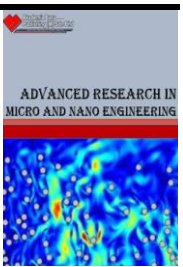
Penerbit Akademia Baru

Journal of Advanced Research in Micro and Nano Engineering

Journal homepage:
https://semarakilmu.com.my/journals/index.php/micro_nano_engineering/index
ISSN: 2756-8210



Effect Of Ultrasonically Vibrated Cutting Tool on Surface Roughness of Micro Turning

Lukman Nul Hakim[1], Rino Andias Anugraha[1,*], Teddy Sjafrizal[1], Nopendri[1], Pratya Poeri Suryadhinia[1], Mohd Rasidi Ibrahim[2]

[1] School of Industrial Engineering, Telkom University, Jl. Telekomunikasi 1, Terusan Buah batu, Bojongsoang 40257, Bandung, Indonesia
[2] Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia

ARTICLE INFO

Article history:
Received
Received in revised form
Accepted
Available online 30 June 2024

Keywords:
Micro turning; ultrasonic vibration assisted turning; ploughing; surface roughness

ABSTRACT

Micro turning is commonly employed in the manufacturing of precision parts. However, the precision may get compromised by the chronic phenomenon of micromachining called ploughing. Ploughing produces extra roughness, as some cut surfaces are ploughed by the cutting tool. It is expected that any disruption to these continuous interactions could mitigate this unwanted condition. Therefore, Ultrasonic Assisted Vibration Turning (UVAT) was proposed, utilizing its intermittent cutting to reduce the contact between the cutting tool and the workpiece. In this study, the impact of Longitudinal (LVAT) and Tangential (TVAT) UVAT on surface roughness in micro turning of aluminium alloy was investigated. The experimental data suggests that LVAT and TVAT affect differently on reducing the surface roughness of the micro-turned Al-6061. However, LVAT proves to be more effective in suppressing the negative effects of ploughing at high feed rate cuttings, as indicated by a smoother machined surface. LVAT reduced surface roughness by 12% greater than TVAT at a cutting feed rate of 0.48 mm/rev. These findings support the potential of UVAT, particularly the LVAT technique, as a viable approach to enhance surface quality in micro turning applications for precision engineering.

1. Introduction

Micro machining has become a critical technology across various industries due to its unique capabilities in creating miniaturized features with high precision [1]. The growing industrial demand for supersmooth surfaces and functional three-dimensional micro/nano-structures (3D-MNS) in ultra-large scale integrated circuits, microelectromechanical systems, miniaturized total analysis systems, and precision optics drives further development and improvements in various micromachining techniques [2]. Among the popular techniques, micro turning plays a vital role in creating miniaturized features with high precision [3,4].

---

[*] *Corresponding author.*
E-mail address: rinoandias@telkomuniversity.ac.id

https://doi.org/10.37934/armne.20.1.3543

Micro turning utilizes a miniature cutting tool to remove material from a rotating workpiece, similar to conventional turning but with a significantly smaller scale. This miniaturization capability is essential for various industries like automobile, aerospace, biomedical and optical industries [5]. Despite its strength, micro turning faces specific challenges that hinder the creation of high-quality micro-features. One critical issue is ploughing, a phenomenon where the cutting tool plastically deforms the machined material instead of cleanly removing it. Ploughing transforms parts of the cutting surface into uncut chips that are ploughed by the cutting tool as the turning progresses. This ploughed surface creates built-up material on the machined surface, resulting in a higher surface roughness [6] (Figure 1), and cutting force [7-9], compromising the functionality and performance of miniaturized components.

