EXPERIMENTAL STUDY OF OIL FILM THICKNESS ON WORKPIECE UNDER MINIMUM QUANTITY LUBRICATION MILLING PROCESS USING LASER INDUCED FLUORESCENCE METHOD

NUR IZZATI KHOIRUNNISA BT ISMAIL

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

We hereby declare that We have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science

_____

(Supervisor's Signature)

Full Name : DR. NURRINA BT ROSLI

Position : SENIOR LECTURER

Date : 8 MARCH 2022

_____

(Co-supervisor's Signature)

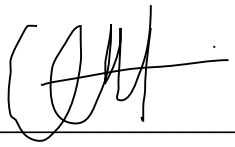
Full Name : DR. AMIRIL SAHAB BIN ABDUL SANI

Position : SENIOR LECTURER

Date : 8 MARCH 2022

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.



(Student's Signature)

Full Name : NUR IZZATI KHOIRUNNISA BT ISMAIL

ID Number : MFI18002

Date : 8 MARCH 2022

EXPERIMENTAL STUDY OF OIL FILM THICKNESS ON WORKPIECE UNDER MINIMUM QUANTITY LUBRICATION MILLING PROCESS USING LASER INDUCED FLUORESCENCE METHOD

NUR IZZATI KHOIRUNNISA BT ISMAIL

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

Faculty of Manufacturing and Mechatronic Engineering Technology

UNIVERSITI MALAYSIA PAHANG

MARCH 2022

ACKNOWLEDGEMENTS

First of all, I want to express my gratitude towards Allah SWT for giving me the opportunity to further and finish my research study. All of this is only possible due to His blessings towards me.

Next, I would like to express my deepest appreciation to my supervisor, Dr. Nurrina Bt Rosli for her guidance by giving me crucial lessons, advices, outstanding opinions and her time spend to give extensive help to me as well as exceptional suggestions in order to make sure that my research is complete. In addition, her continuous motivation has always motivates me to push harder to finish this research. Without her dedication, I would be impossible to me to complete this research.

Furthermore, my sincere thanks to my co-supervisor, Dr. Amiril Sahab Bin Abdul Sani for guide me to finish my research. His wide knowledge about my field of study has been a great help to me to conduct this research. His invaluable opinions and suggestions had provided me more knowledge about this study.

Then, I had like to convey my heartfelt thanks to UMP's lab machining staff, Mr. Shahandzir Bin Baharom and Mr. Syazwan for given me the permission to conduct my research in the lab and for their numerous help to me as well as their outstanding advices and opinions in order to perform my research.

In addition, my earnest thanks goes to my family whose always understand and supportive of my commitment to this study. They always gives me motivation and encouragement in order for me to finish this study.

ABSTRAK

Dalam proses pemesinan, pelincir digunakan untuk meningkatkan pengeluaran bagi tujuan pelinciran dan penyejukan bagi mengurangkan daya, suhu pemotongan dan geseran di zon pemotongan. Penyejukan konvensional adalah medium paling universal yang digunakan oleh pengilang tetapi penggunaan pelincir yang banyak menjejaskan kos pembuatan dan kesihatan pekerja. Usaha berterusan penyelidik untuk menggantikan kaedah itu telah menemui pendekatan yang lebih baik iaitu teknologi pelinciran kuantiti minimum (MQL). MQL memberikan kesan positif kepada kos pembuatan dan kesihatan pekerja. Ini disebabkan MQL menggalakkan pelinciran mencukupi di sepanjang bahagian pemotongan dengan sedikit minyak. Justeru, untuk memastikan minyak pelincir menembusi zon pemotongan, kabus minyak pelincir yang disembur pada bahan kerja semasa pemesinan mesti dianalisis secara mendalam dengan memerhatikan jumlah kabus minyak yang melekat berhampiran bahagian pemotongan. Namun, penyelidik lepas hanya mengambil berat tentang kesan parameter pemesinan terhadap prestasi MQL. Kajian tentang perilaku minyak pelincir semasa pemesinan MQL terhad kerana pemerhatiannya semasa pemesinan adalah mencabar. Selain itu, saiz titisan pada jarak muncung dekat dan tekanan udara sederhana dapat membasahi permukaan pemotongan dengan baik. Bahkan, kadar aliran minyak pelincir MQL membolehkan pelarasan tekanan antara minyak pelincir dalam tangki penjana dan tekanan atmosfera untuk menjana kabus minyak yang mencukupi. Justeru, objektif kajian ini adalah untuk mengukur ketebalan filem minyak pelincir di zon pemotongan, mengkaji kekasaran permukaan bahan kerja di kedudukan muncung MQL dan kadar aliran minyak pelincir yang berbeza menggunakan kaedah pendarfluor teraruh laser (LIF) semasa proses pengilangan MQL dan mengenal pasti hubungan antara ketebalan filem minyak pelincir dan kekasaran permukaan. Ketebalan filem minyak pelincir dinilai menggunakan persamaan daripada prosedur penentukuran dari LIF. Didapati bahawa; julat ketebalan filem minyak pelincir meningkat dengan peningkatan kadar aliran minyak untuk kedua-dua kedudukan muncung MQL 0° dan 45°. Pada kedudukan muncung MQL 0°, ketebalan filem minyak pelincir mencapai julat yang tinggi yang ditunjukkan oleh lebih banyak taburan kecondongan negatif dan hampir simetri berbanding kedudukan muncung 45°. Untuk nilai purata kekasaran permukaan pula, pada kedudukan muncung MQL 0°, semua nilai kekasaran permukaan menurun dengan peningkatan kadar aliran minyak. Ini mungkin kerana penambahan ketebalan filem minyak pada julat tinggi iaitu 0.5 mm hingga 0.9 mm dan ke atas. Namun, pada kedudukan muncung 45°, pada kadar aliran minyak pelincir yang tinggi, kekasaran permukaan lebih tinggi dari kedudukan muncung MQL 0°. Ini boleh dikaitkan dengan ketebalan filem minyak pelincir yang rendah dalam julat 0.3 mm hingga 0.7 mm. Oleh itu, terbukti keberkesanan penghantaran minyak pelincir ke dalam zon pemotongan bahan kerja pada kedudukan muncung MQL 0°, pada kadar aliran MQL yang tinggi. Hubungan antara ketebalan filem minyak pelincir dan kekasaran permukaan berjaya dikenalpasti. Penemuan ini berpotensi memberi manfaat kepada proses pengilangan MQL bahan keras seperti aloi aluminium 6061.

