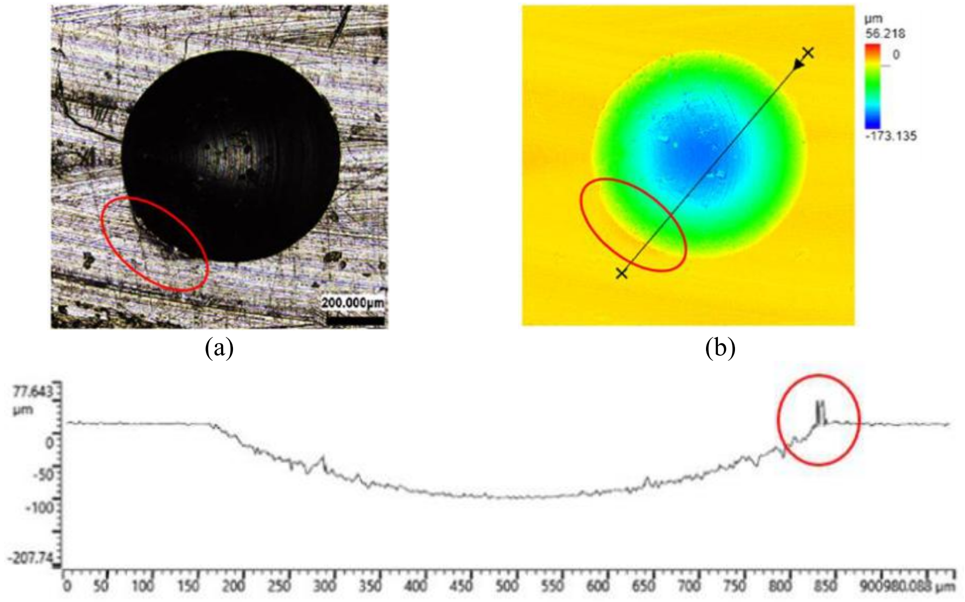
(c)

Figure 10(a) 3-D view of micro dimple machined with inclination angle, θ = 45°, (b) 2-D view of the micro dimple with cross-section profile location, (c) X-X cross-section height graph of micro dimple profile

Another interesting finding from the captured images is the presence of burrs in some of the micro-dimple profiles machined using the inclined milling method. Confocal microscope observations (Figure 11(a)–(c)) of one representative micro-dimple profile reveal that burr formation, or excess material protrusion, consistently appears along the dimple edges, leading to height inconsistencies. This is clearly illustrated in the colour scale image (Figure 11(b)), where the darker brown regions correspond to elevated burr formations around the dimple boundary. Although these burrs do not appear uniformly across all dimples, their localized occurrence is significant and aligns with previous research [28], [29], [30], which has similarly reported burr formation at the tool exit zone as a common phenomenon in micro-milling operations. Compared with earlier studies, the present work provides more detailed visual confirmation of burr characteristics at micro-dimple edges through high-resolution 3D laser confocal imaging. While previous investigations mainly examined burr formation in linear or groove-type micro-features, the current findings highlight that even in circular or complex dimple geometries, burr formation remains concentrated at the tool exit region. Furthermore, although previous studies [21] suggested that higher tool inclination angles can reduce tool–material contact at the dimple center and improve profile symmetry, the present results show that burr formation at the exit zone persists regardless of inclination angle ($\theta \geq 30°$). This suggests that while inclined milling enhances profile quality and symmetry, it does not fully address the issue of burr generation.

From a functional standpoint, the presence of burrs at dimple edges has practical implications for the performance of textured surfaces. Burrs can disrupt the uniformity of contact interfaces, reducing the effectiveness of dimples in applications such as sealing, lubrication retention, and friction reduction. For example, elevated burr ridges may act as unintended asperities that increase localized wear or prevent proper fluid entrapment, thereby diminishing tribological performance. Additionally, the non-uniform distribution of burrs observed in this study suggests that performance variability could arise across a textured surface, with some dimples functioning effectively while others are compromised by edge protrusions.

Taken together, these results underscore the dual effect of inclined milling: while it improves dimple morphology and reduces center mark formation, it leaves burr formation unresolved. This highlights the need for further research into parameter tuning, such as optimized feed per tooth and spindle speed, or tool geometry modification (e.g., sharper cutting edges, higher rake angles, or edge preparation strategies), to effectively suppress burr formation and ensure consistent functional performance of micro-dimpled surfaces.



