MACHINABILITY ASSESSMENT IN TURNING OF INCONEL 718 NICKEL-BASE SUPER ALLOYS: A REVIEW

Pravin P. Pande¹, Dr. Rajeshkumar U. Sambhe²

¹(Assistant Professor, Department of Mechanical Engineering, Rajrshi Shahu College of Engineering Buldana / SGB Amaravti University, India)
²(Associate Professor, Department of Mechanical Engineering, Jawaharlal Darda Institute of Engineering &Technology, Yavatmal / SGB Amaravti University, India)

ABSTRACT

Inconel 718 is nickel-base super alloys known as one of the most difficult to cut material because of the properties high hardness, high strength at high temperature, affinity to react with the tool materials and low thermal diffusivity. In this paper attempt has been made to review recent work and key improvements in machinability and machining characteristics of inconel 718.

Keywords: Difficult to Cut, Inconel 718, Nickel-Based Alloy.

1. INTRODUCTION

Heat resistant alloys used in the manufacture of aero-engine components can be grouped into four major categories: Nickelbase alloys, cobalt base alloys, iron base alloys (e.g. high chromium stainless steel), and titanium alloys [17]. About 50 wt. % of aero-engine alloys are nickel base alloys [4]. Inconel 718 is one of the most widely used nickel base superalloys accounting for around 35% of all production [58]. The properties that make Inconel 718 an important engineering material are also responsible for its generally poor machinability. Low thermal conductivity (11.4 W/m/K) leads to high cutting temperatures being developed in the cutting zone. These have been shown to rise from around 900°C at a relatively low cutting speed of 30 m/min up to 1300°C at 300 m/min [6].
2. MACHINABILITY OF INCONEL 718

Inconel 718 (IN718) is a wrought nickel-iron based alloy for moderately high temperature applications developed by H. L. Eiselstein of the International Nickel Company [44] has become the most widely used, superalloy [14]. The primary uses of these alloys are in: (i) aircraft gas turbines, steam turbine, reciprocating engines, metal processing, medical applications, space vehicles, heat-treating equipment, nuclear power systems, chemical and petrochemical industries, pollution control equipment; and coal gasification and liquefaction systems.[4], rocket engines, nuclear reactors, submarines.[26]. The standard chemical composition of it 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. Usual hardness of $Rc = 41–43$. The properties behind the poor machinability of Inconel 718 are high work-hardening capacities, maintaining high strength during machining due to its high-temperature properties, hard abrasive carbides in the microstructure, low thermal conductivity and specific heat and high cutting temperature, high chemical affinity for many tool materials leading to diffusion wear, and its strong tendency to weld to form built up edge because of its gummy nature at high temperature [10, 5]

3. CUTTING TOOLS FOR MACHINING INCONEL 718

In machining inconel 718 factors that affect the performance of a cutting tool are: (i) high hardness; (ii) wear resistance; (iii) chemical inertness; and (iv) fracture toughness. Conventionally they are machined using coated carbide tools [11] recently more and more often CBN and ceramic tools are used [16]. The ceramic tools are generally much more expensive than carbide tools [66].

