

Tool Texturing and Machinability of Nickel-based Superalloys- A Review

Adam Khan M and Kapil Gupta

Mechanical and Industrial Engineering Technology,
University of Johannesburg, Doornfontein Campus, South Africa
e-mail: adamkhanm@gmail.com, kgupta@uj.ac.za

Abstract

Superalloys are high performance materials used in aerospace, chemical, scientific, and military applications. Machining of these alloys is challenging and to obtain better machinability, it is mandatory to follow some sustainable ways. This paper presents a review of work conducted on machinability of nickel-based superalloys and discusses the novel tool texturing for machinability enhancement of difficult-to-machine materials. It first presents an introduction of nickel-based superalloys, discusses some tool wear aspects, reviews some of the important literature which is then followed by a separate discussion on tool texture based machining. The aim of this paper is to facilitate researchers and scholars working in the field of advanced and sustainable machining of difficult-to-machine materials, and to promote future research and innovations to establish the field further.

Keywords

Machinability, Machining, Superalloy, Texture, Tool wear

1. Introduction

Nickel based superalloys are the high-performance material used for many engineering applications. These alloys are preferably used for high temperature applications such as in aviation jet engines, nuclear reactors, and power plants etc. (Mouritz, 2012; Ezugwu et al., 1999). In the last two decades, the demand of superalloys has been tremendously increased. Superior mechanical properties and performance under high thermal operating conditions have increased its demand. Machining of superalloys is a challenge with the existing conventional machining processes (Pervaiz et al., 2014). Selection of appropriate machining process with optimal process parameter and cutting tool combination is the most important task. These alloys are highly difficult-to-machine (DTM) materials and result in poor machinability while machining by conventional turning, milling, and drilling processes (Guo et al., 2009; Thakur et al., 2009). Low thermal conductivity and high work hardening rate make its machining challenging and result in rapid tool wear, work surface quality deterioration, increased cutting fluid consumption, and overall escalated machining cost. It compels to explore new ways to machine these alloys. Several studies have been conducted on investigation on tool wear and other machinability indicators while machining these alloys (Guo et al., 2009; Thakur et al., 2009; Anthony et al., 2017). It is reported that the poor thermal conductivity and work hardening of the alloy induce to produce high temperature while machining superalloys which results in frequent tool wear under severe machining conditions and consequently escalated machining cost with high energy and resource consumption.

It is important to understand the mechanism of machining involved in various materials. In order to enhance the machinability of engineering materials, specially, DTM materials, there are many ways such as using green lubricants and sustainable lubrication techniques, selection of appropriate tool materials and coatings, tool treatments, and optimizing machining parameters etc (Gupta and Laubscher, 2017).

Study of work-tool interface is also important which leads to the possible interaction and machining mechanism to be happened and consequently the tool behavior and generation of forces etc. It is worth mentioning that based on the cutting tool geometry, the interaction between the cutting tool and the workpiece varies. During machining, with reference to the cutting tool speed and the tool geometry, the materials are induced to remove. Material removal will be in the direction of resultant of shear angle (Grzesik, 2017). Figure 1 illustrates the fundamental of tool velocity and cutting geometry of metal cutting. Where; V_c – chip velocity, V_t – tool velocity, V_s – shear velocity, α – rake angle and ϕ – shear angle. There are two regimes in the chip flow direction. Sliding zone and sticking zone are the two major regimes found influencing the tool failure (Figure 2). Sticking zone is directly induced at the shear plane

and the length depends on the material behaviour. The ductile material leads a maximum sliding zone and brittle material with minimum length. On other hand, the shear force induced during plastic deformation of the material will affect the cutting tool edge. It also depends on the mechanical properties of the work material. When the material hardness is more, the severity of the wear will be high compared to soft material. Figure 3 illustrates the cutting tool nose failure. Flank wear is adjunct to the contact layer and decides the quality of the machined surface. Crater wear remains in direct contact with the sliding of hard metal chips lead to the plugging of cutting tool material.