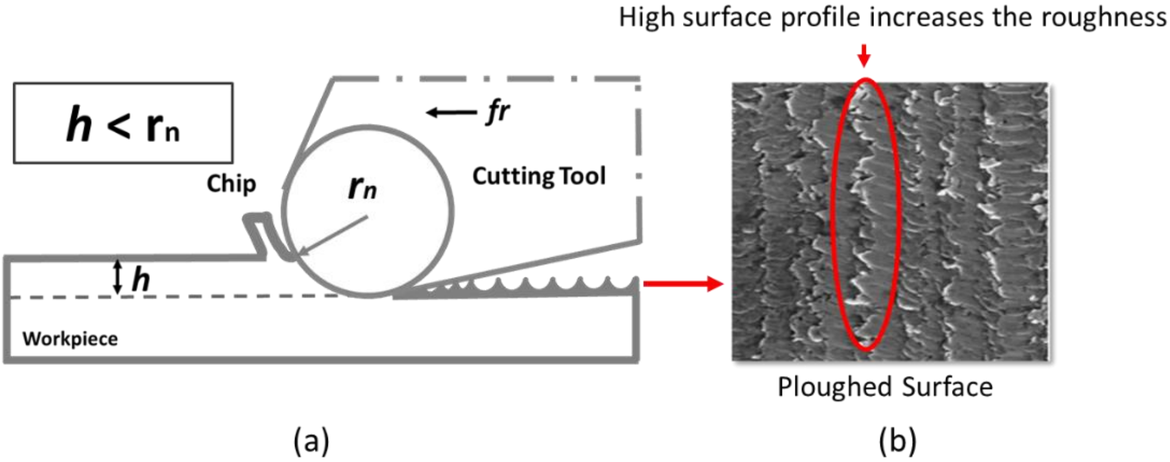


Fig. 1. Micro turning is characterised by the radius of the tool nose (r_n) is greater than the depth of cut (h). This condition is responsible for the presence of a ploughing phenomenon. (b) The surface profile of the ploughed workpiece, which produces a rougher surface profile [10]

Conventional micro turning suffers from ploughing, which degrades surface quality. However, recent advancements offer Ultrasonic-Assisted Vibration Turning (UATV) potential solutions. This innovative technique utilizes ultrasonic vibrations superimposed on the cutting tool during operation. As ploughing occurs due to continuous contact between the tool and workpiece, UATV disrupts this contact, potentially mitigating the negative effects. This is achieved by introducing micro-displacements at the tool-workpiece interface, which may alter chip formation mechanisms and reduce ploughing.

The benefits of ultrasonic vibration extend beyond UVAT and have been widely explored for enhancing various manufacturing processes [11,12]. Its applications are not limited to vibration-assisted machining but have also been found to support advancements in casting [13], forming [14], welding [15], soldering [16], and even powder metallurgy [17]. This demonstrates the versatility of ultrasonic vibration technology in optimizing different stages of manufacturing.

UVAT has proven to improve surface roughness [18] and lowering cutting forces on conventional turning cutting [9]. Xu *et al.,* [19] demonstrated the performance of UVAT to reduce cutting forces by up to 80% compared to vibrationless cutting.

The advantages of employing UVAT are determined by the intermittent cutting mechanism as the cutting tool moves in controllable trajectories. The tool can be moved in many directions, some of which are longitudinal (Figure 2(a)) and tangential (Figure 2(b)). Despite the difference in direction, the longitudinal UVAT (LVAT) behaved similarly to the tangential UVAT (TVAT) in producing a smoother surface and lower cutting force. Xu *et al.,* [20] provided evidence that LVAT reduces surface roughness down to 30%. LVAT also cut the cutting force significantly [21]. Meanwhile, TVAT potentially turns down cutting force by 25% and smoothens the surface of the workpiece [22].

In light of the encouraging results achieved with LVAT and TVAT, and the ongoing challenge of mitigating ploughing in micro turning, this study aims to demonstrate the effect of using LVAT and TVAT on the surface roughness of micro turning. Eventually, the outcome is to contribute to the wider acceptance and implementation of ultrasonic-assisted vibration turning within the precision manufacturing sector

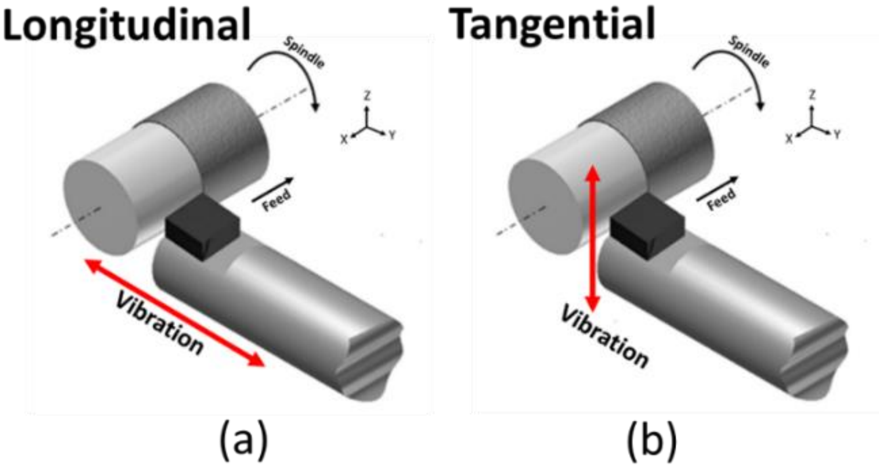


Fig. 2. The vibration-assisted turning mechanism: (a) Longitudinal Vibration-Assisted Turning (LVAT) vibrates along the y-axis normal to the workpiece, (b) Tangential Vibration-Assisted Turning (TVAT) vibrates along the z-axis following the spindle rotation direction

