EXPERIMENTAL INVESTIGATIONS ON MACHINING OF NICKEL BASED AND COBALT BASED ALLOYS

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Abstract: *Need for an efficient cutting tool and machining techniques are the prime requirements of modern machining industries. Certain domains such as defense, aerospace and automobile use the typical 'difficult to cut materials', which has specific applications. Materials' machinability, tool life, surface finish achieved by the machining process, factors affecting surface quality and tool life are the key areas of investigations that researchers are focusing on. In this paper two difficult to machine materials namely Inconel 718 and Stellite 6 have been experimentally investigated for their machining characteristics. The effect of Flood and Jet cooling techniques on the machinability of these materials have been compared with dry machining, having a focus on tool wear, surface roughness, cutting temperature and cutting vibrations.*

Keywords: *Inconel 718, Stellite 6, Jet cooling, Surface finish, Cutting temperature*

1. INTRODUCTION

Nickel and Cobalt based super alloys have grabbed quite a good attention of the application scientists due to their exclusive properties like, high strength, high temperature resistance, maintenance of its strength at higher temperatures in the defense and aerospace sectors. However, the same properties have made these materials to be called as 'difficult to cut materials; which means, lower tool life, lower productivity of machining process, poor surface finish and eventually higher cost of machining [1].

As a hard metal, Inconel 718 has special features like, high strength to weight ratio, corrosion resistance, high heat resistance, creep resistance and for low temperature applications the material possesses a good ductile to brittle transition etc. In aerospace applications, about 50 % by weight of the engine is made of Inconel 718, which performs at elevated temperature and pressure [2]. The temperature difficulties during machining are reduced by utilization of various cooling techniques such as jet cooling, cryogenic cooling, compressed air cooling, hybrid cooling techniques, etc., as the rise in cutting temperature is the cause for increased tool wear, followed by poor surface finish and poor cutting economy [3]. Another class of difficult to machine materials is Stellite-6, a Cobalt-Chromium alloy. These alloys are having high strength and hardness, good biocompatibility, high creep resistance and higher corrosion and wear resistance, than that of a titanium based alloy, which have made it suitable for applications like gas turbine components, nuclear, medical implants, aero-engine, etc., But due to the lower thermal conductivity of the material, there is an increase in temperature of the cutting tool-work piece interface resulting in poor tool life followed by poor surface quality [4].

1.1 Machining of Inconel 718

Most of the research works carried out in the field of machining has been accomplished in a controlled environment, which would not be having most of noise factors affecting the overall machining performance. Nevertheless, wise choice of controllable cutting parameters and cooling techniques would yield better cutting performance.

Several optimization techniques have been widely used to determine the most influencing cutting parameter and optimize its value in machining operations such as Artificial Neural Networks (ANN), Response Surface Methodology (RSM), Taguchi approach, etc., [5, 6]. In any machining industry, manufacturer's primary objective is to achieve better productivity, i.e. to accomplish quality machining operations at the lowest cost. Resistance offered by the hard materials like super alloys would lead to rise in cutting temperature, followed by tool wear and deterioration of fineness of the machined surface. Researchers have tried variety of cooling techniques such as air cooling, flood cooling, jet cooling, cryogenic cooling etc., to address the issues associated with heat dissipation during shearing of chips [3]. Also there is much emphasis on sustainable and eco-friendly type of cooling techniques such as, Minimum Quantity Lubrication (MQL), Cryogenic cooling, Combined MQL and cryogenic cooling (CO_2+MQL), etc., to impart the desired surface finish on the machined surfaces. Researches have shown positive results under these cooling techniques [7]. Nung-Ming Liu, Ko-Ta Chiang & Chen-Ming Hung (2013) developed mathematical models for modeling and studying the machinability of Ti-6Al-4V with air cooling. The models performed will with 95 % confidence interval, compressed cooling air is more effective in penetrating the cutting zone and produces broken chips, results in lower cutting tool temperature and better surface finish [18]. Zhenglong Fang & Toshiyuki Obikawa (2017) proposed use of inserts with cooling channels to improve heat transfer from tool to coolant by causing turbulent flow in the flank clearance face using high pressure coolant. The cooling abilities were studied using cutting experiments and CFD analyses. There was an increase in tool life using through channels compared to use of only high pressure coolant [19]. Functional performance of a product doesn't only depend on surface finish, but also surface integrity features such as subsurface hardness, residual stresses and microstructural changes imparted during machining. Selection of novel and efficient cooling technique has substantially contributed for the improvement in quality of the machined surface and its integrity [8]. A.Thakur and S.Gangopadhyay (2016) presented a review of the state-of-the-art regarding surface integrity during machining of nickel based alloys. They reviewed about 228 research papers and made some conclusions, identified research gaps and provided future directions. They reviewed the influence of cutting parameters, cutting environment, coating, wear and edge geometry of cutting tools on different surface integrity characteristics, which include surface roughness, defects, surface and subsurface microstructure phase transformation, dynamic recrystallization and grain refinement, work hardening and residual stresses [20]. Eren Kaya and Birol Akyuz (2017) presented a review of the influences of the most significant cutting parameters on the machinability characteristics of Nickel based super alloys [17].

