

STUDY ON THE APPLICATION OF IONIC LIQUIDS IN BIO-BASED
LUBRICANT FOR A SUSTAINABLE MACHINING PROCESS

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ABSTRACT

Many factors tend to influence the increased demand in recent years, including state-of-the-art of effective and environmentally friendly metalworking fluids (MWFs). Bio-based lubricants from vegetable oils are highly biodegradable, non-toxic, pose good lubricating properties and low production costs. They have been widely perceived as a potential to reduce or replace the high dependency on the applications of petroleum-based MWFs. However, the inconsistent chemical composition and low thermal and oxidative stabilities of the natural oils leaves significant uncertainties about the overall sustainability performance of the bio-based MWFs. In this study, with the objective of achieving machining sustainability, a novel chemically modified Jatropha-based trimethylolpropane ester (MJO) was refined by mixing it with ionic liquids (ILs) additives. Two biocompatible and oil-miscible ILs; $[P_{6,6,6,14}][[(C_8)_2PO_2]$ (PIL) and $[N_{1,8,8,8}][NTf_2]$ (AIL) were mixed in the MJO at 1, 5, and 10 % weight concentrations. The newly refined mixtures are validated for their physicochemical and tribological properties as well as when being applied for minimum quantity lubrication (MQL) machining (orthogonal and oblique) of AISI 1045 steel. Results showed that, the lubrication performance of MJO+AIL10% and MJO+PIL1% outperformed the other lubricant samples used herein. With improved physicochemical and tribological performances, e.g. corrosion inhibition, friction and wear reduction, smooth surface finish and high machining efficiency, they recorded improvement in machining forces up to 12 %, cutting temperature up to 10 %, surface roughness by 7% and increased cutting tool life up to 50 % compared to the commercial synthetic ester-based MWF. A machining sustainability index evaluation was applied to the MQL machining scenario and based on results, MJO+PIL1% obtained the highest score for minimum lubricant's cost, minimal energy consumption, or the best sustainability performance (4.08/5) and seconded by MJO+AIL10% (4.06). These novel bio-based MWFs provide another alternative to the world dominating mineral oil-based lubricants for "greener" and more sustainable working environment.

ABSTRAK

Dewasa ini penggunaan bendalir kerja logam (MWFs) yang terkini, canggih dan mesra alam adalah semakin meningkat disebabkan pelbagai faktor. Bendalir kerja logam berasaskan minyak tumbuhan adalah terbiodegradasi, tidak toksik, bersifat pelincir yang baik dan tidak menelan kos pembuatan tinggi. Ianya telah diterima secara meluas sebagai suatu potensi untuk mengurangkan atau menggantikan kebergantungan tinggi terhadap penggunaan MWFs berasaskan petroleum. Namun, minyak berasaskan tumbuhan mempunyai sifat komposisi kimia yang tidak konsisten dan kestabilan terma-oksidatif yang rendah menyebabkan prestasi keseluruhan mereka terencat untuk mencapai kelestarian dalam proses pemesinan. Dalam kajian ini, dengan objektif mencapai kelestarian dalam proses pemesinan, ester trimetilolpropana berasas minyak jarak dan diubahsuai secara kimia (MJO) telah disempurnakan dengan bahan tambah cecair ionik (ILs). Kedua-dua ILs; $[P_{6,6,6,14}][C_8]_2PO_2$ (PIL) dan $[N_{1,8,8,8}][NTf_2]$ (AIL), adalah bio-serasi dan larut minyak. Sampel campuran dengan ILs pada kepekatan berbeza 1, 5, dan 10 % berat daripada MJO telah ditentukan melalui sifat fizikokimia, tribologi serta pelinciran kuantiti minimum (MQL) ketika proses pelarikan (ortogonal dan oblik) logam AISI 1045. MJO+AIL10% dan MJO+PIL1% menunjukkan keputusan yang meyakinkan untuk mengatasi prestasi pelincir-pelincir lain yang diuji. Keduanya menunjukkan sifat-sifat fizikokimia dan ujian kelakuan tribologi yang cemerlang seperti perencatan kakisan, pengurangan geseran dan kehausan, penghasilan kualiti kekasaran permukaan yang tinggi serta mencatatkan pengurangan dalam daya pemesinan sehingga 12%, suhu pemotongan sehingga 10%, kekasaran permukaan sebanyak 7% dan peningkatan jangka hayat mata alat sehingga 50% berbanding dengan ester sintetik komersil. Penilaian indeks kelestarian semasa proses pemesinan MQL menunjukkan MJO+PIL1% (4.08) mengatasi MJO+AIL10% (4.06) dalam memperoleh skor tertinggi untuk kos pelincir dan penggunaan tenaga minimum atau prestasi kelestarian terbaik. Suatu sumber alternatif yang lebih mampan telah berjaya dihasilkan untuk membentuk persekitaran kerja yang lebih lestari.

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PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF SYMBOLS AND ABBREVIATIONS

%	- Percent, efficiency
<i>a</i>	- Radius of wear scar diameter
AES	- Auger Electron Spectrometer
AFM	Atomic force microscopy
AIL	- methyltrioctylammonium bis(trifluoromethylsulfonyl)imide; [N _{1,8,8,8}][NTf ₂]
AISI	- American Iron and Steel Institute
Al	Aluminium
AOCS	- American Oil Chemists' Society
ASTM	- American Society for Testing and Materials
AW	- Antiwear additive
BF ₄	- Tetrafluoroborate
BL	- Boundary lubrication
BUE	- Built up edge
C	- Carbon, carbide
C ₃ H ₈ O	- Isopropyl alcohol
CEC	- Coordinating European Council
CH ₄ O	- Methanol
CJO	- Crude jatropha oil
CNC	Computer numerical control
COF	- Coefficient of friction
CrN	- Chromium nitride
<i>d</i>	- Depth of cut
DAQ	- Data acquisition system
DIN	- Deutsches Institut für Normung (German national organization for standardization)

REFERENCES

- Abdalla, H. S., Baines, W., McIntyre, G., & Slade, C. (2007). Development of novel sustainable neat-oil metal working fluids for stainless steel and titanium alloy machining. Part 1. Formulation development. *International Journal of Advanced Manufacturing Technology*, 34(1–2), 21–33.
- Abdalla, H. S., & Patel, S. (2006). The performance and oxidation stability of sustainable metalworking fluid derived from vegetable extracts. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 220, 2027–2040.
- Adhvaryu, A., Erhan, S. Z., & Perez, J. M. (2004). Tribological studies of thermally and chemically modified vegetable oils for use as environmentally friendly lubricants. *Wear*, 257(3–4), 359–367.
- Alias, N. H., Yunus, R., Idris, A., & Omar, R. (2009). Effects of additives on oxidation characteristics of palm oil-based trimethylolpropane ester in hydraulics applications. *European Journal of Lipid Science & Technology*, 111(4), 368–375.
- Anand, M., Hadfield, M., Viesca, J. L., Thomas, B., Hernández Battez, A., & Austen, S. (2015). Ionic liquids as tribological performance improving additive for in-service and used fully-formulated diesel engine lubricants. *Wear*, 334–335, 67–74.
- Andreani, L., & Rocha, J. D. (2012). Use of ionic liquids in biodiesel production: A review. *Brazilian Journal of Chemical Engineering*, 29(1), 1–13.
- Anouti, M., Caillon-Caravanier, M., Dridi, Y., Jacquemin, J., Hardacre, C., & Lemordant, D. (2009). Liquid densities, heat capacities, refractive index and excess quantities for {protic ionic liquids + water} binary system. *Journal of Chemical Thermodynamics*, 41(6), 799–808.
- 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.

- Arora, H., & Cann, P. M. (2010). Lubricant film formation properties of alkyl imidazolium tetrafluoroborate and hexafluorophosphate ionic liquids. *Tribology International*, 43(10), 1908–1916.
- Arrazola, P. J., Aristimuno, P., Soler, D., & Childs, T. (2015). Metal cutting experiments and modelling for improved determination of chip/tool contact temperature by infrared thermography. *CIRP Annals - Manufacturing Technology*, 64(1), 57–60.
- Astakhov, V. P., & Davim, J. P. (2008). Tools (Geometry and Material) and Tool Wear. In *Machining: Fundamental and Recent Advances*. 1st edition. London, UK: Springer. pp. 29–57.
- Astakhov, V. P., & Godlevskiy, V. (2012). Delivery of metalworking fluids in the machining zone. In V. P. Astakhov & S. Joksch (Eds.), *Metalworking Fluids (MWFs) for Cutting and Grinding: Fundamentals and Recent Advances*. Cambridge, UK: Elsevier. pp. 79–134.
- Azhari, Faiz, M., Yunus, R., Mohd Ghazi, T. I., & Yaw, T. C. S. (2008). Reduction of Free Fatty Acids In Crude Jatropha Curcas Oil Via an Esterification Process. *International Journal of Engineering and Technology*, 5(2), 92–98.
- Badurdeen, F., Iyengar, D., Goldsby, T. J., Metta, H., Gupta, S., & Jawahir, I. S. (2009). Extending total life-cycle thinking to sustainable supply chain design. *International Journal of Product Lifecycle Management*, 4(1/2/3), 49–67.
- Barnhill, W. C., Qu, J., Luo, H., Meyer, H. M., Ma, C., Chi, M., & Papke, B. L. (2014). Phosphonium-Organophosphate Ionic Liquids as Lubricant Additives: Effects of Cation Structure on Physicochemical and Tribological Characteristics. *ACS Applied Materials & Interfaces*, 6(24), 22585–22593.
- Bart, J. C. J., Gucciardi, E., & Cavallaro, S. (2013). Advanced lubricant fluids. In *Biolubricants: Science and technology* (pp. 824–846). Cambridge, UK: Woodhead Publishing Limited.
- Bartz, W. J. (1998). Lubricants and the environment. *Tribology International*, 31(1–3), 35–47.
- Battez, A. H., González, R., Viesca, J. L., Blanco, D., Asedegbega, E., & Osorio, A. (2009). Tribological behaviour of two imidazolium ionic liquids as lubricant additives for steel/steel contacts. *Wear*, 266(11–12), 1224–1228.
- Behera, B. C., Chetan, Setti, D., Ghosh, S., & Rao, P. V. (2017). Spreadability studies

of metal working fluids on tool surface and its impact on minimum amount cooling and lubrication turning. *Journal of Materials Processing Technology*, 244, 1–16.

