Journal of Engg. Research Vol. 7 No. (2) June 2019 pp. 315-332

Influence of cutting condition on machinability aspects of Inconel 718: A review paper

Jeyapandiarajan P and Anthony Xavior M*

School of Mechanical Engineering, VIT University, Vellore 632014, India
**Corresponding Author: manthonyxavior@vit.ac.in*

ABSTRACT

An effort has been made to study the cutting conditions and cutting parameters impact on work and tool material during turning of Inconel-718 (In-718) super alloy. The present discussion would be helpful for understanding the machinability aspect such as surface integrity, cutting forces, work hardening, tool wear, and tool life while turning In-718. It is being reported that while machining In-718, tool wear develops quickly owing to increased cutting temperature and tough bond between the work material and the tool, due to its low thermal conductivity and its reactive nature. Uncoated carbide tools performed well for a cutting speed range of 10-30 m/min, and for speeds more than 40 m/min, coated carbide inserts are suited for machining In-718. This review paper also addresses the issues related to tool material selection, cutting environment, tool coating, and insert geometry. Flood cooling system reduces the cutting forces generated during machining and also results in lesser microhardness on the surface of the machined components. Emulsion coolant technique provides better surface than cryogenic cooling system but for better tool life cryogenic cooling system is preferred.

Keywords: Inconel 718; machinability; surface integrity; tool wear.

INTRODUCTION

Nickel based alloys find its application in various components of steam turbine, reciprocating engines, and aircraft gas turbines (Pawade et al., 2007). Petrochemical and chemical industries, space vehicles, nuclear power system, medical applications, heat treating equipment, equipment for pollution control (Ramesh et al., 2015), rocket engines, nuclear reactors, and submarines (Ulutan & Ozel, 2011) are the other areas where these alloys find very wide applications. Approximately 50 % weight of aero-engine contains nickel base alloys. In-718, a nickel based super alloy alone contributes with about 35% as compared to other super alloys (Pande & sambhe, 2014). The standard chemical composition for Inconel 718 is 50-55% Ni, 17-21% Cr, 18% Fe, 1%Co, 2.8-3.3%Mo, 0.3-0.7% Al, 0.08% C, 0.35% Si, 4.8-5.5% Nb-Ta, 0.7-1.15%Ti (Thakur and Ramamoorthy, 2010). Machining of In-718 remains a challenging task due to its improved work-hardening effects, increased strength with high temperature properties, presence of hard abrasive carbides in the microstructure, poor heat conductivity, and material diffusion from work to tool resulting in diffusion wear, which leads to BUE (Erween Rahim et al., 2015). As a result 35% of total manufacturing cost of Inconel 718 lies in hands of machining (Pande & sambhe, 2014).

Advancement in tool technology has given a better solution for machining In-718 by introducing coated, uncoated carbide, CBN/PCBN, and PCD tools, which are having high refractoriness during machining (Ezugwu et al., 2005). The poor machinability of In-718 resulted in the development of various machining techniques like cryogenic machining, hot machining, high pressure coolant (HPC) machining, and self-propelled rotary toll machining system. Basic functions of cutting fluids are to wash away the chips and increase tool life and machining accuracy. The usage of chlorine free coolants in order to avoid the hazards of cutting fluids to the environment is encouraged. Also to encounter the challenges in machining cost, usage of cutting fluids is to be significantly decreased by adopting minimal quantity lubrication (MQL), which is also equally environment friendly (Kamata & Obikawa, 2007). Investigations on machining of In-718 using various cutting environment were conducted and it was reported that

MQL resulted in minimum residual values for all cutting inserts and cutting velocities. A minimum surface roughness was obtained at 100 m/min using a carbide insert under flood cooling condition (Xavior et al., 2017). In order to have optimum responses during machining, all the cutting parameters like cutting speed, feed rate, depth of cut, and cutting conditions like lubrication technique, tool material and its coating choice, tool geometry, and machining strategy must be controlled (Patil Amit et al., 2015). While trying to optimise the machining process a thorough knowledge of the interrelationship between cutting tool material, work material, and cutting conditions is required (Ramesh et al., 2015). Therefore, through this review an attempt is being made to present a comprehensive analysis about the cutting conditions, which directly or indirectly influence the machinability of In-718 material. Various issues related to selection of cutting tool insert, cutting forces, surface integrity, tool wear, cutting parameters, and responses associated with various combinations of them are presented in the forthcoming sections.

TOOL (INSERT) CONSIDERATION

Selection of tool involves various criteria like insert size (l), insert shape, geometry, and insert nose radius (R_E) to achieve good chip control, surface finish, and better tool life. Figure 1 presents the general insert designations, which are commonly used in machining.

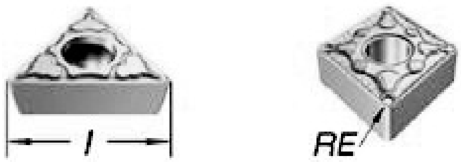

Fig. 1. Insert Geometry and Style.

Nose radius (R_E), of the insert plays a key role during turning operations, which determines the surface quality of the machined components. Selecting the largest possible nose radius for strength economy has been reported in the literature, smaller nose radius for controlling vibration to achieve better surface finish. Figure 2 represents different nose radii, which are generally adopted in inserts. Elmagrahi et al. (2007) have suggested the selection of insert geometry based on the machining method adopted, e.g., finishing or roughing or semi finishing, etc.

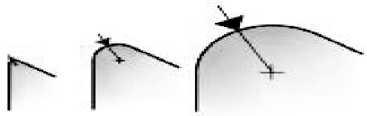

Fig. 2. Nose (Corner) Radius (R_E).

A large nose angle is strong, but requires more machine power and has a higher tendency for vibration. A small nose angle is feebler and has a small cutting edge engagement, both of which can make it more sensitive to the effects of heat. Figure3 shows the correlation between insert shape, productivity, and radial forces (Sandvik Coromant, 2015).

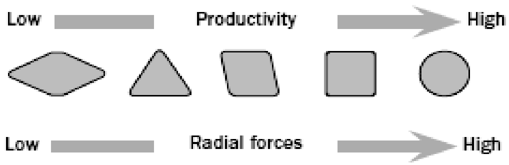

Fig. 3. Insert Shape with respect to radial forces and productivity.

The choice of better machining also depends upon the rake angles of the insert. If the tool insert has 90° angle (0° clearance angle) termed to be a negative insert, the positive angle always remains less than 90° angle (7° clearance angle). Positive inserts have low cutting forces, single sided, with side clearance generally intended for internal turning and for external turning of slender components. Negative inserts are double and/or single sided, high edge strength with 0° clearance angle, which are generally used as first choice for external turning of hard materials (General Turning Sandvik, 2015). Tool nose radius and the feed rate influence the surface hardness in greater level and the degree of work hardening is reduced as the tool nose radius increases (Hua and Liu, 2018).

TOOL MATERIALS

Cutting inserts for machining nickel base super alloys require materials that have enhanced thermal properties and better hardness at elevated temperatures like ceramics, cubic boron nitride (CBN), and cemented carbides (both coated and uncoated). Generally carbide tools are widely meant for machining In-718 with a cutting speed ranging from 10 to 30 m/min and can be continuous in case of cemented tungsten carbide inserts (Pande & sambhe, 2014). The concept of high speed machining with cutting speeds more than 40 m/min came into practice to attain better surface quality and fast material removal rate (Khan et al., 2012). Sharman et al. (2006) has mentioned in their work that coated cemented carbide can be used for higher cutting speed turning of In-718.

Carbide tools are utilized to machine nickel-base super alloys in the speed range of 30-80 m/min. Several research efforts have been made in order to increase the machined surface accuracy, reduce the tool wear, and subsequently extend the tool life, which directly influences the cost of machining and productivity (SANDVIK Coromant, 2015). Cubic Boron Nitride (CBN) has established a significant consideration as a hard part cutting tool material and had already recognised itself in many areas of critical machining. However, during high speed machining of super alloys, the performance of CBN tools is still inadequate. To analyse this problem, orthogonal cutting experiments were conducted by Sugihara and Enomoto (2015) on the super alloy In-718 with different cutting speeds (20 m/min - 300 m/min) so as to learn the wear mechanisms of Cubic-Boron-Nitride tool during high speed machining.