3.1. Machining Inconel 718 with carbide tools

Carbide cutting tools are the oldest amongst the hard cutting tool materials. These tools are used to machine nickel-base superalloys in the speed range of 10–30 m /min [60]. Tungsten-based carbides can be used in high feed-rate cutting and severe interrupted cutting, but because of their poor thermo chemical instability, they cannot be used at high speed. Coated carbides on the other hand, have good wear resistance and strength [10]. The introduction of high-pressure coolant supply has made carbide tools possible to machine these alloys at speeds of the order of 50 m/min [1]. With inserts as K type substrate, TiN PVD coated cemented carbide, and multi $Al_2O_3$ CVD coated cemented carbide. For both the inserts, tool life increases as the SCEA increases. Over this larger portion of improved length of SCE heat and cutting force distributed, reduces tool notching and substantially improves tool life. The $Al_2O_3$ CVD coated cemented carbide exhibited more severe notch wear comparatively [5]. A square tip of cemented carbide P20, multilayered coated with TiN, TiC shows only flank wear at a speed of 30 m/min due to carbide particles. The coating film on the rake face wears off first, and later, then chip flow directly on the cemented carbide material and the rate of wear increases when temperature exceeds 1320 K[9]. The TiAlN multilayer shows some advantages over the TiAlN-monolayer and TiN/TiCN/TiAlN-multilayer coating particularly at the higher speed of 76 m/min. abrasive nose wear accompanied by plastic deformation. Depth-of-cut notching was also observed. The notching was heavily influenced by burr formation on the uncut diameter [45]. PVD TiAlN coated carbide tool shows that depth of cut is a significant influence to the tool life [41]. Using tungsten carbide insert (K20) the cutting force magnitude is found to be higher than feed force. Decrease in both cutting force and feed force is due to decrease in contact area and partly by drop in shear strength in the flow zone as the temperature increases with increase in speed. Surface finish is found to be optimum in the cutting range of 45–55 m/min with tool life 282 s. [32]. At cutting speed of 70 m/min, with coated cemented carbide inserts the cutting tool life has a non-negligible tool life [49].
3.2. Machining Inconel 718 with Cubic boron nitride (CBN) and polycrystalline Cubic boron nitride (PCBN)

CBN is one of the hardest materials available after diamond. The synthesis of polycrystalline CBN is composed of about 50–90% CBN and ceramic binders such as titanium carbide and titanium nitride. A high CBN content is better in cutting super alloys. Higher CBN content generally increases chipping resistance. The hardness increases almost linearly with the CBN content. Compared to ceramics, CBN has better hardness and resistance to fracture but poorer chemical resistance. These tools are used to machine nickel or cobalt-base alloys of hardness equal to or greater than 340HV. The recommended speed range of these tools to machine Inconel 718 is from 120 to 240 m/min [1]. The optimal cutting condition for good surface finish is 60 m/min and 0.15 mm/rev. The tool failure occurs at a speed of 50 m/min and a feed rate of 0.10 mm/rev [51]. As cutting speed was increased to 300 m/min, the presence of grooving and BUE diminished, leading to comparable performance between the C-type and round tools. When turning at 450 m/min however, several instances of catastrophic insert fracture occurred and tool life did not exceed 3.5 min [50]. The effect of PCBN cutting edge preparation when turning Inconel 718 under high cutting speed conditions (up to 1250 m/min) was studied by Uhlmann and Ederer [12], who reported that a range of between 400–600m/min was recommended to minimise flank wear and cutting force levels. They also found that un chamfered inserts were generally preferred over chamfered tool edges, as the former exhibited ~50% higher tool life and ~20% lower cutting forces when machining at 600m/min. Similar trends were observed. Coelho et al. [19] reported that severe depth of cut notching was the primary wear mode when finish turning Inconel 718 at 500 m/min cutting speed, 0.1 mm/rev feed rate and 0.35mm depth of cut using PCBN tools. Notch wear was also observed on the secondary cutting edge while flank wear progression was rapid and reached 300-350µm after a machined length of 185 mm.

3.3. Machining Inconel 718 with ceramic tools

There are two basic ceramic materials that are used as cutting tools. These are aluminum oxide (Al$_2$O$_3$) and silicon nitride (Si$_3$N$_4$). The reinforced ceramic is based on Al$_2$O$_3$ contains silicon carbide (SiC) whiskers which gives it better thermal conductivity and improves its bulk toughness considerably. The silicon nitride (Si$_3$N$_4$) based ceramic known as sialon has better thermal properties and toughness than Al$_2$O$_3$ based ceramic, these tools being used widely to machine super alloys. The introduction of these super abrasive cutting tools has enabled high cutting speeds to be achieved [8].

Alumina ceramics has high hardness; high compressive strength with fracture toughness up to 4.3 MPa m$^{-0.5}$ and low thermal and mechanical shock resistance properties compared to tungsten carbides.