ABSTRACT

In machining process, lubricant is utilized in order to facilitate higher production for lubrication and cooling purpose to reduce cutting force, cutting temperature and friction near the cutting zone. Conventional flooding technique is the most universal medium used by the manufacturer however, the used of large amount of lubricant contributes to high manufacturing cost and jeopardizing workers health. Thus, continuous effort of researchers to substitute the flood cooling has found a better approach that is minimum quantity lubrication (MQL) technology. MQL promotes diverse benefits to the manufacturers, in terms of manufacturing cost and employees' health's. Superior advantage in using MQL is attributed by its compelling performance that promotes sufficient lubrication along the cutting edge with small amount of oil. However, the lubricant oil must be ensured to well penetrate the cutting zone. In order to explain this situation, the lubricant oil mist sprayed onto workpiece upon the on-going operation must be analysed in depth. This can be accomplished by observing the amount of oil mist adhered near the cutting edge. However, past researchers concern merely on the machining parameters effects towards the performance of MQL. The studies on the behavior of lubricant oil during MQL machining operation is limited since it is a challenging task to observe the lubricant oil during MQL machining is on-going. Moreover, the preferable size of droplet obtained at short nozzle distance and medium air pressure can efficiently wet the cutting surface. Furthermore, MQL lubricant oil flow rate is among the factor to enable the adjustment of pressure between lubricant oil in the tank of MQL generator and atmospheric pressure to make sure oil mist generated is sufficient for the lubrication effect. Therefore, the objectives of this study are set to measure lubricant oil film thickness at cutting zone, to examine surface roughness of workpiece under different MQL nozzle positons and lubricant oil flow rates using laser induced fluorescence (LIF) method during MQL milling process and to identify relationship between lubricant oil film thickness and surface roughness. Lubricant oil film thickness was evaluated by applying equation from the calibration procedure for the LIF method. As a result, it was found that; the range of lubricant oil film thickness increased with increasing oil flow rates for both MQL nozzle positions of 0° and 45°. Suggested that at MQL nozzle position of 0°, more lubricant oil film thickness reached higher ranges which were shown by more negative skewness distribution of histogram as well as nearly symmetrical histogram compared to nozzle position of 45°. Then, for average surface roughness it was found that; at 0° MQL nozzle position, all mean roughness values decreased with increasing oil flow rates. This could be due to the gain in oil film thickness at high range which is 0.5 mm until 0.9 mm and above. However, at nozzle position of 45°, for higher lubricant oil flow rates, the values of mean surface roughness were higher compared to mean surface roughness of MQL nozzle position of 0°. This could be associated with lower lubricant oil film thickness gained in the range of 0.3 mm until 0.7 mm. Therefore, it is proven that at 0° MQL nozzle position, increasing MQL flow rate; makes lubricant oil more capable to be effectively delivered into the cutting zone of workpiece. Here, relationship between lubricant oil film thickness and surface roughness was successfully identified in this study. These findings potentially benefit for MQL milling process of hard material such as aluminium alloy 6061.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

REFERENCES

Abbasi, S. A., & Pingfa, F. (2015). Evaluating the effectiveness of various coating layers applied on k-grade cemented carbide cutting tools on machinability of titanium alloy Ti-6Al-4V in high speed end milling. *Proceedings of 2015 12th International Bhurban Conference on Applied Sciences and Technology*, 14–19. https://doi.org/10.1109/IBCAST.2015.7058472