2. Method

The current study examining the cutting surfaces produced by LVAT and TVAT in micro turning cutting was conducted using a high-speed precision lathe (S530×1000, WINHO). This turning machine was equipped with a non-resonant vibration module producing ultrasonic vibrations to the cutting tool (referred to as RNO vibrator). This module optimises the generated vibration from the piezoelectric and the amplifying effect of the flexure hinges, resulting in ultrasonic vibration-assisted turning. The module was set to generate 27 kHz of vibration to the tool tip of the LVAT and TVAT, with an amplitude of approximately 2 µm (Figure 3).

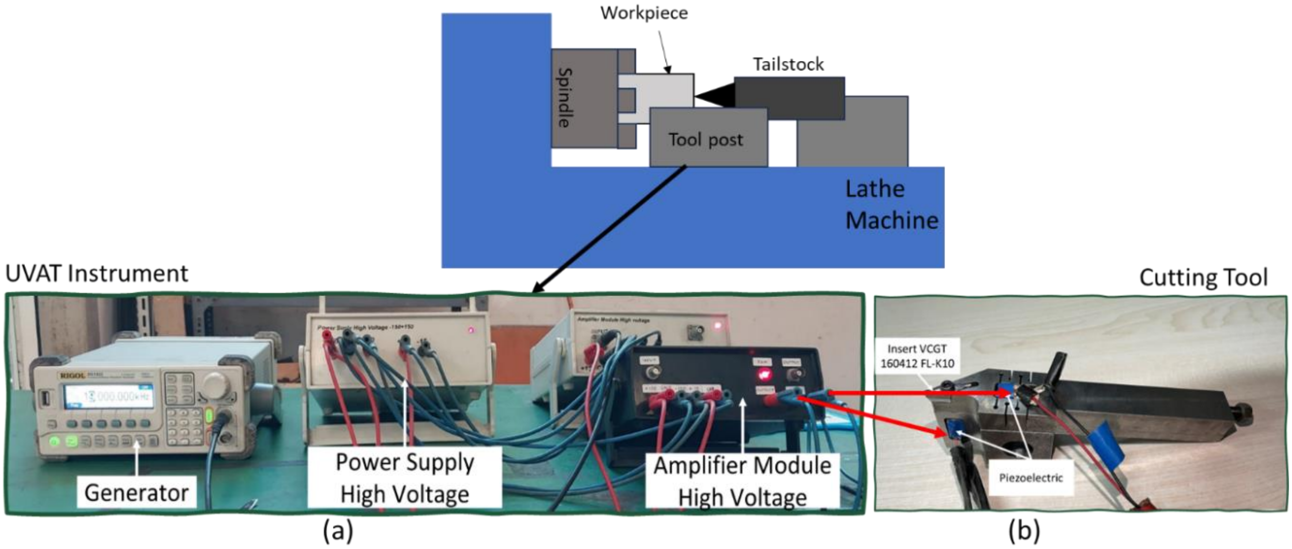


Fig. 3. UVAT cutting set-up, using a specific toolholder connected directly to the UVAT device (RNO vibrator). The tailstock is used to ensure stable rotating of the workpiece

Micro turning is characterised by a high tool nose's radius to a depth of cut ratio [ref]. This condition is fulfilled by selecting a cutting insert with a large nose radius (r_n) and setting the depth of cut (h) to a minimum. Furthermore, the likelihood of the ploughing phenomenon occurs when the selected depth of cut (h) is in between the minimum uncut chip thickness (h_{min}) and the material spring back thickness (h_s) [1]. Unlike h_s which is not well understood, the minimum uncut chip thickness is associated with the workpiece material by [23]

$$h_{min} = k.r_n \quad , \tag{1}$$

where k is the material coefficient and r_n is the nose radius of the cutting tool insert. In this investigation, aluminium 6061 (Al-6061) was chosen as the workpiece material with $k = 0.08$ [23], and VCGT 160412 (TaeguTech) cutting insert with $r_n = 1.2\ mm$ was selected as the cutting insert. Thus, the h_{min} for the current setup was 0.96 mm. The selected h was 0.05 mm, which was smaller than h_{min} and r_n. Eventually, the cuttings were performed at $h = 0.05\ mm$. This selected depth of cut was believed to be well above the h_s. Thus, the condition for ploughing in micro turning, $h_s < h < h_{min}$, was obtained (Figure 4).

