Dry Machining of Superalloys: Difficulties and Remedies

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Abstract: ***These Super alloys sustain its strength at high temperature and pressure conditions. Such materials have great demand in aerospace industry, marine industry, and nuclear power plants. It is particularly used in the hot sections like engines, because of their high strength and corrosion resistance at high temperature and pressure but they are the most difficult to machine materials. Their high strength possesses large amount of heat generation while machining, which reduce life of tool. Strain rate sensitivity, work hardening and precipitation hardening of material leads to more tool wear. Surface integrity obtain while machining of superalloys is poor. Poor surface finish and high residual stresses are the main causes of failure of these material components. Cutting fluid apply at high pressure in chip forming zone. It affects environment and create problem of disposal of cutting fluid. So dry machining should be employed. This article is about the difficulties occurs during dry machining and suggestions to overcome problems during dry machining. Dry machining performed at high speed with special coated carbide tool inserts which helps to avoid the rapid tool wear. This paper discusses the capabilities of dry machining of super alloys using specially coated carbide tool inserts.***

Keywords: Dry machining, Superalloy, Coated carbide tool inserts, Inconel 718

1. Introduction

Superalloys are mainly nickel based alloys. These alloys are the most complex and they are widely used as material for the hottest parts of complex equipments. They currently constitute more than 50% of the weight of advanced aircraft engines made now days. They have a great demand in Nuclear and Aerospace applications because of it retain its properties at temperature over 700 °C. They are difficult to machine because, high shear strength, work hardening, precipitation hardening. High abrasive particles in its microstructure and tendency forming chip to weld to tool and form built up edge (BUE) make it more difficult to machine. Friction between tool and material and its low thermal conductivity results in high temperature generation. They have nickel (Ni), chromium (Cr), ferrous (Fe) or Cobalt (Co) as base contains. Small amount of Al, Ti, Nb, Ta, W, Mo added to this alloys to sustain at high temperature. Cr is important alloying element in order to obtain the hot corrosion resistance property. However there is increase in one element decrease the properties of others [1,2]. In many industries, nickel-base alloys are important to make critical components manufacturing. Cutting tool materials undergoes severe thermal and mechanical changes because of high heat generation. The temperature produced at tool tip results in rapid tool wear; reduce the life of the tool. Dimensional variations of the product cause due to tool wear. Tool failure occur mainly because of combination of problems like high temperature produced, high material strength, work hardening of alloys, abrasive chips formation and very large amount of heat generation. High chemical affinity to number of materials which results in welding of chip to tool materials, it also promotes the diffusion wear of cutting tools [3-5]. They are most difficult to cut materials and machining with good surface finish with cost effectiveness at high machining rate is the main area of research for engineers [6]. Lot of research done for machinability of such superalloys; High pressure jet assisted machining (HSJA) is one of them. The second method used is dry machining with the use of coated tool inserts; which shows better advantages over the HPJA machining and conventional machining. Different types of coatings are used on tool inserts which shows important properties like less friction, toughness at very high temperature for dry machining. Inconel 718 is one of these heat resistant super alloy materials. They possesses very high strength at elevated pressure and temperature atmosphere

2. Literature Survey

Superalloys are difficult to machine conventionally with normal cutting conditions because of high strength. The heat is generated at the area of shear of workpiece forming chips. Because of poor conductivity heat dissipation is difficult. Large amount of heat generation takes place at the tool point. The tool wear takes place because of work hardening in which plastic deformation of workpiece takes place; which increase the strength of the workpiece. With increase in workpiece strength wear rate of tool insert and forces of cutting increase. Tool wear also takes place because of precipitation hardening [7]. BUE formation is takes place while machining the workpiece. Hot chip rolling over face of the tool and from point of contact it try to weld the surface which result in welding of cheap to surface. So we need to avoid BUE formation.

2.1 High Pressure Jet Assisted (HPJA) Machining

HPJA machining is one of the better approaches while machining super alloys. In this method high pressure fluid supplied at the point of cutting where large amount of heat generate. It helps to decrease the temperature while cutting in the shearing zone. It also helps to minimize the friction at tool face and chip interference, it gives lower vibrations. D. Kramer et al tried to machine Inconel 718 with the use of HSJA machining process. TiAlN coating inserts used to perform machining. Conventional and various high pressure levels of conventional fluid tried. Chip produced in machining were dependent on heat produced and friction in cutting zone. It was observed that the cheap breakability is increase with increase in the pressure of cutting fluid. It was found that the surface properties and cheap breakability is highest for highest pressure conditions of fluid [8]. HPJA machining helps to reduce temperature at cutting zone. It helps to easy movement of chip, and reduces the tool wear by avoiding the softening of tool and diffusion of tool material.