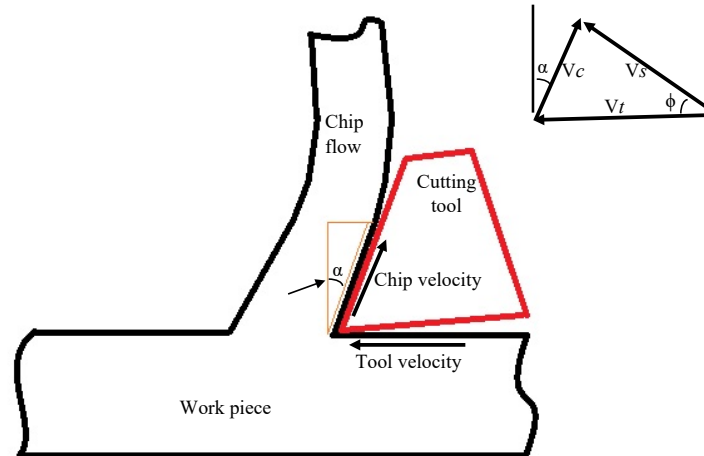


Figure 1. Basic geometry to illustrate the chip-tool interface on metal cutting.

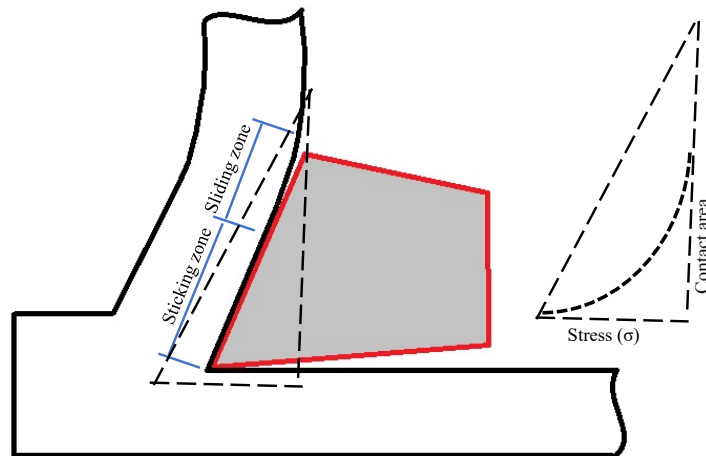


Figure 2. Stress rate distribution on chip and cutting tool interface regimes.

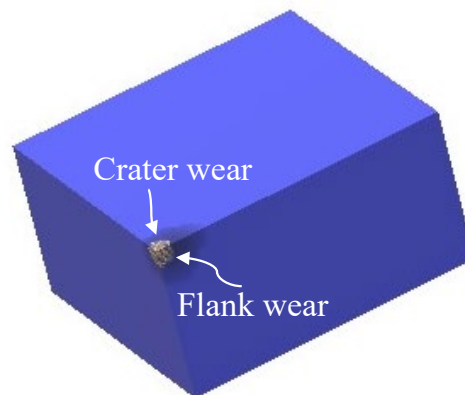


Figure 3. Cutting tool nose failure with flank and crater wear.

Next section reports the review of important literature on tool wear during machining superalloys and provides insights on tool texturing technique for the machinability enhancement.

2. Discussion

Different cutting tools have been used for machining of superalloys. Alumina based ceramic tools and carbide cutting tools have been most commonly used for machining superalloys. Among the cutting tools, carbide inserts are the most affordable. Micro chipping and notch wear are the major issues on machining nickel alloys using carbide tools (Thakur et al., 2009). But, the adhesion wear is the most prominent wear phenomenon while machining superalloys (Akhtar et al., 2014). Notch wear with severe plastic deformation was also reported a major cause of failure on ceramic tools while machining superalloys (Altin et al., 2007). During dry machining, welding and adhesion of the work material onto the rack and flank faces of the tool, due to high friction, was identified as the major reason of the tool failure (Devillez et al., 2007). Another interesting study reports the excellent performance of Borazon cutting tools which facilitated high speed machining of superalloys with less tool wear (Flocke et al., 1978). Even PCBN tools were also recommended for high speed machining of superalloys (Uhlmann and Ederer, 2001). During minimum quantity lubrication based machining of Inconel-718, Xavior et al. (2016) studied that carbide tools are unable to prevent the rapid tool wear with increase in cutting speed, whereas ceramic and CBN outperformed. D' Addona et al. (2017) conducted an analysis of low to high speed machining of Inconel 718 superalloys conducted by coated carbide inserts. At low speed, no tool damages were observed except nose radius wear with traces of peeling coating. But, at high speed, progressive tool wear with heavy notching was observed. The wear behavior of PCBN tool during high speed machining of Inconel-718 alloys was investigated by Tanaka et al. (2016). It was concluded that the cutting speed and material structures play important role in determining tool life. Moreover, PCBN tool with a low CBN content with TiN-based ceramic binder possesses superior resistance to wear when machining at high speed conditions.