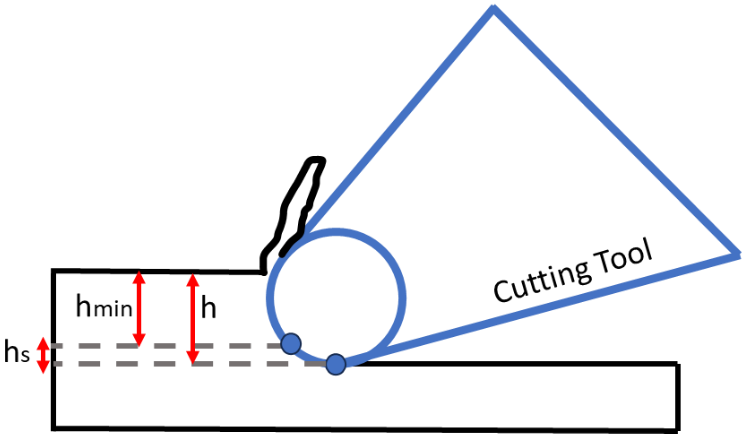


Fig. 4. Ploughing phenomenon occurs when $h_s < h < h_{min}$

Finally, the cutting surface examinations were performed on the machined surface after varying the feed rate (f=0.1, 0.24 and 0.48 mm/rev) and spindle speed (n=1350 rpm). The machined surfaces were measured by the physical probe of the Mitutoyo SJ-410 surface tester. The information obtained was analysed and discussed in the following sections.

3. Results and Discussion

3.1 Effect of Employing TVAT and LVAT on Surface Roughness of Micro Turning

The introduction of TVAT and LVAT significantly improves surface roughness in micro turning compared to the Conventional Turning (CT) method (Figure 5). Across all experimental conditions, both TVAT and LVAT generated smoother surfaces compared to CT. LVAT demonstrated a greater effect on reducing surface roughness (13–22%) compared to TVAT. At a feed rate of 0.1 mm/rev, TVAT produced a 16% smoother surface compared to CT, while LVAT achieved a 7% greater reduction in surface roughness. However, at higher feed rates, the effectiveness of TVAT diminishes, resulting in surface roughness values that are nearly identical to those of CT.

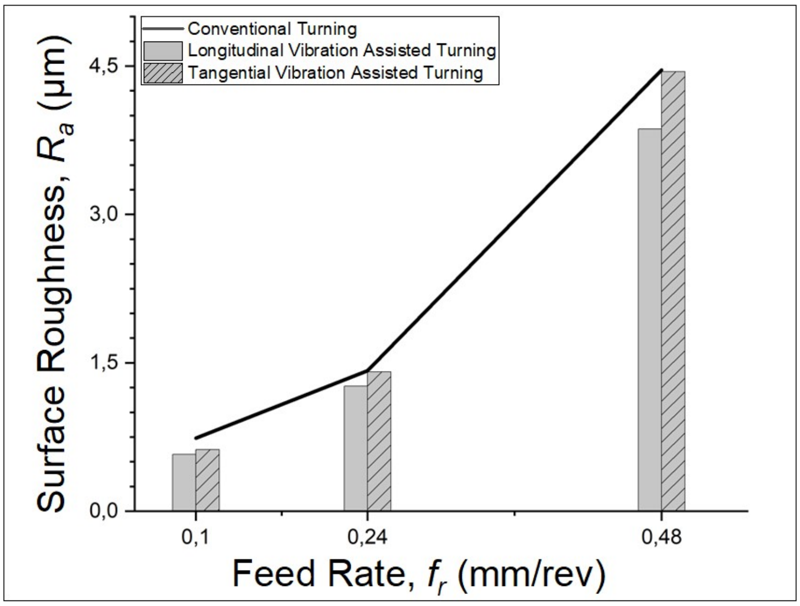


Fig. 5. The effect of feed rate changes on surface roughness. Feed rate correlates positively to the surface roughness at all cutting conditions (CT, LVAT and TVAT). The application of LVAT could minimise the negative effects of ploughing, leading to a smoother surface

