Scientific Journal of Impact Factor (SJIF): 4.72
e-ISSN (O): 2348-4470
p-ISSN (P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 4, Issue 10, October -2017

# Machining of difficult-to-cut Super alloys: A Review

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**Abstract —** *Excellent physical, mechanical and chemical properties at high temperatures, toughness and ductility, high resistance to corrosion, resistance to thermal distortion are making super alloys favorable in the industries. They are on high demand in the chemical, marine, and aerospace industries. Improvements are suggested in the area of machining of difficult to cut materials having poor machinability due to low thermal conductivity, to maintain high strength at elevated temperature and chemical reaction. The most affecting factors which governs the machinability of Super alloys are machined surface of work material and tool life. A Proper selection of cutting tool materials, cutting parameters and conditions, as well as the functional behavior of machined specimen gives efficient machining of super alloys. This paper presents an overview of advancement in the machining techniques which can improve the productivity along with cost reduction without compromising dimensional and geometrical accuracy, machined surface quality in terms of roughness, finish, subsurface quality and hardness. Various cutting parameters, cutting environment and tool geometry on different features of machined surface quality has been presented. These includes surface roughness, surface defects in the form of cavities, metal debris, smeared material, feed marks etc., metallurgical and microstructural aspects.*

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***Keywords***- *High temperature super alloy, Machining techniques, Surface quality, Microstructure.*

## I. INTRODUCTION

The machining process is a special technique which transforms the particular material in to a required component for an application with desired accuracy, reliability and surface quality. It is consisting of turning, milling, drilling, grinding processes. Some of these processes are complex because it accounts for a large percentage of the entire volume removed. In the fabrication of mechanical components these processes have considerable economic implications. Super alloys are one of the tested high performance materials used in various industries due to their superior properties like high strength to weight ratio, high tensile and compressive strength, lower density, higher fatigue resistance in sea and air and high corrosion resistance. Super alloys are classified as difficult-to-machine materials because of their non-favorable properties such as poor thermal conductivity, low modulus of elasticity, strong chemical reaction to tool materials at higher temperatures. Due to increase in the usage of super alloys in to aerospace and other applications, their fabrication with higher efficiency, safety and reliability shows a lot of importance. In the machining system, cutting tool, work-piece and machine and out of these, cutting tool plays an important role because the cutting speed relies upon the cutting tool materials on greater extent. Researcher are continuously exploring the tool work piece interaction for getting better machined surface. In this regard, efforts have been made for developing novel tool materials which can sustain extreme conditions at the cutting zone. One of the objective of machining research is to optimize the cutting conditions so that we can lower down operational cost and improve product quality. We can define the term machinability which means the easiness of cutting the material and getting desired shape with required surface finish and geometrical tolerances with the reference to the tool and process associated with it. To measure machinability, tool life, surface finish of machined component, chip morphology, cutting forces and torque are used as parameters. It is also evident that the material used for machining process, cutting tool, cutting conditions and environments are significantly affect the machinability index. To improve machinability, selection of right combinations of tool, machine tool, cutting conditions and high speed machining will result in economic machining of difficult-to-cut alloys. Figure1 shows schematic diagram of issues in the machining area.