The use of diamond as a coating material due to its excellent friction and thermal properties has been reported by Ulutan and Ozel (2011). Though the practice of polycrystalline diamond tool has been increasing due to its better performance in producing excellent surface, the wear rate of diamond is found to be significantly low as compared to carbide tool. In spite of various developments on the tool materials over the period of time, machinability of nickel base super alloys at increased cutting speeds usually decreases the mechanical properties of cutting tools. The usage of tool materials like ceramic with Al_2O_3 mixed TiC, Si_3N_4 ceramics, Sialon (TiN/TiCN/TiN) multilayer coated carbide tools made by the physical vapour deposition (PVD) technique, etc., performs to give a good total value than cemented-WC. In the recent past, whisker reinforced (SiC) Al_2O_3 ceramic tools were established and they exhibited enhanced cutting performance with outstanding wear resistance and thermal properties (Sugihara & Enomoto, 2015). (Al,Ti)N coated carbide negative insert shows better tool life, then TiAlN coated carbide positive and negative inserts but surface hardness remains high **(**Zhang Bo et al., 2018**).** However, the cost of these tools has an upper edge over the machining process, which has to be compromised.

TOOL COATINGS

In demand to attain greater cutting speed, coated cemented carbide has been developed. The AlTiN coating appears to remain the finest coat, which shows worthy wear behaviour that helps limit unsteady built-up-edge; its excellent hardness boosted by the presence of ultra-fine crystalline lowers the abrasive wear (Pande & sambhe, 2014). Titanium nitride (TiN) coating offers outstanding wear resistance for an extensive series of materials and permits the use of greater feed and speed. Conservatively estimated tool life has increased to 200–300%, although in some applications it is seen as high as 800%. Titanium Aluminium nitride (TiAlN) coating is known for its great performance, which surpasses at machining of abrasive and difficult-to-machine material such as tool steels, cast and nickel alloys. TiAlNs can be the excellent choice for interrupted machining and high temperature machining due its enhanced ductility and oxidation resistance, respectively (Astakhov & Davim, 2008).

CUTTING FLUID

Cutting fluid in metal cutting operation serves as a coolant as well as a lubricant. Cutting fluid reduces thermal dispassion and cleaning of machined chips improves tool life and affects good surface finish (Hamdan et al., 2005). The objective of any metal cutting operation is high productivity to decrease the cost by machining at the highest possible speed along with extended tool life, minimum rejection, and minimizing downtime, improved surface finish, and dimensional accuracy (Cookson, 1977). The proper selection of cutting fluids in machining processes is as significant as machining parameters selection like machine tool, speed, and feed since it has impact on the output parameters. In addition fluids ability to penetrate into cutting zone is more critical and without this, the function of the fluid remains uncompleted (Dudzinski et al., 2004). The application of cutting fluid provides greater cutting velocity, improved feed rates, increased depth of cut and results in longer tool life, lesser surface irregularities, high dimensional accuracy, and less power consumption (Hamdan et al., 2005). Classifications of cutting fluids are important to understand better since varieties of cutting fluids are extensively available. Chemically, cutting fluids are classified as cutting oils, soluble oils (emulsions, emulsified oils), synthetic fluid (chemical), and semi-synthetic fluid (semi-chemical). Cutting oils were derived from petroleum, animal, or vegetables. Cutting oils are named neat oil or straight oil (Cookson, 1977). Cutting fluids in nature have very good lubrication properties, poor cooling properties, and increased fire risk, which led to the dilution of cutting fluid. Fluids also cause smoke or mist that is hazardous to operator's health. Fluids are restricted to low speed and low temperature cutting (Kuram and Ozcelik, 2013).

Difficult-to-cut materials such as heat-resistant super alloys (HRSA) and titanium create more heat during the machining process than steel. Heat-resistant super alloys (HRSA), which are poor conductor of heat when combined with high hardness levels, make the cutting zone much hotter, especially at the tool/workpiece interface. To maintain dimensional stability and prolonged cutting tool life, volume and pressure of coolant need to be at optimum level for these operations than those used to machine more common steels. Soluble water base fluids are commonly used in turning operation where heat removal is crucial. Straight oils for ceramic tools cause fire risk. Water-base fluids may be used for high speed turning with greater cooling effect. It may be soluble oils or chemical solutions; some chemical activities are desired and generally prevented by adding amine, chlorine, or other chemicals (Davim et al., 2013). While cutting super alloys, the best place for coolant is just before the cut, at the cutting edge of the tool, and at the tool's wear surface. Basically, coolant should be everywhere on the work/tool interface (Pande & sambhe, 2014).

Flood Cooling Method: In flood cooling technique entire machining area gets submerged with high volume of fluid that removes the heat generated during machining effectively (Hamdan et al., 2010). Use of flood coolant reduces cutting force required for material removal. In-718 poor thermal conductivity nature causes the material to retain the heat generated from tool-work piece interface. The generated heat causes adhesion of the work material to tool, which also affects the tool life and the wear propagation. Dissipation of heat can be made easy by using coolants. Coolant system comprises conventional coolant, refrigerator coolant, and cryogenic fluid. This system reduces the heat generated at the tool-work piece interface.

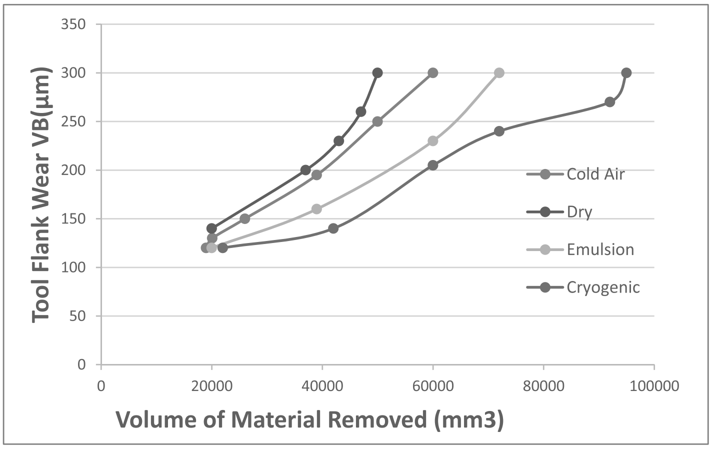

Fig. 4. Propagation of flank wear under different coolant system.

Figure 4 shows that the propagation of flank wear for a different metal removal rate of In-718 is subjected to machining under different coolant system. It is inferred that cryogenic flood cooling system results in minimum flank wear for any metal removal rate.

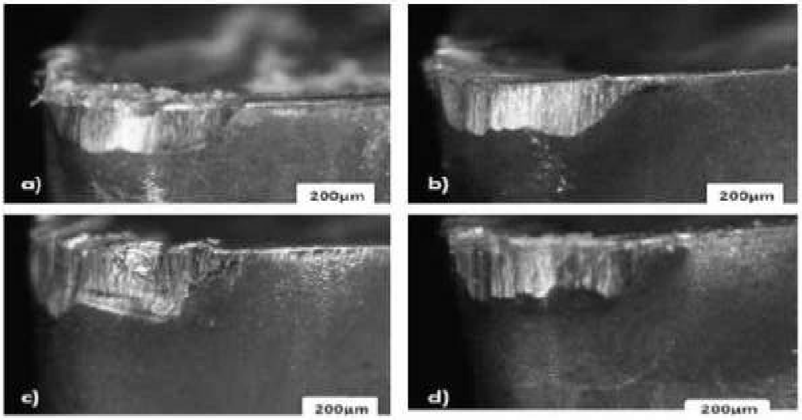

Fig. 5 (a-d). Flank wear observed for different cooling system after 17 minutes of machining.

Figure 5(a-d) indicates the wear observed on the inserts subjected to conventional turning of In-718 at 17 minutes of machining. Figure 5a indicates the flank wear on the insert subjected to cryogenic cooling. Likewise Figures 5b,5c, and 5d represent the wear observed on the inserts subjected to emulsion type coolant, dry machining, and cold air machining, respectively.

