A Comprehensive Review on Friction and Wear Behaviour in Cutting Tools

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Abstract: Friction and wear are essential tribological processes that directly affect the life, machining precision, energy usage and total productivity used in manufacturing processes. The review will offer an in depth study of frictional interactions and dominant wear mechanisms that take place at the tools-chip and tools-workpiece interfaces during metal cutting. The experiment generalizes the results of a broad selection of materials of the tools, surfaces, lubrication methods and machining conditions. Disproportionate attention is given to adhesive, abrasive, diffusion, and oxidative wear mechanisms and their behavior with respect to cutting temperature, stress distribution, work material properties, and tool geometry. Recent developments in surface engineering which include multilayer nanocomposite coatings, DLC coatings, plasma nitriding and laser texturing- are pointed out as effective in friction reduction and wear resistance. Also, new cooling and lubrication methods such as cryogenic machining, nanofluid-assisted MQL, and hybrid cooling systems have been mentioned with regard to their role in sustainable machining. Computation modelling techniques such as FEM and molecular dynamics analysis are also discussed due to their emergent application in the prediction of frictional behaviour and tool degradation. On the whole, the given review determines the main technological advances, current shortcomings, and the prospective research areas that should be addressed to improve the performance of tools used in contemporary high-speed and precision machining.

Keywords: Cutting tools; Friction behaviour; Wear mechanisms; Tool–chip interface; Adhesive wear; Abrasive wear; Diffusion wear; Oxidation wear; Tool coatings; Surface texturing; DLC coatings; TiAlN coatings; Cryogenic machining;

I. INTRODUCTION

Machining is a basic manufacturing process in the automotive industry, aerospace, biomedical, energy, defence and as a precision engineering process. The performance and the durability of cutting tools is a crucial factor to the functional effectiveness of machining processes, stability, and economic viability. The environment in cutting tools is highly aggressive in nature, as there are high contact pressure, severe plastic deformation, high temperature, dynamic mechanical loading and complex chemical interaction between the tool-work-chip interfaces. In these circumstances, the prevailing tribological processes that control tool life, tool failure processes, machining forces, heat production, chip morphology, surface integrity of the machined part, and productivity in general are friction and wear. Frictional behaviour of cutting tools depends on a number of coupled parameters which include tool material composition, microstructure, coating architecture, topography of the surface, lubrication and cooling strategy, cutting parameter, and workpiece material thermo-mechanical properties. The coefficient of friction at the tool-chip interface during machining is generally larger than that of a conventional tribological contact because the strain-rate effects are extremely strong and the temperatures at the chip interface are very high. These high levels of friction cause the excessive heat production that leads to localized softening, oxidation, diffusion or thermal cracking of the tool material. Therefore, friction control is key to the control of wear advancement and tool stability in diverse machining conditions. The wear of cutting tools is expressed in different forms such as adhesive wear, abrasive wear, diffusion wear, oxidation wear, thermal-fatigue wear, chipping and coating delamination. The interaction between local temperature, chemical reactivity between tool and workpiece materials, environmental conditions, and mechanical stresses at the cutting edges affect each wear mechanism. As an example, carbide tools undergo diffusion wear when machining nickel-based alloys at high speeds, but PCD and PCBN tools are very resistant to abrasive wear but quite vulnerable to thermal wear. Knowledge of such wear modes is fundamental to the development of predictive relationships that can identify the relationships between cutting conditions and tool degradation and machining quality. Other factors that have worsened tribological issues are the increased industrial applications of high work materials like titanium alloys, Inconel, hardened steel, fibre reinforced composite, and high-entropy alloys. These materials are usually low thermal conductivity, hard and chemically drawn to tool materials as well as have complex microstructure heterogeneity. Consequently, friction and wear behaviour is intensified resulting in premature failure of the tool, unstable machining behaviour and high production costs. Therefore, the need to have cutting tools with high tribological capability led to the development of tool coating and textured tool, nano-composite and self-lubricating material systems. A further significant aspect is the development of lubrication and cooling policies. The environmental and operational challenges of the traditional flood cooling are also a problem, although effective. Recent methods, including minimum quantity lubrication (MQL), cryogenic lubrication either with LN2 or CO2, hybrid cryo-MQL, and nano-lubricant compositions have demonstrated the possibility of reducing significantly the cutting temperatures, friction coefficients and wear rates. These plans are in line with the worldwide trend of sustainable and green manufacturing whereby the concern of reducing the use of coolant and energy is put at the forefront.