Åkesjö, A., Vamling, L., Sasic, S., Olausson, L., Innings, F., & Gourdon, M. (2018). On the measuring of film thickness profiles and local heat transfer coefficients in falling films. *Experimental Thermal and Fluid Science*, *99*(4), 287–296. https://doi.org/10.1016/j.expthermflusci.2018.07.028

Al-Zubaidi, S., Ghani, J. A., & Che Haron, C. H. (2013). Prediction of tool life in end milling of Ti-6Al-4V alloy using artificial neural network and multiple regression models. *Sains Malaysiana*, *42*(12), 1735–1741. http://www.ukm.my/jsm/pdf_files/SM-PDF-42-12-2013/07%20Salah%20Al-Zubaidi.pdf

Alekseenko, S., Cherdantsev, A., Cherdantsev, M., Isaenkov, S., Kharlamov, S., & Markovich, D. (2012). Application of a high-speed laser-induced fluorescence technique for studying the three-dimensional structure of annular gas-liquid flow. *Experiments in Fluids*, *53*(1), 77–89. https://doi.org/10.1007/s00348-011-1200-5

Alves, S., & Oliveira, J. De. (2008). Vegetable based cutting fluid–an environmental alternative to grinding process. *15th CIRP International Conference on Life Cycle Engineering*, 1–5. http://www.notox.com.br/pdf/artigo01.pdf

Amrita, M., Srikant, R., Sitaramaraju, A., Prasad, M., & Krishna, V. (2013). Experimental investigations on influence of mist cooling using nanofluids on machining parameters in turning AISI 1040 steel. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, *227*, 1334–1346. https://doi.org/10.1177/1350650113491934

Anton, S., Andreas, S., & Friedrich, B. (2015). Heat dissipation in turning operations by means of internal cooling. *Procedia Engineering*, *100*, 1116–1123. https://doi.org/10.1016/j.proeng.2015.01.474

Araújo Junior, A. S., Sales, W. F., da Silva, R. B., Costa, E. S., & Rocha Machado, Á. (2017). Lubri-cooling and tribological behavior of vegetable oils during milling of AISI 1045 steel focusing on sustainable manufacturing. *Journal of Cleaner Production*, *156*, 635–647. https://doi.org/10.1016/j.jclepro.2017.04.061

Attanasio, A., Gelfi, M., Giardini, C., & Remino, C. (2006). Minimal quantity lubrication in turning: Effect on tool wear. *Wear*, *260*(3), 333–338. https://doi.org/10.1016/j.wear.2005.04.024

Bai, X., Zhou, F., Li, C., Dong, L., Lv, X., & Yin, Q. (2020). Physicochemical properties of degradable vegetable-based oils on minimum quantity lubrication milling. *The International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-019-04695-x

Bashir, M. Al, Mia, M., & Dhar, N. R. (2018). Investigations on surface milling of hardened AISI 4140 steel with pulse jet MQL applicator. *Journal of The Institution of Engineers (India)*, *99*(3), 301–314. https://doi.org/10.1007/s40032-016-0277-2

Bermingham, M. J., Sim, W. M., Kent, D., Gardiner, S., & Dargusch, M. S. (2015). Tool life and wear mechanisms in laser assisted milling Ti-6Al-4V. *Wear*, *322–323*, 151–163. https://doi.org/10.1016/j.wear.2014.11.001

Bhan, S., Tiwari, O. M., & Yadav, Aniv. (2018). Study and analysis of Minimum Quantity Lubricant (MQL) using various oils for machining of mild steel (AISI 1006) in turning operation. *International Journal of Advance Engineering and Research Development*, 5(7), 10–21.

Boutar, Y., Naïmi, S., Mezlini, S., Carbas, R. J. C., da Silva, L. F. M., & Ben Sik Ali, M. (2018). Fatigue resistance of an aluminium one-component polyurethane adhesive joint for the automotive industry: Effect of surface roughness and adhesive thickness. *International Journal of Adhesion and Adhesives*, *83*(3), 143–152. https://doi.org/10.1016/j.ijadhadh.2018.02.012

Brinksmeier, E., Meyer, D., Huesmann-cordes, A. G., & Herrmann, C. (2015). Metalworking fluids — Mechanisms and performance, *CIRP Annals - Manufacturing Technology*, *64*, 605–628. http://dx.doi.org/10.1016/j.cirp.2015.05.003

Cai, X., Liu, Z., Chen, M., & An, Q. (2012). An experimental investigation on effects of minimum quantity lubrication oil supply rate in high-speed end milling of Ti-6Al-4V. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *226*, 1784–1792. https://doi.org/10.1177/0954405412458492

Charogiannis, A., & Markides, C. N. (2014). Experimental study of falling films by simultaneous laser-induced fluorescence , particle image velocimetry and particle tracking velocimetry. *International Symposium on Applications of Laser Techniques to Fluid Mechanics*, 7–10.