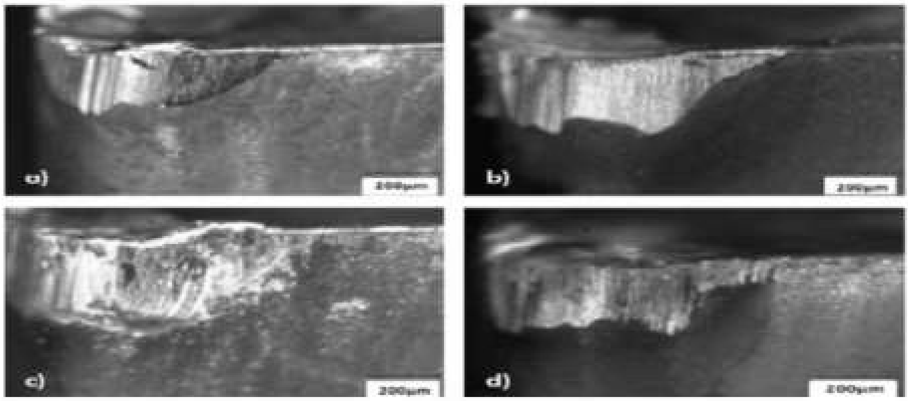

Fig. 6 (a-d). Flank wear observed for different cooling system after 21 minutes of machining.

Figure 6(a-d) indicates the wear observed on the inserts subjected to conventional turning of In-718 at 21 minutes of machining. Figure 6a indicates the flank wear on the insert subjected to cryogenic cooling. Likewise Figures 6b, 6c, and 6d represent the wear observed on the inserts subjected to emulsion type coolant, dry machining, and cold air machining, respectively. From figure 5 and figure 6 it can be inferred that cryogenic cooling system is preferred for machining of In-718 with better tool life.

Figure 7 shows the surface roughness generated on In-718 subjected to machining under different coolant system. It is clearly understood that emulsion coolant technique provides the best surface finish and cryogenic technique remains best for a prolonged machining.

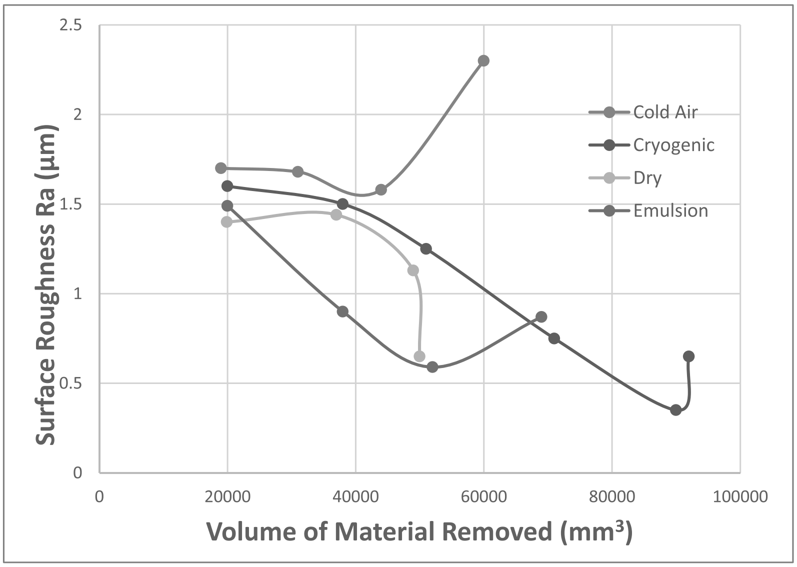

Fig. 7. Surface roughness generated for various coolant system.

Dry Machining: Advancement in production technology has led to the modern machining technique by using coated cutting tools and also the need for environmental-friendly machining processes has restricted the usage of cutting fluids to minimum quantity or complete omission of cutting fluids (Rao et al., 2014). By introducing dry machining concept in the machining of super alloys, the workpiece cost by 17% can be cut down. This reduction in cost comes mainly from the cutting fluid elimination (Pande & samble, 2014). Dry cutting has one of the key advantages of hard part turning using CBN inserts, which can withstand cutting temperature of about 1000°C. In general, the usage of CBN insert in dry conditions has given a positive effect on tool life, particularly in interrupted machining. Elimination of coolant leads to cost reduction easier chip handling, and more environmentally friendly operation (Sugihara & Enomoto, 2015). During dry cutting operation, heat dissipation, build-up edge above critical temperature, and also chip removal aspects remain the critical factors of machining. For automatic manufacturing systems, the cutting tool that provides good surface integrity, steady tool wear, high refractivity, high hot hardness, low friction coefficient, and low-adhesion coating on tools would provide a greater effect in dry machining (Dudzinski et. al., 2014).

Minimum Quantity Liquid (MQL): Many researchers have suggested that MQL is the best lubrication/cooling technique in machining processes (Fan et al., 2013). MQL is known as near dry lubrication and during this process a low volume of cutting fluid is utilized. During MQL small volume of synthetic bio-degradable ester or vegetable oil is sprayed over cutting edge along with compressed air with a volume of 10-100ml/h (Obikawa et al., 2008). Cutting fluid's fine particles penetrate through tool-work interface, chip-tool interface, and lubricate the cutting zone and reduce the friction during machining. In-718 machined surface undergoes damage like creep, stress cracking, and fatigue due to its low thermal conductivity (Hamdan et al., 2010). Thakur et al. (2009) have mentioned that, due to low thermal conductivity and high super heat properties of In-718, it can be machined by MQL pulsed jet mode. This method also avoids the detrimental effect caused by the fluids to both operator's health and environment.

SURFACE INTEGRITY

Surface integrity is considered as the main prerequisite of engineers to learn the changes induced to work piece during manufacturing processes. Those modifications were assessed from two key standpoints: surface alteration and geometrical irregularities. Surface alterations were linked with residual stresses, cracks, and metallurgical alterations. Geometrical irregularities were linked with surface texture, geometric and dimensional deviation (Jafarian et al., 2014). Surface integrity is evaluated in terms of toughness, residual stress, and micro-hardness at the machined surface (Díaz et al., 2013). Machined parts, surface integrity, and tool life results are dependent on different configurations of machining conditions adopted in each work but high levels of tensile residual stresses were commonly observed while machining of In-718, which are detrimental to component service life (Díaz et al., 2013).

Surface Roughness: Surface roughness diminishes as the cutting speed rises due to thermal softening effect and as the feed rate increases, it delivers greater surface roughness owing to friction between work material and cutting tool. Surface roughness sensitivity towards feed rate followed by the depth of cut and cutting speed was reported by Prasad et al. (2014).

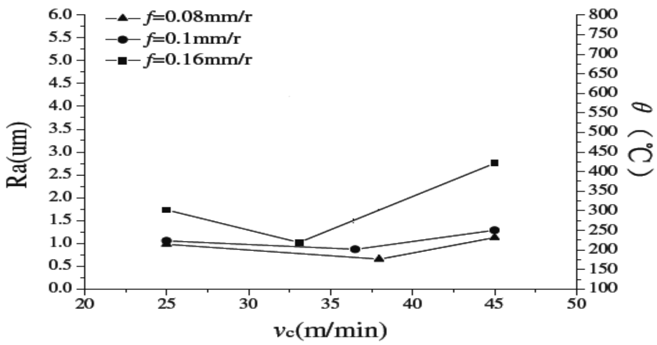

Fig. 8. Surface roughness with different cutting parameters.

Figure 8 represents the variation of surface roughness values at different feed rate and different cutting speeds. The graph also indicates the value of heat generated at the cutting zone for the combination of various cutting speed and feed rate. The observation clearly states that, for various feed rates, there existed a minimal surface roughness during optimal cutting speed of 35 m/min (Fan et al., 2013).