Mixed alumina or alumina-Tic: Due to addition of zirconium oxide (ZrO$_2$) ceramics tool has improved fracture toughness up to 4.5 MPa m$^{-0.5}$. The range of cutting speed 120–240 m/min, the speed range being almost ten times higher than for plain carbides. Its thermal shock resistance properties can be improved by the addition of titanium carbide or titanium nitride.

Whisker-reinforced alumina ceramics (Al$_2$O$_3$+SiC$_w$): In this fibers or whiskers of silicon carbide are added (25% by vol.) for reinforcement of an alumina matrix to improve toughness up to 8 MPa m$^{-0.5}$ The range of cutting speed is from 200 to 750 m/min, with corresponding feed rates of 0.18–0.375 mm/rev. The thermal conductivity is also increased by 40% over that of alumina, thereby reducing thermal gradients and improving its ability to withstand thermal shock.
Sialon or Silicon nitride ceramics (Si₃N₄): is known to be one of the toughest ceramic materials has toughness up to 6.8 MPa m⁰.⁵, and is used for the rough machining. The silicon materials have a low coefficient of thermal expansion (a half of that of cemented carbide and one third of that of alumina) At a speed of 152 m/min with round and rhomboid shaped pure oxide (Al₂O₃ + ZrO₂) and mixed oxide (Al₂O₃ + TiC) ceramic tool without coolant (because of the low thermal shock properties of ceramic) machining surface tears and reduces its fatigue strength [2]. SiC whisker-reinforced alumina Al₂O₃ ceramic tool at cutting speeds were 410 and 810 m/min was followed by a layer with compressive stresses that is several times thicker than the tensile layer. The tensile and the compressive stresses increased with increase in cutting speed and the depth of the layer also increased [37]. Sialon (Si₃N₄–Al₂O₃) ceramic tools lead prone to notch wear, with minimum damage to the tool nose at lower speeds (120 m/min). A transition is observed at 240 m/min. Further increase in the speed to 300 m/min leads to reduction in notching and increase in nose and flank wear [46].

3.3. Machining Inconel 718 with cermets tools
Cermets have small, well controlled grain structures leads in to higher wear resistance. In addition, cermets maintain a sharp edge longer than carbide. Cermets have superior resistance to built-up edge. Less affinity with the study piece results in superior micro-finishes. Aruna [38] studied finish turning with cermets tools TNMA 160408. The surface finish measurement is carried at the various cutting conditions as cutting speed (100, 150 and 200 m/min), feed (0.04, 0.06 and 0.08 mm/rev), depth of cut (0.5 mm), Cutting tool geometry and type of chip formation affect cutting forces. Increasing the negative rake angle increase the tool chip contact area, causing larger cutting forces because of high friction forces in tool–chip interface.

