The Comprehensive Review on machining of Inconel 718 superalloy

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Abstract. Inconel 718 is nickel based alloy, difficult to machine and precipitate which having tremendous mechanical properties. It has outstanding features like high shear strength, low thermal conductivity, potential to sustain its strength and hardness at prominent temperature. It plays a crucial role in various manufacturing applications for instance aircraft, defence, aviation and gas turbines. Numerous efforts have been to produce the workability of Inconel 718 indifferent operating conditions; different tool electrodes and tool geometry. The main objectives which are focused in this review study are drilling, milling and turning. Finally, a brief idea of non-traditional cutting fluid over traditional cutting fluid is also discussed.

1. Introduction
The processing of aerospace material Inconel 718 is very challenging due to its outstanding mechanical properties and low thermal conductivity. Due to small processability of this material, the operating surface and subsurface are simply influenced or involved under the machining operation [1,2,3]. The use of this alloy is not only limited to the above given applications but also chemical, naval and high-speed cars. Its employ in such environments indicates its potential to sustain high corrosion-resistant, mechanical and thermal fatigue, creep wear and tear at prominent temperatures. Higher efficiency, lower processing costs linked with superb surface finishes and dimensional precision are the reason of safety critical industries like SNECMA Moteurs that develops engines for military airplane and space engines. By reason of thermal and mechanical loading, several problems occur including overheating, surface irregularities, built-up-edges, macro, micro-cracks, cavities and micro-defects etc [4]. In order to maintain surface integrity aspects for Inconel 718 [5], cutting conditions, tool material, tool geometry, coatings for tool material should be chosen wisely. Severe and rapid tool electrode wear has also been acknowledged as another major complicated issue. The occurrence of hard stages in the micro-structure like nitrites, oxides, etc enhances tool abrasion [2]. Therefore, it can be concluded that tool life and surface quality are the two main issues which arise during processing of Inconel 718 [6]. In order to
ensure the productivity of machined parts and avoid above given problems, improved organization of the processing method related to cutting tool-system tool work piece grouping to move in the direction of more quick material removal rate [7]. The micro pattern of Inconel 718 is involved of a face centred cubic (FCC) matrix stage, that is a austenitic of Fe, Cr and Mo in nickel collectively each other secondary stages. Precipitate gamma double prime is the main strengthening phase. Evaluation of machining of the superalloys had been studied through last three decades [8]. This paper displays a brief discussion on the working of Inconel 718 superalloy. Basically, review paper is divided into three categories: Turning, Milling and Drilling.

Turning is the operation where the maximum material removal occurs and is also used to give the basic size of the part to be machined. Therefore, optimum cutting conditions and tool geometry must be selected in this operation. Milling is also used to give shape and size to the material. Finally, drilling is the last operation performed, so it must be performed with the selection of the input parameters being done wisely.

2. Effect of various machining operation on the performance of Inconel 718 superalloy

2.1 TURNING

Pawade et al. [9] conducted an investigational analysis on cutting forces (CF) and surface quality in high-speed turning of Inconel 718 work piece with PCBN tools. It was found that the main CF was two-three times of radial and feed forces while later were almost equal when they performed the experiment with following input parameters $V = 125$- $475$ m/ min, $f = 0.05$- $0.15$ mm/rev, $d = 0.50$ – $1.0$ mm and boundary geometry as: $30^\circ$ chamfer, $20^\circ$ chamfer and $30^\circ$ chamfer plus sharpened. It was seen that radial forces were not affected much on varying the input parameters but honed plus cutting-edge geometry was helpful at lower cutting speeds as low cutting forces were produced. Also, surface damage was lower at higher cutting speeds as CF decreased with a raise in cutting speed. Pawade et. al [10] studied the chip morphology during ultra-rapid turning of Inconel 718 in dry condition with PCBN tools. Throughout processing of Inconel 718, serrated chips were produced due to paramount thermally assisted deformation because of high temperature generated during machining. Shear cracks were observed at the open surface of chips, which minimize the shear plane towards the tool tip. It was seen that the chip width ratio reduces with a raise in cutting speed. Also, chips produced were continuous and having snarled appearance. It was also seen that chip width ratio was directly related to FR but inversely related to the depth of cut. Also, on reducing the chamfer angle, chip width increases. Thakur et al. [11] investigated the influence of work hardening and electrode life due to cutting parameters when the machining Inconel 718 with untreated tungsten carbide tool electrode and cryogenic tungsten carbide tool.
It was found that cryogenic treated tool has more tool life with more uniform flank wear than the untreated tool as less cutting forces were produced during machining with cryogenic treated tool. It was seen that cryogenic treated tool produced less residual stresses than untreated tool. Patil et al. [12] did a comparison of high-speed working of Inconel 718 in dry situation and using compressed cold CO2 gas as a coolant. They concluded that SR and TW were less in CO2 processing with low cutting speed and high FR as compared with dry machining. Micro resistance of the machined surface increased during CO2 machining, which was credited to cold work hardening of work part.