Birmingham, M. J., Kirsch, J., Sun, S., Palanisamy, S., & Dargusch, M. S. (2011). New observations on tool life, cutting forces and chip morphology in cryogenic machining Ti-6Al-4V. *International Journal of Machine Tools and Manufacture*, 51(6), 500–511.

Bermúdez, M. D. (2010). Introduction to the ionic liquids special issue. *Tribology Letters*, 40(2), 213.

Bermúdez, M. D., Jiménez, A. E., & Martínez-Nicolás, G. (2007). Study of surface interactions of ionic liquids with aluminium alloys in corrosion and erosion-corrosion processes. *Applied Surface Science*, 253(17), 7295–7302.

Bermúdez, M. D., Jiménez, A. E., Sanes, J., & Carrión, F. J. (2009). Ionic liquids as advanced lubricant fluids. *Molecules*, 14(8), 2888–2908.

Bhushan, B. (2013). *Principles and Applications of Tribology* (Second). Ohio, USA: John Wiley & Sons.

Biesinger, M. C., Payne, B. P., Grosvenor, A. P., Lau, L. W. M., Gerson, A. R., & Smart, R. S. C. (2011). Resolving surface chemical states in XPS analysis of first row transition metals, oxides and hydroxides: Cr, Mn, Fe, Co and Ni. *Applied Surface Science*, 257(7), 2717–2730.

Blanchard, L. A., & Brennecke, J. F. (2001). Recovery of Organic Products from Ionic Liquids Using Supercritical Carbon Dioxide. *Industrial & Engineering Chemistry Research*, 40(11), 2550–2550.

Blanco, D., Viesca, J. L., Mallada, M. T., Ramajo, B., González, R., & Battez, A. H. (2016). Wettability and corrosion of [NTf₂] anion-based ionic liquids on steel and PVD (TiN, CrN, ZrN) coatings. *Surface and Coatings Technology*, 302, 13–21.

Böllinghaus, T., Byrne, G., Ilich, B., Chlebus, E., Cross, C. E., Denkena, B., & Woeste, K. (2009). Manufacturing Engineering. In K.-H. Grote & E. K. Antonsson (Eds.), *Springer Handbook of Mechanical Engineering*. Berlin, Germany: Springer. pp. 523–785.

Bongfa, B., Syahrullail, S., Abdul Hamid, M. K., & Samin, P. M. (2016). Suitable additives for vegetable oil-based automotive shock absorber fluids: an overview. *Lubrication Science*, 28(6), 381–404.

- Bork, C. A. S., Gonçalves, J. F. D. S., Gomes, J. D. O., & Gheller, J. (2014). Performance of the jatropha vegetable-base soluble cutting oil as a renewable source in the aluminum alloy 7050-T7451 milling. *CIRP Journal of Manufacturing Science and Technology*, 7(3), 210–221.
- Bork, C. A. S., de Souza, J. F., de Oliveira Gomes, J., Venancio Pappetti Canhete, V., & De Barba, D. J. (2016). Methodological tools for assessing the sustainability index (SI) of industrial production processes. *International Journal of Advanced Manufacturing Technology*, 87(5–8), 1313–1325.
- Boubekri, N., & Shaikh, V. (2015). Minimum Quantity Lubrication (MQL) in Machining: Benefits and Drawbacks. *Journal of Industrial and Intelligent Information*, 3(3), 205–209.
- Brennecke, J. F., Rogers, R. D., & Seddon, K. R. (2007). *Ionic Liquids IV: Not Just Solvents Anymore*. Washington, DC: American Chemical Society.
- Brinksmeier, E., Meyer, D., Huesmann-Cordes, A. G., & Herrmann, C. (2015). Metalworking fluids - Mechanisms and performance. *CIRP Annals - Manufacturing Technology*, 64(2), 605–628.
- British Petroleum. (2015). BP Statistical Review of World Energy June 2015, (June), 48.
- Byers, J. P. (1994). *Metalworking Fluids*. (J. P. Byers, Ed.). New York: Marcel Dekker, Inc.
- Cai, M., Liang, Y., Zhou, F., & Liu, W. (2011). Tribological properties of novel imidazolium ionic liquids bearing benzotriazole group as the antiwear/anticorrosion additive in poly(ethylene glycol) and polyurea grease for steel/steel contacts. *ACS Applied Materials and Interfaces*, 3(12), 4580–4592.
- Cai, Z., Meyer, H. M., Ma, C., Chi, M., Luo, H., & Qu, J. (2014). Comparison of the tribological behavior of steel–steel and Si₃N₄–steel contacts in lubricants with ZDDP or ionic liquid. *Wear*, 319(1–2), 172–183.
- Chetan, Behera, B. C., Ghosh, S., & Rao, P. V. (2016). Wear behavior of PVD TiN coated carbide inserts during machining of Nimonic 90 and Ti6Al4V superalloys under dry and MQL conditions. *Ceramics International*, 42(13), 14873–14885.
- Chetan, Ghosh, S., & Venkateswara Rao, P. (2015). Application of sustainable techniques in metal cutting for enhanced machinability: a review. *Journal of Cleaner Production*, 100, 17–34.
- Chetan, Narasimhulu, A., Ghosh, S., & Rao, P. V. (2014). Study of Tool Wear

- Mechanisms and Mathematical Modeling of Flank Wear During Machining of Ti Alloy (Ti6Al4V). *Journal of The Institution of Engineers (India): Series C*, 96(3), 279-285.
- Childs, T., Maekawa, K., Obikawa, T., & Yamane, Y. (2000). *Metal Machining Theory and Applications. Materials Technology*. London: Arnold.
- Cieniecka-Roslonkiewicz, A., Pernak, J., Kubis-Feder, J., Ramani, A., Robertson, A. J., & Seddon, K. R. (2005). Synthesis, anti-microbial activities and anti-electrostatic properties of phosphonium-based ionic liquids. *Green Chemistry*, (12), 855–862.
- Cigno, E., Magagnoli, C., Pierce, M. S., & Iglesias, P. (2017). Lubricating ability of two phosphonium-based ionic liquids as additives of a bio-oil for use in wind turbines gearboxes. *Wear*, 376–377, 756–765.
- Cornmell, R. J., Winder, C. L., Schuler, S., Goodacre, R., & Stephens, G. (2008a). Using a biphasic ionic liquid/water reaction system to improve oxygenase-catalysed biotransformation with whole cells. *Green Chemistry*, 10(6), 685–691.
- Cornmell, R. J., Winder, C. L., Tiddy, G. J. T., Goodacre, R., & Stephens, G. (2008b). Accumulation of ionic liquids in *Escherichia coli* cells. *Green Chemistry*, 10(8), 836.
- Das, S. R., Dhupal, D., & Kumar, A. (2015). Study of surface roughness and flank wear in hard turning of AISI 4140 steel with coated ceramic inserts. *Journal of Mechanical Science and Technology*, 29(10), 4329–4340.
- Dambhare, S., Deshmukh, S., Borade, A., Digalwar, A., & Phate, M. (2015). Sustainability issues in turning process: A study in Indian machining industry. *Procedia CIRP*, 26, 379–384.
- Davies, M. A., Cooke, A. L., & Larsen, E. R. (2005). High Bandwidth Thermal Microscopy of Machining AISI 1045 Steel. *CIRP Annals - Manufacturing Technology*, 54(1), 63–66.
- Davis, B., Schueller, J. K., & Huang, Y. (2015). Study of ionic liquid as effective additive for minimum quantity lubrication during titanium machining. *Manufacturing Letters*, 5, 1–6.
- DeVries, W. R. (1991). *Analysis of Material Removal Processes*. New York, USA: Springer-Verlag.
- Dewes, R., Ng, E., Chua, K., Newton, P., & Aspinwall, D. (1999). Temperature measurement when high speed machining hardened mould/die steel. *Journal of*

Materials Processing Technology, 92–93, 293–301.