Oguz colak also performed the Inconel 718 machining in conventional and HPJA cooling conditions. TiAlN+TiN coated inserts used in this research. He specifies the various reasons of failure of tool inserts in machining and advantages of use HPJA machining Inconel 718 alloy. It observed that with increase in feed, but with the increase in fluid pressure the cutting forces also decrease significantly. With the application of fluid chip movement easy and reduces the friction between tool and chip by reducing contact area. Chips analyzed and found that continuous chips at low fluid pressure and short chips at high pressure conditions. The flank wear was reduced by increasing fluid pressure. At rake face rake wear was observed is very less than normal cutting conditions because of reduction in contact length between tool and chip [9]. This method utilizes the large amount of cutting fluid. Cutting fluid creates the disposal problem, it may be expensive. It requires proper recycling and treatment. It cause biological and environmental hazard. The cost of treatment is more for these fluids. It is not easily disposable; cost of machining increases. Human health may gets affected. For this reason this method of machining should not used [1]. Special equipment require for the recycling and separation of chips and fluid. Cost of machining increases. For different machines it may require special such type of equipments.

2.2 Dry Machining with Coated Carbide Tools

Dry machining is a good approach for machining of super alloys. Dry machining is generally associated with high speed machining with the use of coated carbide inserts. Tool coating sustain at very high temperature and gives good tool life even large heat is generated. It does not require cutting fluid for lubrication and cooling purpose. The coatings are mainly of TiAlN, TiN, TiCN, TiAlN+TiN, PCBN and other materials having special coating characteristics. Multilayer coating uses various layers of different coating materials. This approach is increasing rapidly for machining hard materials. At higher speed of machining the chip formed are easily conveyed from machining zone. Chips contains large amount of heat so the tool wear reduces, which generally occurs because of thermal phenomenon at cutting zone [1]. Dry machining is generally associated with high speed therefore amount of heat dissipate with the chip is more and has less contact time of chip to transfer heat to tool material.

K. Kadirgama et al. tried to find out effect of dry cutting on Haynes 242 which is a nickel based super alloy. It was observed that TiAlN coating gives better cutting condition than TiN/MT-TiCN/TiN coating in dry machining. Wear was dominant at the flank of tool than face of tool [1]. Satyanarayana B. et al tried to optimize the parameters of dry turning of Inconel 718. Three different types of tool inserts used. Genetically Optimized Neural Network System (GONNS) employed to get relation between input and output parameters. They used three levels of cutting speeds, feed and depth of cut. Tool materials used were uncoated tool, TiN/TiAlN PVD coated tool, and TiN/Al2O3/TiCN CVD coated tool. Tool wear while machining Inconel 718 was predicted. PVD coating gave very good performance than the tool used with the CVD coating. The PVD coated tools should employed for the high speed dry machining of Inconel 718. The optimum conditions of speed, feed and depth of cut can be predicted [10].

D. G. Thakur et al investigated the high speed dry turning of Inconel 718. Cemented tungsten carbide tool insert (K20) used for machining. Cutting forces were observed and it was found that the cutting forces decrease as the speed increases. The cutting force was high for large depth of cut. At the high speed material removal rate was more and forces were less, because material was softened as the heat generated was taken away from cutting zone quickly. At low machining speed cheep thickness was large, which make large contact area of chip and tool. At high speed thin chips produced and area of contact was less and heat dissipates through chips easily. As the cutting speed increases the region of plastic deformation decreases, which result in lower forces require for chip formation. It was also observed that metallurgical transformation of chips not happened, that means heat generated in cutting zone was not very high. It is observed that tool geometry, cutting conditions and material directly affect the tool life. Diffusion, thermal softening of tool, trailing edges and notching occurs at depth of cut was mostly responsible reasons for tool wear. The temperature and stresses were rise when high heat generated in primary zone and secondary zone [11]. Chip produced in machining represent the performance of machining. Smaller, thin and discontinuous chip gives good machining conditions.