(a) (b)

(c)

Figure 11(a) 3-D view of micro dimple machined with inclination angle, $\theta = 45°$, (b) 2-D view of the micro dimple with cross-section profile location, (c) X-X cross-section height graph of micro dimple profile

4. CONCLUSIONS

This study emphasizes the critical role of the inclination angle in controlling the formation of milling center marks during micro-dimple fabrication via the inclined milling method. Experimental results and dimple morphology analysis demonstrate that the optimum inclination angle ($\theta > 30°$) can effectively minimize or eliminate center marks while reducing surface roughness by nearly 70% compared with the perpendicular milling method ($\theta = 0°$). Despite these promising findings, the study also highlights the need for further investigation into burr formation and the key factors governing its occurrence. Future work should aim to establish a clearer correlation between machining conditions and burr formation in inclined milling. Potential approaches to suppress burr growth include optimizing machining parameters, such as selecting an appropriate spindle speed and feed rate to balance material removal efficiency and dimensional accuracy. In addition, careful refinement of tool geometry, for instance by employing sharper cutting edges or higher rake angles, has been shown to significantly reduce burr size. Collectively, these strategies highlight the importance of integrating both tool design and process optimization to enhance dimple quality while simultaneously mitigating burr formation.

Nonetheless, this study is limited by its focus on a narrow range of machining parameters and tool geometries, primarily emphasizing the effects of the inclination angle on center mark formation. While these findings provide valuable insights, they do not fully capture the broader interplay between tool geometry, material properties, and machining dynamics that may also influence burr formation. Future work should therefore expand the parameter space to include a broader range of feed rates, spindle speeds, and exit angles, and systematically investigate different tool geometries and coatings. Such studies would help establish a more comprehensive understanding of burr suppression strategies and enhance the applicability of inclined milling for micro-dimple fabrication in diverse industrial contexts."

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest, whether financial or non-financial, that could be perceived as having influenced the content, findings, or interpretations presented in this manuscript. This includes, but is not limited to, financial interests as well as non-financial interests that may be viewed as potential sources of bias.

AUTHORS' CONTRIBUTION

A. R. Yusoff (Conceptualization; Supervision)

M. A. Hanafiah (Methodology; Data curation; Writing - original draft; Resources)

REFERENCES

[1] S. Ali, R. Kurniawan, X. Moran, F. Ahmed, M. Danish, and K. Aslantas, "Effect of micro-dimple geometry on the tribological characteristics of textured surfaces," *Lubricants*, vol. 10, no. 12, p. 328, 2022.

[2] V. Zambrano, M. Brase, B. Hernández-Gascón, M. Wangenheim, L. A. Gracia, I. Viejo, et al., "A digital twin for friction prediction in dynamic rubber applications with surface textures," *Lubricants*, vol. 9, p. 57, p. 57, 2021.

[3] G. Vignesh, D. Barik, S. Aravind, P. Ragupathi, and M. Arun, "Numerical investigation of dimple-texturing on the turning performance of hardened AISI H-13 steel," *International Journal for Simulation and Multidisciplinary Design Optimization*, vol. 13, p. 10, 2022.

[4] A. Schubert, R. Neugebauer, D. Sylla, M. Avila, and M. Hackert, "Manufacturing of surface microstructures for improved tribological efficiency of powertrain components and forming tools," *CIRP Journal of Manufacturing Science and Technology*, vol. 4, no. 2, pp. 200–207.

[5] T. Matsumura and S. Takahashi, "Micro dimple milling on cylinder surfaces," *Journal of Manufacturing Processes*, vol. 14, no. 2, pp. 135–140, 2012.

[6] B. Denkena, T. Grove, and C. Schmidt, "Machining of micro dimples for friction reduction in cylinder liners," *Procedia CIRP*, vol. 78, pp. 318–322, 2018.

[7] W. B. Bennett and M. Zou, "Small laser-textured dimples for improved tribological performance of CoCrMo in artificial hip joints," *Lubricants*, vol. 13, no. 4, p. 158, 2025.

[8] T. Sugihara, P. Singh, and T. Enomoto, "Development of novel cutting tools with dimple textured surfaces for dry machining of aluminum alloys," *Procedia Manufacturing*, vol. 14, pp. 111–117, 2017.

[9] C. Phun, W. Daodon, K. Septham, P. Kumkhuntod, H. Zhu, and V. Saetang, "Laser-fabricated micro-dimples for improving frictional property of SKH51 tool steel surfaces," *Lubricants*, vol. 11, no. 11, p. 456, 2023.

[10] Jie Ying and A. R. . Abdul Manaf, "Investigation of optimum EDM die sinking parameters in micro dimple machining," *Journal of Modern Manufacturing Systems and Technology*, vol. 6, no. 1, pp. 58–65, 2022.

[11] Z. Gu, X. Chen, Z. Xu, Z. Ye, and G. Li, "Investigation on bidirectional pulse electrochemical micromachining of micro dimples," *Micromachines (Basel)*, vol. 12, no. 9, p. 1108, 2021.

[12] A. Kumar, A. Alok, and M. Das, "Surface texturing by electrochemical micromachining: A review surface texturing by electrochemical micromachining: A review," *IOP Conference Series: Materials Science and Engineering*, vol. 804, no. 1, p. 012011, 2020.