3.4 Different tool geometries and coating options
The cutting tool edge geometry significantly influences many fundamental aspects such as cutting forces, chip formation, cutting temperature, tool wear, tool-life and characteristics like surface roughness and surface damage [24]. For finishing and semi finishing operations it is recommended to use cutting tool insert with positive rake geometry, shears the chips away from the work piece reduces work hardening and built-up-edge. Very or even light hone sharp insert edges are more fragile and susceptible to chipping thus honed edges are recommended for most roughing operations [16, 17]. Mostly use relatively sharp edges, strong geometry, rigid set-up, part deflection prevention, high lead angle and when more than one pass is required, vary the depth of cut is recommended [2]. When machining with cemented carbides, application of coatings allows an increase in cutting speed from 30 m/min up to 60-100 m/min [63]. The negative rake angle tends to generate compressive residual stress whereas positive rake angle tends to induce tensile residual stress. The chamfer on the cutting edge has a similar effect as negative rake angle, due to which compressive residual stress can be increased [65]. The ceramic tools, the round inserts produced better surface finish than the rhomboid inserts. All the rhomboid-shaped ceramic tools failed after machining for 1 min due to severe notching at the depth of cut. With the rhomboid shaped insert give a higher microhardness as compared to the round inserts [2]. Altin et al. [24] Whisker reinforced aluminum insert (Al₂O₃ + SiCw) KYON 4300 SNGN and silicon nitrite based ceramic KYON 2100 SNGN inserts are used below 150 m/min cutting speed. Square type inserts showed good performance compared to round type inserts at low cutting speeds. The square type KYON 4300 insert at low cutting speeds whilst round type KYON 4300 insert was recommended at high cutting speeds.
The negative chip angle has caused an increase in the main cutting force [26]. With PCBN tools cutting force component is significantly higher (two to three times) in magnitude than the other force components. This can be attributed to the increased thermal softening of the work material at higher cutting speed[64]. Coated hard PVD TiAlN and AlTiN carbide tools have good tribological behavior limits welding and unstable built-up-edge phenomena; abrasive wear is also reduced by its very high hardness due to its ultra-fine crystalline [7]. Jindal et al. [11] studied the relative merits of PVD– TiN, TiCN and TiAlN coatings on cemented carbide, TiAlN has the lowest thermal conductivity among the three coatings tested. This should result in lower tool tip temperatures as much of the heat generated during machining would be carried away by the chip. As a result, the TiAlN coating imparts excellent crater resistance. Prengel et al. [45] confirmed the conclusion of the previous work but with a multilayer coated tool has been shown that the PVD (Ti, Al) N coating is most suitable in dry machining. Superior oxidation resistance, high-temperature chemical stability, high hot hardness and low thermal conductivity are the principal reasons of its performance [11]. Recently, a TiN/AlTiN nanolayer coating gave good results with low BUE phenomenon and reduced abrasion wear [47]. It was found that protective function of the coating, increasing tool life up to 20%, is limited to low cutting speed range Tool life was found to be highly sensitive to cutting speed, where it decreased by 250% with increase in speed from 250 m/min to 350 m/min of PCBN tools [56].

4. MACHINING CHARACTERISTICS OF INCONEL 718

4.1 Surface integrity and Residual stresses when machining Inconel 718

In machining processes, a major quality related output is integrity of the machined part surface. Ezugwu et al. [20] Whisker reinforced ceramic tool gave improved surface roughness values, well below the stipulated rejection criterion of 3 µm, when machining with the SiC whisker reinforced Al₂O₃ ceramic tools. The round shape (RNGN 120700) of the ceramic tool, with a large contact radius (6 mm) with the workpiece material, thus its ability to produce high quality surface finish. J.diaz-Alvarez et al. [52] attempted work shows the relation between tools wear and surface integrity and residual stress. Pawade et al. [29] Degree of work hardening (DWH) at different depths beneath the machined surfaces has been investigated to determine and understand the integrity of machined surfaces in Inconel 718. As cutting speed was increased the surface residual tensile stress dropped while an increase in feed rate resulted in a slight increase in both the surface tensile stress and the depth of the compressive stress layer. As cutting speed was increased the surface residual tensile stress dropped while an increase in feed rate resulted in a slight increase in both the surface tensile stress and the depth of the compressive stress layer [23]. Less tool wear and good surface finish are obtained using ceramic tool when finish turning. The optimal cutting condition for good
surface finish is 100 m/min and 0.1 mm/rev. The tool failure occurs at a speed of 200 m/min and a feed rate of 0.15 mm/rev. Finally, it is concluded that the performance of ceramic tool is better at low cutting speeds [38].