Literature review reveals that the different grades of cutting tools have been used to machine the nickel-based superalloys. Specifically, research studies on machining of Inconel 718 have been conducted more and still researchers can show attention to investigate the machinability of other nickel alloys such as Inconel 600, hastelloy, udimet, etc. The modifications and treatment on cutting tool inserts for machinability enhancement can also be considered as an innovative aspect in future research. Tool texturing, coating, and cryogenic treatment etc. can be novel aspects. Research on cutting tool texture for superalloy machining was found as a major research gap.

2.1 Cutting Tool Texturing

During machining, cutting fluids are used to reduce the friction and thermal effect on the cutting edge of the tool inserts. As an outcome, serious, health issues are raised on using different cutting fluids. To eliminate these severity, the cutting tool modifications are introduced. One of the methods used on cutting tool modification is tool texturing. The tool texture dimensions can be in the range of nano-to-micro level. The aim of tool texturing is to reduce the friction, manage the machining heat, and facilitate chip removal (Gajrani et al., 2018). There are different shape and size of the tool texture exist in the current research. Some of the common textures are dimples, holes, grooves and tracks in different angles.

Tool texturing deals with the wettability, friction and surface mechanism. There are different techniques followed to make tool texture on the cutting tools. In current research scenario, the tool texturing is accomplished from laser engraving, ion beam texture process, electro-discharge machining, electrochemical processing and photolithography techniques (Wu et al., 2012; Wong et al., 2003; Etsion, 2005; Chang et al., 2011; Chen et al., 2016). Laser source texturing has high demand and remarkable benefits compared to other techniques.

Xing et al. 2014 explored the tool wear and its mechanism on textured cutting tool. It has been confirmed that the tool wear has been drastically reduced with textured cutting tool. Especially, the cutting force and tool wear on conventional tool was more when compared to textured tool. It has been reported that the life of the cutting tool has been increased up to 30% with reference to regular conventional cutting tool. The main aim of the tool texturing is to reduce the work-cutting tool contact area, entrapped the metal chips and wear debris, to stockpile lubricants and also to increase the load carrying capacity of the cutting tool.

Different design in texture may support to reduce the tool-work interface and reduction in friction. Figure 4 shows the different types of micro channels and patterns used for cutting tool texturing.