II. LITERATURE REVIEW

Smith and Rao (2015) have conducted an initial study of tribological processes at the toolchip interface during high-speed machining of hardened steels. The experiment also measured the coefficients of friction as variables of cutting speed, rake angle and tool-work-material combinations. A close relationship between the temperature of contact and the wear intensity of adhesive was found by using in-situ force sensors and embedded thermocouples. It was noted that an increased cutting speed decreased the built-up of edges and at the same time increased crater wear rate by transferring material to the cutting edge by diffusion. Besides, it was also observed that the rake angle variations had a strong influence on the stress distribution and chip-flow mechanics, which influenced the friction magnitude. The paper has emphasised the need to maximize the geometry of the tool and control thermal loads to reduce the rate of wear. In general, the study presented valuable theoretical and experimental knowledge that can be used to develop predictive models of friction and enhanced tool designs in high speed machining conditions.

Kumar et al. (2016) studied the progression of the wear in uncoated carbide inserts during machining of the Inconel 718, which is a high thermal conductivity and severe work hardening material. Abrasive and diffusion wear were found to be the dominant wear mechanisms at high temperatures as a result of extended machining tests with SEM and EDX analysis. Flank wear was significantly greater after interface temperatures had reached 850 o C, which was a sign of rapidly softening carbide substrate and micro-structural instability. The results indicated the prone nature of WC-Co tools to cobalt wear and grain pull out, during the high-temperature machining. The paper also highlighted the importance of thermally resistant coating, more effective cooling procedures, and better lubrication schemes as one of the ways of controlling superalloy machining heat. The authors added valuable knowledge by describing temperature-based degradation processes, which are helpful in the selection of materials to be used in tools and process-parameter optimisation of hard-to-machine aerospace alloys.

Zhang and Chen (2017) conducted an organized literature review to determine the usefulness of tool-surface texturing as a friction-reduction method during dry machining. There were micro-dimples made on carbide inserts of different diameter and density by laser light, and they were evaluated under conditions of control machining. The findings indicated high decreases in friction coefficient, cutting forces and interface temperature with the use of textured tools.

The micro-dimples served as micro-reservoirs that trapped debris and weakened adhesion, as well as in the discontinuous contact of chip and tool surface. SEM analysis showed less adhesive wear and a less rugged wear, when compared to non-textured tools. The authors were able to conclude that surface texturing has an effect on the dynamics of chip-flow, reduces accumulated edges, and promotes tribological stability. The research presented good pieces of evidence to support the concept of texturing as a passive and sustainable method of lengthening tool life in dry machining and where lubricants are limited or otherwise unwarranted by environmental reasons.

The study by Lee et al. (2017) involved an in-depth analysis of TiAlN PVD coating when machining titanium alloys with a high-speed tool. They used microhardness tests, XRD phase analysis, and detailed crater-wear mapping, which revealed that TiAlN coating retains hot hardness and structural stability at temperatures that are above 800 C. It was revealed that as machining continues, the coating develops a protective Al 2 O 3 tribo -film, which provides thermal protection and greatly prevents oxidation and diffusion wear. The paper has brought to the fore the capacity of the coating to alleviate crater wear on rake faces and flank wear on cutting edges. Moreover, it was determined that thermal conductivity discrepancy between the workpiece and tool has a powerful influence on heat partitioning and tribological reaction, especially in low-conductivity titanium alloys. The authors concluded that significant selection of coating chemistry and deposition structure is necessary in order to attain a longer tool life, and a uniform behavior at high-temperature cutting.