López et al., [13] examined the turning of low machinability alloys (Inconel 718) with ceramic and sialon tool inserts having round and rhombic geometry. They found that thin chips were produced when round tools were used. Optimal cutting speed, as well as feed rate was high during working with ceramic
tools while sialon tools were more stable at medium cutting speeds. Ezugwu et al., [14] conducted tests on Inconel 718 to examine tool life and surface reliability when working by PVD coated carbide tool and CVD coated carbide tool. TiN PVD coated tool with less tool life provided better surface quality as compared with TiN/TiC/TiN PVD coated and TiC/Al2O3/TiN CVD coated carbide tools. Also, tool life of all the tools was negatively influenced by cutting speed and feed rate. PVD coated tool showed more flank wear as well as excessive chipping. TiC/Al2O3/TiN CVD coated tool failed due to delamination of rake face and notching. Coelho et al., [15] determined the impacts of cutting boundary development and geometric changes in high-speed turning of Inconel 718 through tools having a different geometry. Round tools produced a better surface finish. They found that surface finish improved when tool geometry was changed as follows:

| Geometry   | Chamfer | Chamfer length | Rₜ  | Edge preparation |
|------------|---------|----------------|------|------------------|
| Commercial | 20°     | 0.10mm         | 0.8mm| Sharped          |
| Modified   | 15°     | 0.15mm         | 0.8mm| Honed with 13-38μm radius |

Also, modified geometry generated low temperature with tool being more uniform and progressive in nature. S.M. Darwish [16] analysed the dependency of SR on tool material and the cutting variables through dry machining of Inconel 718. Darwish used two different tools namely ceramic tool and CBN tool with constant nose radius of 0.5mm and found that ceramic tool inserts gave better surface finish. Ceramic inserts gave better surface quality at lower FR. SR was affected mostly by feed rate (irrespective of tool material used) pursued by intensity of cut and cutting speed. Nalbant et al., [6] to study the effects of cutting speed and cutting tool shape on processability properties of Inconel 718 did an investigation by different ceramic cutting tools. They reported that the main cutting force (CF) decreased with raise in cutting speed up till an optimal cutting speed (~ 250m/min ). Furthermore, rising tool-tip radius caused important CF to increase and lowest main CF was achieved by silicon-nitride ceramic tool. The effect on the main cutting force due to tool material was much clearer than cutting speed. Rahman et al., [17] presented the result of cutting circumstances on machining of Inconel 718. They used coated cemented carbide inserts with various combination of tool geometry, cutting speed and feed rate. An increase in tool life was seen while i) approach angle increased ii) cutting speed decreased. Moderate cutting speed and feed rate generated continuous chips. They found an increase in radial cutting force and vibration on increasing approach angle while axial forces decreased. Lesser wear rate was seen for TiN PVD coated tool than Al₂O₃ CVD coated tool. Costes et al., [18] investigated on tool-life and wear mechanism of CBN tools in working of Inconel 718. Tool life was greatly influenced by CBN content in tool. Tool life reduced with a raise in CBN content in the tool and grain size of the binder. Dominant wearing system of the CBN cutting tool was bond, diffusion and finally abrasion. Binder material used in tool influenced the tool life to a great extent. Ezugwu and Tang [19] conducted experiments to study the surface finish and surface damage while machining Inconel 718 through ceramic tools having rhomboid and round geometry. Surface finish was reduced owing to high flank wear and worsened on prolonged machining with round inserts. Ceramic tools ailed due to unnecessary indentation at the intensity of cut section. Round places armed better surface quality. Prolonged machining result in an enlarge in the stiffness of the surface level to it over the standard hardness values because of high rate of work hardening, improved compressive stresses and plastic deformation. Li et al., [20] conducted a sequence of tool life tests on high speed turning of Inconel 718 with coated carbide tool and ceramic tool places to optimize the cutting speed. Abrasive wear, bond wear, micro-breakout and chipping were reported as major tool wears during turning of Inconel 718. Rise in cutting speed led to reduce in notching at depth of cut whereas rake and lank wear increased. Ceramic tools with negative rake angles produced better results or high-level machining of Inconel 718. Above cutting speeds of 300m/min, tools failed due to crack destruction under the tool’s rake surface. Domenico Umbrello [21] investigated the surface reliability in dry machining of work piece (Inconel 718) using coated
DNMG Sandvik tool (WASO S-DNMG150616) having rake and clearance angle of 6° and 4° in that order. When coated tool were used at an arrangement of high CS and low FR, machined surface produced was comparable to the surface produced during finishing operations such as grinding. High grain refinement was noted when higher cutting speeds and feed rates were applied. Furthermore, the effect of the feed rate looked to be paramount on grain refinement towards cutting speed [22].