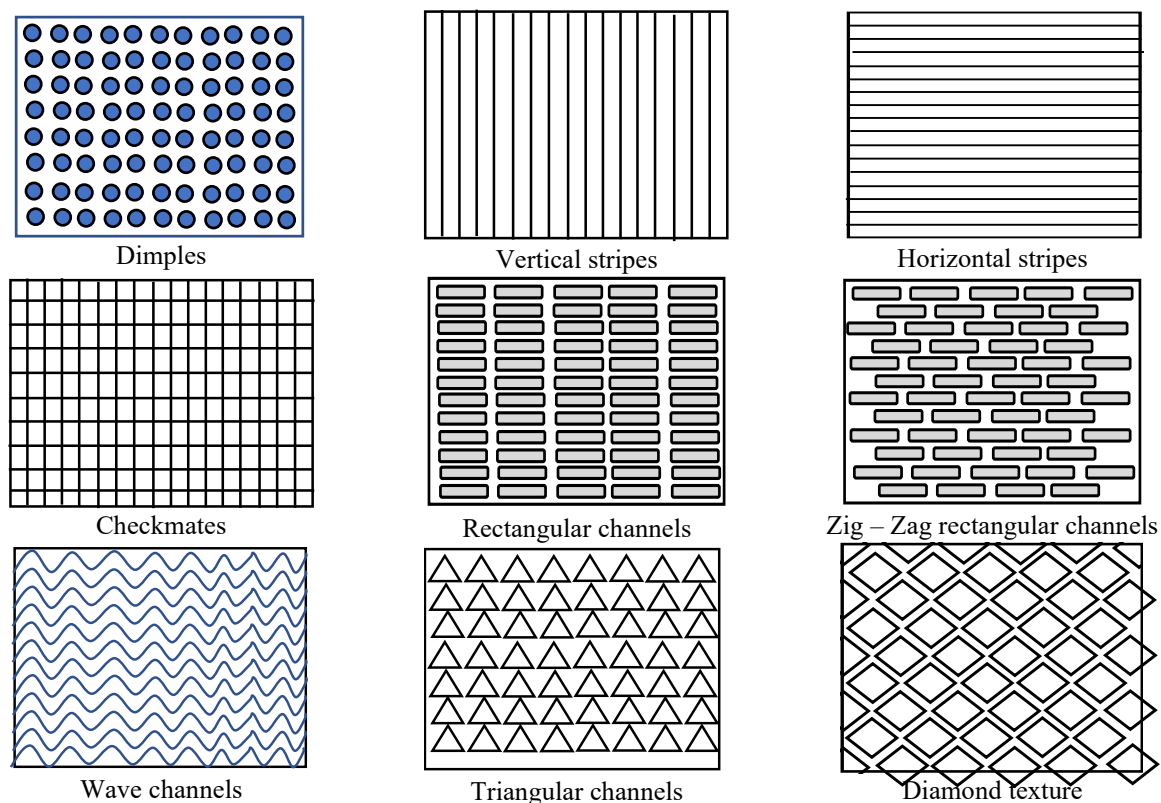


Figure 4. Representation of different cutting tool textures used for machinability enhancement for various engineering materials.

For texture design, the minimum dimension of 2 x 2 mm surface area is required for laser surface engraving. The allowable depth of laser engraving is to a limit of 50 microns. The regular pitch dimensions should be maintained in all direction for better heat dissipation. The inability in design of effective cutting tool texture may lead to induce maximum cutting force and thermal stress. Thus, the geometry of every cutting tool surface texture after engraving is very important to analyze. Figure 5 shows the actual images of the texture patterns used over carbide cutting tool. The surface texture has a uniform dimension throughout the surface texture of the laser engraved samples. Dimensional clearance on embossed surface can be maintained with optimized laser process parameters and laser sources. Tatsuya 2017 developed dimple textures on cutting tool with standard dimensional clearances. From the series of experiments performed, the wear mechanism and welding of work material towards the dimple are investigated. It has been conferred that texture dimensions and nomenclatures are high influencing the anti-adhesion of work material.

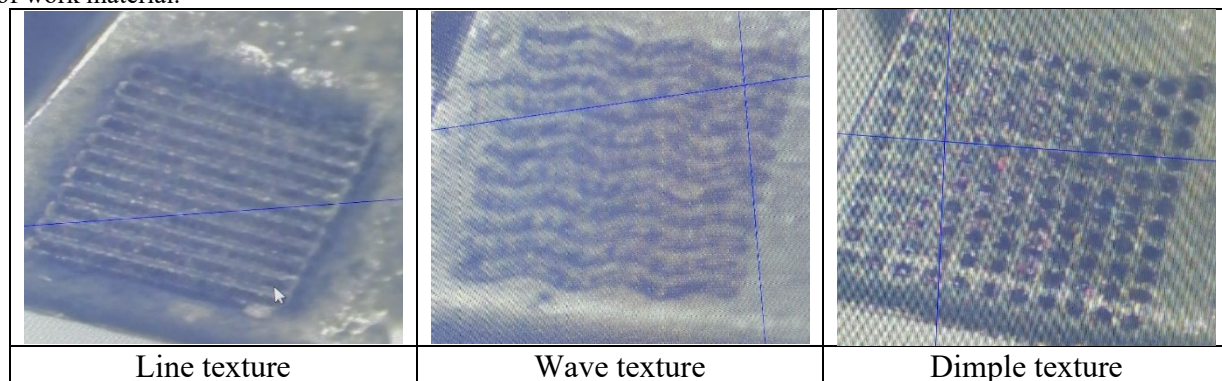


Figure 5. Actual images of the textures

The basic dimensional requirements for tool texturing are important and mandatory to be considered. Some of the nomenclatures are texture external diameter (D_{ext}), internal diameter (D_{int}), horizontal pitch (P_H), vertical pitch (P_V) and tool nose clearance (T_c). Figure 6 represents the geometrical design for dimple texture. Same parameters have to be maintained in parallel or zig – zag texturing of cutting tool. The reason for these dimensions is to avoid thermal stress and surface damage due to the laser heat source used for engraving the cutting tool.