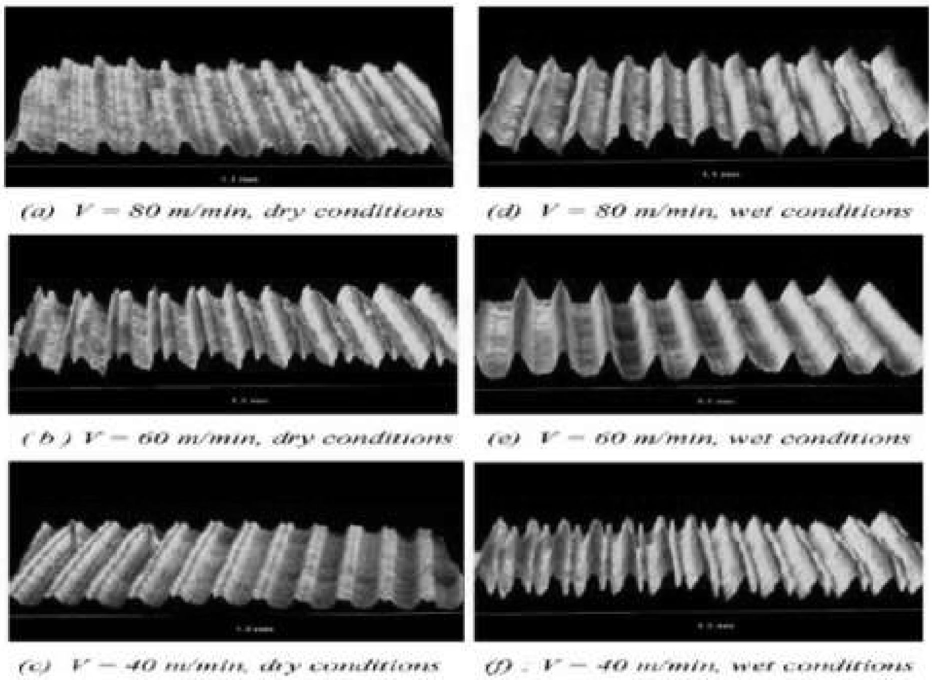

Fig. 9. Surface quality observations for various cutting conditions, using the white light interferometry technique.

Figures 9 (a-c) represent surface irregularities obtained at different cutting conditions for different feed under dry machining. During dry machining of In-718 surface irregularities for various speeds show the adhesion of work material on the tool surface to form Built Up Edges and Built Up Layers. Due to high pressure and temperature, the BUE plastically deform and move in the direction of chip flow. Figures 9 d-f show the surface roughness generated for various cutting speeds during wet machining. In wet machining, tool faces are cooler than dry machining, which prevents adhesion and controls the tool wear. BUE at the machined surface remain condensed or cancelled and as a result machined surface quality for wet condition improves. Work piece material is squeezed, ploughed, and plastically deformed by tool nose when minimum chip thickness is maintained. Material flow along the side of tool edge fills the groove with plastically deformed material (Devillez.A et al., 2011).

Work Hardening and Micro-hardness: For successful machining of In-718, reduction of work hardening effect is most important. Thermal stress concentration can be reduced by reducing the contact tip area between tool and work piece. A technique that plays major role in minimizing the work hardening effect includes the use of sharp cutting edge, adequate rake, and clearance angle to avoid dwelling, suitable cutting fluid supply, machine tool with correct specification, power, and rigidity to minimize the vibration (Guide, Kennametal, 2015). Lesser work hardening effect results in improvement of tool life and surface integrity. Degree of work hardening (DWH) on varying depth of penetration on In-718 has been reported, to understand the integrity of machined surface (Pande & Sambhe, 2014). Strong work hardening induced during machining of Ni alloys influences both surface integrity and tool wear. Highly deformed material at the machined surface was related to elevated hardness and residual stress affecting service life of the component (Díaz et al., 2013). Cutting conditions and the type of machining play a vital role in influencing the microstructure and micro-hardness values of machined In-718. Figure 10 shows the microstructure examination of the machined surface showing metallurgical phase changes and in dry cutting condition sub-surface damage is caused due to plastic deformation of the matrix. Machined surface beneath undergoes plastic deformation and its depth is affected by austenitic matrix phase. By using proper optimization technique cutting parameters and with advanced coated tools under high speed machining, work hardening effect can be reduced (A. Thakur and Gangopadhyay, 2014).

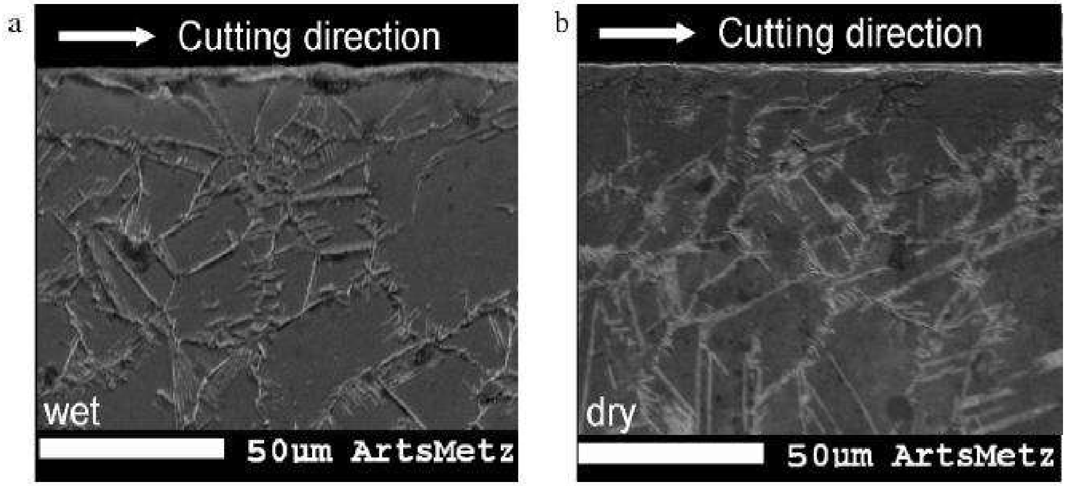

Fig. 10. Microstructure of Inconel 718.

Measurements of micro-hardness at numerous places beneath the machined surface subjected to wet and dry condition at 60 m/min cutting speed (two conditions) are illustrated in Figure 11.

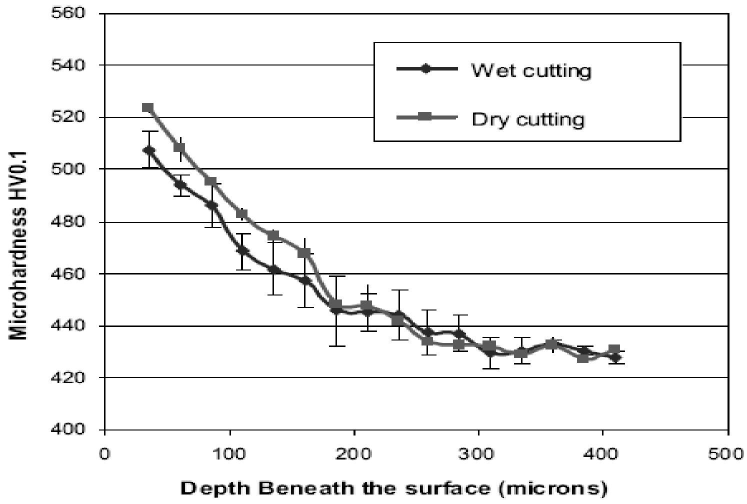

Fig. 11. Microhardness measured at various subsurface depth.

Figure 11 shows the maximum micro hardness value 525HV for dry machining and 510HV for wet machining on the surface. As the depth increases, the hardness values decreases gradually to bulk value of 430-440 HV at about 250 micrometer depth (Devillez.A et al., 2011).

Residual Stresses: Residual stresses and microstructure of alloy are altered by the heat generation during machining. Residual stresses are caused by plastic deformation without heat; they are generally compression stresses. Heat causes cracks, microstrual changes, and large variations in micro-hardness (Devillez.A et al., 2007). Residual stresses get induced after machining processes, which remain a key for crack initiation, propagation and lead to fatigue failure at end products. Such failures can be avoided by either removing tensile residual stresses or preventing them from occurring during machining processes (Ulutan & Ozel, 2011). Increased cutting speed and surface residual tensile stress fall though a rise in feed rate results in a minor rise in both the surface tensile stress and the compressive stress at the depth (Sharman et al., 2006).

Residual stress phenomenon is difficult to measure and model. Many scholars reported that residual stresses are tensile in nature and some others have reported them as being compressive (Pawade et al., 2008). This deviation in result can be due to different cutting conditions and tool parameters used. Literature revealed that residual stresses are more tensile at the machined surface of the workpiece and become compressive at the sub-surfaces. Tensile stresses were due to thermal effect caused during machining while compressive stresses were due to mechanical influences. Compressive stresses in the work piece surface are caused mainly due to insert geometry. Particularly large corner radius and large nose radius result in multiple deformation of the machined surface (Ulutan & Ozel, 2011). Figure 12 shows residual stresses at various cutting speed and feed induced on In-718 work piece subjected to dry and wet machining. Residual stresses remain tensile at the external surfaces for both wet and dry condition regardless of its cutting speed. Its clear that residual tensile stress value remains low for the wet condition, which is caused due to the presence of cutting fluid. Tensile residual stress on the external surface moves to compressive residual stresses as depth increases in both wet and dry machining.