2.2 DRILLING
An investigation on wear method when drilling Inconel 718 super alloy through TiAlN coated carbide tool was done by Chen and Liao [23]. It was found that tool wear and drilling forces increase due to hardening of work material. Comparison to the primary cutting force and torque, the increase of torque was considerably better than the thrust force. Tool wear took place in four levels:
(i) coated layer was abraded off
(ii) friction forces increased until BUE started
(iii) flow stresses caused cracks in chipped region
(iv) Serious flank and crater wear were present

The use of nano-modifier fluid can enhance the tool life. Sharman et al., [24] investigated on tool life and surface integrity aspects in drilling of Inconel 718 with the help of three drill bits (SS, CS and DS). Drill SS had minimum tool life with periphery chipping and wear while Drill DS had maximum tool life with delayed periphery wear and no chipping observed. Although drill CS showed good tool life, but it suffered from chipping at periphery and failed due to catastrophic chipping. Drill CS produced the lowest surface roughness in new and worn conditions. The secondary processes showed better performance over drilling alone in terms of surface finish. Kitagawa et al., [25] reported the effect on cutting temperature and tool wear when high-speed machining Inconel 718. They found that edge wear decreased at low and high cutting speed with a rise in between. The flank wear was found to be low than that of boundary wear. Indentation edge wear governed the tool life under a cutting speed of 300m/ min. Surface wear, flank temperature and crater temperature improved with the rise in cutting speed. It was reported that wear was created by abrasion instead of thermally stimulated device.
KIVAK et al. [26] in their analysis showed the influence of cutting variables on surface quality and tool wear though drilling Inconel 718. Roundedness of the crater was spoiled because of the increase vibrations based on the improved loads on the tool at high cutting speed and feed rate. The Lowest variation values were achieved with the uncoated tools and the maximum were achieved with the TiAlN coated tools. BUE was found to be responsible for spoilage of hole quality. Also, no usage of coolant also caused wear. Beer et al., [27] reported the drilling of Inconel 718 with shape personalized twist drills. It was found that the modified geometry of tool had a great impact on tool life and its performance. Due to modified geometry of twist drills, tool life increased and coolant supply became better for the thermally high loaded external area where the utmost wear occurred. The tool life improved because the width of the flank wear was restricted Khanna et al. [5]. A study during drilling of Inconel was done by Vimalesh M et al. [28] at four different cutting speeds. It was informed that thrust force improved up to a speed of 27 m/min due to work hardening effect but then decreased because thermal softening influence was dominated over work hardening influence. Saw tooth development controlled the chip development method although at higher cutting speeds, their size decreased which facilitated the fast discrimination of the tool and no difficulty of machinability. López de Lacalle et al. [29] examined the drilling of low machinability alloys using high pressure coolant. Drilling with coated TiAlN produced good results. When drilling was done with high pressure, using coatings results were poor. On the edges, wear resistance and fracture take place in which material was separated from tool. Tools with internal cooling may have avoided these mishaps. Farid et al., [2] reported that smoother end was achieved at high cutting speed and low feed rate. Holes produced with new tools had more dimensional accuracy. Also, by increasing point angle, burr height could be reduced. Subsurface micro structural damage in holes was due to worn tools. The progression in white layer was due to increase in flank wear and cutting speed. Xavior M et al. [30] examined tool wear during machining of Inconel 718. They concluded that tool electrode wear is significantly affected by variables such as thermal softening, adhesion, dispersion, indentation and thermal cracking. Thermal cracking was reported on rake face of CBN at low CS and high FR. CBN tool showed serious wear pattern and higher tool wear value over ceramic and carbide tools. For flood cooled cutting condition higher flank tool wear value are noted for all category of tool electrodes.