Figure 6. Basic geometrical consideration for dimple tool texturing

Other than laser texturing, researchers have also used some conventional and unconventional techniques to modify the cutting tool radius. To improve the efficiency of cutting tool-work interface efficiency, Jesudass et al. 2017 applied conventional diamond tips of vickers hardness, rockwell hardness and diamond dressing tool to mark profile. Using these tools, dimples and scratches are produced for machining of stainless steel.

While machining with the textured tools, powder solid particle lubricants are widely used. The solid particle lubricants are spreaded to be filled in the texture pattern before machining. Presence of solid lubricants during machining manages the amount of heat generated. In the above shown laser textures, the surface area developed is in line tracks. Literatures are available and discuss the combined effect of tool texture and solid lubricants. The maximum amount of lubricants is stored over the surface textures and supports to dissipate the heat on machining.

From the literature, it is clear to infer that the grooves, lines and waves are more effective than the simple dimples textures. Deng et al. 2012, used MoS_2 as a solid lubricant with surface texture cutting tools for machining studies. Research explored with different patterns, in which elliptical grooves filled with MoS_2 solid lubricant has produced good results compared to the parallel or perpendicular grooves. Especially, the patterns and textures designed parallel to the cutting edge has produced better results than the perpendicular textures (Obikawa et al., 2011; Obikawa and Kani, 2012). Subsequently, it has been proved that the continuous texture has high efficiency with less cutting force, minimum tool wear and best surface finish than the spotted texture (Koshy and Tovey, 2011). Xing et al. 2014 stated that the tungsten disulphide (WS_2) coated ceramic cutting tools with nano textures created by laser texturing had considerably improved the lubricity. Reduction in cutting force, coefficient of friction, tool wear, and cutting temperature were reported for nano textured tools with coatings. It is also suggested that the tool texturing can be done on flank face rather than rake face (Anand et al., 2012).

A detailed study has been made to discuss about the superalloys, machinability of superalloys, machining process and different modifications on cutting tool. Enormous work has been carried out in machining Inconel 718. There are many grades of nickel-based superalloys which has not been focused by many researchers in last two decades. On other hand, in the view of research scope, machining superalloys can be explored more with conventional machining process, modified cutting tool and its process conditions. Therefore, machinability studies can be performed on superalloys with modified cutting tools.

3. Conclusions

Machinability aspects of nickel-based superalloys are discussed in this paper. It presents the review of some past work conducted on its machinability investigation and discusses tool texturing techniques for machinability enhancement. The following points are drawn as a conclusion:

1. Extensive research work has been conducted on investigation on machinability of nickel-based superalloys. Especially Inconel 718 has been investigated in detail which creates a future scope to study the machinability of other superalloys.
2. Conventional cutting tools especially made of carbides are widely used in existing research. The modification in cutting tool can be the major topic in forth coming research.

3. Textured tools have potential to overcome the machining challenges and can be explored in case of nickel-based superalloys.

Acknowledgments

This work is supported by DHET University Capacity Development Grant (UCDG) 2019, University of Johannesburg, South Africa.