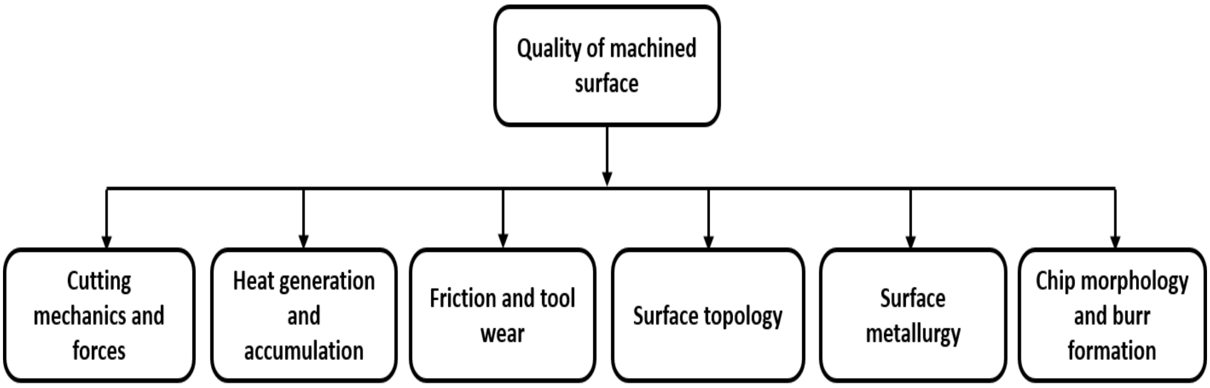


*Figure 1. Challenges and issues in machining of super alloys*

## II. SUPER ALLOYS IN AEROSPACE INDUSTRY

The heat generation is a common occurrence in most of the machining processes, but the rate of heat generation is different in each one. It is reported that, the temperature generated during machining of super alloys is a single source of all the problems occurring during machining. Therefore, it should be minimized. Nickel and titanium based super alloys and other advance engineering materials also used for the manufacturing of components for aerospace, defence, medical etc. due to their unique properties like higher strength at elevated temperature, resistance to chemical reaction and resistance tow wear. The poor thermal conductivity of such alloys tend to increase the temperature at the tool-work piece interface during machining process [1]. The extensive application of jet engines has demand for the materials having excellent high temperature mechanical and chemical properties compare to steels and alloys. [2]. Super alloys with higher melting temperature are the prime materials used in the manufacturing of aerospace components. These materials can be categorized in to four main types.

1. Nickel based alloy
2. Cobalt based alloy
3. Titanium based alloy
4. Iron based alloy (higher percentage of chromium in the stainless steel)

Figure 2 shows the highest consumption of super alloy is in the name of aerospace industry for the fabrication of jet engines and aircraft components [2]. Components made from super alloys are compact in size and lighter than conventional steel material which can save fuel and reduce pollution as well [3]. Approximately 50% weightage of the aero-engine alloys are nickel based alloys [5]. Nickel based super alloys are also utilized such as nuclear reactors, petrochemical plants, marine industry, food processing industry due to their ability to maintain high resistance to mechanical and thermal loading, erosion at higher temperature and high resistance to corrosion.

Titanium and its alloys satisfy the requirement of strong and lightweight materials for an aircraft engine and frame structures due to their superior strength to weight ratio, exceptional resistance to corrosion, which is saving of coating. The titanium alloys can also be used to fabricate airframe structure where the operating temperature is more than 1300 $^{0}$C which is the conventional operating temperature of aluminum alloys [6,7].

## III. MACHINING OF SUPERALLOYS AND EFFECT OF CUTTING TOOL MATERIALS

While applying heat treatment on Ni and Ti based super alloys, their hardness is increased. Second phase particles make both the alloys stronger and abrasive thus more difficult to cut. So if the machining is done in the softer state of material, then it is beneficial. The machinability of super alloys can be improved by applying high pressure coolant supply technique, host machining, Cryogenic machining etc. The cutting tool materials used for the machining of super alloys must have hot hardness to sustain a very high temperature generated at the cutting zone. The majority of the cutting tool materials lose their hardness at elevated temperatures which tends to increase tool wear and failure afterwards. Ceramics, coated carbide tools, Coated carbide tools, ceramics, Cubic boron nitride (CBN)/Poly crystalline cubic boron nitride (PCBN) and Poly crystalline diamond (PCD) are used for high speed machining of Ni and Ti based alloys. Ceramics and CBN/PCBN are not preferred for machining of Ti alloys due to their tendency of excessive wear as a result of the high reactivity of Ti alloy with ceramics [8,9]. Advancement in the cutting tool materials and machining techniques showed remarkable increment in the metal removal rate while cutting difficult to cut super alloys.