[13] G. Wang, L. Zhao, Q. Liu, X. Li, Y. Sun, and M. Chen, "Modelling and experimental investigation of micro-dimpled structures milling with spiral trajectory tool reciprocating motion," *Chinese Journal of Aeronautics*, vol. 38, no. 2, p. 102990, 2025.

[14] S. Hassan, J. A. Ghani, C. H. C. Haron, M. N. A. M. Dali, and M. Rizal, "A review of the milling process to fabricate a dimple structure," *Journal of Mechanical Engineering*, vol. 1, no. S1, pp. 175–192, 2017.

[15] S. P. Singh, K. Patra, A. Kumar, and S. Gangopadhyay, "Wettability enhancement of Inconel 625 alloy by fabricating ordered micro-textures through micro-milling," *Journal of Micromanufacturing*, p. 25165984251342304, 2025.

[16] H. Hassim and A. R. Abdul Manaf, "Investigation of optimum milling parameters in micro dimples machining," *Journal of Modern Manufacturing Systems and Technology*, vol. 6, no. 1, pp. 73–81, 2022.

[17] M. A. H. Shaharudin and A. R. Yusoff, "Experimental and simulation approach; Investigation effect of axial feed rate to the cutting force in dimple milling using ball end mill tool," *Proceedings of the International Manufacturing Engineering Conference & The Asia Pacific Conference on Manufacturing Systems*, 2022, pp. 33-50.

[18] C. Gachot, A. Rosenkranz, S. M. Hsu, and H. L. Costa, "A critical assessment of surface texturing for friction and wear improvement," *Wear*, vol. 372–373, pp. 21–41, 2017.

[19] T. Pratap and K. Patra, "Micro ball-end milling—an emerging manufacturing technology for micro-feature patterns," *International Journal of Advanced Manufacturing Technology*, vol. 94, no. 5–8, pp. 2821–2845, 2018.

[20] M. A. Hanafiah, A. A. Aziz, and A. R. Yusoff, "Influence of cutting parameters to surface area roughness in dimple machining using milling process," *International Journal of Automotive and Mechanical Engineering*, vol. 18, no. 3, pp. 9094 – 9100, 2021.

[21] T. Pratap and K. Patra, "Micro ball-end milling—an emerging manufacturing technology for micro-feature patterns," *International Journal of Advanced Manufacturing Technology*, vol. 94, no. 5–8, pp. 2821–2845, 2018.

[22] T. Matsumura and S. Takahashi, "Micro dimple milling on cylinder surfaces," *Journal of Manufacturing Processes*, vol. 14, no. 2, pp. 135–140, 2012.

[23] S. Kogusu, T. Ishimatsu, Y. Ougiya, T. Yazawa, and S. Moromugi, "Decoration of metal surface by dimples using ball-end milling process," in *2008 IEEE International Conference on Industrial Technology*, 2008, pp. 1–6.

[24] E. Graham, C. I. Park, and S. S. Park, "Force modeling and applications of inclined ball end milling of micro-dimpled surfaces," *International Journal of Advanced Manufacturing Technology*, vol. 70, no. 1–4, pp. 689–700, 2014.

[25] V. Ezhilmaran, N. J. Vasa, and L. Vijayaraghavan, "Investigation on generation of laser assisted dimples on piston ring surface and influence of dimple parameters on friction," *Surface and Coatings Technology*, vol. 335, pp. 314–326, 2018.

[26] S. Wojciechowski and K. Mrozek, "Mechanical and technological aspects of micro ball end milling with various tool inclinations," *International Journal of Mechanical Sciences*, vol. 134, pp. 424–435, 2017.

[27] A. Schubert, R. Neugebauer, D. Sylla, M. Avila, and M. Hackert, "Manufacturing of surface microstructures for improved tribological efficiency of powertrain components and forming tools," *CIRP Journal of Manufacturing Science and Technology*, vol. 4, no. 2, pp. 200–207, 2011.

[28] M. Chen, H. Ni, Z. Wang, and Y. Jiang, "Research on the modeling of burr formation process in micro-ball end milling operation on Ti–6Al–4V," *The International Journal of Advanced Manufacturing Technology*, vol. 62, pp. 901–912, 2012.

[29] M. S. M. Mokhtar, A. R. Yusoff, and M. S. Y. Lubis, "Effect of machining parameters on micro-burrs formation of aluminium puncher using high-speed machining process," *Journal of Advanced Research in Applied Mechanics*, vol. 115 no. 1, pp. 47-60, 2024.

[30] R. Ferreira, G. L. de Castro Martinelli, A. R. Rodrigues, and R. T. Coelho, "Tool feed and burr size influence on wettability of Ti6Al4V micro end-milled," *International Journal of Engineering Materials and Manufacture*, vol. 6, no. 3, pp. 114–23, 2021.