Chen, X., Shen, S., Wang, Y., Chen, J., & Zhang, J. (2015). Measurement on falling film thickness distribution around horizontal tube with laser-induced fluorescence technology. *International Journal of Heat and Mass Transfer*, *89*, 707–713. https://doi.org/10.1016/j.ijheatmasstransfer.2015.05.016

Davey, Reginald. (2021, April 21). Why is surface roughness analysis important. AZoM. Retrieved from https://www.azom.com/article.aspx?ArticleID=20341.

De Melo, A. C. A., Milan, J. C. G., Da Silva, M. B., & Machado, Á. R. (2006). Some observations on wear and damages in cemented carbide tools. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *28*(3), 269–277. https://doi.org/10.1590/s1678-58782006000300004

Desevaux, P., Homescu, D., Panday, P. K., & Prenel, J. P. (2002). Interface measurement technique for liquid film flowing inside small grooves by laser induced fluorescence. *Applied Thermal Engineering*, *22*(5), 521–534. https://doi.org/10.1016/S1359-4311(01)00105-3

Dragičević, M. (2018). The application of alternative techniques for cooling, flushing and lubrication to improve efficiency of machining processes. *Tehnicki Vjesnik*, *25*(5), 1561–1568. https://doi.org/10.17559/TV-20170114155652

Duan, Z., Li, C., Zhang, Y., Dong, L., Bai, X., Yang, M., Jia, D., Li, R., Cao, H., & Xu, X. (2020). Milling surface roughness for 7050 aluminum alloy cavity influenced by nozzle position of nanofluid minimum quantity lubrication. *Chinese Journal of Aeronautics*. https://doi.org/10.1016/j.cja.2020.04.029

Duchosal, A., Leroy, R., Vecellio, L., Louste, C., & Ranganathan, N. (2013). An experimental investigation on oil mist characterization used in MQL milling process, 1003–1014. https://doi.org/10.1007/s00170-012-4384-9

Eltaggaz, A., Hegab, H., Deiab, I., & Kishawy, H. A. (2018). Hybrid nano-fluid-minimum quantity lubrication strategy for machining austempered ductile iron (ADI). *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *12*(4), 1273–1281. https://doi.org/10.1007/s12008-018-0491-7

El Baradie, M. A. (1996). Cutting fluids: Part 1 characterisation. *Journal of Materials Processing Technology*, *56*, 786-797. https://doi.org/10.1016/0924-0136(95)01892-1

Fontanive, F., Zeilmann, R. P., & Schenkel, J. D. (2019). Surface quality evaluation after milling Inconel 718 with cutting edge preparation. *International Journal of Advanced Manufacturing Technology*, *104*(1–4), 1087–1098. https://doi.org/10.1007/s00170-018-03260-2

Goindi, G. S., & Sarkar, P. (2017). Dry machining: A step towards sustainable machining – Challenges and future directions. *Journal of Cleaner Production*, *165*, 1557–1571. https://doi.org/10.1016/j.jclepro.2017.07.235

Gupta, M. K., Mia, M., Singh, G. R., Pimenov, D. Y., Sarikaya, M., & Sharma, V. S. (2019). Hybrid cooling-lubrication strategies to improve surface topography and tool wear in sustainable turning of Al 7075-T6 alloy. *International Journal of Advanced Manufacturing Technology*, *101*(1–4), 55–69. https://doi.org/10.1007/s00170-018-2870-4

Hamran, N. N. N., Ghani, J. A., Ramli, R., & Haron, C. H. C. (2020). A review on recent

development of minimum quantity lubrication for sustainable machining. *Journal of Cleaner Production*, *268*. https://doi.org/10.1016/j.jclepro.2020.122165

Huang, C. Y., Murthy, T. G., & Chandrasekar, S. (2014). Simultaneous measurements of thickness and temperature profile of the lubricant film at chip-tool interface during machining process using luminescent sensors. *Procedia Engineering*, *79*(1), 9–16. https://doi.org/10.1016/j.proeng.2014.06.303

Jadhav, P. A., & Deivanathan, R. (2020). Numerical analysis of the effect of air pressure and oil flow rate on droplet size and tool temperature in MQL machining. *Materials Today: Proceedings*, (xxxx), 0–6. https://doi.org/10.1016/j.matpr.2020.07.518

Khan, M. M. A., Mithu, M. A. H., & Dhar, N. R. (2009). Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid. *Journal of Materials Processing Technology*, *209*(15–16), 5573–5583. https://doi.org/10.1016/j.jmatprotec.2009.05.014

Khan, W. A., Hoang, N. M., Tai, B., & Hung, W. N. P. (2018). Through-tool minimum quantity lubrication and effect on machinability. *Journal of Manufacturing Processes*, *34*(3), 750–757. https://doi.org/10.1016/j.jmapro.2018.03.047

Khatri, A., & Jahan, M. P. (2018). Investigating tool wear mechanisms in machining of Ti-6Al-4V in flood coolant, dry and MQL conditions. *46th SME North American Manufacturing Research Conference*, *26*, 434–445. https://doi.org/10.1016/j.promfg.2018.07.051