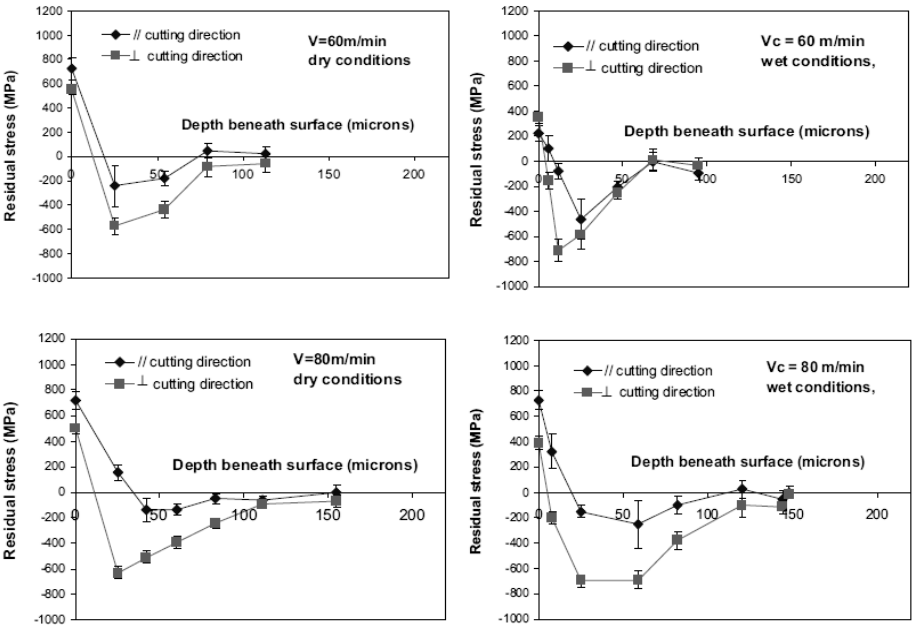

Fig. 12. Residual stresses along the depth beneath surface.

Residual stresses analysis shows that cutting fluid controls the heat generated on the newly generated surface, which resulted in reduced stress values. This also confirms that compressive residual stress generated beneath the tensile residual stresses remains unaltered for both cutting conditions and cutting speed (Devillez.A et al., 2011). Residual stresses at the surface turn out to be less tensile, whereas the compressive stresses dominate as the depth increases from the free surface (Ulutan & Ozel, 2011).

CUTTING FORCES

Main cutting force (Fc) decides on cutting power, heat generation in the cutting zone, and the surface integrity of the component. Passive force (Fp) is primarily important because it is directed against the machined surface that strongly influences the surface integrity distortion like residual stresses (Jemielniak, 2009). In general, cutting force increases with the feed rate and it was also noted that all the cutting force components decrease considerably with the increase in fluid pressure (Çolak, 2012). As the depth of cut increases the radial forces that push the insert away from the cutting surface become more axial. It is preferable to have more axial forces instead of radial, which have a negative effect on the cutting action, e.g., with more tendency to vibrate and bad surface finish with increased radial forces (Herbert et al., 2012). While Inconel 718 is machined with SiC whisker reinforced ceramic tool, it was observed that cutting forces decrease as coolant supply pressure increases (Altin et al., 2007).

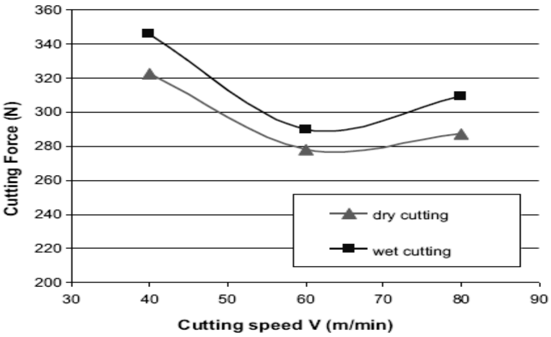

Fig. 13. Effect of lubrication and cutting speed over cutting force.

Figure 13 shows that there is a reduction in cutting forces initially as the cutting speed increases and a maximum reduction in cutting force was inferred at a cutting speed of 60 m/min. Dry cutting condition always provides lower cutting force as compared to wet cutting condition. In primary shear zone, the temperature should have been raised drastically when the cutting speed raised from 40 to 60 m/min. The increase in temperature had led to thermal softening of the workpiece and this results in reduction of cutting force. As the cutting speed increases behind 60 m/min cutting forces were observed to raise gradually; this appeared to be as a result of strain rate sensitivity that in turn seems to be predominant over thermal softening. In-718 was known for very high strain rate sensitivity (Devillez.A et al., 2011).

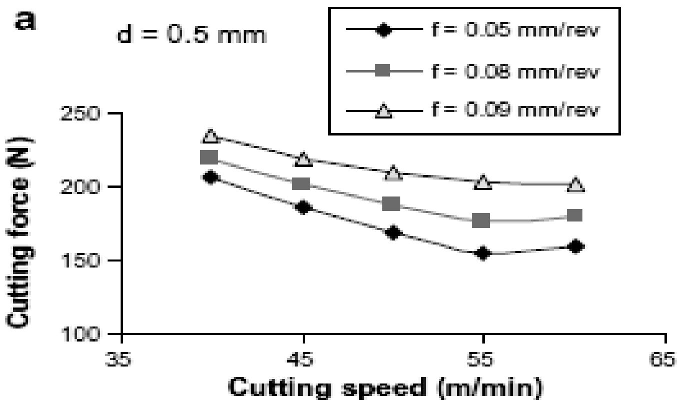

Fig. 14. Cutting force variation with cutting speed and feed at 0.5 mm depth of cut.

Figure 14 shows that, at constant depth of cut, 0.5 mm, cutting force varies with various cutting speed and feed rates. Cutting force decreases as the cutting speed increases and also tends to remain constant at higher feed rate (D.G.Thakur et al., 2009).

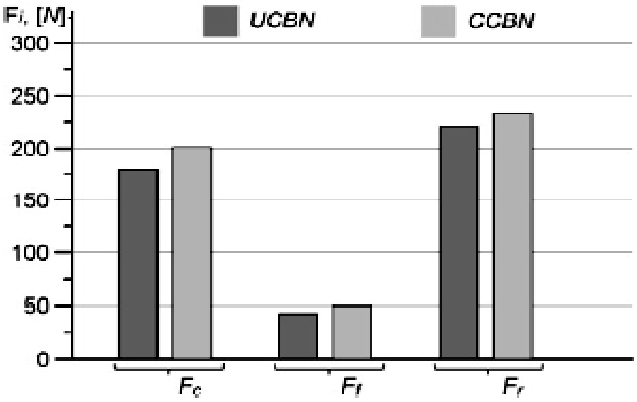

Fig. 15. Cutting force comparison (*vc* =350 m/min, *f* =0.15 mm/rev).

Figure 15 shows the quantum of cutting force generated for coated and uncoated tools. It was noted that uncoated CBN inserts generate 10% less cutting forces when compared to coated CBN inserts (Bushlya et al., 2012).

TOOL WEAR

Production cost and the machining specification (product quality) have direct influence on wear rate and tool life, respectively. As the tool life improves, production cost of the products is reduced. Improvement of tool life is a major challenging task as the tool undergoes an unavoidable wear and subsequent failure. In general cutting tool fails either by a gradual and progressive wearing of its edge due to chipping or by plastic deformation (Khidhir & Mohamed, 2010). Usually cutting tool wear is considered as predetermined threshold value of tool life. It is clear that any improvement in tool or work material that improves tool life will be beneficial (Altin et al., 2007). During low cutting speed, round insert tools have 5 times greater life as compared to the C-type (rhombic shape) tool. The increase in cutting speed to 300m/min results in presence of grooving and BUE diminishes, which leads to comparable performance between c-type and round tools(Khan et al., 2012). Tool life test was performed upto 7min of cutting time or to tool wear threatening with catastrophic tool failure (CTF) while roughing or prominent worsening of surface finish while finishing (Jemielniak, 2009). It is generally agreed that the application of cutting fluids can improve the tool life by reducing the wear rate (Hamdan et al., 2010). By modification of the micro geometry of the inserts its life is often significantly extended. Tool life is significantly increased with an increase in the SCEA (side cutting edge angle) (Kuljianic et al., 2010). SCEA has strong influence in the wear analysis. Dry machining has less values compared to flood and MQL (Cantero, J.L., 2013).