1.2 Machining of Stellite 6

Cobalt-based super alloys possess great corrosion resistance at temperatures above 1093˚C and find application in hot sections of gas turbines. Lower thermal conductivity of the alloy can be attributed to more heat transferred to cutting tool which would reduce tool life due to excessive tool wear [9]. Important factor in hard machining of Cobalt –chromium type of heat resistant materials is to produce the surfaces with least microstructural changes, such as generation of 'white layer' and residual stresses which dominantly influence the rate of cutting tool wear [8]. Because of these issues the research on machinability studies of these alloys are majorly limited to nonconventional machining processes such as Laser Beam Machining (LBM), Electric Discharge Machining (EDM), etc., [10]. However there are some attempts made in machining cobalt-based alloys using conventional machining processes. Eyup Bagci & Seref Aykut (2006) applied taguchi optimization method for obtaining low surface roughness using cutting parameters when face milling stellite 6. Surface roughness is significantly influenced by cutting speed, feed rate and depth of cut. The optimum machining conditions required for minimum surface roughness has been identified [24]. Seref Aykut et al. (2007) studied the effects of cutting speed, feed rate and depth of cut on tool wear, chip morphology and cutting forces in symmetric face milling of cobalt-base super alloy using coated and uncoated inserts. Cutting forces increased with feed and depth of cut, but cutting speed has no effect. But it accelerated tool wear. Different chip shapes were observed [21]. H.Shao et al.(2013) investigated machinability of Stellite 12 alloys with uncoated and coated carbide tool under dry conditions. The tool wear forms, wear mechanism and tool life were studied. Coated tools gave better performance. Tool life reduced with increased cutting speed and feed rate [22]. Alborz Shokrani et al. (2016) studied the effect of various cooling methods during CNC milling of Cobalt-Chromium alloys. Experiments were conducted at 200 m/min cutting speed using cryogenic cooling, MQL and flood cooling with water-based emulsion. Cryogenic cooling reduced surface roughness by 35 % and 42 % compared to MQL and flood cooling. There was a drastic reduction in flank wear. Diffusion and abrasive wear were dominant irrespective of the cooling environment [23].

Accordingly this work attempts to investigate surface roughness and other parameters like tool wear, cutting tool temperature and cutting tool vibrations at different cutting speed and feeds during turning of Inconel 718 and Stellite 6. Effect of jet cooling on all these parameters during machining and its comparison with use of flood cooling and dry machining is discussed.

2. EXPERIMENTAL SETUP

In this section details of the work piece material composition, machine tool & cutting tool, machining conditions, experimental setup, measurement systems used and experimental procedures adopted have been discussed in brief.