The observed reduction in surface roughness strengthens the argument that vibration-assisted turning techniques are applicable to micro turning. UVAT technology, known for its intermittent cutting mechanism, demonstrably reduces cutting force and generates smoother surfaces [24]. The influence of this intermittent cutting on surface roughness can be explained by analysing the cutting surface profile captured by a roughness tester (Figure 6). In conventional turning (Figure 6(a)), the profile exhibits a series of peaks and valleys corresponding to the tool's trajectory. Conversely, ultrasonic vibration of the tool in UVAT creates finer and more frequent tool paths across the surface, effectively reducing the peak-to-valley height (Figure 6(b)). This flattening effect translates to a lower average surface roughness. While this study focused on micro turning, the observed benefits of UVAT suggest a similar flattening effect occurs with LVAT. Furthermore, the wider and more pronounced flattening observed in the LVAT profile (Figure 6(c)) compared to TVAT (Figure 6(c)) supports the superior performance of LVAT in reducing surface roughness.

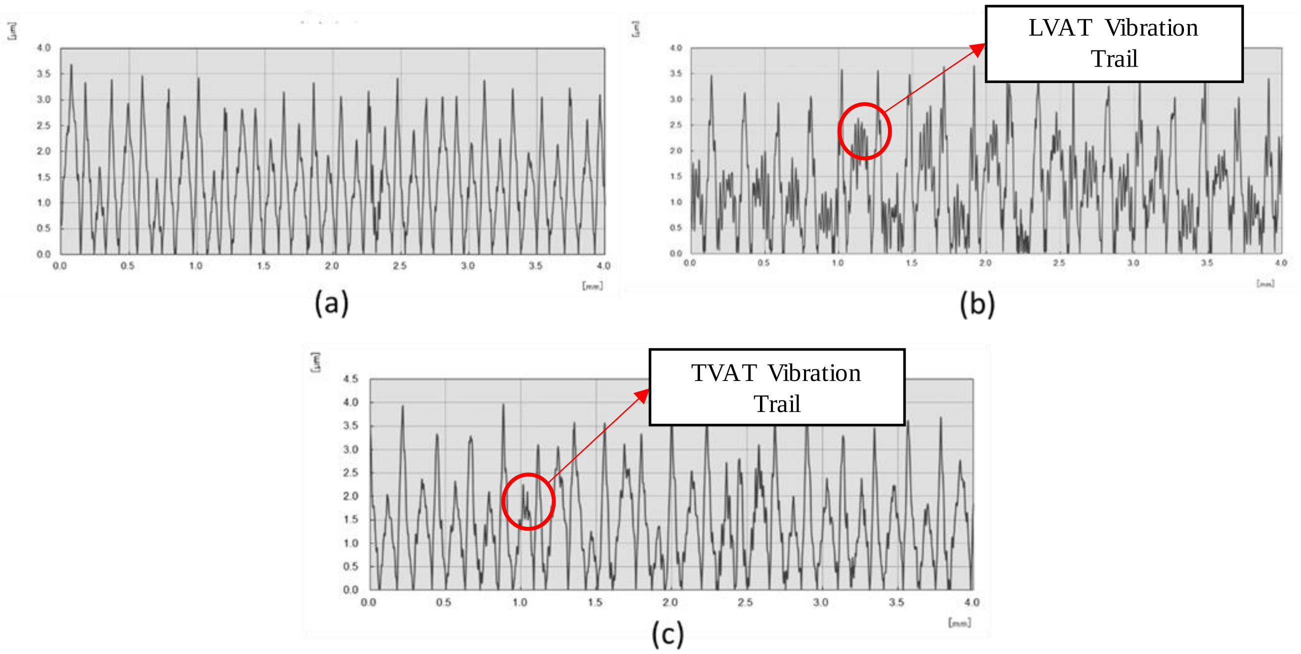


Fig. 1. Surface profile of (a) CT ($R_a = 1.41\ \mu m$), (b) LVAT ($R_a = 1.27\ \mu m$)) and (c) TVAT ($R_a = 1.41\ \mu m$). CT displays sharp peaks, whereas the application of LVAT and TVAT removes the portions of the sharp peaks, resulting in a lower R_a value compared to CT. (note: CT = conventional turning, LVAT = longitudinal vibration-assisted turning, TVAT = tangential vibration-assisted turning)