To compare the effect of flood cooling and minimum-quantity lubrication (MQL) in machining of AISI 1045 steel, a comparative analysis was performed by Hussain and Patel (2018) in order to determine their effect on friction and tool wear. As a result of their experiments, they found MQL reduced cutting temperature and friction coefficient considerably because of developing a thin lubricating film at the tool–chip interface. Nevertheless, the nozzle positioning, the direction of spray and the flow rate of lubricant were very critical to the effectiveness. SEM inspection showed significant less wear of adhesives and smoother surface on tools in the MQL circumstances. The authors highlighted the fact that MQL was much more energy efficient in its lubrication and used significantly less fluid hence it is an environmentally friendly and economical substitute to flood cooling. Their results highlighted the increased use of MQL in the industrial machining, especially when the machining environment requires better environmental regulation, which involves lowering the use of coolants but without affecting the lifespan of the tool and the machining process.

The paper by Sivakumar et al. (2018) explored the mechanisms of diffusion wear in WC-Co carbide tools when in continuous machining of hardened steel, where high temperatures have a strong impact on wear behaviour. With the help of SEM, EDX, and cross-sectional analysis, significant cobalt binder depletion in the area of the cutting edge was revealed. This loss undermined the carbide structure and made WC grains detach and increase the speed of tool wear. The analysis showed in the study that the diffusion wear increased exponentially with the cutting speed because there was more thermal activation which allowed the tool and the workpiece material to exchange chemical elements. They also found that with long machining, the carbide substrate experiences micro-structural change together with the formation of compositional gradient. To reduce the material transfer between the interface, the authors suggested the use of protective coating that possessed high diffusion-barrier characteristics. Their work provides the fundamental information on the thermally-driven degradation processes and the necessity to control the thermal loads in machining hardened steels.

Thermo-mechanical finite element model (FEM) has been developed by Ozturk and Budak (2019) to forecast the frictional behaviour and temperature development and heat generation during orthogonal cutting. Their simulation consisted of strain-rate sensitivity, material properties that were dependent on temperature, and realistic tool-chip contact conditions. The predictive performance was observed to be high when compared to experimental force and temperature measurements. An important point to note was that of the total heat produced during cutting, frictional heating contributed more than 60 percent, and thus, had a great effect on the tool wear progression. The FEM findings indicated that the effects of tool geometry, friction coefficient and chip formation mechanisms on thermal gradients are significant. Their method made it possible to visualize the stress fields and temperature distributions, which are hard to measure experimentally. This study was a significant breakthrough in computational tribology and implied that the tools of FEM prediction could significantly optimize processes, improve the choice of tools materials, and predict wear during machining.

Garcia et al. (2019) have assessed the ability of diamond-like carbon (DLC)-coated carbide tools to perform the machining of aluminium alloys, materials that experience adhesion-relation wear. They found that their experiments had exceptionally low friction coefficient, and a low rate of built-up edge formation as a result of a smooth, chemically inert surface of DLC coatings. Raman spectroscopy was used to verify Stability of coating in terms of resistance to micro-fracturing after prolonged cutting periods. The SEM analysis indicated that wear at adhesion was significantly lower and surface finish on machined components was also enhanced. These authors credited increased performance levels to the low surface energy and high hardness of the coating which all inhibited material transfer and galling. Their research established that DLC coating is effective in improving the life of tools and machining efficiency especially in cutting soft ductile materials, which tend to stick to the cutting tool. The results justify the wider industrial implementation of DLC-coated tools to reduce the number of failures due to wear and enhance the machining productivity.

Narayanan and Singh (2020) investigated the effects of cryogenic liquid nitrogen (LN2) cooling on turning titanium alloys, paying attention to the minimization of friction and wear. Titanium has low thermal conductivity leading to high intensity of heat around the cutting zone hence beneficial in cryogenic intervention. Their findings indicated that there were significant changes in temperature of tool-chip interface and enhanced heat dissipation. Cryogenic cooling inhibited diffusion wear, softened tools and alleviated damage associated with adhesion. The tool life was more than 40 percent of dry machining and the cutting forces were also observed to be improved. There were reduced shear localizations and smoother flow of chips as found in high-speed imaging. The research paper has shown that cryogenic cooling has tribological and environmental advantages since it lowers the use of traditional flood coolants. Their results give a good basis towards the application of cryogenic systems to high-performance aerospace machining.