Khettabi, R., Nouioua, M., Djebara, A., & Songmene, V. (2017). Effect of MQL and dry processes on the particle emission and part quality during milling of aluminum alloys. *International Journal of Advanced Manufacturing Technology*, *92*(5–8), 2593–2598. https://doi.org/10.1007/s00170-017-0339-5

Kim, S. H., Lee, S. W., Han, S., & Kim, S. M. (2019). Numerical investigation of thermal characteristics of spray cooling with minimum quantity lubrication in milling process. *Applied Mathematical Modelling*, *65*, 137–147. https://doi.org/10.1016/j.apm.2018.08.011

Kishawy, H. A., Dumitrescu, M., Ng, E. G., & Elbestawi, M. A. (2005). Effect of coolant strategy on tool performance, chip morphology and surface quality during high-speed machining of A356 aluminum alloy. *International Journal of Machine Tools and Manufacture*, *45*(2), 219–227. https://doi.org/10.1016/j.ijmachtools.2004.07.003

Kiswanto, G., Zariatin, D. L., & Ko, T. J. (2015). The effect of spindle speed, feed-rate and machining time to the surface roughness and burr formation of Aluminum Alloy 1100 in micro-milling operation. *Journal of Manufacturing Processes*, *16*(4), 435–450. https://doi.org/10.1016/j.jmapro.2014.05.003

Lee, G., Kim, J., Kim, S. Y., Kim, D. E., & Joo, T. (2017). Vibrational spectrum of an excited state and huang–rhys factors by coherent wave packets in time-resolved fluorescence

spectroscopy. *ChemPhysChem*, *18*(6), 670–676. https://doi.org/10.1002/cphc.201601295

Lel, V. V., Al-Sibai, F., Leefken, A., & Renz, U. (2005). Local thickness and wave velocity measurement of wavy films with a chromatic confocal imaging method and a fluorescence intensity technique. *Experiments in Fluids*, *39*(5), 856–864. https://doi.org/10.1007/s00348-005-0020-x

Li, M., Yu, T., Yang, L., Li, H., Zhang, R., & Wang, W. (2019). Parameter optimization during minimum quantity lubrication milling of TC4 alloy with graphene-dispersed vegetable-oil-based cutting fluid. *Journal of Cleaner Production*, *209*, 1508–1522. https://doi.org/10.1016/j.jclepro.2018.11.147

Li, M., Yu, T., Zhang, R., Yang, L., Li, H., Wang, W., & Yang, L. (2018). MQL milling of TC4 alloy by dispersing graphene into vegetable oil-based cutting fluid. T*he International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-018-2576-7

Liao, Y. S., Liao, C. H., & Lin, H. M. (2017). Study of oil-water ratio and flow rate of MQL fluid in high speed milling of Inconel 718. *International Journal of Precision Engineering and Manufacturing*, *18*(2), 257–262. https://doi.org/10.1007/s12541-017-0033-4

Liu, G., Li, X., Qin, B., Xing, D., Guo, Y., & Fan, R. (2004). Investigation of the mending effect and mechanism of copper nano-particles on a tribologically stressed surface. *Tribology Letters*, *17*(4), 961–966. https://doi.org/10.1007/s11249-004-8109-6

López De Lacalle, L. N., Angulo, C., Lamikiz, A., & Sánchez, J. A. (2006). Experimental and numerical investigation of the effect of spray cutting fluids in high speed milling. *Journal of Materials Processing Technology*, *172*(1), 11–15. https://doi.org/10.1016/j.jmatprotec.2005.08.014

Lv, T., Xu, X., Yu, A., & Hu, X. (2021). Oil mist concentration and machining characteristics of SiO_2 water-based nano-lubricants in electrostatic minimum quantity lubrication-EMQL milling. *Journal of Materials Processing Technology*, *290*. https://doi.org/10.1016/j.jmatprotec.2020.116964

Madhukar, S., Shravan, A., Vidyanand, P., & Reddy, G. S. (2016). A Critical review on Minimum Quantity Lubrication (MQL) coolant system for machining operations. *International Journal of Current Engineering International Journal of Current Engineering and Technology*, *6*(5), 1745–1751. http://inpressco.com/category/ijcet

Marques, A., Paipa Suarez, M., Falco Sales, W., & Rocha Machado, Á. (2019). Turning of Inconel 718 with whisker-reinforced ceramic tools applying vegetable-based cutting fluid mixed with solid lubricants by MQL. *Journal of Materials Processing Technology*, *266*(8), 530–543. https://doi.org/10.1016/j.jmatprotec.2018.11.032

Maruda, R. W., Krolczyk, G. M., Feldshtein, E., Pusavec, F., Szydlowski, M., Legutko, S., &

Sobczak-Kupiec, A. (2016). A study on droplets sizes, their distribution and heat exchange for minimum quantity cooling lubrication (MQCL). *International Journal of Machine Tools and Manufacture*, *100*, 81–92. https://doi.org/10.1016/j.ijmachtools.2015.10.008