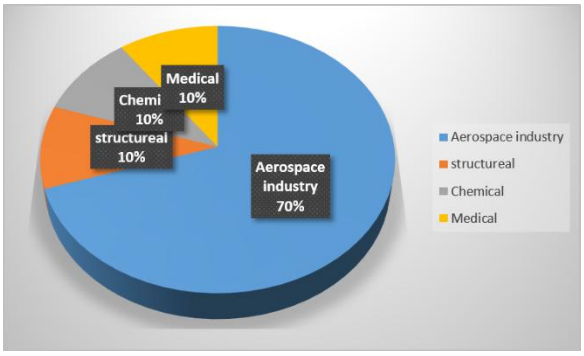


*Figure 2. Bifurcation of percentage sharing of super alloys. [2]*

*Figure 3. High pressure coolant in machining*

## IV. APPLICATION OF HIGH PRESSURE COOLANT IN MACHINING

The intension of this technique is to reduce the cutting temperature generated at the tool work piece and tool chip interfaces especially at higher speed conditions. In this technique, coolant is directed under high pressure at the cutting zone as shown in figure 3. Better chip evacuation is the benefit due to this technique. Flood cooling also reduce cutting zone temperature while machining at the lower cutting speeds. The coolant acts as a lubricant thus reduced friction and cutting forces results in improvement in tool life. At the higher speed coolant vaporized, forming a high temperature cover neat tool edge so its cooling is not much effective [10]. Impact of jet of coolant at high pressure can improve the machinability at higher speed conditions. The coolant jet penetrates into the tool chip interface reduce the temperature and lubricate the surface at the cutting zone with the remarkable reduction in friction. Improvement in the cutting tool life can be achieved while machining nickel based, Inconel 718, alloy with coated carbide tools at the cutting speed up to 50 m/min. with high pressure coolant supply as shown in table-1, while lower tool life was attained in the case of machining with ceramic tools. With high pressure coolant supply as shown in table-2 [11,12].

***Table 1***
***Percentage enhancement in tool life comparative to conventional coolant supply after machining Inconel 718 with coated carbide tool [11]***

| **Cutting Speed(m/min.)** | **Feed rate(mm/rev.)** | **Coolant pressure** | | |
|---|---|---|---|---|
| | | 110bar | 150 bar | 203 bar |
| 20 | 0.25 | 8 | 9.8 | -33.8 |
| 30 | 0.25 | 87.7 | 50.6 | 64.1 |
| 50 | 0.25 | 335 | 411.1 | 462.8 |
| 20 | 0.3 | 8.6 | 11.5 | -43.9 |
| 30 | 0.3 | 27.05 | 95.2 | 104.5 |
| 50 | 0.3 | 517.6 | 647.2 | 739.8 |

***Table 2***
***Percentage reduction in tool life comparative to conventional coolant supply when machining Inconel 718 with SiC whisker reinforced alumina ceramic tool [11]***

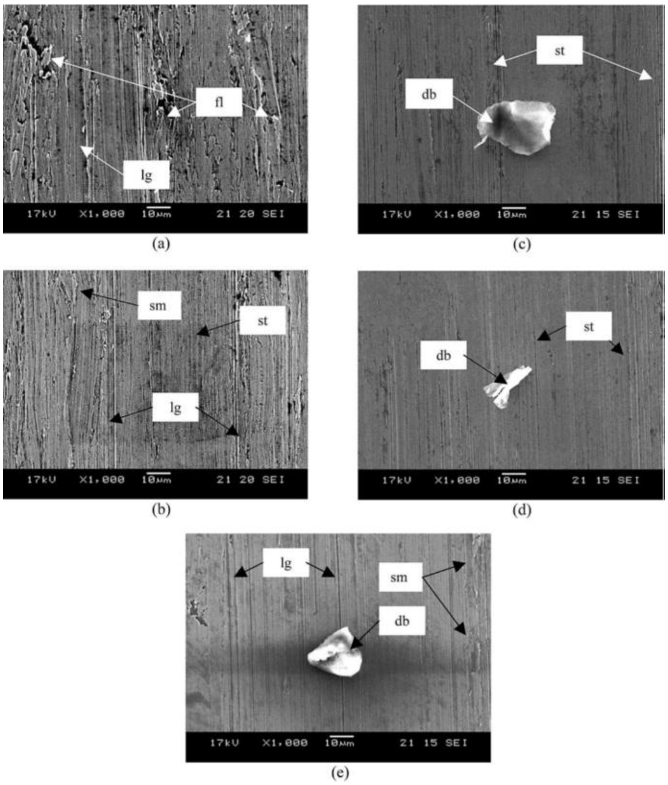
| **Cutting Speed(m/min.)** | **Feed rate(mm/rev.)** | **Coolant pressure** | | |
|---|---|---|---|---|
| | | 110bar | 150 bar | 203 bar |
| 200 | 0.15 | -48.6 | -51.6 | -49.6 |
| 250 | 0.15 | -45.7 | -38.8 | -69.7 |
| 300 | 0.15 | -44.7 | -34.1 | -63.1 |
| 200 | 0.25 | -4.5 | -35.0 | -35.0 |
| 250 | 0.25 | -47.9 | -63.0 | -61.7 |
| 300 | 0.25 | -68.8 | -67.5 | -65.6 |