- Dhar, N. R., Kamruzzaman, M., & Ahmed, M. (2006). Effect of minimum quantity lubrication (MQL) on tool wear and surface roughness in turning AISI-4340 steel. *Journal of Materials Processing Technology*, 172(2), 299–304.
- Ding, J., Xia, Z., & Lu, J. (2012). Esterification and deacidification of a waste cooking oil (TAN 68.81 mg KOH/g) for biodiesel production. *Energies*, 5(8), 2683–2691.
- Diniz, A. E., Machado, Á. R., & Corrêa, J. G. (2016). Tool wear mechanisms in the machining of steels and stainless steels. *International Journal of Advanced Manufacturing Technology*, 87(9–12), 3157–3168.
- Diniz, A. E., & Micaroni, R. (2007). Influence of the direction and flow rate of the cutting fluid on tool life in turning process of AISI 1045 steel. *International Journal of Machine Tools and Manufacture*, 47(2), 247–254.
- Dixit, U. S., Sarma, D. K., & Davim, J. P. (2012). *Environmentally Friendly Machining*. 1st edition. New York, USA: Springer.
- Dörr, N. (2012). Special Issue on Ionic Liquids as Lubricants. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 226(11), 889–890.
- Dowson, D. (1979). *History of Tribology* (2nd ed.). London: Longman.
- Dwuletzki, H. (2012). Replacement of metalworking fluids. In V. P. Astakhov & S. Joksch (Eds.), *Metalworking fluids (MWFs) for cutting and grinding: Fundamentals and recent advances*. Cambridge: Woodhead Publishing Limited. pp. 368–388
- Earle, M. J., Esperança, J. M. S. S., Gilea, M. A., Lopes, J. N. C., Rebelo, L. P. N., Magee, J. W., Seddon, K. R., & Widegren, J. A. (2006). The distillation and volatility of ionic liquids. *Nature*, 439(7078), 831–834.
- El-Hofy, H. (2014). *Machining processes, Conventional and Nonconventional* (2nd ed.). Boca Raton, Florida: CRC Press.
- Erhan, S. Z., Sharma, B. K., Liu, Z., & Adhvaryu, A. (2008). Lubricant base stock potential of chemically modified vegetable oils. *Journal of Agricultural and Food Chemistry*, 56(19), 8919–8925.
- Evans, R. (2012). Selection and testing of metalworking fluids. In V. P. Astakhov & S. Joksch (Eds.), *Metalworking Fluids (MWFs) for Cutting and Grinding: Fundamentals and Recent Advances*. Cambridge: Elsevier. pp. 23–78.
- Fan, M., Song, Z., Liang, Y., Zhou, F., & Liu, W. (2012). In situ formed ionic liquids

- in synthetic esters for significantly improved lubrication. *ACS Applied Materials and Interfaces*, 4(12), 6683–6689.
- Fan, M., Wang, X., Yang, D., Wang, D., Yan, Y., Zhang, C., & Liu, X. (2015). New ionic liquid lubricants derived from nonnutritive sweeteners. *Tribology International*, 92(2015), 344–352.
- Fatima, A., & Mativenga, P. T. (2013). A review of tool-chip contact length models in machining and future direction for improvement. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 227(3), 345–356.
- Fernandes, C. M. C. G., Hernández Battez, A., González, R., Monge, R., Viesca, J. L., García, A., Martins, R. C., & Seabra, J. H. O. (2015). Torque loss and wear of FZG gears lubricated with wind turbine gear oils using an ionic liquid as additive. *Tribology International*, 90(2015), 306–314.s
- Fernández-González, A., Mallada, M. T., Viesca, J. L., González, R., Badía, R., & Hernández-Battez, A. (2017). Corrosion activity and solubility in polar oils of three bis(trifluoromethylsulfonyl) imide/bis(trifluoromethylsulfonyl) amide ([NTF2]) anion-based ionic liquids. *Journal of Industrial and Engineering Chemistry*, 56, 292–298.
- Firestone, D. (1989). *Official methods and recommended practices of the American Oil Chemists' Society*. American Oil Chemists' Society. 4th edition. Champaign: AOCS press.
- Forson, F. K., Oduro, E. K., & Hammond-Donkoh, E. (2004). Performance of jatropha oil blends in a diesel engine. *Renewable Energy*, 29(7), 1135–1145.
- Fox, M. F., & Priest, M. (2008). Tribological properties of ionic liquids as lubricants and additives. Part 1: synergistic tribofilm formation between ionic liquids and tricresyl phosphate. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 222(3), 291–303.
- García, A., González, R., Hernández Battez, A., Viesca, J. L., Monge, R., Fernández-González, A., & Hadfield, M. (2014). Ionic liquids as a neat lubricant applied to steel-steel contacts. *Tribology International*, 72(2014), 42–50.
- Ge, R., Hardacre, C., Jacquemin, J., & Rooney, D. W. (2009). Thermophysical properties of ionic liquids. In N. V. Plechkova, R. D. Rogers, & K. R. Seddon (Eds.), *Ionic Liquids: From Knowledge to Application*. Washington DC: American Chemical Society. pp. 43–60.

- Godlevskiy, V. (2012). Mechanisms of action of metalworking fluids in metal cutting. In V. P. Astakhov & S. Joksch (Eds.), *Metalworking Fluids (MWFs) for Cutting and Grinding: Fundamentals and Recent Advances*. Cambridge: Elsevier. pp. 1–22.
- Goindi, G. S., Chavan, S. N., Mandal, D., Sarkar, P., & Jayal, A. D. (2015). Investigation of Ionic Liquids as Novel Metalworking Fluids during Minimum Quantity Lubrication Machining of a Plain Carbon Steel. *Procedia CIRP*, 26, 341–345.
- Goindi, G. S., Sarkar, P., Jayal, A. D., Chavan, S. N., & Mandal, D. (2017). Investigation of ionic liquids as additives to canola oil in minimum quantity lubrication milling of plain medium carbon steel. *The International Journal of Advanced Manufacturing Technology*.
- González, R., Bartolomé, M., Blanco, D., Viesca, J. L., Fernández-González, A., & Battez, A. H. (2016). Effectiveness of phosphonium cation-based ionic liquids as lubricant additive. *Tribology International*, 98(2016), 82–93.
- Groover, M. P. (2013a). *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*. 5th. edition. USA: John Wiley & Sons.
- Groover, M. P. (2013b). Theory of Metal Machining. In *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*. 5th. ed. United States of America: John Willey & Sons. pp. 522–547.
- Grzesik, W. (2017). *Advanced Machining Processes of Metallic Materials: Theory, Modelling and Applications*. 2nd ed. Amsterdam, Netherlands: Elsevier B.V.
- Grzesik, W., Kruszynski, B., & Ruszaj, A. (2010). Surface Integrity of Machined Surfaces. In J. P. Davim (Ed.), *Surface Integrity in Machining*. London: Springer-Verlag. pp. 143–179.
- Gunam Resul, M. F. M., Tinia, T. I., & Idris, A. (2012). Kinetic study of jatropha biolubricant from transesterification of jatropha curcas oil with trimethylolpropane: Effects of temperature. *Industrial Crops and Products*, 38(1), 87–92.
- Guo, S., Li, C., Zhang, Y., Wang, Y., Li, B., Yang, M., Zhang, X., & Liu, G. (2017). Experimental evaluation of the lubrication performance of mixtures of castor oil with other vegetable oils in MQL grinding of nickel-based alloy. *Journal of Cleaner Production*, 140, 1060–1076.
- Halmos, G. T., Kiuchi, M., Horvath, J., Ivaska, J., & Shah, A. (2006). *Roll Forming*

Handbook. United States of America: CRC Press.

- Hamid, H. A., Yunus, R., Rashid, U., Choong, T. S. Y., Ali, S., & Syam, A. M. (2016). Synthesis of high oleic palm oil-based trimethylolpropane esters in a vacuum operated pulsed loop reactor. *Fuel*, *166*, 560–566.
- Hammond, D. (2013). *An Investigation Of The Impact Of Selected Cooling Strategies On Milling Of Difficult-To-Cut Materials With An Emphasis On Titanium Alloys And Hardened Steel*. Stellenbosch University: Master's Thesis.
- Handy, S. T. (2011). *Applications of ionic liquids in science and technology*. Rijeka, Croatia: InTech.
- Hannu, T., Suuronen, K., Aalto-Korte, K., Alanko, K., Luukkonen, R., Järvelä, M., Jolanki, R., & Jaakkola, M. S. (2013). Occupational respiratory and skin diseases among Finnish machinists: Findings of a large clinical study. *International Archives of Occupational and Environmental Health*, *86*(2), 189–197.
- Heikal, E. K., Elmelawy, M. S., Khalil, S. A., & Elbasuny, N. M. (2017). Manufacturing of environment friendly biolubricants from vegetable oils. *Egyptian Journal of Petroleum*, *26*(1), 53–59.
- Hegab, H. A., Darras, B., & Kishawy, H. A. (2018). Towards sustainability assessment of machining processes. *Journal of Cleaner Production*, *170*, 694–703.
- Hernández Battez, A., Bartolomé, M., Blanco, D., Viesca, J. L., Fernández-González, A., & González, R. (2016a). Phosphonium cation-based ionic liquids as neat lubricants: Physicochemical and tribological performance. *Tribology International*, *95*(2016), 118–131.
- Hernández Battez, A., Blanco, D., Fernández-González, A., Mallada, M. T., González, R., & Viesca, J. L. (2016b). Friction, wear and tribofilm formation with a [NTf₂] anion-based ionic liquid as neat lubricant. *Tribology International*, *103*(2016), 73–86.
- Hernández Battez, A., Fernandes, C. M. C. G., Martins, R. C., Bartolomé, M., González, R., & Seabra, J. H. O. (2017). Two phosphonium cation-based ionic liquids used as lubricant additive: Part I: Film thickness and friction characteristics. *Tribology International*, *107*(2017), 233–239.
- Honary, L. A. T., & Richter, E. (2013). *Biobased Lubricants and Greases: Technology and Products*. 1st ed. United Kingdom: John Wiley & Sons.
- Imbrogno, S., Sartori, S., Bordin, A., Bruschi, S., & Umbrello, D. (2017). Machining Simulation of Ti6Al4V under Dry and Cryogenic Conditions. *Procedia CIRP*,

58, 475–480.