Ezugwu et al. [14] performed an investigation to tool electrode life and surface reliability when machining Inconel 718 with PVD tool and CVD coated tool. They found that PVD-coated tool illustrated most excellent efficiency in terms of tool life due to higher stiffness, robustness and abrasion resistance. Stoppage mode of PVD coated tools were edge wear, unnecessary chipping and cracking of tools. TiN
coated carbide provided improved surface finish after polishing work of honed cutting edge. Excessive plastic deformation occurred due to joint work of thrust force, high temperature and pressure after prolonged machining. Devillez et al. [1] reported that as the cutting speed increase, cutting force decreased initially. Dry conditions provided low cutting force values. High temperature was produced in primary shear zone due to high cutting speed or by choosing dry conditions. With the increase in temperature, cutting force and mechanical properties of work piece decreased. Surface quality was better in wet conditions due to reduced tool wear and residual built-up edge (BUE). Poor surface quality and low surface roughness occurred in dry conditions at the same speed only. Dry conditions showed to be superior in terms of tool life as it did not reduce drastically. Altin et al. [7] carried out an investigational study on the influences of cutting speed on tool wear and tool life during processing of Inconel 718 with ceramic tools. It was found that wear of ceramic tools at high cutting speed was less than cutting tools at low speed. Square type places illustrated better act as compared with round form at low cutting speed. Tools having negative and larger clearance angle must be used to solve indentation wear problem. It was found that apply of 15 MPa coolant provide pressure suppressed notching during processing therefore better tool life, as the employ of higher coolant provide pressure of 20.3 MPa did not illustrate enhancement in tool life almost certainly due to rapid indentation wear caused by water jet impact wearing away. Devillez et al. [7] reported the measure of cutting forces and tool wear in dry machining of Inconel 718 with coated carbide tools. Through dry machining a coating is essential to maintain a good tool life and surface reliability for machined elements. Adhesion of work part and welding was the most common wear during dry machining. There was an increase in cutting force ratio due to occurrence of a wear on rake face, thus helping in determining most favourable cutting situations for dry machining of work material. AlTiN was found to be the best coating as it has good tribological performance. Pawade et al., [8] examined the influence of working variables and cutting-edge shape on surface reliability in turning of Inconel 718 at high speed. They reported that chips’ heat dissipation ability governs the supremacy of mechanical or thermal type deformation in machining. Mechanically dominated deformation is progressed by high cutting speed, low feed rate, moderate depth of cut and honed cutting edge because thermal induced stress become compressive in these conditions. It was observed that there is a main increase in the work hardening within the machined sub surface. Ezugwu et al. [22] considered the processing of Inconel 718 with ceramic tools under concluding conditions and various coolants provide pressures. It was found that there is an increase in tool life when high coolant pressure up to 15MPa was applied while machining with SiC forced alumina ceramic tool. Notching phenomenon was observed under the effect of high-pressure water jet cutting stroke on an unsystematic source as movable ceramic tool materials are simply eroded resultant in the lower tool life noted after machining with 20. 3MPa coolant provide pressure. Higher forces were noted when machining with conventional coolant flow where permanent type chips were produced. Bigger the nose radius the better the surface finishes generated. Superior surface finish was created with round whisker reinforces Al₂O₃ ceramic tools under highpressure and conventional coolant. Arunachalam et al. [31] examined the results of surface reliability in machining of Inconel 718 work piece through coated carbide tools. It was found that residual stress measurements are necessary to be made as they contribute to be an important selection condition for selection of suitable cutting tools. This is so as they are sensitive to the deviations in tool variables. It was observed that coated carbide tool places of round form with chamfered cutting boundary, negative rake and minute nose radius when employed with coolant generated less residual stresses.