A. Devillez et al tried to find out workpiece surface integrity of Inconel 718 in dry turning. The experiment was carried out at dry and wet cooling conditions. The depth of cut and feed was kept constant and the results were obtained at different speeds. The tool used was sandvik-made S05F having TiCN-Al_2O_3-TiN CVD coated tool. The coating had 4μm thickness with 0.4 mm tool radius. Cutting forces were initially decreases with increasing cutting speeds. Dry machining gave lower cutting forces. After this there was increase in cutting forces, this was because of strain rate sensitivity which predominant than material softening. For surface roughness the dry and wet machining conditions were compared. Surface roughness was decreased with increase in speed of machining in dry conditions. Dry machining gives optimum cutting conditions and good surface finish. It is observed that cutting forces were similar in dry and wet machining but in dry machining surface roughness was largely reduced. Comparing microstructure in wet and dry conditions in cutting direction, it was observe that very little plastic deformation in wet conditions compared to dry machining [12]. Cutting conditions have to ensure carefully due to machining difficulty and heat generation in machining superalloys. Good surface finish and better surface integrity insure quality of product.

3. Experimental Work

3.1. Work material

Inconel 718 is a Nickel-Iron based super alloy. It is one of the hard to cut material. It is highly stable and corrosion resistance at very high temperature and pressure. Inconel 718 was used to find out machining difficulties of superalloys. Chemical compositions and its properties are shown in Table 1 and Table 2.

Table 1: Inconel 718 chemical composition

Sr. No.	*Element*	*Content by weight (%)*
1	Nickel (plus Cobalt)	50.00-55.00
2	Chromium	17.00-21.00
3	Iron	Balance
4	Niobium (plus Tantalum)	4.75-5.50
5	Molybdenum	2.80-3.30
6	Aluminum	0.20-0.80
7	Carbon	0.08 max
8	Manganese	0.35 max
9	Silicon	0.35 max
10	Phosphorus	0.015 max
11	Sulfur	0.015 max
12	Boron	0.006 max

Table 2: Properties of Inconel 718

No.	*Physical Property*	*Value*
1	Density	8.2 g/mm^3
2	Melting point	1260-1336 ºc
3	Specific heat	435 J/Kg K
4	Coefficient of thermal expansion	13 µm/m K
5	Thermal conductivity	11.4 W/m K
6	Ultimate tensile strength	1240 Mpa
7	Yield strength	1036 Mpa
8	Hardness	38-40 HRC
9	Young's Modulus	206 Gpa
10	Strain hardening coefficient	1370 Mpa
11	Magnetic permeability	1.001
12	Electrical resistivity	753µΩ-cm

Niobium gets reacted with Nickel at high temperature and forms Ni_3Nb molecule particles. Precipitation hardening because of Ni_3Nb gave the strength to Inconel 718 even at very high temperature. Round bar of Inconel 718of diameter 17.3 mm and length 120 mm was employed for experiment.

3.2 Machine tool and insert

Dry turning of Inconel 718 was performed on MTAB make MaxTurn Plus+ CNC machining center shown in Figure 1. Dry machining was employed in machining. To measure cutting forces Kistler's Multicomponent Force dynamometer will be used shown in the Figure 2. For trial Taguchi L_9 array was employed. Minitab 16 software will be used for analysis.

Figure 1: CNC machine tool used for experiment

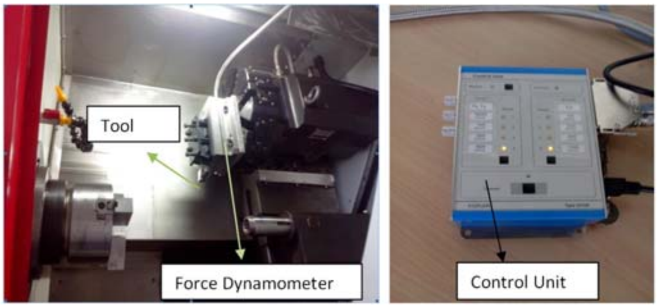

Figure 2: Force Dynamometer

Sandvik made CNMG 120408 FS – 1125 having very hard multilayer PVD TiAlN coated carbide tool Insert used. Insert geometry and properties are shown in Table 3.

Table 3: Insert Properties

Sr. No.	*Description*	*Parameters*
1	Tool nose radius	0.8 mm
2	Coating	Multilayer PVD TiAlN
3	Insert included angle	80º
4	Clearance angle major	0 º
5	Grade	FS 1125
6	Insert thickness	4.7625 mm
7	No of cutting sides	2

3.3 Process parameters and responses

Based on the literature review, following parameters and their levels are decided for trials. The levels are shown in Table 4. The levels are kept at very large and very small intentionally to find out variation of responses over wide region of parameters.