4.3 Cutting force when machining Inconel 718

Lower cutting forces were recorded with increasing coolant supply pressure when machining Inconel 718 with SiC whisker reinforced alumina ceramic tool. Fang et al. [35] in high speed finish machining, where the tool edge geometry plays a significant role. (1) The cutting force \( F_c \), (2) the thrust force \( F_t \), (3) the resultant force \( R \), and (4) the force ratio \( F_c/F_t \). Tool inserts investigated. TPG432 (Kennametal Inc) Tool material Cemented carbide (KC 8050) with TiC/TiN/TiCN coating 1) for both materials: as the cutting speed increases, the cutting force, the thrust force, and the resultant force all decrease; however, the force ratio increases. (2) For both materials: as the feed rate increases, the cutting force, the thrust force, the resultant force, as well as the force ratio all increase. (3) Under the same cutting conditions, the cutting force and the thrust force in machining Inconel 718 are higher than those in machining Ti–6Al–4V. (4) The variation of the thrust force with the feed rate is smaller in machining Ti–6Al–4V than that in machining Inconel 718, especially at the lower cutting speeds.

4.4 Tool wears when machining Inconel 718

Tool wear mechanisms are generally influenced by three phenomenons; namely thermal softening, diffusion and notching at the depth of cut and trailing edge. Nickel-base super alloys have a tendency to work harden and retain the major part of their strength during machining [67, 8]. At cutting speed above 30 m/min, carbide tools fail due to thermal softening of the cobalt binder phase and subsequent plastic deformation of the cutting edge. The main reason which causes cutting tool wear was that the tool materials fall off from the tool substrate in the form of wear debris. In addition, element diffusion between tool and workpiece and oxidation reaction all accelerate the formation and the peeling of the wear debris [77]. Narutaki et al. [61] have investigated the influence of the cutting speed on the wear of ceramic tools and observed that the notch wear (VBN) at the depth of cut line was the biggest problem. SiC whisker reinforced ceramic tools showed the least fluctuation of VBN. Altin et al [29] studied the effects of cutting speed on tool wear and tool life using silicon nitride based and whisker reinforced ceramic tools. Cantero et al. [73] Commercial coated carbide tools (multilayer coating TiAl/TiAlN recommended for machining Ni alloys) for dry cutting and found that the great influence of side cutting edge angle in tool wear mode. Kejia Zhuang et al [74] investigated that sharp temperature rise mainly caused by excessive plastic deformation and the friction alumina-based ceramic cutting tools causes’ notch wear. Gómez-Parra et al. [76] Direct and secondary adhesion affects to the tool wear in two ways. First, tool geometry changes by the material incorporation. In a second place, when these fragments are removed, they can drag out tool particles causing tool wear. Indirect adhesion can be located in the tool edge, giving rise to the (BUE) and/or in the tool rake face giving rise to the (BUL). BUL and BUE formation and their evolutions affects to the workpiece quality. Observed results have confirmed that BUE changes the tool position angle giving rise to a reduction of Ra.

4.5 Tool life when machining Inconel 718

In turning operation, friction and heat generation at the cutting zone are the frequent problems, which affect the tool life and surface finish. This generation plays quite a negative role in machining hard materials [75]. Li et al. [6] Tool life of ceramic tools is severely limited by excessive notching due to the relatively low mechanical toughness of ceramic tools. Chen and Liao [15] recommended use of cutting fluid mixed with nano-particles to reduce friction force and triple the tool life. Rahman et al. [5] Tool life is significantly increased with an increase in the SCEA’s.
Krzysztof [36] presents comparison of cutting performance of several cemented carbide, CBN and whiskers tools in rough turning. PVD TiAlN carbide tools for rigid parts and in turning of flexible parts PVD TiAlN used in turning of rigid parts, Gusri Akhyar Ibrahim et al [41] showed that depth of cut is a significant influence to the tool life.

![Tool Wears Mechanism](image)

**Fig 2:** The tool wears mechanism under dry cutting condition [41].

### 4.6 Material Removal Rate (MRR) when machining Inconel 718

The material removal rate (MRR) in turning operations is the volume of material/metal that is removed per unit time in mm³/min. The excellent material toughness results in difficulty in chip breaking during the process. In addition, precipitate hardening of γ” secondary phase (Ni₃Nb) together with work-hardening during machining makes the cutting condition even worse. All these difficulties lead to serious tool wear and less material remove rate (MRR) [5, 8].