2.3. MILLING

Li et al. [32] considered the electrode wear generation and cutting forces deviation in the up and down end milling of Inconel 718 using coated carbide tools. They concluded that lank wear and chipping was the dominating tool wear. They observed that propagation of tool wear was aster in up milling over down milling. As the tool wear propagated, peak values of cutting forces in all direction showed a
For a single cutting pass, peak value of force varied due to thermal effect whereas gradual increase in peak force was owing to tool wear propagation. S. Zhang et al. [33] explained the influence of minimum quantity cooling lubrication (MQCL) on the tool wear propagation and cutting forces in the end milling of Inconel 718. They reported that tool life below MQCL cutting state was 1.57 times of the tool life below dry cutting state because the tiny droplet of the lubricate formed a film at the tool/chip face and work piece surface which reduced the friction and cryogenic compressed air was applied to cool the cutting edge so temperature was reduced. The lower cutting forces were also observed under MQCL cutting condition due to which friction force was decreased and hence tool life improved. Jawaid et al., [34] investigated the cutting efficiency and tool wear qualities of Inconel 718 in the face milling using the PVD-TiN coated carbide tool and uncoated carbide tool. They concluded that uncoated carbide tool carried out superior at lower cutting speed because of more sustainable to abrasion wear as PVD-TiN coated tool performed superior at high cutting speed due to high wear ability and low thermal conductivity of TiN coating. At higher cutting speed (above 75m/mm) PVD coated tool gave tool life under1 min because of the flank wear and machining of cutting boundary. Alauddin et al.,[35] tested the tool life in full attention and half attention end milling of Inconel 718 using uncoated tungsten carbide tool places under dry state. They concluded that full raptness end milling gave the better tool life than half raptness end milling because of the induced stresses caused by variation in heating and cooling moment of tool during cutting. Liao et al., [36] examined the behaviour of Inconel 718 in the end milling (slot and side milling) using cemented carbide tools. It was found that low speed cutting was difficult due to increase in temperature and strain hardening. With increase in speed tool life was improved and cutting speed reduced because of thermal strength property of precipitation of Inconel 718 which softened the work material. In slot milling if the cutting speed (above 113.1m/min) was urether increased, chip flow retarded because the chips got welded on the both side of slot. Inside milling, very small quantity of flank abrasion was observed at low cutting speed. At higher cutting speed (above 135.7m/min), chips got welded together due to which cutting forces and temperature increased. Sharman et al., [24] studied the tool life of Inconel 718 in ball nose milling at high-speed by TiAIN an CrN coated tungsten carbide ball end mills. They concluded that at 90 m/min best tool life was achieved when TiAIN coated tool was employed while shortest tool life appeared at 150 m/min cutting rate through CrN coated tool when work piece at 45° inclined from horizontal was machined. A BUE formation was observed in both tools since adhesion was the most important tool wear method. Coating peeling and BUE formation was more with CrN coated tool at 90 m/min which indicated the chemical affinity of CrN towards Inconel 718. Rahman et al., [37] examined the machinability of Inconel 718 using two coated carbide tool, grades EH20Z-UP (PVD-TiN coated) and AC25 (CVD-TiN Coated) on the basis of experiments they found that tools performed best at side cutting edge angle (SCEA) 45° as best tool life was observed at 45°. Tool life reduced as the cutting speed and feed rate raised owing to generation of extra heat caused by friction. Flank wear was the major component which affects the tool life of EH20Z-UP introduce, whereas for the AC25 introduce, depth of cut (DOC) indentation wear was the major criteria for the tool life. It was noted that for processing of Inconel 718, the allowable speed and feed range was at low level. Tian et al., [38] performed a investigate on the impact of cutting speed (600-3000 m/min) on cutting forces and abrasion system of Inconel 718 in the high-speed face milling (up and down mode) using Sialon ceramic tools. They concluded that as cutting speed improved, the resulting cutting force decreased firstly then increased. At low cutting speed, the resulting cutting force in down milling is better. indentation wear was the leading failure mode of tool whereas at higher cutting speed, resultant cutting force was smaller under down milling over up milling and adhesion wear was dominant failure mode. Up milling was preferred over down milling due to flanking on the rake face and indentation on the flank face was more serious in down milling. Li et al., [39] did a investigate on the influences of tool wear on surface reliability and wear life of Inconel 718 with PVD-TiN coated carbide places. It was found that higher surface roughness was produced less tool wear. For higher tool wear levels, thermal caused white layers were not seen due to improvement in the cooling influence...
from periodic contact in milling over the constant contact. A certain degree of tool wear did not influence the wear life as no fatigue was observed inside four million cycles for all the processed specimens up to tool wear VB 0.2 mm. Altin et al., [6] reported the effect of cutting speed on tool wear and tool life of Inconel 718 in the machining with ceramic tools. They observed that at round type places, edge and indentation wear was dominant tool wear while flank and hole wear was dominant tool wear at square type insets. Experimentally, the advantageous cutting speed was deduced as 250 m/min as there was a negative effect on tool life over this speed. Square type places were preferred at low cutting speed and round type places were preferred for higher cutting speed [40]. Round places enhanced the cutting performance in evaluation with square ones, because they provided stronger cutting-edge aiding indentation wear ability. The tool wear rate was accelerated, if the depth of cut, feed rate and immersion ratio was reduced. The average cutting force decreased with an increase in cutting speed, lower axial and radial depth of cut. Aramcharoen and Chuan [41] performed an investigational study on Inconel 718 in the cryogenic milling and its sustainability assessment. They revealed that cryogenic cooling acceptably decreased the temperature in the cutting region and better the cooling availability through the tool/chip boundary over the conventional cooling process. By using cryogenic cooling, the efficiency of the lubricating action increased and contact friction between tool-chip boundaries was decreased. The growth of electrode wear below cryogenic cooling circumstance was similar to that under conventional oil-based coolant.