## V. MINIMUM QUANTITY LUBRICATION (MQL)

In this technique, a small quantity of lubricant is splashed at the tool-work piece interface through compressed air. Compare to other traditional ways, MQL was found better to reduce the friction and cutting temperature. Traditional cutting fluids contain oil in it which adversely affect to the environment and operator of the machine. Nowadays a clean machining concept is used in which a minimum amount of coolants or environment friendly coolants are used for machining [13]. Temperature reduction at the cutting zone in MQL is acquired due to the cooling effect of compressed air and evaporation. A significant heat is used in evaporation of the lubricants, thus reduced temperature at the cutting zone. The MQL technique is having potential for precision machining at a high speed and lower federate. [14]. The main problem of this technique is mist-causing which is hazardous to the operators of the machine. This can be minimized by good quality mist extractors.

## VI. SURFACE TOPOGRAPHY OF SUPER ALLOYS

This is the feature of surface consists of surface roughness, waviness and lay combined with other features of machined surface called as defects. Surface roughness is defining as irregularities on the surface caused by interactions of the material microstructure and the action of cutting tool along with periodic nature of surface defects [15]. Surface roughness is denoted by centre line average $R_a$, maximum profile height $R_t$ and ten-point average roughness $R_z$. The factors affecting surface roughness are built-up edge formation, chip plastic side flow and tool wear equality [16]. Other than cutting parameters, friction occurring at chip-tool and work piece-tool interface also play an important part in altering surface roughness [17]. So the properties of both the tool and work-piece materials joined with cutting environment should also be considered. Efficiency of the coolant can be evaluated for different machining operations by considering surface roughness as one of the important output response [18]. During machining some surface defects are visible and have significant impact on surface quality. Some visible surface defects in the machining of Ni based super alloys such as metal debris, cavity in surface, smeared material, feed marks. These unwanted features off machined surface tend to cause high thermal and mechanical loading especially in machining of nickel based super alloys [19]. The characterization of these surface defects can be characterized with optical microscopy and scanning electron microscopy.



(a) (c) (b) (d) (e)

***Figure 4. SEM images of the machined surface during face turning of Inconel 718 at cutting speed of 60 m/min., feed rate of 0.10 mm/rev. and $a_p$ of 0.5 mm produced at distance of (a) 5 mm, (b) 10 mm, (c) 15 mm, (d) 20 mm and (e) 25 mm from the periphery on the X-axis (lg: long grooves; sm: smeared material; db: metal debris; fl: flash; mf: micro fracture; st: streak) [20]***