The specific movement mechanism of LVAT, characterized by its approach towards the depth of cut, offers a distinct advantage in reducing the inherent surface roughness challenges associated with micro turning. The increased tool trajectory amplitude effectively expands the actual depth of cut for LVAT, bringing it closer to h_{min} (Figure 7). As this actual depth of cut approaches h_{min}, the likelihood of encountering ploughing during the cutting process diminishes [1]. Consequently, the LVAT technique mitigates the formation of additional roughness typically induced by the ploughing effect in micro turning by increasing the actual depth of cut. In contrast, TVAT does not experience any additional depth of cut as it moves perpendicular to the workpiece or toward the spindle. As a result, the triggering point for ploughing formation remains unchanged, leading to a less pronounced effect on reducing micro turning roughness.

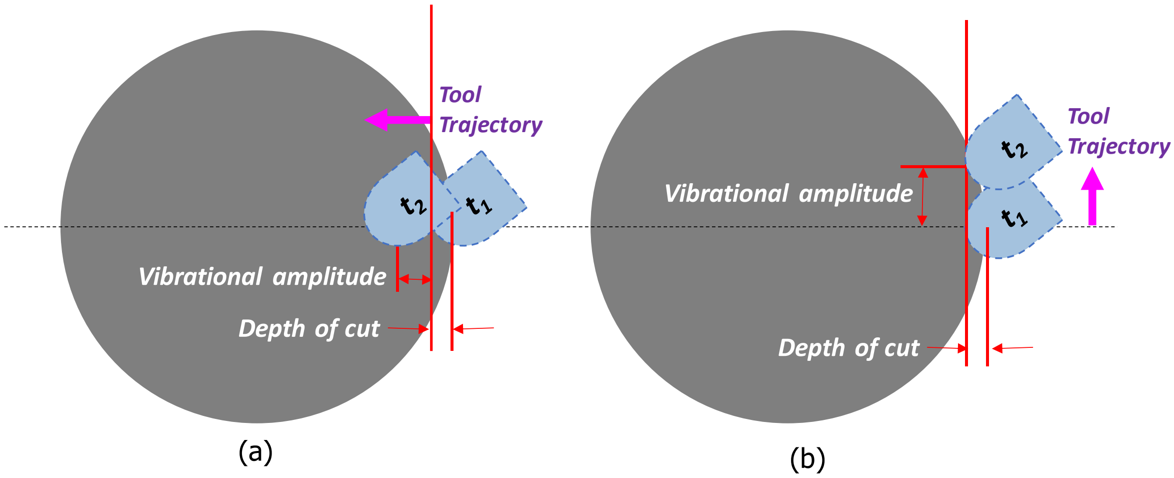


Fig. 2. The cross-sectional view of (a) Longitudinal Vibration-Assisted Turning (LVAT) and (b) Tangential Vibration-Assisted Turning (TVAT). LVAT achieves a deeper actual depth of cut in the cutting direction, while TVAT maintains a consistent depth of cut

3.2 Effect of Changing Micro Turning Feed Rate on Surface Roughness of Micro Turning

Existing research has established a direct correlation between increasing feed rate and increasing surface roughness in conventional turning [25] by,

$$R_a = \frac{{f_r}^2}{32 \times r_n}, \tag{2}$$

where f_r is feed rate and r_n is the nose radius of the cutting tool. This relationship also appears to be applicable for micro turning cutting as depicted in Figure 5. Surface roughness increased for both CT and UVAT methods (encompassing LVAT and TVAT) as the micro turning feed rate increased. Notably, the surface roughness of micro turned surfaces increased up to fourfold when the feed rate was adjusted from 0.1 mm/rev to 0.48 mm/rev. This behaviour could be modelled by [26],

$$R_a{}' = \frac{{f_r}^2}{32 \times r_n} + \frac{h_{min}}{32} \times (1 + \frac{h_{min} \times r_n}{{f_r}^2}) \quad . \tag{3}$$

where $\frac{h_{min}}{32} \times (1 + \frac{h_{min} \times r_n}{{f_r}^2})$ represents the additional roughness attributed specifically to the ploughing effect prevalent in micro turning.

Overall, UVAT methods demonstrably mitigate the increased roughness caused by micro turning's ploughing effect. TVAT and LVAT consistently produced lower roughness compared to CT across all feed rates. At a feed rate of 0.1 mm/rev, LVAT achieved a 22% reduction in surface roughness compared to only 16% for TVAT. When the feed rate was increased to 0.24 mm/rev and 0.48 mm/rev, TVAT exhibited minimal roughness reduction, while LVAT maintained at 10–13% reduction capability. Notably, closer examination revealed a distinct difference in roughness suppression between LVAT and TVAT, with LVAT consistently achieving a more significant reduction.