Table 4: Parameters and their levels

Sr. No.	*Parameters*	*Unit*	*Levels*
1	Cutting Speed (Vc)	m/min	40, 80, 120
2	Depth of Cut (DoC)	mm	0.4, 0.8, 1.2
3	Feed (f)	mm/rev	0.05, 0.1, 0.15

Based on the literature review and available instrument constraints following parameters were selected as the response variables.

a. Surface Roughness

Surface Characteristics plays very important role in functioning of material for a particular application. Better the surface better the working of the component. It also helps to reduce corrosion of material. Tool wear adversely affect the surface finish so it also shows characteristic of tool wear.

b. Material removal rate

To improve productivity MRR should be high. MRR gives the productivity of any system. It is a very important parameter for selection of tool materials.

c. Cutting forces

Cutting forces gives the ease or machinability of the material. Effectiveness of cutting and energy required for machining is obtained from forces.

Taguchi design was employed to decide final experiment levels. L_9 array was used because of three level three parameters in machining Inconel 718 for trial experimentation.

4. Result and Analysis

The DOE array formed for experimentation is shown in Table 5. This table also contains responses obtained when trials taken. Surface roughness was measured with the help of Taylors-Hubson surface roughness tester. Cutting forces are measured with the using the kistler multi-component force dynamometer. Material removal rate is calculated using weight difference machining workpiece.

Table 5: Taguchi L_9 array with responses

Speed m/min	*DoC mm*	*Feed mm/rev*	*MRR gms/sec*	*SR Ra*	*Fc N*
40	0.4	0.05	0.11592	1.61	144.00
40	0.8	0.1	0.33679	1.19	149.82
40	1.2	0.15	0.54294	1.68	371.33
80	0.4	0.1	0.3293	1.346	247.60
80	0.8	0.15	0.69016	1.241	409.80
80	1.2	0.05	0.3724	1.771	65.91
120	0.4	0.15	0.26818	1.00	222.81
120	0.8	0.05	0.277	2.00	285.73
120	1.2	0.1	0.3419	2.10	191.81

Figure 3 shows machined workpieces. It showed that while machining Inconel 718 at 120 m/min the tool wear was rapid. So material surface has poor surface finish and the burnt chips were formed during machining due to tool wear. Figure 4.17 shows that the workpiece machined in trial7, trial8 and trial 9 did not gave continuous turning. The dimensional deviations were occurred because tool got wear rapidly. In case of trial 1, trial 2, trial3, and other trials the continuous machining was take place. Cutting forces are very high at high speed and large depth of cut. It was also found that the cutting forces vary significantly with the variation in feed and depth of cut. Inconel is difficult to machine at 120 m/min so avoid such high speed for machining. Large depth of cut above tool nose radius should be avoided.

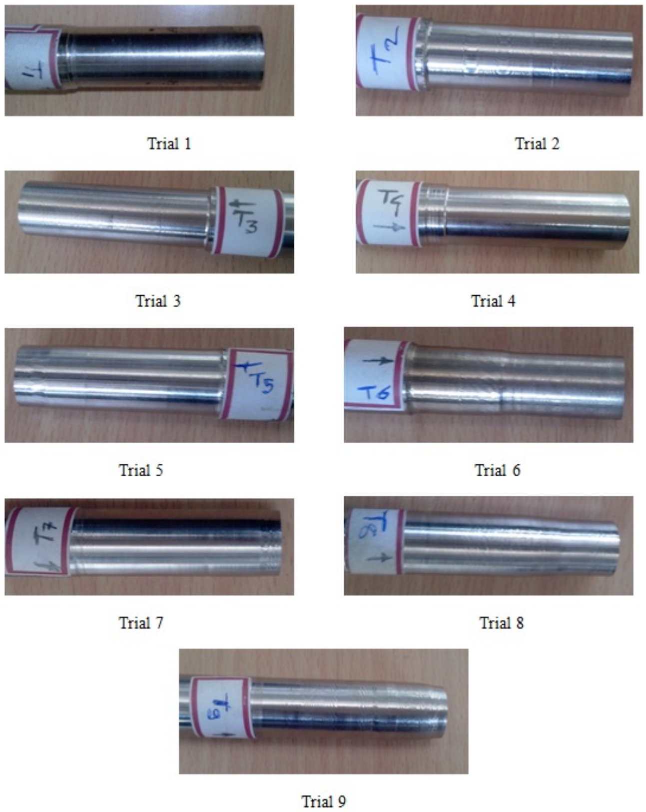

Figure 3: Machined workpieces for main experiment

Figure 4 shows chips formed during machining. It was found that the burnt chips were obtained in very high speed cutting conditions. Continuous type of chips was formed in medium and low speed cutting conditions. No discontinuous types of chips were formed during machining. These types of chips can sometimes come into contact with tool tip and machined surface; these can result in poor surface finish. High speed, high feed and large depth of cut results in the uneven machining and increase in cutting forces. There is also need to avoid continuous type of chip which can come into contact of work surface.