Ahmed et al. (2020) have studied the tribological behaviour of multilayer TiSiN-TiAlN coating developed through sophisticated PVD coating methods. Nanoindentation was found to be very hard in nature, whereas tribo-tests had better abrasion resistance because of the alternating nano-layered architecture. The multilayers prevented the crack propagation by facilitating deflection at layers boundaries, which increased toughness of the coating. Experiments with machining proved that it had reduced friction, lower temperature increase and prolonged the beginning of the crater-wear activities contrary to monolayer coating. They found that the layers rich in Si lead to thermal stability whereas those rich in Al lead to the formation of protective oxide during the cutting process. The paper has pointed to the use of Multilayer Coatings as an effective remedy to high-speed machining environment with the need to have enhanced thermal resistance. Their conclusions are applicable to the development of future generations of tool coating with higher level of microstructure and tribo-mechanical characteristics.

Bianchi et al. (2021) examined wear processes in polycrystalline cubic boron nitride (PCBN) tools when hard turning of bearing steels. The use of microscopic observations on them showed that abrasive wear was dominant with micro-chipping being observed along the tool edge. Localized thermal cracks were produced by intermittent cutting conditions which indicated that PCBN tools are susceptible to cyclic heating. PCBN tools could be used with good dimensional accuracy and surface finish, even after usage. The authors pointed out that the tool-edge preparation is important in the control of chipping, whereas the stable cutting parameters minimize the damage due to the thermal fluctuations. Their findings allowed them to gain a better insight into wear behaviour of a superhard tool, and they noted both the benefits and shortcomings of PCBN in machining with high stress.

Wang and Zhao (2021) assessed hybrid lubrication with MQL that uses nanofluids to machine the AISI steels and added Al2O3 nanoparticles in bio-degradable oil. Their experiments exhibited better thermal conductivity and the stability of the lubrication film because of the dispersion of nanoparticles. Friction coefficients and temperatures were reduced considerably resulting in decreased flank wear as well as reduced surface finish. The SEM analysis showed that there was a thin tribo-film that was formed on nanoparticles and it served as protective coating against adhesion and abrasion. Their experiment established that nanofluid-MQL lubrication is more effective in wear reduction and environmental sustainability as compared to conventional MQL and flood cooling. They also came to the conclusion that the size of nanoparticles properties, their concentration, dispersion stability determine the performance of lubrication and machinability significantly.

Thomas et al. (2021) concentrated on the mechanics of built-up edge (BUE) formation during machining of the low-carbon steels. Their experiments have confirmed that the rate of cutting, the rake angle and workpiece microstructure are some critical factors that affect the stability of BUE. The adhesion caused excessive sticking together of the tool and work material resulting in erratic friction behaviour and abrupt variation of cutting forces. Formation of BUE changed geometry of the tool, as well as accelerating the wear rate of the tools and worsening surface quality. SEM visualized that the interface had repeated adhesion-fracture cycles. The authors stressed that it is necessary to optimize the geometry of tools and machining parameters in order to inhibit BUE. Their results were useful towards making improvements on the reliability of the tools and the machining stability of ductile materials.

Kawamura et al. (2022) studied CVD AlCrN coating when machining nickel-based superalloys, paying attention to the oxidation and high-temperature wear behaviour. Their findings revealed that the coating generates a thick Cr2O3 protective layer during cutting, and thus the coating minimizes crater wear and stabilizes friction at high temperatures. Tests of hardness and thermal stability proved that AlCrN coating is superior to those based on Ti when used in intense machining. Characteristics of SEM and XRD showed the delayed crack initiation and higher strength of adhesion. The authors came to the conclusion that AlCrN coating is the best to use in extreme machining conditions at high thermal loads and at high chemical reactivity. Their labor justifies the use of high-technology ceramic-based howe in the energy and aerospace fields.