- Imran, A., Masjuki, H. H., Kalam, M. A., Varman, M., Hasmelidin, M., Al Mahmud, K. A. H., Shahir, S. A., & Habibullah, M. (2013). Study of friction and wear characteristic of Jatropha oil blended lube oil. *Procedia Engineering*, 68, 178–185.
- Iqbal, S. A., Mativenga, P. T., & Sheikh, M. A. (2009). A comparative study of the tool-chip contact length in turning of two engineering alloys for a wide range of cutting speeds. *International Journal of Advanced Manufacturing Technology*, 42(1–2), 30–40.
- Jaafar, I. H., Venkatachalam, A., Joshi, K., Ungureanu, A. C., Silva, N. De, Rouch, K. E., & Jawahir, I. S. (2007). Product Design for Sustainability: A New Assessment Methodology and Case Studies. In M. Kutz (Ed.), *Environmentally Conscious Mechanical Design*. New Jersey: John Wiley & Sons. p. 25-65.
- Jawahir, I. S., Badurdeen, F., & Rouch, K. E. (2013). Innovation in Sustainable Manufacturing Education. *Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions*, 9–16.
- Jayal, A. D., Badurdeen, F., Dillon, O. W., & Jawahir, I. S. (2010). Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. *CIRP Journal of Manufacturing Science and Technology*, 2(3), 144–152.
- Jiang, D., Hu, L., & Feng, D. (2013). Tribological behaviors of novel crown-type phosphate ionic liquids as lubricants for steel/aluminum contacts. *Industrial Lubrication and Tribology*, 65(4), 219–225.
- Jiménez, A. E., & Bermúdez, M. D. (2007). Ionic liquids as lubricants for steel-aluminum contacts at low and elevated temperatures. *Tribology Letters*, 26(1), 53–60.
- Jiménez, A. E., & Bermúdez, M. D. (2008). Imidazolium ionic liquids as additives of the synthetic ester propylene glycol dioleate in aluminium-steel lubrication. *Wear*, 265(5–6), 787–798.
- Jiménez, A. E., Bermúdez, M. D., Iglesias, P., Carrión, F. J., & Martínez-Nicolás, G. (2006). 1-N-alkyl-3-methylimidazolium ionic liquids as neat lubricants and lubricant additives in steel-aluminium contacts. *Wear*, 260(7–8), 766–782.
- Kamimura, H., Chiba, T., Kubo, T., Nanao, H., Minami, I., & Mori, S. (2006). Relationship between structure and tribological properties of ionic liquids

- composed of imidazolium cations. *Japanese Journal of Tribology*, 51(6), 675–687.
- Kania, D., Yunus, R., Omar, R., Abdul Rashid, S., & Mohamad Jan, B. (2015). A review of biolubricants in drilling fluids: Recent research, performance, and applications. *Journal of Petroleum Science and Engineering*, 135, 177–184.
- Kennametal. (2018). Turning Tools. Retrieved February 28, 2018, from <https://www.kennametal.com/en/resources/metalworking-literature.html>
- Keskin, S., Kayrak-Talay, D., Akman, U., & Hortaçsu, Ö. (2007). A review of ionic liquids towards supercritical fluid applications. *Journal of Supercritical Fluids*, 43(1), 150–180.
- Khemchandani, B., Somers, A. E., Howlett, P. C., Jaiswal, A. K., Sayanna, E., & Forsyth, M. (2014). A biocompatible ionic liquid as an antiwear additive for biodegradable lubricants. *Tribology International*, 77(2014), 171–177.
- Kim, H. (2012). Friction and lubrication: Fundamentals. In T. Altan & A. E. Tekkaya (Eds.), *Sheet metal forming*. United States of America: ASM International. pp. 89–103.
- Kim, H., Altan, T., & Yan, Q. (2009). Evaluation of stamping lubricants in forming advanced high strength steels (AHSS) using deep drawing and ironing tests. *Journal of Materials Processing Technology*, 209(8), 4122–4133.
- Klocke, F., & Eisenblätter, G. (1997). Dry Cutting. *CIRP Annals-Manufacturing Technology*, 46(2).
- Klocke, F., & König, W. (2008). *Fertigungsverfahren 1: Drehen, Fräsen, Bohren*. Heidelberg, Germany: Springer-Verlag.
- Klocke, F., & König, W. (2005). *Fertigungsverfahren 2: Schleifen, Honen, Läppen*. Heidelberg, Germany: Springer-Verlag.
- Koel, M. (2009). *Ionic Liquids in Chemical Analysis*. USA: CRC Press.
- Kronberger, M., Pejakovic, V., Gabler, C., & Kalin, M. (2012). How anion and cation species influence the tribology of a green lubricant based on ionic liquids. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 226(11), 933–951.
- Kumar, S. (2008). *Technology of Metal Forming Processes*. PHI Learning Pvt. Ltd, New Delhi, India.
- Kus, A., Isik, Y., Cemal Cakir, M., Coşkun, S., & Özdemir, K. (2015). Thermocouple and infrared sensor-based measurement of temperature distribution in metal

- cutting. *Sensors (Switzerland)*, *15*(1), 1274–1291.
- Lawal, S. A., Choudhury, I. A., & Nukman, Y. (2012). Application of vegetable oil-based metalworking fluids in machining ferrous metals - A review. *International Journal of Machine Tools and Manufacture*, *52*(1), 1–12.
- Lawal, S. A., Choudhury, I. A., & Nukman, Y. (2013). Developments in the formulation and application of vegetable oil-based metalworking fluids in turning process. *International Journal of Advanced Manufacturing Technology*, *67*(5–8), 1765–1776.
- Li, B., Li, C., Zhang, Y., Wang, Y., Jia, D., & Yang, M. (2016). Grinding temperature and energy ratio coefficient in MQL grinding of high-temperature nickel-base alloy by using different vegetable oils as base oil. *Chinese Journal of Aeronautics*, *29*(4), 1084–1095.
- Li, B., Li, C., Zhang, Y., Wang, Y., Jia, D., Yang, M., Zhang, N., Wu, Q., Han, Z., & Sun, K. (2017). Heat transfer performance of MQL grinding with different nanofluids for Ni-based alloys using vegetable oil. *Journal of Cleaner Production*, *154*, 1–11.
- Li, D., Cai, M., Feng, D., Zhou, F., & Liu, W. (2011). Excellent lubrication performance and superior corrosion resistance of vinyl functionalized ionic liquid lubricants at elevated temperature. *Tribology International*, *44*(10), 1111–1117.
- Li, G., Xu, X., Han, R., & Ma, J. (2016). Synthesis and superior electrochemical properties of shaggy hollow Zn-doped Fe₂O₃ nanospheres for high-performance lithium-ion batteries. *CrystEngComm*, *18*(16), 2949–2955.
- Li, J., Li, D., Zhou, F., Feng, D., Xia, Y., & Liu, W. (2015). Tribological and corrosive properties of ionic liquids containing triazole functional groups. *Industrial Lubrication and Tribology*, *67*(3), 210–215.
- Li, X., Zhao, D., Fei, Z., & Wang, L. (2006). Applications of functionalized ionic liquids. *Science in China, Series B: Chemistry*, *49*(5), 385–401.
- Liang, S., Chen, W., & Cheng, K. (2011). The Latent Application of Ionic Liquids in Absorption Refrigeration. In S. T. Handy (Ed.), *Applications of Ionic Liquids in Science and Technology*. Rijeka, Croatia: InTech. pp. 467–494.
- Liaw, H. J., Chen, C. C., Chen, Y. C., Chen, J. R., Huang, S. K., & Liu, S. N. (2012). Relationship between flash point of ionic liquids and their thermal decomposition. *Green Chemistry*, *14*(7), 2001–2008.
- Libardi, A., Schmid, S. R., Sen, M., & Schneider, W. (2013). Evaluation of ionic fluids