Masmiati, N., Sarhan, A. A. D., Hassan, M. A. N., & Hamdi, M. (2016). Optimization of cutting conditions for minimum residual stress, cutting force and surface roughness in end milling of S50C medium carbon steel. *Measurement: Journal of the International Measurement Confederation*, *86*, 253–265. https://doi.org/10.1016/j.measurement.2016.02.049

Mia, M., Bashir, M. Al, Khan, M. A., & Dhar, N. R. (2017). Optimization of MQL flow rate for minimum cutting force and surface roughness in end milling of hardened steel (HRC 40). *International Journal of Advanced Manufacturing Technology*, *89*(1–4), 675–690. https://doi.org/10.1007/s00170-016-9080-8

Mia, M., Dey, P. R., Hossain, M. S., Arafat, M. T., Asaduzzaman, M., Shoriat Ullah, M., & Tareq Zobaer, S. M. (2018). Taguchi S/N based optimization of machining parameters for surface roughness, tool wear and material removal rate in hard turning under MQL cutting condition. *Measurement: Journal of the International Measurement Confederation*, *122*(12), 380–391. https://doi.org/10.1016/j.measurement.2018.02.016

Mitutoyo America Corporation. (2016). *Quick guide to surface roughness measurement* [Cumulative File]. Aurora, Illinois: Author, 1–8. https://doi.org/10.3886/ICPSR31521.v1

Mouza, A. A., Vlachos, N. A., Paras, S. V., & Karabelas, A. J. (2000). Measurement of liquid film thickness using a laser light absorption method. *Experiments in Fluids*, *28*(4), 355–359. https://doi.org/10.1007/s003480050394

Mulyadi, I. H., & Mativenga, P. T. (2014). Random or intuitive nozzle position in high-speed milling using minimum quantity lubricant. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *228*(1), 21–30. https://doi.org/10.1177/0954405413495536

Najiha, M. S., & Rahman, M. M. (2014). A computational fluid dynamics analysis of single and three nozzles minimum quantity lubricant flow for milling. *International Journal of Automotive and Mechanical Engineering*, *10*(1), 1891–1900. https://doi.org/10.15282/ijame.10.2014.6.0157

Najiha, M. S., & Rahman, M. M. (2015). Experimental study on minimum quantity lubrication in end milling of AA6061-t6 using TiAlN coated carbide tools. *International Journal of Automotive and Mechanical Engineering*, *11*(1), 2771–2785. https://doi.org/10.15282/ijame.11.2015.52.0233

Najiha, M. S., & Rahman, M. M. (2016). Experimental investigation of flank wear in end milling of aluminum alloy with water-based TiO_2 nanofluid lubricant in minimum quantity lubrication technique. *International Journal of Advanced Manufacturing*

Technology, *86*(9–12), 2527–2537. https://doi.org/10.1007/s00170-015-8256-y

Najiha, M. S., Rahman, M. M., & Kadirgama, K. (2015). Experimental investigation and optimization of minimum quantity lubrication for machining of AA6061-T6. *International Journal of Automotive and Mechanical Engineering*, *11*(1), 2722–2737. https://doi.org/10.15282/ijame.11.2015.48.0228

Obert, P., Füßer, H. J., & Bartel, D. (2019). Oil distribution and oil film thickness within the piston ring-liner contact measured by laser-induced fluorescence in a reciprocating model test under starved lubrication conditions. *Tribology International*, *129*(6), 191–201. https://doi.org/10.1016/j.triboint.2018.07.022

Okada, M., Hosokawa, A., Asakawa, N., & Ueda, T. (2014). End milling of stainless steel and titanium alloy in an oil mist environment. *International Journal of Advanced Manufacturing Technology*, *74*(9–12), 1255–1266. https://doi.org/10.1007/s00170-014-6060-8

Okafor, A. C., & Nwoguh, T. O. (2020). Comparative evaluation of soybean oil – based MQL flow rates and emulsion flood cooling strategy in high-speed face milling of Inconel 718. *The International Journal of Advanced Manufacturing Technology*, *107*, 3779–3793. https://doi.org/10.1007/s00170-020-05248-3

Osman, K. A., Ünver, H. Ö., & Şeker, U. (2019). Application of minimum quantity lubrication techniques in machining process of titanium alloy for sustainability: a review. *International Journal of Advanced Manufacturing Technology*, *100*(9–12), 2311–2332. https://doi.org/10.1007/s00170-018-2813-0

Park, K. H., Olortegui-Yume, J., Yoon, M. C., & Kwon, P. (2010). A study on droplets and their distribution for minimum quantity lubrication (MQL). *International Journal of Machine Tools and Manufacture*, *50*(9), 824–833. https://doi.org/10.1016/j.ijmachtools.2010.05.001

Park, K. H., Suhaimi, M. A., Yang, G. D., Lee, D. Y., Lee, S. W., & Kwon, P. (2017). Milling of titanium alloy with cryogenic cooling and minimum quantity lubrication (MQL). *International Journal of Precision Engineering and Manufacturing*, *18*(1), 5–14. https://doi.org/10.1007/s12541-017-0001-z