In their study, Reddy and George (2022) examined ultrasonic-assisted machining (UAM) as an approach to minimize friction and tool wear in machining hard-to-cut materials. They found that the intermittent contact between the tool and the workpiece associated with high frequency ultrasonic vibrations superimposed on cutting motion reduced friction and heat generation. The forces required to cut were reduced to a minimum of 25 percent and SEM images showed lesser adhesive and abrasive wear of tool edges. The authors have observed the enhanced chip breakability and surface integrity. They were able to show that UAM has an effect on contact mechanics and chip flow behaviour, providing significant advantages to machining hard-to-cut materials. They promoted the additional enhancements of the UAM industrial tools.

The article by Morita et al. (2022) examines tribo-chemical wear in ceramic tools when machining cast iron and particularly the formation of the oxide-layer and the fracture behaviour. They found that machining temperatures favored the development of brittle oxide layers, which fractured on shear loads many times, increasing the rate of edge wear in tools. SEM and XRD analysis proved the existence of Fe-O and Si-O compounds that caused micro-cracking. The authors noted that despite ceramic tools being excellent in terms of hardness and thermal stability, they have low fracture toughness hence easily worn out in thermally varying conditions. They argued that better ceramic formulations and coating strategies should be developed in order to increase the wear life of tools.

Silva and Rodrigues (2023) conducted the FEM-based study of coating delamination in multilayer PVD-coated tools under the influence of high temperatures and cyclic forces. Their model took into account the interlayer adhesion strength, residual stresses and thermal mismatch between the coating and substrate. Findings indicated that delamination mainly happened at high tensile stress concentration interfaces. The model was proven accurate by machining trials that were experimental and predicted delamination regions. Their results revealed that the coating architecture such as the layer thickness and the composition is a decisive factor towards wear resistance. The article justifies the application of simulation tools to optimize coating structures and enhance the reliability of tools in terms of extreme machining conditions.

Lopez et al. (2023) researched the micro-geometry of edges on friction and wear of carbide tools. Comparing sharp, honed and chamfered edges in machining tests and they found that the honed edges shared stresses more equally, greatly decreasing micro-chipping and stabilizing frictional response. High stress concentration brought about by sharp edges resulted in wear initiation and irregular surface finish. Unflanked edges enhanced the life of the tools, but raised cutting forces. The conclusion of the authors was that edge preparation should be optimized to work material and cutting conditions in order to control optimally tool wear behaviour. Their labor gave valuable guidelines in production of cutting tools of high performance.

Banerjee and Mukherjee (2023) analyzed the surface modification process of high-speed steel (HSS) tools plasma nitriding. Their results indicated that they greatly enhanced their hardness, reduced their friction and wear resistances because of the development of a hard Nitrogen-laden diffusion layer. The nitrided surface provided a hard lubricant, which minimized adhesive wear and improved the load-bearing capacity. The trials of machining showed reduced flank wearing and fewer tool-chip interactions. The authors emphasized the use of nitriding as an inexpensive improvement technique to increase the service life of the HSS tools in the moderate duty machining processes.

Yadav et al. (2024) compared the hybrid cooling with the combination of CO2 cryogenic jets and MQL lubrication on hardened steels machining. Their experiment showed that cutting temperature, friction coefficient and tool wear was reduced significantly when one of the two cooling methods was used independently. The hybrid system enhanced the chip movement, minimized cutting forces, and better surface finish. SEM analysis revealed low adhesion and less wear patterns. In their work, they have shown that synergistic action of cryogenic cooling and MQL forms an optimum thermal-lubrication environment and hence hybrid cooling is a good solution towards the sustainable high-performance machining.

Park and Kim (2024) examined the thermo-mechanical fatigue in carbide tools in interrupted machining of alloy steels. They monitored rapid oscillations in temperature using the infrared thermography and cyclic loading simulations which created micro-cracks beginning at the edges of the tool. These cracks were spread by repeated hits of the chip, and this aided in the rapid failure of tools. Their results indicated a high thermal shock resistance coating had a significant effect on less crack development. It has been noted in the study that transient frictional heating and mechanical effects during periodic cutting are crucial and thus provide a good guide on the production of tool materials and coating.