- as lubricants in manufacturing. *Journal of Manufacturing Processes*, 15(4), 414–418.
- Liu, J., Wang, F., Zhang, L., Fang, X., & Zhang, Z. (2014). Thermodynamic properties and thermal stability of ionic liquid-based nanofluids containing graphene as advanced heat transfer fluids for medium-to-high-temperature applications. *Renewable Energy*, 63(2014), 519–523.
- Liu, W., Ye, C., Gong, Q., Wang, H., & Wang, P. (2002). Tribological performance of room-temperature ionic liquids as lubricant. *Tribology Letters*, 13(2), 81–85.
- Longbottom, J. M., & Lanham, J. D. (2005). Cutting temperature measurement while machining – A review. *Aircraft Engineering and Aerospace Technology*, 77(2), 122–130.
- Lu, Q., Wang, H., Ye, C., Liu, W., & Xue, Q. (2004). Room temperature ionic liquid 1-ethyl-3-hexylimidazolium- bis(trifluoromethylsulfonyl)-imide as lubricant for steel-steel contact. *Tribology International*, 37(7), 547–552.
- Lu, T. (2014). *A Metrics-based Sustainability Assessment of Cryogenic Machining Using Modeling and Optimization of Process Performance*. University of Kentucky: Ph.D. Thesis.
- Lu, T., Rotella, G., Badurdeen, F., Dillon, O. W., Rouch, K. E., & Jawahir, I. S. (2012). A metrics-based sustainability assessment for different coolant applications in a turning process. *Proceedings of the CIRP GCSM*, 564–569.
- Maegawa, S., Koseki, A., Itoigawa, F., & Nakamura, T. (2016). In situ observation of adsorbed fatty acid films using surface plasmon resonance. *Tribology International*, 97(2016), 228–233.
- Mang, T., & Dresel, W. (2007). *Lubricants and Lubrication*. 2nd ed. Weinheim, Germany: John Wiley & Sons.
- Marksberry, P. W. (2007). Micro-flood (MF) technology for sustainable manufacturing operations that are coolant less and occupationally friendly. *Journal of Cleaner Production*, 15(10), 958–971.
- Maruda, R. W., Krolczyk, G. M., Feldshtein, E., Nieslony, P., Tyliczszak, B., & Pusavec, F. (2017). Tool wear characterizations in finish turning of AISI 1045 carbon steel for MQCL conditions. *Wear*, 372–373, 54–67.
- Mendonça, A. C. F., Malfreyt, P., & Pádua, A. A. H. (2012). Interactions and ordering of ionic liquids at a metal surface. *Journal of Chemical Theory and Computation*, 8(9), 3348–3355.

- Menezes, P. L., Ingole, S. P., Nosonovsky, M., Kailas, S. V., & Lovell, M. R. (2013). *Tribology for Scientists and Engineers: From Basics to Advanced Concepts*. United States of America: Springer.
- Menkiti, M. C., Ocheje, O., & Agu, C. M. (2017). Production of environmentally adapted lubricant basestock from jatropha curcas specie seed oil. *International Journal of Industrial Chemistry*, 8(2), 133–144.
- Mijanovic, K., & Sokovic, M. (2001). Ecological aspects of the cutting fluids and its influence on quantifiable parameters of the cutting processes. *Journal of Materials Processing Technology*, 109, 181–189.
- Minami, I. (2009). Ionic liquids in tribology. *Molecules*, 14(6), 2286–2305.
- Minami, I. (2017). Molecular Science of Lubricant Additives. *Applied Sciences*, 7(5), 445.
- Minami, I., Kamimura, H., & Mori, S. (2007). Thermo-oxidative stability of ionic liquids as lubricating fluid. *Journal of Synthetic Lubrication*, 24, 135–147.
- Minami, I., Kita, M., Kubo, T., Nanao, H., & Mori, S. (2008). The tribological properties of ionic liquids composed of trifluorotris(pentafluoroethyl) phosphate as a hydrophobic anion. *Tribology Letters*, 30(3), 215–223.
- Missan, H. P. S., & Singh, M. (2012). Brønsted Acid-Base Ionic Liquids and Membranes as Ion Conducting Materials. In J. Mun & H. Sim (Eds.), *Handbook of Ionic Liquids: Properties, Applications and Hazards*. Nova Science Publishers Inc., New York, pp. 113–144.
- Monge, R., González, R., Hernández Battez, A., Fernández-González, A., Viesca, J. L., García, A., & Hadfield, M. (2015). Ionic liquids as an additive in fully formulated wind turbine gearbox oils. *Wear*, 328–329, 50–63.
- Mordukhovich, G., Qu, J., Howe, J. Y., Bair, S., Yu, B., Luo, H., Smolenski, D.J., Blau, P.J., Bunting, B.G., & Dai, S. (2013). A low-viscosity ionic liquid demonstrating superior lubricating performance from mixed to boundary lubrication. *Wear*, 301(1–2), 740–746.
- Mu, Z., Zhou, F., Zhang, S., Liang, Y., & Liu, W. (2005). Effect of the functional groups in ionic liquid molecules on the friction and wear behavior of aluminum alloy in lubricated aluminum-on-steel contact. *Tribology International*, 38(8), 725–731.
- Muhammad, R., Maurotto, A., Demiral, M., Roy, A., & Silberschmidt, V. V. (2014). Thermally enhanced ultrasonically assisted machining of Ti alloy. *CIRP Journal*

of Manufacturing Science and Technology, 7(2), 159–167.

- Mulyana, T., Rahim, E. A., & Md Yahaya, S. N. (2017). The influence of cryogenic supercritical carbon dioxide cooling on tool wear during machining high thermal conductivity steel. *Journal of Cleaner Production*, 164, 950–962.
- Najiha, M. S., Rahman, M. M., & Yusoff, A. R. (2016). Environmental impacts and hazards associated with metal working fluids and recent advances in the sustainable systems: A review. *Renewable and Sustainable Energy Reviews*, 60, 1008–1031.
- Nakpong, P., & Wootthikanokkhan, S. (2010). Optimization of Biodiesel Production from Jatropha Oil (*Jatropha curcas* L.) using Response Surface Methodology. *Journal of Sustainable Energy & Environment*, 3(1), 105–109.
- Omotowa, B. A., Phillips, B. S., Zabinski, J. S., & Shreeve, J. M. (2004). Phosphazene-based ionic liquids: Synthesis, temperature-dependent viscosity, and effect as additives in water lubrication of silicon nitride ceramics. *Inorganic Chemistry*, 43(17), 5466–5471.
- Ong, H. C., Mahlia, T. M. I., Masjuki, H. H., & Norhasyima, R. S. (2011). Comparison of palm oil, *Jatropha curcas* and *Calophyllum inophyllum* for biodiesel: A review. *Renewable and Sustainable Energy Reviews*, 15(8), 3501–3515.
- Osama, M., Singh, A., Walvekar, R., Khalid, M., Gupta, T. C. S. M., & Yin, W. W. (2017). Recent developments and performance review of metal working fluids. *Tribology International*, 114(2017), 389–401.
- Otero, I., López, E. R., Reichelt, M., & Fernández, J. (2014). Friction and anti-wear properties of two tris(pentafluoroethyl) trifluorophosphate ionic liquids as neat lubricants. *Tribology International*, 70(2014), 104–111.
- Otero, I., López, E. R., Reichelt, M., Villanueva, M., Salgado, J., & Fernández, J. (2014). Ionic liquids based on phosphonium cations as neat lubricants or lubricant additives for a steel/steel contact. *ACS Applied Materials & Interfaces*, 6(15), 13115–13128.
- Pagano, F., Gabler, C., Zare, P., Mahrova, M., Dörr, N., Bayon, R., Fernandez, X., Binder, W. H., Hernaiz, M., Tojo, E., & Igartua, A. (2012). Dicationic ionic liquids as lubricants. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 226(11), 952–964.
- Palacio, M., & Bhushan, B. (2010). A review of ionic liquids for green molecular lubrication in nanotechnology. *Tribology Letters*, 40(2), 247–268.