In the majority of test results the predominant wear mode is flank wear. The main cause of flank wear is abrasion. While c-type inserts were used with high cutting speed, insert fracture, chipping, and thermal cracks give out severe grooving and BUE (Khan et al., 2012). Flank wear can be minimized by applying a high pressure coolant to tool-chip interface. This confirms that high pressure coolant has better lubrication and cooling than other conventional cooling methods. In addition, high pressure jet assisted (HPJA) lubrication/cooling helps in minimizing tool-chip interaction length and elongation of tool life (Cloak, 2012). During low cutting speed, the crater wear development by the progress of adhesions of workpiece material and their removals (i.e) when adhered material is removed; severe crater wear occurs by flaking the tool substrate (Sugihara & Economoto, 2015). In turning operation, frictional heat generation at the tool-chip interface remains a common issues that impacts the tool life and surface finish. This heat generation shows fairly a negative role in machining hard materials. Ceramic tool life is severely limited by excessive notching due to the relatively low mechanical toughness in ceramic tools. Usage of cutting fluid mixed with nano-particle to diminish friction force and triple the life of tool (Rao et al., 2014).

Tool wear mechanisms also depend on the elevated temperatures and stresses at the cutting edge. Notch formation is commonly detected when machining Ni alloys due to work-hardened layer. Flank wear, chipping, BUE, and catastrophic failure also cause tool rejection during machining of Ni alloys (Diaz et al., 2013). Less tool wear and good surface finish are obtained using ceramic tool during finish turning. The failure of tool arises at a speed of 200 m/min and a feed rate of 0.15 mm/rev. Finally, it was concluded that the performance of ceramic tool is better at intermediate cutting speeds (Aruna et al., 2010). Three phenomena that generally influence the tool wear mechanisms are thermal softening, diffusion, and notching. Thermal softening of cobalt binder phase and subsequent plastic deformation of the cutting edge result in failure of carbide tool as the cutting speed increases above 30 m/min. The significant reason that causes cutting tool wear was that the tool material falls off from the tool substrate in the form of wear debris. In addition, diffusion of elements within tool and workpiece and oxidation reaction of both accelerate the formation and peeling of the wear debris (Akhtar et al., 2014). As cutting speed rises above 100 m/min, cutting temperature also increases due to friction. This rise in cutting temperature leads to diffusion, which is the leading factor for stimulating crater wear. Crater wear progresses proportionally to the cutting length (Khan et al., 2012). Crater wear deteriorates the cutting edge, leading to catastrophic failure. For machining of High-Temperature alloys, crater wear resistance acts as important tooling property. The hard, abrasive intermetallic compounds in the microstructure cause severe abrasive wear on the tool tip (Bengoetxea, 2014).

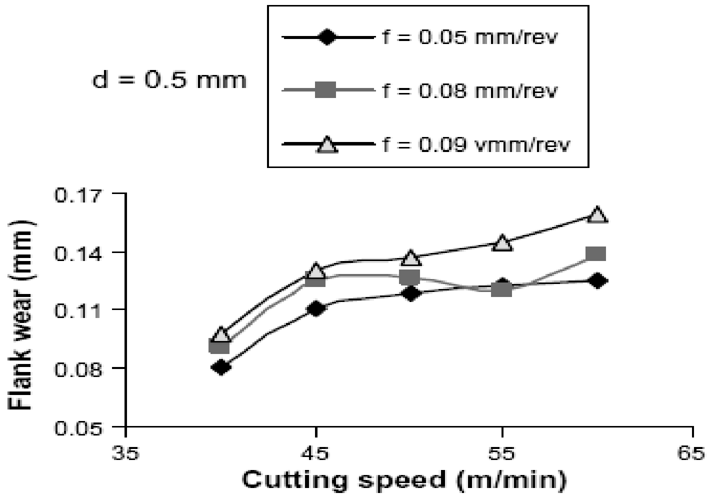

Fig. 16. Flank wear variation with cutting speed and feed at a constant depth of cut.

The experimental results obtained show that flank wear and tool life were affected significantly by the cutting parameters like cutting speed and feed rate as shown in Figure 16. As cutting speed increases, feed rate causes a greater increase in cutting temperature in the region of cutting tool edge. The higher temperature causes the tool to lose its strength and also deform plastically. Thus the increase in cutting speed results in higher flank wear and cutting edge deformation (D.G thakur et al., 2009). Notch wear was the predominant wear observed and it was more evident in dry machining process of Inconel 718 with ceramic tool (Zeilmann, R.P., 2017). Figure 17 displays the coated carbide and PCBN tool wear curves obtained when employed in their respective cutting regime. In general, considerably greater amount of flank wear is noticed in CBN tool than coated carbide when higher cutting speed is employed. Figure 18 shows the SEM images of wear scars. It was reported that wear mode domination in CBN is the combined effect of crater and flank wear. In coated carbide inserts depth of cut notch and minor cutting edge notch wear were observed (M'Saoubi et al., 2012).

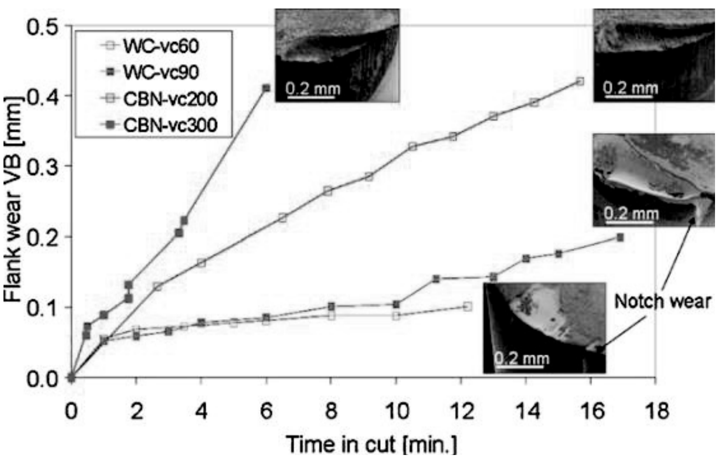

Fig. 17. Flank wear variation with respect to cutting time for various cutting speed.

Fig. 18a. Flank wear observed at 200 m/min, 0.2 mm/rev, 0.5 mm **Fig.18b**. SEM micrograph showing adhesion on rake face.

Bonding between chip-tool interface occurred and clearly indicated as a visible sticking layer on tool face near cutting edge. This has been originated due to its high chemical affinity. The upper part of the flank wear land has the appearance of fracture surface. This was due to small chipping along the edge line as shown in Figure 18a. A strong adhesive layer of the work piece materials on the tool rake face can be seen in figure 18b. During 200 m/min feed of 0.15 mm/rev cutting condition, adhesive wear is stimulated and increases by increasing the cutting speed. Adhesion of work piece material that formed on tool cutting edge during every cutting operation increases the wear propagation on the cutting edge and severe flaking is observed at this condition (Aruna et al., 2010)

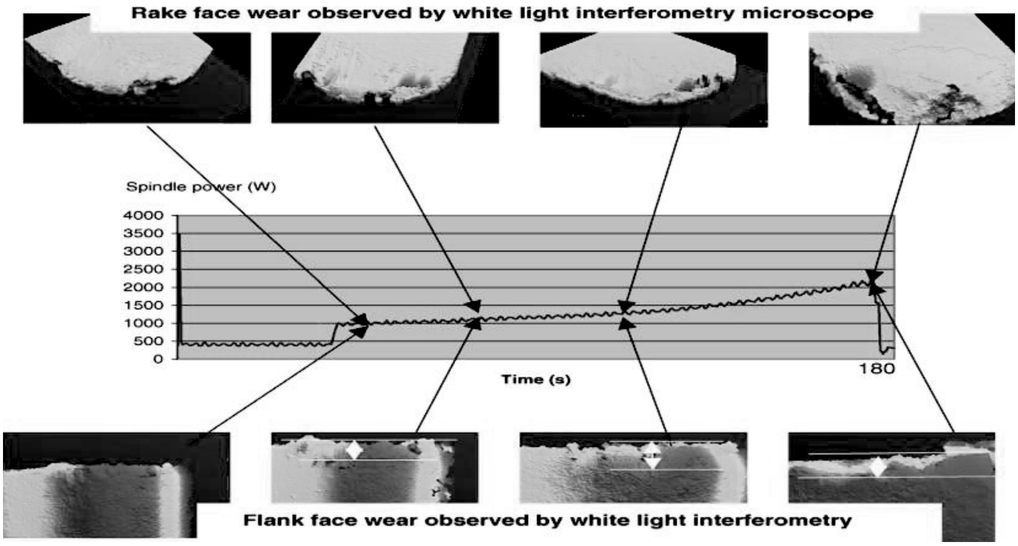

Fig. 19. Evaluation of tool wear and spindle power consumed in bar turning with AlTiN coated tool.