Gupta et al. (2024) examined nano-lubricants with graphene in machining aluminium alloys in MQL. Their findings demonstrated that friction coefficient was greatly reduced as a result of the development of a fine layer of graphene tribo-film that enhanced lubricity. Reductions were made on temperatures which dropped by approximately 18 percent and flank wear was also greatly diminished. SEM analysis established a confirmation of a smoother surface and reduced adhesion tendency. The authors reached the conclusion that graphene nanoparticles increase the efficiency of lubrication and sustainability of machining, and therefore are promising additives to use in advanced MQL systems.

Henriquez and Silva (2024) compared wear behaviour of PCBN tools used in high speed machining of hardened die steels. They found that the wear of the craters was caused by the chemical affinity and diffusion at high temperatures. XRD and TEM metamorphoses revealed the presence of phase changes at interfaces of the tool-chip, which showed that the thermal stability of both tools was destabilized under extreme cutting circumstances. The authors concluded that PCBN tools are superior in terms of hardness though they need optimal cutting parameters in order to reduce the degradation of thermal. The results of their study offer more insight into wear mechanisms in cutting tools of superhard materials.

Ramos et al. (2024) examined the effect of chip morphology on the development of friction and contact stresses in machining of titanium. They proved that serrated chips cause periodical stress variations, which increase friction and speed wear. Unstable shear bands that had led to variable tool-chip contact were observed by high-speed imaging. Their results highlighted the fact that chip segmentation has a severe impact on thermal and mechanical loading on the tool. The research has made the importance of pay attention to chip mechanics during the design of instruments and optimization of the process working with titanium alloys.

Zhou and Fang (2024) created a molecular dynamics simulation to investigate the atomic scale friction processes at the interface between the tool and work. Their computations demonstrated that frictional resistance is caused by their combination of adhesion, atomic diffusion and dislocation motion. The interatomic bonding forces were changed by temperature rise and it was more likely to transfer materials. Their model has been able to reproduce wear patterns that were experimentally observed and also give nanoscale understanding of coating behaviour. The authors came to the conclusion that the creation of the superior tribological performance of the atomistic modelling could help develop advanced materials into coatings that are superior in extreme cutting environments.

III. CONCLUSION

The review thoroughly discussed the complex tribological processes that control the friction and wear behaviour in cutting tools and the importance of these two in the determination of tool performance, machining efficiency, and the overall sustainability of the process. In the reviewed literature, one can notice that complex thermo-mechanical and chemical interactions at the tool workpiece and tool chip interfaces are the sources of friction and wear. Cutting parameters, tool material properties, workpiece, lubrication strategies, and the environment are very powerful factors affecting these interactions. All the four primary mechanisms that were identified were adhesive, abrasive, diffusion, and oxidative wear, which play a different role depending on the machine environment. High-performance coating like TiAlN, AlCrN, DLC, and multi-layered nano-structured films have been found to be useful in reducing friction and enhancing wear resistance especially in high-speed and high-temperature machining of hard-to-cut materials. Tribological performance is even improved further by surface texturing, plasma nitriding and engineered micro-geometries that alter the conditions of contact and permit stable chip flow. Similarly, cooling and lubrication advances such as, MQL, nanofluid-aided lubrication, cryogenic cooling, and hybrid cooling systems have proven to have significant advantages in the form of cut down thermal loads, enhanced machine quality, and promoted environmental sustainability. Finite element modelling and molecular dynamics simulation are some of the computational tools that have helped in improving predictive abilities in wear progression, frictional heating and coating failure. These approaches offer more mechanistic insights and present effective guidelines on how to maximize the future tool design and machining approaches. In general, the evidence provided in the review shows that proper management of friction and wear is critical in increasing the lifespan of the tools, improving the quality of the surface, reducing energy use, and ensuring consistent machining performance. The combination of future materials engineering with sustainable lubrication schemes and high-fidelity modelling will be important in solving tribological issues in the new engineering materials and more demanding production conditions.

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