References

- Akhtar, W.; Sun, J.; Sun, P.; Chen, W.; Saleem, Z, Tool wear mechanisms in the machining of Nickel based superalloys: A review. *Frontiers of Mechanical Engineering*, 9 (2), 106–119, 2014.
- Mouritz, A.P., *Introduction to Aerospace Materials*, Woodhead Publishing Limited, Cambridge UK, 2012.
- Ezugwu, E.O., Wang, Z.M., and Machado, A.R., The machinability of nickel-based alloys: a review, *Journal of Materials Processing Technology*, vol. 86, pp. 1 – 16, 1999.
- Pervaiz, S., Rashid, A., Deiab, I., and Nicolescu, M., Influence of Tool Materials on Machinability of Titanium- and Nickel-Based Alloys: A Review, *Materials and Manufacturing Processes*, vol. 29, pp. 219 – 252, 2014.
- Guo, Y.B., Li, W., and Jawahir, I.S., Surface integrity characterization and prediction in machining of hardened and difficult – to – machine alloys; a state-of-the-art research review and analysis, *Machining Science Technology*, vol. 13, pp. 437 – 70, 2009.
- Thakur, D.G., Ramamoorthy, B., and Vijayaraghavan, L., Study on the machinability characteristics of superalloy Inconel 718 during highspeed turning, *Materials and Design*, vol. 30, pp. 1718–1725, 2009.
- Xavior, M.A., Manohar, M., Jeyapandiarajan, P., and Madhukar, P.M., Tool wear assessment during machining of inconel 718, *Procedia Engineering*, vol. 174, pp. 1000 – 1008, 2017.
- Thakur D.G., Ramamoorthy, B., and Vijayaraghavan, L., Machinability investigation of Inconel 718 in high-speed turning, *International Journal of Advance Manufacturing Technology*, vol. 45, pp. 421–429, 2009.
- Nalbant, A.A., and Taskesenl A., The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools, *Materials and Design*, vol. 28, pp. 2518–2522, 2007.
- Devillez, A., Coz, G.L., Dominiak, S., and Dudzinski, D., Cutting forces and wear in dry machining of Inconel 718 with coated carbide tools, *Wear*, vol. 262, pp. 931–942, 2007.
- Focke, A.E., Westermann, F.E., Kemphaus, J., Shih, W.T., and Hoch, M., Wear of super hard materials when cutting superalloys, *Wear*, vol. 46, pp. 65-79, 1978.
- Uhlmann, E., and Ederer, G., High speed turning of Inconel 718, *Industrial Diamond Review*, vol. 61, pp. 169-74, 2001.
- Wu, Z., Deng, J.Z., Xing, Y.Q., Cheng, H., and Zhao, J., Effect of surface texturing on friction properties of WC/Co cemented carbide, *Materials and Design*, vol. 41, pp. 142–149, 2012.
- Wong, W., Chan, K., Yeung, K.W., and Kai, S.L., Surface structuring of poly (ethylene terephthalate) by UVexcimer laser, *Journal of Materials Processing Technology*, vol. 132, no. 1–3, pp. 114–118, 2003.
- Etsion, I., State of the art in laser surface texturing, *Journal of Tribology*, vol. 127, no. 1, pp. 761–762, 2005.
- Chang, W.L., Sun, J.N., and Luo, X.C., Investigation of micro structured milling tool for deferring tool wear, *Wear*, vol. 271, no. 9, pp. 2433–2437, 2011.
- Chen, X.L., Qu, N.S., Li, H.S., Xu, Z.Y., Electrochemical micromachining of micro-dimple arrays using a polydimethylsiloxane (PDMS) mask, *Journal of Materials Processing Technology*, vol. 229, pp. 102–110, 2016.
- Xing, Y.Q., Deng, J.X., Zhao, J., Zhang, G., and Zhang, K., Cutting performance and wear mechanism of nanoscale and microscale textured Al₂O₃/TiC ceramic tools in dry cutting of hardened steel, *International Journal of Refractory Metals and Hard Materials*, vol. 43, no. 3, pp. 46–58, 2014.
- Sugihara, T., Singh, P., and Enomoto, T., Development of novel cutting tools with dimple textured surfaces for dry machining of aluminium alloys, *Procedia Manufacturing*, vol. 14, pp. 111 – 117, 2017.
- Thomas S.J., and Kalaichelvan K., Comparative study of effect of surface texturing on cutting tool in dry cutting, *Materials and Manufacturing Processes*, vol. 33, no. 6, pp. 683 – 694, 2017.
- Deng, J.X., Wu, Z., Lian, Y.S., Qi, T., and Cheng, J., Performance of Carbide Tools With Textured Rake-face Filled with Solid Lubricants in Dry Cutting Processes, *International Journal of Refractory Metals and Hard Materials*, vol. 30, pp. 164-172, 2012.