Significant built-up-edge, abrasive flank wear, wear patterns at flank and rake faces on tool nose and coating delamination erosion in rake face were depicted as shown in Figure 19. The test can be concluded that tool wear and the spindle power consumption have a relationship with the cutting edge chipping (Devillez.A et al., 2007).

CONCLUSION

This review paper provides an insight into the issues associated with the machinability aspects of In-718. In general all the machinability aspects such as surface finish, cutting forces, flank wear, work hardening effect, and induced stresses on the work pieces are addressed. Important conclusions are summarized as follows:

1. It has been inferred that uncoated carbide tools can perform well for a cutting speed range of 10-30 m/min. and for speeds more than 40 m/min coated carbide inserts are suited for overall best performance of machining.

2. MQL resulted in minimum residual values for all cutting inserts and cutting velocities. A minimum surface roughness was obtained at 100 m/min using a carbide insert under flood cooling condition

3. For high speed machining CBN and whisker reinforced ceramic inserts perform better in terms of tool life.

4. It is also being inferred that flood cooling system reduces the cutting forces generated during machining and also results in lesser microhardness on the surface of the machined components. Emulsion coolant technique provides better surface than cryogenic cooling system but for better tool life cryogenic cooling system is preferred.

5. Surface roughness values remain optimal at 30-40 m/min cutting speed with feed range of 0.05- 0.1 mm/rev.

6. Residual stresses at the surface turn out to be more tensile, whereas the compressive stresses dominate as the depth increases form the free surface regardless of cutting speed, tool, and cutting condition. Tensile stresses were due to thermal effect caused during machining, while compressive stresses were due to mechanical influences.

7. Microhardness value 525HV for dry machining and 510HV for wet machining remains varied on an average of 20HV. As the depth increases, the hardness values reduce gradually to bulk value of 430-440 HV at about 250 micrometer depth.

REFERENCES

Altin, A., Nalbant, M. & Taskesen, A. 2007. The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools. Materials & Design, **28**(9): 2518–2522.

Aruna, M. & Dr. V. Dhanalakshmis, M. 2010. Wear Analysis Of Ceramic Cutting Tools In Finish Turning Of Inconel 718. Journal of Engineering Science and Technology, **2**(9): 4253–4262.

Akhtar, W., Sun, J., Sun, P., Chen, W. & Saleem, Z. 2014. Tool wear mechanisms in the machining of Nickel based super-alloys Frontiers of Mechanical Engineering, **9**(2), 106–119.

Astakhov, V. P. & Davim, J. P. 2008. Tools (geometry and material) and tool wear. Machining: Fundamentals and Recent Advances, 29–57.

Bushlya, V., Zhou, J. & Ståhl, J. E. 2012. Effect of cutting conditions on machinability of superalloy inconel 718 during high speed turning with coated and uncoated PCBN tools. Procedia CIRP, (**3**)**:** 370–375.

Cantero, J.L., J. Díaz-Álvarez, M.H. Miguélez & N.C. Marín. 2013. Analysis of tool wear patterns in finishing turning of Inconel 718. Wear **297**(1–2), 885–894.

Çolak, O. 2012. Investigation on machining performance of Inconel 718 under high pressure cooling conditions. Strojniski Vestnik/ Journal of Mechanical Engineering, **58**(11), 683–690.

Cookson, J. O. 1977. An introduction to cutting fluids. Tribology International, **10**(1)**,**5–11.

Davim, J. P. 2013. Green Manufacturing - Processes and Systems, 130.

Devillez, A., Schneider, F., Dominiak, S., Dudzinski, D. & Larrouquere, D. 2007. Cutting forces and wear in dry machining of Inconel 718 with coated carbide tools. Wear, **262**(7-8): 931–942.

Díaz, J., Soldani, X., Cantero, J. L. & Miguélez, H. 2013. Surface integrity in finishing turning of Inconel 718. Proceedings of the 5th Manufacturing Engineering Society International Conference – Zaragoza.

Dudzinski, D., Devillez, A., Moufki, A., Larrouquère, D., Zerrouki, V. & Vigneau, J. 2004. A review of developments towards dry and high speed machining of Inconel 718 alloy. International Journal of Machine Tools and Manufacture, **44**(4)**:** 439–456.

D. Fernández, V. García Navasa. Sandá & I. Bengoetxea. 2014. Comparison of machining inconel 718 with conventional and sustainable coolant. http://www.mmscience.eu/content/file/archives/MM_Science_201415.pdf

Elmagrabi, N. H., Shuaeib, F. M. & Engineering, M. 2007. An overview on the cutting tool factors in machinability assessment. Journal of Achievements in Materials and Manufacturing Engineering, **23**(2)**:** 87–90.

Erween Rahim, Norazlan Warap & Zazuli Mohid. 2015. Thermal-Assisted Machining of Nickel-based Alloy. Intechopen, http://dx.doi.org/10.5772/61101

Ezugwu, E. O., Fadare, D. a., Bonney, J., Da Silva, R. B. & Sales, W. F. 2005. Modelling the correlation between cutting and process parameters in high-speed machining of Inconel 718 alloy using an artificial neural network. International Journal of Machine Tools and Manufacture, **45**(12-13): 1375–1385.

Fan, Y., Hao, Z., Zheng, M., Sun, F. & Yang, S. 2013. Study of surface quality in machining nickel-based alloy Inconel 718. The International Journal of Advanced Manufacturing Technology, **69**(9-12): 2659–2667.

Hamdan, A., Fadzil, M., & Hamdi, M. 2016. Procitan Rad --- Performance Evaluation of Different Types of Cutting Fluid in the Machining of Aisi 01 Hardened Steel Using Pulsed Jet Minimal Quantity Lubrication System. Proceedings of 47th IRF International Conference, ISBN: 978-93-82702-14-6.

Herbert, C. R. J., Kwong, J., Kong, M. C., Axinte, D. a., Hardy, M. C. & Withers, P. J. 2012. An evaluation of the evolution of workpiece surface integrity in hole making operations for a nickel-based superalloy. Journal of Materials Processing Technology, **212**(8)**:** 1723–1730.

Hua, Y. & Liu, Z. 2018. Effects of cutting parameters and tool nose radius on surface roughness and work hardening during dry turning Inconel 718. The International Journal of Advanced Manufacturing Technology, **96**(5-8): 2421-2430.

Jafarian, F., Amirabadi, H., Sadri, J. & Banooie, H. R. 2014. Simultaneous Optimizing Residual Stress and Surface Roughness in Turning of Inconel718 Superalloy. Materials and Manufacturing Processes, 29(February), 337–343.

Jemielniak, K. 2009. Rough Turning of Inconel 718. Advance in Manufacturing Science and Technology, **33(3)**, 309–316.

Kamata, Y. & Obikawa, T. 2007. High speed MQL finish-turning of Inconel 718 with different coated tools. Journal of Materials Processing Technology, (192-193): 281–286.

Khan, S. A., Soo, S. L., Aspinwall, D. K., Sage, C., Harden, P., Fleming, M. & M'Saoubi, R. 2012. Tool wear/life evaluation when finish turning Inconel 718 using PCBN tooling. Procedia CIRP, (1): 283–288.