### 4.7 Chip morphology when machining Inconel 718

While machining Inconel 718 with coated carbide tools effective chip segmented can be achieved when machining with high pressure coolant supply, unlike long continuous chips produced when machining with conventional coolant supply. Three types of chips are observed. Machining under conventional coolant flow produces long continuous tubular chips (Figure: 3a). Machining with coolant pressures up to 150 bar produces short continuous tubular chips (Figure: 3b) and smaller arc shape (C-type) chips when machining Inconel 718 with coated carbide tools [22].

![Chip Morphology](image)

**Fig: 3** (a) with conventional flow (b) coolant supplies up to 150 bar (c) at 203 bar [22].
The mechanism of the formation of chips during the machining of Inconel 718 (400 BHN) is observed to change with cutting speed [23]. Słodki et al. [27] develop correlation between chip shapes and tested factors forces and temperature.

5. MACHINING WAYS, OPTIMIZATION AND AI APPROACH

The machinability of nickel and titanium alloys can be improved by employing ramping (or taper turning) technique, high pressure coolant supply technology, hot machining, cryogenic machining and the use of Self-Propelled Rotary Tooling (SPRT) technique [22].

Cost savings up to 17% of the total workpiece cost can be made by introducing dry machining. This is mainly due to the elimination of coolant supply [41, 42]. Kamata and Obikawa [62] HPC at reduced flow rates, the friction and the heat induced in tool chip interface can be reduced [30]. An extensive investigations performed in the last decade a pressurized water-based coolant was directed into the tool-chip interface from an external nozzle [14, 15, 16 and 20]. The credibility of this coolant delivery technique has been thoroughly investigated and performed on nickel-based alloys [21, 18, and 20]. The advantages of high cooling technology include significant improvement to tool life, effective chip segmentation and efficient cooling and lubrication. Ezugwu [22] Minimal Quantity Lubrication (MQL) improves the tool life by 38% and 50% for MQL 50 and MQL 100 ml/h respectively [33,53]. Ezugwu [17] cryogenic cooling is an efficient way of maintaining the temperature at the cutting interface well below the softening temperature of the cutting tool material. Sharma et al. [75] presents an overview of major advances in techniques. Pusavec et al. [78] evaluated cryogenic machining for machining performance to improve product quality level. Lokman et al. [57] presented the results of Taguchi DOE for High pressure jet assisted coolant on surface integrity in machining. Whereas Mark Anderson et al. [69] stated laser-assisted machining (LAM) the benefit of LAM is demonstrated by a 25% decrease in specific cutting energy. Thakur et al [33] optimized the machining factors. Saravanakumar et al [70] investigated the influence of machining parameters on MRR and surface roughness by genetic algorithm. Prete et al [71] described the development of a hardness-based flow stress and fracture models by FE on some characteristic features of the chip formation process. Satyanarayana et al [54] developed mathematical model to optimize parameters for better surface finish. Pravin Pande et al [72], an adaptive neuro-fuzzy inference system (ANFIS) were used to develop predictive model for surface roughness.

6. CONCLUSIONS

It makes difficult to maintain tolerances and critical metallurgical integrity of the machined part of inconel 718 due to rapid work hardening during machining. However, carbide tools cannot be used for high-speed machining since energy caused by high cutting speed can cause surface integrity damage, uncoated carbide tools are better than the coated tools; the coating does not improve the performance of coated tools. Surface finish is found to be optimum in the cutting range of 45–55 m/min. Cutting forces not always are higher using CBN tools than using carbide tools. Tool life increases as the SCEA increases. Tool life of the best carbide tools appeared to be comparable with some of CBN tools optimum in the cutting range of 120 to 240 m/min and for ceramic above 250 m/min.

REFERENCES


[74] Kejia Zhuang, Dahu Zhu, Xiaoming Zhang, Han Ding, Notch wear prediction model in turning of Inconel 718 with ceramic tools considering the influence of work hardened layer, Wear, 313(1–2, 15), 2014, 63–74.