- Paulechka, Y. U. (2010). Heat capacity of room-temperature ionic liquids: A critical review. *Journal of Physical and Chemical Reference Data*, 39(3), 1-23.
- Pejaković, V., Kronberger, M., & Kalin, M. (2013). Influence of temperature on tribological behaviour of ionic liquids as lubricants and lubricant additives. *Lubrication Science*, 26(2), 107–115.
- Pereira, O., Martín-Alfonso, J. E., Rodríguez, A., Calleja, A., Fernández-Valdivielso, A., & López de Lacalle, L. N. (2017). Sustainability analysis of lubricant oils for minimum quantity lubrication based on their tribo-rheological performance. *Journal of Cleaner Production*, 164, 1419–1429.
- Pham, M. Q., Yoon, H. S., Khare, V., & Ahn, S. H. (2014). Evaluation of ionic liquids as lubricants in micro milling - Process capability and sustainability. *Journal of Cleaner Production*, 76, 167–173.
- Phillips, B. S., John, G., & Zabinski, J. S. (2007). Surface chemistry of fluorine containing ionic liquids on steel substrates at elevated temperature using Mössbauer spectroscopy. *Tribology Letters*, 26(2), 85–91.
- Phillips, B. S., & Zabinski, J. S. (2004). Ionic liquid lubrication effects on ceramics in a water environment. *Tribology Letters*, 17(3), 533–541.
- Plechkova, N. V., Rogers, R. D., & Seddon, K. R. (2010). *Ionic Liquids: From Knowledge to Application*. Washington, DC: American Chemical Society.
- Popov, V. L. (2010). *Contact mechanics and friction. Physical principles and applications*. Berlin: Springer-Verlag.
- Pusavec, F., Krajnik, P., & Kopac, J. (2010). Transitioning to sustainable production - Part I: application on machining technologies. *Journal of Cleaner Production*, 18(2), 174–184.
- Qu, J., Bansal, D. G., Yu, B., Howe, J. Y., Luo, H., Dai, S., Li, H., Blau, P.J., Bunting, B.G., Mordukhovich, G., & Smolenski, D. J. (2012). Antiwear performance and mechanism of an oil-miscible ionic liquid as a lubricant additive. *ACS Applied Materials and Interfaces*, 4(2), 997–1002.
- Qu, J., Blau, P. J., Dai, S., Luo, H., & Meyer, H. M. (2009). Ionic Liquids as Novel Lubricants and Additives for Diesel Engine Applications. *Tribology Letters*, 35(3), 181–189.
- Qu, J., Luo, H., Chi, M., Ma, C., Blau, P. J., Dai, S., & Viola, M. B. (2014). Comparison of an oil-miscible ionic liquid and ZDDP as a lubricant anti-wear additive. *Tribology International*, 71(2014), 88–97.

- Qu, J., Truhan, J. J., Dai, S., Luo, H., & Blau, P. J. (2006). Ionic liquids with ammonium cations as lubricants or additives. *Tribology Letters*, 22(3), 207–214.
- Rabiei, F., Rahimi, A. R., Hadad, M. J., & Ashrafi Jou, M. (2015). Performance improvement of minimum quantity lubrication (MQL) technique in surface grinding by modeling and optimization. *Journal of Cleaner Production*, 86, 447–460.
- Rahim, E. A., Amiril, S. A. S., & Talib, N. (2018). Tribological Interaction of Bio-Based Metalworking Fluids in Machining Process. In D. Johnson (Ed.), *Tribology, Lubricants and Additives*. Rijeka, Croatia: IntechOpen. pp. 45–63.
- Rahim, E. A., Dorairaju, H., Asmuin, N., & Mantari, M. H. A. R. (2015). Determination of Mist Flow Characteristic for MQL Technique Using Particle Image Velocimetry (PIV) and Computer Fluid Dynamics (CFD). *Applied Mechanics and Materials*, 773–774, 403–407.
- Rahim, E. A., & Sasahara, H. (2011a). A study of the effect of palm oil as MQL lubricant on high speed drilling of titanium alloys. *Tribology International*, 44(3), 309–317.
- Rahim, E. A., & Sasahara, H. (2011b). An Analysis of Surface Integrity When Drilling Inconel 718 Using Palm Oil and Synthetic Ester Under MQL Condition. *Machining Science and Technology*, 15(1), 76–90.
- Rahim, E. A., & Sasahara, H. (2011c). Investigation of Tool Wear and Surface Integrity on MQL Machining of Ti-6AL-4V Using Biodegradable Oil. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 225, 1505–1511.
- Reeves, C. J. (2013). *An Experimental Investigation Characterizing the Tribological Performance of Natural and Synthetic Biolubricants Composed of Carboxylic Acids for Energy Conservation and Sustainability*. University of Wisconsin-Milwaukee: Ph.D. Thesis.
- Reeves, C. J., Siddaiah, A., & Menezes, P. L. (2018). Tribological study of imidazolium and phosphonium ionic liquid-based lubricants as additives in carboxylic acid-based natural oil: Advancements in environmentally friendly lubricants. *Journal of Cleaner Production*, 176, 241–250.
- Regueira, T., Lugo, L., & Fernández, J. (2014). Ionic liquids as hydraulic fluids: comparison of several properties with those of conventional oils. *Lubrication Science*, 26(7–8), 488–499.

- Ribeiro Filho, S. L. M., Vieira, J. T., de Oliveira, J. A., Arruda, É. M., & Brandão, L. C. (2017). Comparison among different vegetable fluids used in minimum quantity lubrication systems in the tapping process of cast aluminum alloy. *Journal of Cleaner Production*, *140*, 1255–1262.
- Rotella, G., Dillon, O. W., Umbrello, D., Settineri, L., & Jawahir, I. S. (2014). The effects of cooling conditions on surface integrity in machining of Ti6Al4V alloy. *The International Journal of Advanced Manufacturing Technology*, *71*(1–4), 47–55.
- Rukunudin, I. H., White, P. J., Bern, C. J., & Bailey, T. B. (1998). A modified method for determining free fatty acids from small soybean oil sample sizes. *Journal of the American Oil Chemists' Society*, *75*(5), 563–568.
- Saini, A., Dhiman, S., Sharma, R., & Setia, S. (2014). Experimental estimation and optimization of process parameters under minimum quantity lubrication and dry turning of AISI-4340 with different carbide inserts. *Journal of Mechanical Science and Technology*, *28*(6), 2307–2318.
- Salimon, J., Salih, N., & Yousif, E. (2012). Industrial development and applications of plant oils and their biobased oleochemicals. *Arabian Journal of Chemistry*, *5*(2), 135–145.
- Sani, A. S. A., Sousa, F. J. P., Hamedon, Z., & Azhari, A. (2016). Contact pressure distribution during the polishing process of ceramic tiles: A laboratory investigation. *IOP Conference Series: Materials Science and Engineering*, *114*, 12008.
- Schultheiss, F., Zhou, J., Gröntoft, E., & Ståhl, J. E. (2013). Sustainable machining through increasing the cutting tool utilization. *Journal of Cleaner Production*, *59*, 298–307.
- Schulz, J., Brinksmeier, E., & Meyer, D. (2013). On the Interactions of Additives in Metalworking Fluids with Metal Surfaces. *Lubricants*, *1*(4), 75–94.
- Shahabuddin, M., Masjuki, H. H., & Kalam, M. A. (2013). Experimental investigation into tribological characteristics of biolubricant formulated from Jatropha oil. *Procedia Engineering*, *56*, 597–606.
- Shahabuddin, M., Masjuki, H. H., Kalam, M. A., Bhuiya, M. M. K., & Mehat, H. (2013). Comparative tribological investigation of bio-lubricant formulated from a non-edible oil source (Jatropha oil). *Industrial Crops and Products*, *47*, 323–330.

- 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.
- Sharma, B. K., Adhvaryu, A., Liu, Z., & Erhan, S. Z. (2006). Chemical modification of vegetable oils for lubricant applications. *Journal of the American Oil Chemists' Society*, 83(2), 129–136.
- Sharma, J., & Sidhu, B. S. (2014). Investigation of effects of dry and near dry machining on AISI D2 steel using vegetable oil. *Journal of Cleaner Production*, 66, 619–623.
- Sharma, V., Doerr, N., & Aswath, P. B. (2016). Chemical–mechanical properties of tribofilms and their relationship to ionic liquid chemistry. *RSC Advances*, 6(27), 22341–22356.
- Sharma, V. S., Dogra, M., & Suri, N. M. (2009). Cooling techniques for improved productivity in turning. *International Journal of Machine Tools and Manufacture*, 49(6), 435–453.
- Shet, C., & Deng, X. (2003). Residual stresses and strains in orthogonal metal cutting. *International Journal of Machine Tools and Manufacture*, 43(6), 573–587.
- Shuaib, M., Seevers, D., Zhang, X., Badurdeen, F., Rouch, K. E., & Jawahir, I. S. (2014). A metrics-based framework to evaluate the total life cycle sustainability of manufactured products. *Journal of Industrial Ecology*, 18(4), 491–507.
- Siangproh, W., Duangcha, W., & Chailapakul, O. (2012). Ionic Liquids in Electroanalytical Chemistry: A Review for Further Development and Applications. In J. Mun & H. Sim (Eds.), *Handbook of Ionic Liquids: Properties, Applications and Hazards*. Nova Science Publishers Inc., New York, pp. 79–112.
- Silva, N. De, Jawahir, I. S., Dillon, O., & Russell, M. (2009). A New Comprehensive Methodology for the Evaluation of Product Sustainability at the Design and Development Stage of Consumer Electronic Products. *International Journal of Sustainable Manufacturing*, 1(3), 335–340.
- Somers, A. E., Biddulph, S. M., Howlett, P. C., Sun, J., MacFarlane, D. R., & Forsyth, M. (2012). A comparison of phosphorus and fluorine containing IL lubricants for steel on aluminium. *Physical Chemistry Chemical Physics*, 14(22), 8224.
- Somers, A. E., Howlett, P. C., MacFarlane, D. R., & Forsyth, M. (2013). A review of ionic liquid lubricants. *Lubricants*, 1(1), 3–21.