Furthermore, the effectiveness of LVAT in mitigating roughness increased as the feed rate increased. The difference in LVAT and TVAT roughness reduction at a feed rate of 0.1 mm/rev was 7%. However, when feed rates of 0.24 mm/rev and 0.48 mm/rev were implemented, the difference between LVAT and TVAT reached 12%. This trend suggests that LVAT offers a progressively greater contribution to reducing the heightened roughness caused by the ploughing effect of micro turning at higher feed rates.

4. Conclusion

This study investigated the application of Longitudinal and Tangential UVAT on micro turning cutting conditions. The findings suggest that LVAT is the superior UVAT technique compared to TVAT in suppressing the negative effects of ploughing in micro turning. LVAT consistently produced smoother surfaces than TVAT, with this roughness reduction becoming more prominent at higher feed rates. Ultimately, this investigation provides additional experimental evidence supporting the use of UVAT, particularly LVAT, as a viable machining method for producing high-quality micro and precision parts.

Acknowledgement

This work is supported by Telkom University (Penelitian Dana Internal Periode 1-2023)

References

[1] Wojciechowski, Szymon. "Estimation of minimum uncut chip thickness during precision and micro-machining processes of various materials—a critical review." *Materials* 15, no. 1 (2021): 59. https://doi.org/10.3390/ma15010059

[2] Zhan, Dongping, Lianhuan Han, Jie Zhang, Quanfeng He, Zhao-Wu Tian, and Zhong-Qun Tian. "Electrochemical micro/nano-machining: principles and practices." *Chemical Society Reviews* 46, no. 5 (2017): 1526-1544. https://doi.org/10.1039/C6CS00735J

[3] Senthilkumar, V., and S. Muruganandam. "State of the art of micro turning process." International Journal of Emerging Technology and Advanced Engineering, ISSN (2012): 2250-2459.

[4] Rahman, M. A., M. Rahman, A. Senthil Kumar, H. S. Lim, and A. B. M. A. Asad. "Fabrication of miniature components using microturning." In Proceedings of the Fifth International Conference on Mechanical Engineering, Dhaka. 2003.

[5] Das, Arnab, and Vivek Bajpai. "Fabrication of super-finished surfaces in high-speed turning and micro turning: A review."

[6] Ramos, A. Cuba, H. Autenrieth, T. Strauß, M. Deuchert, J. Hoffmeister, and V. Schulze. "Characterization of the transition from ploughing to cutting in micro machining and evaluation of the minimum thickness of cut." Journal of Materials Processing Technology 212, no. 3 (2012): 594-600. https://doi.org/10.1016/j.jmatprotec.2011.07.007

[7] Guo, Y. B., and Y. K. Chou. "The determination of ploughing force and its influence on material properties in metal cutting." Journal of Materials Processing Technology 148, no. 3 (2004): 368-375. https://doi.org/10.1016/j.jmatprotec.2004.02.052

[8] Zhu, Lida, Chenbing Ni, Zhichao Yang, and Changfu Liu. "Investigations of micro-textured surface generation mechanism and tribological properties in ultrasonic vibration-assisted milling of Ti–6Al–4V." Precision Engineering 57 (2019): 229-243. https://doi.org/10.1016/j.precisioneng.2019.04.010

[9] Wu, Xian, Liang Li, Ning He, Xiuqing Hao, Chenjiao Yao, and Li Zhong. "Investigation on the ploughing force in microcutting considering the cutting edge radius." The International Journal of Advanced Manufacturing Technology 86 (2016): 2441-2447. https://doi.org/10.1007/s00170-016-8386-x

[10] Bissacco, Giuliano, Hans Nørgaard Hansen, and Leonardo De Chiffre. "Micromilling of hardened tool steel for mould making applications." Journal of Materials Processing Technology 167, no. 2-3 (2005): 201-207. https://doi.org/10.1016/j.jmatprotec.2005.05.029

[11] Ning, Fuda, and Weilong Cong. "Ultrasonic vibration-assisted (UV-A) manufacturing processes: State of the art and future perspectives." Journal of Manufacturing Processes 51 (2020): 174-190. https://doi.org/10.1016/j.jmapro.2020.01.028