3. Conclusion and Summary
From this paper, the following points can be summarized:
In the present study efforts have been made to investigation the cutting force in turning operation on Inconel 718. The magnitude of cutting force is two to three times higher than that of the other force components. The modification of the flank face can improve the overall performance of cemented carbide drills while machining with Inconel 718. The designed grooves the tool life up to 50 % and additionally leads to a much better coolant supply to the high loaded parts of the drill. Full-immersion, end-milling increased the tool life when compared to half-immersion end milling. The tool life in down-cut end-milling is greater than that in up-cut end-milling. The cutting speed influences the tool life significantly in full-immersion end-milling. Chip is very difficult to be disposed in high-speed slot milling of Inconel 718 alloys. So, one can conclude that cutting temperature is related to cutting speed, proper selection of cutting speed is essential. Cutting speed is related closely to cutting force and tool wear/failure in slot milling of Inconel 718 alloys. The effect of feed is relatively insignificant. Cutting temperature and chip low condition are two most important factors affecting high speed milling of Inconel 718 alloys while strength of cutting edge is not the pertinent actor. Inconel 718 has broad functions in various areas. Tesla Company, now days with Inconel-718 instead of steel to improve the key battery pack. To produce turbine wheel in the turbocharger in diesel engines, Ford motor company also use Inconel. One of the luxury car “BMW”, has employed Inconel in the wear out, which leads to its high efficiency. The “BMW M5 E34” with the iconic “S38” engine, withstands higher temperatures and decreasing backpressure. Jaguar Cars has it, in their Jaguar F-Type SVR high efficiency sports car, a new light-weight Inconel titanium fatigue method as standard which withstand higher peak temperatures, decreases backpressure. Inconel has various chemical applications or instance scrubbers, columns, reactors, and pipes are hastelloy perfluoro alkoxy (PFA) lined carbon steel or fibre reinforced plastic.

Conflict of Interest: The authors declare that they have no conflict of interest.

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