- Somers, A. E., Howlett, P. C., Sun, J., MacFarlane, D. R., & Forsyth, M. (2010). Transition in wear performance for ionic liquid lubricants under increasing load. *Tribology Letters*, 40(2), 279–284.
- Somers, A. E., Khemchandani, B., Howlett, P. C., Sun, J., MacFarlane, D. R., & Forsyth, M. (2013). Ionic Liquids as Anti-wear Additives in Base Oils: Influence of Structure on Miscibility and Wear Performance for Steel on Aluminium. *ACS Applied Materials & Interfaces*, 5(22), 11544–11553.
- Song, Z., Yu, Q., Cai, M., Huang, G., Yao, M., Li, D., Liang, Y., Fan, M., & Zhou, F. (2015). Green Ionic Liquid Lubricants Prepared from Anti-Inflammatory Drug. *Tribology Letters*, 60(3), 1–11.
- Sousa, F. (2014). Polishing. In L. Laperrière & G. Reinhart (Eds.), *CIRP Encyclopedia of Production Engineering*. Berlin: Springer. pp. 957–962.
- Stephenson, D. A., & Agapiou, J. S. (2016). *Metal Cutting Theory and Practice*. 3rd ed. Boca Raton, Florida: CRC Press.
- Stepnowski, P. (2007). Potential environmental impact of imidazolium ionic liquids. In J. F. Brennecke, R. D. Rogers, & K. R. Seddon (Eds.), *Ionic Liquids IV Not Just Solvents Anymore*. Washington, DC: ACS Symposium Series. pp. 10–20.
- Suda, S., Yokota, H., Inasaki, I. & Wakabayashi, T. (2002). A Synthetic Ester as an Optimal Cutting Fluid for Minimal Quantity Lubrication Machining. *CIRP Annals - Manufacturing Technology*, 51(1), 95–98.
- Sumitomo Electric Carbide Inc. (2016). High Performance Cutting Tools. Retrieved February 28, 2018, from http://sumicarbide.com/download_product/catalog/
- Syahir, A. Z., Zulkifli, N. W. M., Masjuki, H. H., Kalam, M. A., Alabdulkarem, A., Gulzar, M., Khuong, L. S., & Harith, M. H. (2017). A review on bio-based lubricants and their applications. *Journal of Cleaner Production*, 168, 997–1016.
- Syahrullail, S., Izhan, M. I., & Mohammed Rafiq, A. K. (2014). Tribological investigation of RBD palm olein in different sliding speeds using pin-on-disk tribotester. *Scientia Iranica B*, 21(1), 162–170.
- Syahrullail, S., Kamitani, S., & Shakirin, A. (2013). Performance of vegetable oil as lubricant in extreme pressure condition. *Procedia Engineering*, 68, 172–177.
- Taher, M. (2012). *Novel Boron Compounds in Lubrication*. Luleå University of Technology, Sweden: Ph.D. Thesis.
- Talib, N., Nasir, R. M., & Rahim, E. A. (2017a). Tribological behaviour of modified jatropa oil by mixing hexagonal boron nitride nanoparticles as a bio-based

- lubricant for machining processes. *Journal of Cleaner Production*, 147, 360–378.
- Talib, N., & Rahim, E. A. (2014). The Performance of Modified Jatropha Oil Based Trimethylolpropane (TMP) Ester on Tribology Characteristic for Sustainable Metalworking Fluids (MWFs). *Applied Mechanics and Materials*, 660, 357–361.
- Talib, N., & Rahim, E. A. (2015). Performance Evaluation of Chemically Modified Crude Jatropha Oil as a Bio-based Metalworking Fluids for Machining Process. *Procedia CIRP*, 26, 346–350.
- Talib, N., & Rahim, E. A. (2016). The effect of tribology behavior on machining performances when using bio-based lubricant as a sustainable metalworking fluid. *Procedia CIRP*, 40, 504–508.
- Talib, N., & Rahim, E. A. (2017b). Experimental evaluation of physicochemical properties and tapping torque of hexagonal boron nitride in modified jatropha oils-based as sustainable metalworking fluids. *Journal of Cleaner Production*, 171, 743–755.
- Talib, N., & Rahim, E. A. (2018). Performance of modified jatropha oil in combination with hexagonal boron nitride particles as a bio-based lubricant for green machining. *Tribology International*, 118(2017), 89–104.
- Talib, N., Sasahara, H., & Rahim, E. A. (2017c). Evaluation of modified jatropha-based oil with hexagonal boron nitride particle as a biolubricant in orthogonal cutting process. *International Journal of Advanced Manufacturing Technology*, 1–21.
- Tasdelen, B., Thordenberg, H., & Olofsson, D. (2008). An experimental investigation on contact length during minimum quantity lubrication (MQL) machining. *Journal of Materials Processing Technology*, 203(1–3), 221–231.
- Tebaldo, V., di Confiengo, G. G., & Faga, M. G. (2017). Sustainability in machining: “Eco-friendly” turning of Inconel 718. Surface characterisation and economic analysis. *Journal of Cleaner Production*, 140, 1567–1577.
- Thuy Pham, T. P., Cho, C.-W., & Yun, Y.-S. (2009). Environmental fate and toxicity of ionic liquids: A review. *Water Research*, 44(2), 352–372.
- Tomida, D., Kenmochi, S., Tsukada, T., Qiao, K., & Yokoyama, C. (2007). Thermal conductivities of [bmim][PF 6], [hmim][PF 6], and [omim][PF 6] from 294 to 335 K at pressures up to 20 MPa. *International Journal of Thermophysics*, 28(4), 1147–1160.
- Tomida, D., Kenmochi, S., Tsukada, T., & Yokoyama, C. (2007). Measurements of

- thermal conductivity of 1-butyl-3-methylimidazolium tetrafluoroborate at high pressure. *Heat Transfer - Asian Research*, 36(6), 361–372.
- Torimoto, T., Tsuda, T., Okazaki, K. I., & Kuwabata, S. (2010). New frontiers in materials science opened by ionic liquids. *Advanced Materials*, 22(11), 1196–1221.
- Totolin, V., Minami, I., Gabler, C., & Dörr, N. (2013). Halogen-free borate ionic liquids as novel lubricants for tribological applications. *Tribology International*, 67(2013), 191–198.
- Trent, E. M. (1984). *Metal Cutting*. 2nd ed. London: Butterworths & Co Ltd.
- Trent, E. M., & Wright, P. K. (2000). *Metal Cutting*. 4th ed. USA: Butterworth–Heinemann.
- Uerdingen, M. (2010). Ionic Liquids as Lubricants. In P. T. Anastas, P. Wasserscheid, & A. Stark (Eds.), *Handbook of Green Chemistry - Green Solvents: Volume 6 - Ionic Liquids*. Weinheim, Germany: Wiley-VCH Verlag. pp. 203–219.
- Uhlig, H. H., & Revie, R. W. (2008). *Corrosion and Corrosion Control: An introduction to corrosion science and engineering*. 4th ed., Vol. 7. United States of America: John Wiley & Sons.
- Viesca, J. L., Battez, A. H., González, R., Reddyhoff, T., Pérez, A. T., & Spikes, H. A. (2010). Assessing boundary film formation of lubricant additivised with 1-hexyl-3-methylimidazolium tetrafluoroborate using ECR as qualitative indicator. *Wear*, 269(1–2), 112–117.
- Viesca, J. L., Mallada, M. T., Blanco, D., Fernández-González, A., Espina-Casado, J., González, R., & Hernández Battez, A. (2017). Lubrication performance of an ammonium cation-based ionic liquid used as an additive in a polar oil. *Tribology International*, 116(2017), 422–430.
- Waara, P., Hannu, J., Norrby, T., & Byheden, Å. (2001). Additive influence on wear and friction performance of environmentally adapted lubricants. *Tribology International*, 34(8), 547–556.
- Wakabayashi, T., Inasaki, I., Suda, S., & Yokota, H. (2003). Tribological Characteristics and Cutting Performance of Lubricant Esters for Semi-dry Machining. *CIRP Annals - Manufacturing Technology*, 52(1), 61–64.
- Walden, P. (1914). Molecular weights and electrical conductivity of several fused salts. *Bull. Acad. Imper. Sci.(St. Petersburg)*, 405–422.
- Wang, Y., Li, C., Zhang, Y., Yang, M., Li, B., Jia, D., Hou, Y., & Mao, C. (2016).

Experimental evaluation of the lubrication properties of the wheel/workpiece interface in minimum quantity lubrication (MQL) grinding using different types of vegetable oils. *Journal of Cleaner Production*, 127, 487–499.