Paturi, U. M. R., Maddu, Y. R., Maruri, R. R., & Narala, S. K. R. (2016). Measurement and analysis of surface roughness in WS2 solid lubricant assisted Minimum Quantity Lubrication (MQL) turning of Inconel 718. *13th Global Conference on Sustainable Manufacturing*, *40*, 138–143. https://doi.org/10.1016/j.procir.2016.01.082

Peng, D. X., Kang, Y., Hwang, R. M., Shyr, S. S., & Chang, Y. P. (2009). Tribological properties of diamond and SiO2 nanoparticles added in paraffin. *Tribology International*, *42*(6), 911–917. https://doi.org/10.1016/j.triboint.2008.12.015

Pereira, O., Català, P., Rodríguez, A., Ostra, T., Vivancos, J., Rivero, A., & López-De-Lacalle, L. N. (2015). The use of hybrid CO_2+MQL in machining operations. *The Manufacturing Engineering Society International Conference, MESIC 2015*, *132*, 492–499. https://doi.org/10.1016/j.proeng.2015.12.524

Puvanesan, M., Rahman, M. M., Najiha, M. S., & Kadirgama, K. (2014). Experimental investigation of minimum quantity. lubrication on tool wear in aluminum alloy 6061-T6 using different cutting tools. *International Journal of Automotive and Mechanical Engineering (IJAME), 53*(9), 1689–1699. http://dx.doi.org/10.15282/ijame.9.2013.5.0127

Rahim, E. A., Ibrahim, M. R., Rahim, A. A., Aziz, S., & Mohid, Z. (2015). Experimental investigation of minimum quantity lubrication (MQL) as a sustainable cooling technique. *12th Global Conference on Sustainable Manufacturing*, *26*, 351–354. https://doi.org/10.1016/j.procir.2014.07.029

Rajeshkumar, N., & Ramesh, S. (2020). Design & optimization of machining parameters of minimum quantity lubrication in milling of Ti-6Al-4V. *Materials Today: Proceedings*, (xxxx). https://doi.org/10.1016/j.matpr.2020.10.474

Raza, M. H., Hafeez, F., Zhong, R. Y., & Imran, A. (2020). Investigation of surface roughness in face milling processes. *International Journal of Advanced Manufacturing Technology*, *111*(9–10), 2589–2599. https://doi.org/10.1007/s00170-020-06188-8

Ren, L., Wang, S., Yi, L., & Sun, S. (2016). An accurate method for five-axis flute grinding in cylindrical end-mills using standard 1V1 / 1A1 grinding wheels. *Precision Engineering*, *43*, 387–394. https://doi.org/10.1016/j.precisioneng.2015.09.002

Rohit, J. N., Surendra Kumar, K., Sura Reddy, N., Kuppan, P., & Balan, A. S. S. (2018). Computational fluid dynamics analysis of MQL spray parameters and its influence on MQL milling of SS304. *Simulations for Design and Manufacturing*. 45-78. https://doi.org/10.1007/978-981-10-8518-5

Sasahara, H., Satake, K., Takahashi, W., Goto, M., & Yamamoto, H. (2017). The effect of oil mist supply on cutting point temperature and tool wear in driven rotary cutting. *Precision Engineering*, *48*, 158–163. https://doi.org/10.1016/j.precisioneng.2016.11.016

Sayuti, M., Erh, O. M., Sarhan, A. A. D., & Hamdi, M. (2014). Investigation on the morphology of the machined surface in end milling of aerospace AL6061-T6 for novel uses of SiO_2 nanolubrication system. *Journal of Cleaner Production*, *66*, 655–663. https://doi.org/10.1016/j.jclepro.2013.11.058

Sharif, M. N., Pervaiz, S., & Deiab, I. (2017). Potential of alternative lubrication strategies for metal cutting processes: a review. *International Journal of Advanced Manufacturing Technology*, *89*, 2447-2479. https://doi.org/10.1007/s00170-016-9298-5

Sharma, A. K., Tiwari, A. K., & Dixit, A. R. (2016). Effects of Minimum Quantity Lubrication

(MQL) in machining processes using conventional and nanofluid based cutting fluids: A comprehensive review. *Journal of Cleaner Production*, *127*, 1–18. https://doi.org/10.1016/j.jclepro.2016.03.146

Shaw, M. C. (2005). *Metal cutting principles*. Oxford University Press. Retrieved from www.knovel.com

Singh, K., Singh, A. K., & Chattopadhyay, K. D. (2019). Selection of optimal cutting conditions and coolant flow rate (CFR) for enhancing surface finish in milling of aluminium alloy. Materials Today : Proceedings. https://doi.org/10.1016/j.matpr.2019.11.076

Sivaiah, P., & Chakradhar, D. (2018). Effect of cryogenic coolant on turning performance characteristics during machining of 17-4 PH stainless steel: A comparison with MQL, wet, dry machining. *Journal of Manufacturing Science and Technology*, *21*, 86–96. https://doi.org/10.1016/j.cirpj.2018.02.004