- D' Addona, D.M.; Raykar, S.J.; Narke, M.M., High speed machining of Inconel 718: tool wear and surface roughness analysis. *Procedia CIRP* 62, 269 – 274, 2017.
- Obikawa, T., Kamio, A., Takaoka, H., and Osada, A., Micro-texture at the Coated Tool Face for High Performance Cutting, *International Journal of Machine Tools and Manufacture*, vol. 51, no. 12, pp. 966 – 972, 2011.
- Obikawa, T., and Kani, B., Micro Ball End Milling of Titanium Alloy Using A Tool with A Microstructured Rake Face, *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, vol. 6, no. 7, pp. 1121-1131. 2012.
- Koshy, P., and Tovey, J., Performance of electrical discharge textured cutting tools, *CIRP Annals – Manufacturing Technology*, vol. 60, no. 1, pp. 153-156, 2011.
- Xing, Y.; Deng, J.; Li, S.; Yue, H.; Meng, R.; and Gao, P., Cutting Performance and Wear Characteristics of Al₂O₃/TiC Ceramic Cutting Tools with WS₂/Zr Soft-Coatings and Nano-Textures in Dry Cutting. *Wear*, vol. 318, pp. 12–26, 2014.
- Xavior, M.A.; Patil, M.; Maiti, A.; Raj, M.; Lohia, N., Machinability studies on INCONEL 718. IOP Conf. Series: Materials Science and Engineering 149 (2016) 012019 doi:10.1088/1757-899X/149/1/012019.
- Anand, A., Yadav, A.K.S., and Jayal, A.D., Influence of cutting tool flank surface texture in dry metal machining, *Proceedings of the International Conference on Advancements and Futuristic Trends in Mechanical and Materials Engineering*, Punjab Technical University, Kapurthala, India, October 5-7, 2012, 2012.
- Gupta, K., and Laubscher, R.F., Sustainable Machining of Titanium Alloys- A Critical Review, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 231, no. 14, pp. 2543 – 2560, 2017.
- Grzesik, W., *Advanced Machining Processes of Metallic Materials: Theory, Modelling and Applications*, 2nd Edition, Elsevier, Amsterdam, Netherland, 2017.
- Gajrani, K.K., Suresh, S., and Sankar, S.M., Environmental friendly hard machining performance of uncoated and MoS₂ coated mechanical micro-textured tungsten carbide cutting tools, *Tribology International*, vol. 125, pp. 141 – 155, 2018.
- Tanaka, H.; Sugihara, T.; Enomoto, T., High speed machining of Inconel 718 focusing on wear behaviors of PCBN cutting tool. *Procedia CIRP* 46, 545 – 548, 2016.

Biographies

Adam Khan M is working as a Post-Doctoral Research Fellow in the Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, South Africa. He received his Doctoral Degree from National Institute of Technology, Tiruchirappalli, India for his research in Surface Engineering studies on high temperature materials. His Bachelor and Master Degrees are from Anna University, Chennai in the specialization of Production and Design. Materials processing, surface engineering, advanced machining, and metallurgy are the areas of his interest and specialization. He has published over twenty five articles in the international journals of repute.

Kapil Gupta is working as Associate Professor in the Dept. of Mechanical and Industrial Engineering Technology at the University of Johannesburg. He obtained Ph.D. in mechanical engineering with specialization in Advanced Manufacturing from Indian Institute of Technology Indore, India in 2014. Advanced machining processes, sustainable manufacturing, green machining, precision engineering and gear technology are the areas of his interest. He has authored several SCI/ISI Journal and International Conference articles. He also authored and edited 10 international books on hybrid machining, advanced gear manufacturing, micro and precision manufacturing, and sustainable manufacturing with the renowned international publishers. He has also successfully guest edited special issues of a Scopus indexed journals and he is currently editing a series of handbooks on Advanced Manufacturing as a series editor. He is a recognized reviewer of many international journals and in the advisor/technical committees of international conferences. He has also delivered invited speeches in international conferences and symposiums, and seminar talks at international universities. Kapil Gupta is a NRF [National Research Foundation] rated Researcher in South Africa. Currently, he is supervising 8 Masters and 4 Doctorate students who are busy conducting research in advanced manufacturing and industrial engineering fields.