- Wasserscheid, P., & Joni, J. (2010). Green Organic Synthesis in Ionic Liquids. In P. T. Anastas, P. Wasserscheid, & A. Stark (Eds.), *Handbook of Green Chemistry - Green Solvents: Volume 6 - Ionic Liquids*. Weinheim, Germany: Wiley-VCH Verlag. pp. 41–63.
- Wasserscheid, P. & Welton, T. (2007). *Ionic Liquids in Synthesis*. 2nd ed. Weinheim, Germany: Wiley-VCH Verlag.
- Watts, J. F. & Wolstenholme, J. (2003). *An Introduction to Surface Analysis by XPS and AES*. West Sussex, England: John Wiley & Sons Ltd.
- Weinert, K., Inasaki, I., Sutherland, J. W., & Wakabayashi, T. (2004). Dry Machining and Minimum Quantity Lubrication. *CIRP Annals - Manufacturing Technology*, 53(2), 511–537.
- Wells, A. S., & Coombe, V. T. (2006). On the freshwater ecotoxicity and biodegradation properties of some common ionic liquids. *Organic Process Research and Development*, 10(4), 794–798.
- Wen, S., & Huang, P. (2012). *Principles of Tribology*. *Principles of Tribology*. Singapore: John Wiley & Sons (Asia) Pte Ltd.
- Werda, S., Duchosal, A., Le Quilliec, G., Morandea, A., & Leroy, R. (2016). Minimum Quantity Lubrication: Influence of the Oil Nature on Surface Integrity. *Procedia CIRP*, 45, 287–290.
- Wertheim, R., Rotberg, J., & Ber, A. (1992). Influence of High-pressure Flushing through the Rake Face of the Cutting Tool. *CIRP Annals - Manufacturing Technology*, 41(1), 101–106.
- Westerholt, A., Weschta, M., Bösmann, A., Tremmel, S., Korth, Y., Wolf, M., Schlücker, E., Wehrum, N., Lennert, A., Uerdingen, M., Holweger, W., Wartzack, S., & Wasserscheid, P. (2015). Halide-Free Synthesis and Tribological Performance of Oil-Miscible Ammonium and Phosphonium-Based Ionic Liquids. *ACS Sustainable Chemistry and Engineering*, 3(5), 797–808.
- Wichmann, H., Stache, H., Schmidt, C., Winter, M., Bock, R., Herrmann, C., & Bahadir, M. (2013). Ecological and economic evaluation of a novel glycerol based metalworking fluid. *Journal of Cleaner Production*, 43, 12–19.
- Wilkes, J. S., Levisky, J. A., Wilson, R. A., & Hussey, C. L. (1982).

- Dialkylimidazolium chloroaluminate melts: a new class of room-temperature ionic liquids for electrochemistry, spectroscopy and synthesis. *Inorganic Chemistry*, 21(3), 1263–1264.
- Wilkes, J. S., & Zaworotko, M. J. (1992). Air and water stable 1- ethyl-3-methylimidazolium based ionic liquids. *Journal of the Chemical Society, Chemical Communications*, (13), 965–967.
- Xia, Y., Wang, Z., & Song, Y. (2014). Influence of hydroxyl group functionalization and alkyl chain length on physicochemical and antiwear properties of hexafluorophosphate imidazolium ionic liquids. *Industrial Lubrication and Tribology*, 66(3), 443–451.
- Xiao, H., Guo, D., Liu, S., Pan, G., & Lu, X. (2011). Film thickness of ionic liquids under high contact pressures as a function of alkyl chain length. *Tribology Letters*, 41(2), 471–477.
- Yamashita, T., & Hayes, P. (2008). Analysis of XPS spectra of Fe²⁺ and Fe³⁺ ions in oxide materials. *Applied Surface Science*, 254(8), 2441–2449.
- Yan, P., Rong, Y., & Wang, G. (2016). The effect of cutting fluids applied in metal cutting process. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 230(1), 19–37.
- Yao, M., Fan, M., Liang, Y., Zhou, F., & Xia, Y. (2010). Imidazolium hexafluorophosphate ionic liquids as high temperature lubricants for steel–steel contacts. *Wear*, 268(1–2), 67–71.
- Yao, M., Liang, Y., Xia, Y., & Zhou, F. (2009). Bisimidazolium ionic liquids as the high-performance antiwear additives in poly(ethylene glycol) for steel–steel contacts. *ACS Applied Materials and Interfaces*, 1(2), 467–471.
- Ye, C., Liu, W., Chen, Y., & Yu, L. (2001). Room-temperature ionic liquids: a novel versatile lubricant. *Chemical Communications*, (21), 2244–2245.
- Yildiz, Y., & Nalbant, M. (2008). A review of cryogenic cooling in machining processes. *International Journal of Machine Tools and Manufacture*, 48(9), 947–964.
- Yu, B., Bansal, D. G., Qu, J., Sun, X., Luo, H., Dai, S., Blau, P.J., Bunting, B.G., Mordukhovich, G., & Smolenski, D. J. (2012). Oil-miscible and non-corrosive phosphonium-based ionic liquids as candidate lubricant additives. *Wear*, 289, 58–64.
- Zainal, N. A., Zulkifli, N. W. M., Gulzar, M., & Masjuki, H. H. (2018). A review on

- the chemistry, production, and technological potential of bio-based lubricants. *Renewable and Sustainable Energy Reviews*, 82(June 2016), 80–102.
- Zamratul, M. I. M., Syaima, M. T. S., Noor, I. M., & Materials, A. (2014). Development of bio-lubricant from *Jatropha curcas* oils. *International Journal of Research in Chemical, Metallurgical and Civil Engineering*, 1(1), 10–12.
- Zhang, L., Feng, D., & Xu, B. (2009). Tribological characteristics of alkyimidazolium diethyl phosphates ionic liquids as lubricants for steel-steel contact. *Tribology Letters*, 34(2), 95–101.
- Zhang, L., Liu, J., He, G., Ye, Z., Fang, X., & Zhang, Z. (2014). Radiative properties of ionic liquid-based nanofluids for medium-to-high-temperature direct absorption solar collectors. *Solar Energy Materials and Solar Cells*, 130, 521–528.
- Zhang, S., Sun, N., He, X., Lu, X., & Zhang, X. (2006). Physical properties of ionic liquids: Database and evaluation. *Journal of Physical and Chemical Reference Data*, 35(4), 1475–1517.
- Zhang, S., Wang, J., Lu, X., & Zhou, Q. (2014). *Structures and Interactions of Ionic Liquids*. Springer, Heidelberg, Germany.
- Zhang, Y. F., Hinton, B., Wallace, G., Liu, X., & Forsyth, M. (2012). On corrosion behavior of magnesium alloy AZ31 in simulated body fluids and influence of ionic liquid pretreatments. *Corrosion Engineering, Science and Technology*, 47(5), 374–382.
- Zhang, Y., Forsyth, M., & Hinton, B. R. W. (2014). The Effect of Treatment Temperature on Corrosion Resistance and Hydrophilicity of an Ionic Liquid Coating for Mg-Based Stents. *ACS Applied Materials and Interfaces*, 6(21), 18989–18997.
- Zhang, Y., Li, C., Yang, M., Jia, D., Wang, Y., Li, B., Hou, Y., Zhang, N., & Wu, Q. (2016). Experimental evaluation of cooling performance by friction coefficient and specific friction energy in nanofluid minimum quantity lubrication grinding with different types of vegetable oil. *Journal of Cleaner Production*, 139, 685–705.
- Zhao, D., Liao, Y., & Zhang, Z. D. (2007). Toxicity of ionic liquids. *Clean - Soil, Air, Water*, 35(1), 42–48.
- Zhao, H. (2006). Innovative Applications of Ionic Liquids As “Green” Engineering Liquids. *Chemical Engineering Communications*, 193(12), 1660–1677.

- Zhao, H., Barber, G. C., & Zou, Q. (2002). A study of flank wear in orthogonal cutting with internal cooling. *Wear*, 253(9–10), 957–962.
- Zhou, F., Liang, Y., & Liu, W. (2009). Ionic liquid lubricants: designed chemistry for engineering applications. *Chemical Society Reviews*, 38(9), 2590–2599.
- Zhou, Y., Dyck, J., Graham, T. W., Luo, H., Leonard, D. N., & Qu, J. (2014). Ionic liquids composed of phosphonium cations and organophosphate, carboxylate, and sulfonate anions as lubricant antiwear additives. *Langmuir*, 30(44), 13301–13311.
- Zhou, Y., & Qu, J. (2017). Ionic liquids as lubricant additives: A review. *ACS Applied Materials and Interfaces*, 9(4), 3209–3222.
- Zhu, L., Zhao, G., & Wang, X. (2017). Investigation on three oil-miscible ionic liquids as antiwear additives for polyol esters at elevated temperature. *Tribology International*, 109(2017), 336–345.
- Zhu, L., Zhao, Q., Wu, X., Zhao, G., & Wang, X. (2016). A novel phosphate ionic liquid plays dual role in synthetic ester oil: From synthetic catalyst to anti-wear additive. *Tribology International*, 97(2016), 192–199.
- Zulkifli, N. W. M., Azman, S. S. N., Kalam, M. A., Masjuki, H. H., Yunus, R., & Gulzar, M. (2016). Lubricity of bio-based lubricant derived from different chemically modified fatty acid methyl ester. *Tribology International*, 93(2016), 555–562.
- Zulkifli, N. W. M., Kalam, M. A., Masjuki, H. H., Shahabuddin, M., & Yunus, R. (2013). Wear prevention characteristics of a palm oil-based TMP (trimethylolpropane) ester as an engine lubricant. *Energy*, 54, 167–173.
- Zulkifli, N. W. M., Kalam, M. A., Yunus, R., & Masjuki, H. H. (2011). Anti-Wear Characteristics of Jatropa Trimethylolpropane (TMP) Ester. *Proceedings of Regional Tribology Conference 2011*, 6(2), 1–4.