Khidhir, B. A. & Mohamed, B. 2010. Machining of Nickel Based Alloys Using Different Cemented Carbide Tools. Journal of Engineering Science and Technology, **5**(3)**:** 264–271.

Kuljanic, E., Sortino, M. & Totis, G. 2010. Machinability of Difficult Machining Materials. 14th International Research/Expert Conference, (September): 11–18.

Liao, Y.S. & R.H. Shiue. 1996. Carbide tool wear mechanism in turning of Inconel 718 superalloy. wear(193):16-24 ·

M'Saoubi, R., Larsson, T., Outeiro, J., Guo, Y., Suslov, S., Saldana, C. & Chandrasekar, S. 2012. Surface integrity analysis of machined Inconel 718 over multiple length scales. CIRP Annals - Manufacturing Technology, **61**(1), 99–102.

Obikawa, T., Kamata, Y., Asano, Y., Nakayama, K. & Otieno, A. W. 2008. Micro-liter lubrication machining of Inconel 718. International Journal of Machine Tools and Manufacture, **48**(15), 1605–1612.

Pawade, R. S., Joshi, S. S. & Brahmankar, P. K. 2008. Effect of machining parameters and cutting edge geometry on surface integrity of high-speed turned Inconel 718. International Journal of Machine Tools and Manufacture, **48**(1)**:** 15–28.

Pande, P. P. R.U sambhe 2014. Machinability Assessment In Turning Of Inconel 718 Nickel-Base Super Alloy. International Journal of Mechanical Engineering and Technology (IJMET), ISSN 0976 – 6340 (**5**)**:** 94-105

Pawade, R. S., Joshi, S. S., Brahmankar, P. K. & Rahman, M. 2007. An investigation of cutting forces and surface damage in high-speed turning of Inconel 718. Journal of Materials Processing Technology, (192-193)**:** 139–146.

Rao, P. V. Bikash Chandra Behera1* & Chetan2, Sudarsan Ghosh. 2014. Effects on Forces and Surface Roughness During Machining Inconel 718 Alloy Using Minimum Quantity Lubrication, (AIMTDR): 1–6.

Ramamoorthy, B. & Vijayaraghavan, L. 2010. Effect of High Speed Cutting Parameters on the Surface Characteristics of Superalloy Inconel. Proceedings of the World Congress on Engineering, (3)**:** 2108-2111.

Ramesh, C., Prathap, J. & Pamanabhan, P. 2015. Experimental Investigation Of Tool Wear In Turning Of Inconel718 Material. International Journal of Advance Engineering and Research Experimental Investigation Of Tool Wear In Turning Of Inconel718 Material, 37-44

SANDVIK Coromant.. Hard part turning with CBN Choose the right solution, 19. http://www.sandvik.coromant.com/sitecollectiondocuments/downloads/global/catalogues/en-gb/c-2940-137.pdf

SANDVIK Coromant. 2015. Insert shape, Metalcutting Technical Guide, general turning Sandvik Coromant, (V), 36–46. Retrieved from http://www2.coromant.sandvik.com/coromant/pdf/Metalworking_Products_061/tech_a_5.pdf **Sharman, A. R. C., Hughes, J. I. & Ridgway, K. 2006.** An analysis of the residual stresses generated in Inconel 718™ when turning. Journal of Materials Processing Technology, **173**(3): 359–367.

Strnad, G. & Buhagiar, J. 2010. Latest developments in PVD coatings for tooling. Scientific Bulletin of the“ Petru Major” University of Targu Mures, (7)**:** 32–37.

Sugihara, T. & Enomoto, T. 2015. High Speed Machining of Inconel 718 Focusing on Tool Surface Topography of CBN Tool. Procedia Manufacturing (1): 675–682.

Sugihara, Tatsuya, Shota Takemura & Toshiyuki Enomoto. 2015. Study on high-speed machining of Inconel 718 focusing on tool surface topography of CBN cutting tool. The International Journal of Advanced Manufacturing Technology, (0268-**37**68): 1433-3015.

Thakur, A., Gangopadhyay, S. & Maity, K. P. 2014. Effect of Cutting Speed and Tool Coating on Machined Surface Integrity of Ni-based Super Alloy. Procedia CIRP, **14**, 541–545.

Thakur, D. G. 2009. An experimental analysis of effective high speed turning of superalloy Inconel 718. Journal of Materials Science, **44**(12): 3296-3304

Thakur, D. G., Ramamoorthy, B. & Vijayaraghavan, L. 2008. Some experimental investigations on the surface integrity aspects of superalloy Inconel 718 in high speed turning. International Journal of Materials and Structural Integrity, **2**(3)**:** 265-279.

Thakur, D. G., Ramamoorthy, B. & Vijayaraghavan, L. 2009. Optimization of Minimum Quantity Lubrication Parameters in High Speed Turning of Superalloy Inconel 718 for Sustainable Development. World Academy of Science, Engineering and Technology, **54**: 224–226.

Turning, G. 2015b. General turning Metal working product main, *5005*, 67–89. Retrieved fromhttp://www2.coromant.sandvik.com/coromant/pdf/Metalworking_Products_061/main_a_1.pdf

Ulutan, D. & Ozel, T. 2011. Machining induced surface integrity in titanium and nickel alloys. International Journal of Machine Tools and Manufacture, **51**(3)**:** 250–280.

Xavior, M. Anthony, M. Manohar, Patil Mahesh Madhukar & P. Jeyapandiarajan. 2017. Experimental investigation of work hardening, residual stress and microstructure during machining Inconel 718. Journal of Mechanical Science and Technology, **31**(10)**:** 4789-4794.

Zeilmann, Rodrigo P., Fernanda Fontanive & Rafael M. Soares. 2017. Wear mechanisms during dry and wet turning of Inconel 718 with ceramic tools.” The International Journal of Advanced Manufacturing Technology, **92**(5-8)**:** 2705-2714.

Zhang, Bo, Mwangi Jessee Njora & Yoshiki Sato. 2018. High-speed turning of Inconel 718 by using TiAlN-and (Al, Ti) N-coated carbide tools. The International Journal of Advanced Manufacturing Technology, **96**(5-8): 2141–2147.

Submitted: 29/06/2016
Revised: 10/05/2018
Accepted: 02/07/2018

تأثير حالة القطع على قابلية التشغيل جوانب من إنكنل 718 – ورقة مراجعة توثيقية

جياباندياراجان ب وأنتوني كزافيور م
كلية الهندسة الميكانيكية، جامعة فيت، الهند

الخلاصة

تم بذل جهد لدراسة ظروف وتأثير معلمات القطع على مواد وأدوات العمل أثناء تشغيل سبيكة انكونيل – 718 (In-718). والمناقشة الحالية مفيدة لفهم جوانب قابلية التشغيل الآلي، مثل: سلامة السطح، وقوة القطع، والصلابة؛ تآكل الآلة وعمرها الافتراضي أثناء تشغيل In-718. لُوحظ أنه في حين تصنيع In-718، فإن تآكل الأدوات يتطور بسرعة بسبب زيادة درجة حرارة القطع والربط القوي بين مواد العمل والأداة، نتيجة لانخفاض التوصيل الحراري وطبيعتها التفاعلية. أداء الأدوات المُصنعة من الكربيد غير المطلي جيداً بسرعة قطع تتراوح من 10-30 م / دقيقة. وللحصول على سرعات أكثر من 40 م / دقيقة، فإن الحشوات المطلية بالكربيد تتناسب مع تصنيع أدوات In-718. وكذلك، تتناول ورقة المراجعة هذه المشكلات المتعلقة باختيار المواد التي يتم تصنيع الأداة منها، وبيئة القطع، وطلاء الأداة، وهندسة الإدخال. إن نظام التبريد بالتغطية يقلل من قوى القطع المتولدة أثناء التشغيل الآلي، كما يؤدي إلى تقليل درجة الحرارة الصغرى على سطح المكونات المُصنعة. وتوفر تقنية التبريد بالتنقيط سطحاً أفضل مقارنةً بنظام التبريد بالتجميد، ولكن يُفضل استخدام نظام التبريد بالتجميد لتوفير عمر افتراضي أفضل للأداة.