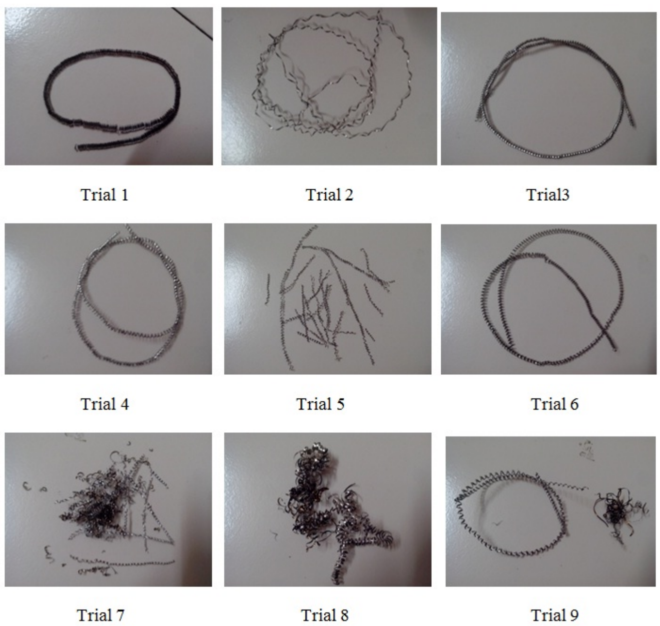

Figure 4: Chips formed during main experiment

New trials were conducted to decide levels for final experiments using response surface methodology with the new SM geometry of CNMG 1125 grade. New trial parameters were selected randomly based on previous trials and observations. Table 6 shows the parameters which were selected for new trials.

Table 6: Parameters for random trials

Sr. No.	*Cutting Velocity in m/min*	*Feed in mm*	*Depth of Cut in mm/rev*
1	30	0.3	1.2
2	70	0.3	0.8
3	90	0.2	0.6

Figure 5 shows the machined workpiece and figure 6 shows chips formed during machining.

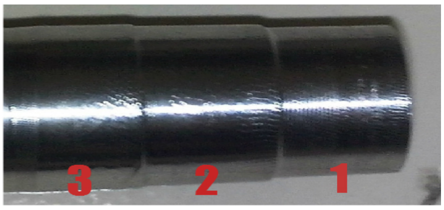

Figure 5: Workpiece machined in random trials

Figure 6: Chips formed during random trials

It was found that in random trials the chips form easily. Discontinuous types of chips were formed. No chip were interference with tool-tip so no mark of chips on workpiece. Improvement in chip breaking of machined work piece obtained. But good surface finish not obtained than previous results in these random second trials. These were happened because of very large feed so it will better to take feed value less than 0.2 in actual machining.

5. Conclusions

After successful completion of experiment, some observations were found out they are as follows:

- Machining of Inconel 718 was not possible at very high speed of 120 m/min the tool tip wear out suddenely producing burnt chip shown in figure 4. Trial 7, trial8 and trial 9 shows this type of burned chips because of tool wear. Its main reason was very high temperature generation takes place at cutting zone. Uneven machining also found out on this workpieces shown in figure 3. So it is very important to machine workpiece below the speed of 100 m/min.
- While machining Inconel 718 it was also observed that at high speed if we would take depth of cut more than tool nose radius that was 0.8 mm it support to rapid wear of the tool so it is strongly recommended to limit the depth of cut up to 0.8 mm at high speed machining.
- For experimentation SF (Finish Geometry) were used. Insert doesn't keep its strength for such a geometry used; Material removal rate is important response so large depth of cut and feed should be taken as processing parameters. So new SM (Medium Geometry) should be employed.
- From second random trial experiments, it was found that large feed that was 0.3 mm/rev result in discontinuous type of chips. But surface roughness of machined workpiece was also increased. So feed should be limited to 0.2 mm/rev.

6. Future Scope

There is scope for finding out optimized machining condition for superalloy using CNMG FS – 1125 all the responses like surface finish, material removal rate, cutting forces etc which is under process. There is scope to develop new tools and machining methods, which will give good machining conditions. Proper modeling for machining superalloy is important to understand and define behavior while machining such materials. There is scope for research in environment friendly machining of superalloys with minimum quantity lubrication. There is scope for high speed finishing of superalloys and find out residual stresses and change in microstructure can be found out. One can do research to find out tool life while machining superalloys.

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