[12] Kumar, Sudhir, Dinesh Kumar, Inderjeet Singh, and Debabrata Rath. "An insight into ultrasonic vibration assisted conventional manufacturing processes: A comprehensive review." Advances in Mechanical Engineering 14, no. 6 (2022): 16878132221107812. https://doi.org/10.1177/16878132221107812

[13] Nie, K. B., X. J. Wang, K. Wu, L. Xu, M. Y. Zheng, and X. S. Hu. "Processing, microstructure and mechanical properties of magnesium matrix nanocomposites fabricated by semisolid stirring assisted ultrasonic vibration." Journal of alloys and compounds 509, no. 35 (2011): 8664-8669. https://doi.org/10.1016/j.jallcom.2011.06.091

[14] Zhou, Tianfeng, and Chunfeng Ma. "Study of ultrasonic vibration-assisted forming in copper cylinder compression." Procedia Manufacturing 50 (2020): 199-202. https://doi.org/10.1016/j.promfg.2020.08.037

[15] Muhammad, Najib A., and C. S. Wu. "Ultrasonic vibration assisted friction stir welding of aluminium alloy and pure copper." Journal of Manufacturing Processes 39 (2019): 114-127. https://doi.org/10.1016/j.jmapro.2019.02.011

[16] Jalil, Nawal Aswan Abdul, Hussein Kadhim Sharaf, and Sadeq Salman. "A simulation on the effect of ultrasonic vibration on ultrasonic assisted soldering of Cu/SAC305/Cu joint." Journal of Advanced Research in Applied Mechanics 36, no. 1 (2017): 1-9.

[17] Cha, H. R. "Densification of the nanopowder by using ultrasonic vibration compaction." Rev. Adv. Mater. Sci 28, no. 1 (2011): 90-93.

[18] Nosouhi, Reza, Saeed Behbahani, Saeed Amini, and Mohammad Reza Khosrojerdi. "An experimental study on the cutting forces, surface roughness and the hardness of Al 6061 in 1D and 2D ultrasonic assisted turning." Applied Mechanics and Materials 680 (2014): 224-227. https://doi.org/10.4028/www.scientific.net/AMM.680.224

[19] Xu, Yingshuai, Zhihui Wan, Ping Zou, Weili Huang, and Guoqing Zhang. "Experimental study on cutting force in ultrasonic vibration-assisted turning of 304 austenitic stainless steel." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 235, no. 3 (2021): 494-513. https://doi.org/10.1177/0954405420957127

[20] Xu, Yingshuai, Fei Gao, Ping Zou, Qinjian Zhang, and Fanglei Fan. "Theoretical and experimental investigations of surface roughness, surface topography, and chip shape in ultrasonic vibration-assisted turning of Inconel 718." Journal of Mechanical Science and Technology 34, no. 9 (2020): 3791-3806. https://doi.org/10.1007/s12206-020-0830-x

[21] Shan, S., P. Feng, H. Zha, and F. Feng. "Building of longitudinal ultrasonic assisted turning system and its cutting simulation study on bulk metallic glass. Materials 13 (14): 3131." (2020). https://doi.org/10.3390/ma13143131

[22] Nath, Chandra, and M. Rahman. "Effect of machining parameters in ultrasonic vibration cutting." International Journal of Machine Tools and Manufacture 48, no. 9 (2008): 965-974. https://doi.org/10.1016/j.ijmachtools.2008.01.013

[23] Rahman, M. Azizur, Mustafizur Rahman, and A. Senthil Kumar. "Chip perforation and 'burnishing–like'finishing of Al alloy in precision machining." Precision Engineering 50 (2017): 393-409. https://doi.org/10.1016/j.precisioneng.2017.06.014

[24] Yang, Zhichao, Lida Zhu, Guixiang Zhang, Chenbing Ni, and Bin Lin. "Review of ultrasonic vibration-assisted machining in advanced materials." International Journal of Machine Tools and Manufacture 156 (2020): 103594. https://doi.org/10.1016/j.ijmachtools.2020.103594

[25] Wang, X., and C. X. Feng. "Development of empirical models for surface roughness prediction in finish turning." The International Journal of Advanced Manufacturing Technology 20 (2002): 348-356. https://doi.org/10.1007/s001700200162

[26] Brown, Ian, and Julius Schoop. "An Iterative Size Effect Model of Surface Generation in Finish Machining." Journal of Manufacturing and Materials Processing 4, no. 3 (2020): 63. https://doi.org/10.3390/jmmp4030063