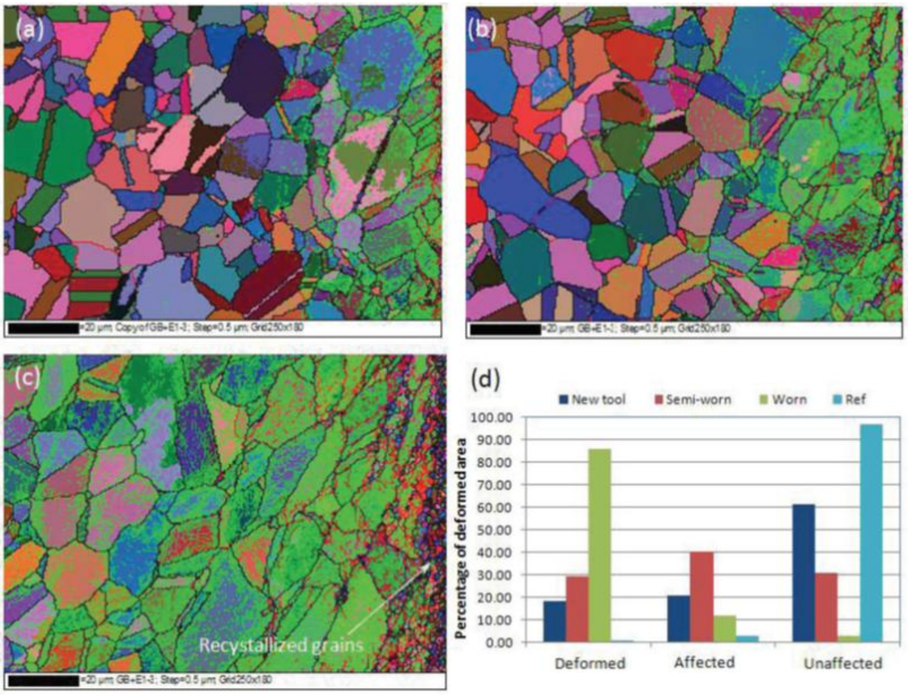


*Figure 5.* ***EBSD maps showing the depth of deformed sub-surface layer in the turning of Inconel 718 at cutting speed of 300 m/min, feed of 0.2 mm/rev and ap of 0.3mm with (a) New tool, (b) Semi-worn tool, (c) Worn tool and (d) Graphical representation of recrystallized microstructure [22].***

## VII. SURFACE METALLURGY

It consists of metallurgical alterations of machined surface and sub-surface layer. Microstructural and metallurgical alterations caused because of high mechanical and thermal loading in the machining of nickel-based super alloys [21]. The alterations are in the form of deformed and recrystallized grains in the surface and sub-surface of the component. Various characteristics analysis of these surface and sub-surface alteration can be carried out with the use of advance imaging techniques like scanning electron microscopy (SEM), X-ray diffraction (XRD), electron backscattered diffraction (EBSD) and transmission electron microscopy (TEM). Figure-4 shows SEM along with EBSD maps which indicates three different zones in sub-surface microstructure of nickel-based super alloys. Zone 1 is highly deformed region due to reason of high mechanical and thermal loading. Zone 2 creates partially deformed and elongated grains while zone 3 is unreformed layer [22]. Proper machining conditions can eliminate such sub-surface deformation in the microstructure. EBSD is an advance characterization technique to study machined induced deformation providing quantitative information about grain size, orientation as shown in figure 5 [22]. In zone 1, the mis-orientation angles evenly distributed over the grains, whereas the grains are elongated and bent in the cutting direction in zone 2. The mis-orientation angles are to be sprayed around grain boundaries. The intensity of plastic deformation is increased while moving from bulk material to top deformed surface.

## CONCLUSIUONS

1. The remarkable machined surface finish and quality in the machining of super alloys are attained with the novel tool materials and techniques. This is achieved by reducing the generation of the heat at the cutting zone.
2. Machining performance are obtained as per expectations while machining of super alloys with ceramic and boron nitride tool materials.
3. Super alloys which are difficult to machine at normal temperature can be machined well at a higher temperature at particular level. The combination of heating and cooling of the cutting interface area can improve the machinability of nickel and titanium base super alloys.
4. As a general observation, the surface roughness is more close to thermal and mechanical deformation of the work piece surface. Getting the desired level of surface finish in components made up of super alloys face challenge in applications and at last super finishing operations are required.
5. In the machining of nickel based super alloy, some visible defects such as feed marks, smeared materials, surface cavities are observed. One possible reason behind these defects is improper selectin of cutting parameters and tooling conditions. So final finish operations are to be required or best suitable cutting fluid is to be used in the process.

6. Tool wear deteriorates the surface quality and enhanced the deformed layer of machine surface. So it is desired to develop novel cutting tools and coolant strategies to reduce tool wear.
7. Surface finish quality which is achieved in the dry machining can be improved by applying coolants to reduce thermal effects, while MQL, Cryogenics and high pressure coolant also performed their better role in this context.

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