Stachurski, W., Sawicki, J., Wójcik, R., & Nadolny, K. (2018). Influence of application of hybrid MQL-CCA method of applying coolant during hob cutter sharpening on cutting blade surface condition. *Journal of Cleaner Production*, *171*, 892–910. https://doi.org/10.1016/j.jclepro.2017.10.059

Subtractive manufacturing technology (n.d.) [Web log post]. Retrieved from https://dryfinish.wordpress.com/2020/10/15/why-is-surface-roughness-so-important-in-manufacturing/amp/

Tai, B. L., Stephenson, D. A., Furness, R. J., & Shih, A. J. (2014a). Minimum quantity lubrication (MQL) in automotive powertrain machining. *6th CIRP International Conference on High Performance Cutting, HPC2014*, *14*, 523–528. https://doi.org/10.1016/j.procir.2014.03.044

Tosun, N., & Pihtili, H. (2010). Gray relational analysis of performance characteristics in MQL milling of 7075 Al alloy. *International Journal of Advanced Manufacturing Technology*, *46*(5–8), 509–515. https://doi.org/10.1007/s00170-009-2118-4

Tunc, L. T., Gu, Y., & Burke, M. G. (2016). Effects of Minimal Quantity Lubrication (MQL) on surface integrity in robotic milling of austenitic stainless steel. *3rd CIRP Conference on Surface Integrity (CIRP CSI)*, *45*, 215–218. https://doi.org/10.1016/j.procir.2016.02.337

Unist. (n.d.). *Uni-max revolution* [Brochure]. Grand Rapids, USA: Author.

Uysal, A., Demiren, F., & Altan, E. (2015). Applying Minimum Quantity Lubrication (MQL) method on milling of martensitic stainless steel by using nano Mos_2 reinforced vegetable cutting fluid. *Procedia - Social and Behavioral Sciences*, *195*, 2742–2747. https://doi.org/10.1016/j.sbspro.2015.06.384

Volkov, R. S., & Strizhak, P. A. (2021). Using planar laser induced fluorescence and micro particle image velocimetry to study the heating of a droplet with different tracers and schemes of attaching it on a holder. *International Journal of Thermal Sciences*, *159*(8). https://doi.org/10.1016/j.ijthermalsci.2020.106603

Wandra, R., Prakash, C., & Singh, S. (2021). Experimental investigation and optimization of surface roughness of β-Phase titanium alloy by ball burnishing assisted electrical discharge cladding for implant applications. *Materials Today: Proceedings*, (xxxx). https://doi.org/10.1016/j.matpr.2021.06.070

Wang, C., Li, K., Chen, M., & Liu, Z. (2015). Evaluation of minimum quantity lubrication effects by cutting force signals in face milling of Inconel 182 overlays. *Journal of Cleaner Production*, *108*, 145–157. https://doi.org/10.1016/j.jclepro.2015.06.095

Wang, X., He, M., Fan, H., & Zhang, Y. (2009). Measurement of falling film thickness around a horizontal tube using laser-induced fluorescence technique. *Journal of Physics: Conference Series*, *147*, 12039. https://doi.org/10.1088/1742-6596/147/1/012039

Xu, X., Huang, S., Wang, M., & Yao, W. (2017). A study on process parameters in end milling of AISI-304 stainless steel under electrostatic minimum quantity lubrication conditions. *International Journal of Advanced Manufacturing Technology*, *90*(1–4), 979–989. https://doi.org/10.1007/s00170-016-9417-3

Yan, L., Yuan, S., & Liu, Q. (2012). Influence of minimum quantity lubrication parameters on tool wear and surface roughness in milling of forged steel. *Chinese Journal of Mechanical Engineering (English Edition)*, *25*(3), 419–429. https://doi.org/10.3901/CJME.2012.03.419

Yuan, S., Hou, X., Wang, L., & Chen, B. (2018). Experimental Investigation on the compatibility of nanoparticles with vegetable oils for nanofluid Minimum Quantity Lubrication machining. *Tribology Letters*, *66*(3), 1–10. https://doi.org/10.1007/s11249-018-1059-1

Yuan, S. M., Yan, L. T., Liu, W. D., & Liu, Q. (2011). Effects of cooling air temperature on cryogenic machining of Ti-6Al-4V alloy. *Journal of Materials Processing Technology*, *211*(3), 356–362. https://doi.org/10.1016/j.jmatprotec.2010.10.009

Zare, R. N. (2012). My life with LIF: A personal account of developing laser-induced fluorescence. *Annual Review of Analytical Chemistry*, *5*, 1–14. https://doi.org/10.1146/annurev-anchem-062011-143148

Zhu, G., Yuan, S., & Chen, B. (2019). Numerical and experimental optimizations of nozzle distance in minimum quantity lubrication (MQL) milling process. *International Journal of Advanced Manufacturing Technology*, *101*(1–4), 565–578. https://doi.org/10.1007/s00170-018-2928-3