2.1 Work Piece Materials

Inconel 718 bar of diameter 50mm and length 200mm is utilized as work piece. The chemical composition of specimen is given in Table 1.

Stellite 6 bar of 60mm diameter and 260 mm length is used as specimen. The chemical composition of Stellite 6 is shown in Table 2.

2.2 Machine Tool & Cutting Tools

The plain turning experiments were carried out on HMT Stallion 100SU CNC turning centre. Experiments were conducted in dry, flood cooling and jet cooling conditions. Uncoated carbide inserts 883 (SECO) with MR4 chip breaker, nose radius of 0.8mm with back and side rake angle of -6° and end cutting edge angle of 5° have been used with tool holder PCLNL 2020K12 (SECO).

2.3 Cutting Conditions and Experimental Plan

In this work, it was planned to conduct

Table 1: Chemical composition of inconel 718

Element	Ni	Cr	Nb	Mo	Ti	Al	Co	Mn	Fe
% age	52.15	18.18	4.98	3.02	0.89	0.58	0.53	0.12	Balance

Table 2: Chemical composition of stellite 6

Element	Co	Cr	Mo	Fe	Si	Mn
% age	63.5	27.8	6.6	0.9	0.8	0.4

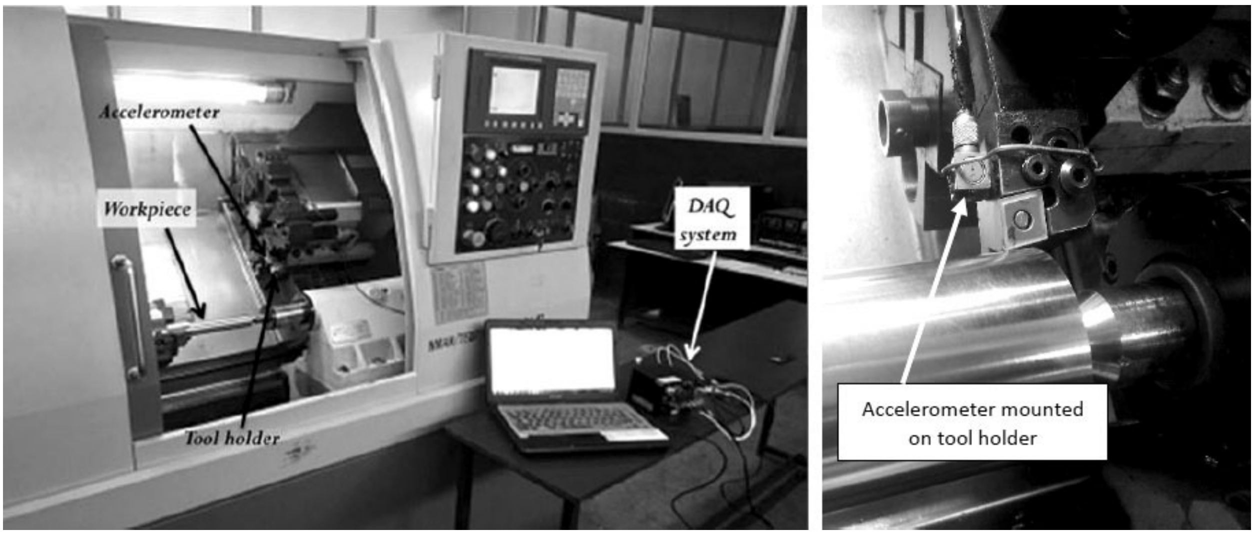

Fig. 2.1 Experimental setup

experiments using three level full factorial design. Experiments were conducted by considering three machining conditions; cutting speed in m/min, feed rate in mm/rev and depth of cut in mm. However, nine experiments have been conducted keeping depth of cut as constant for both materials as depth of cut does not show any significant effect during machining of these materials. Fig. 2.1 shows the experimental setup with a focused view of the accelerometer for measuring cutting tool vibrations.

An advanced double jet streaming type of tool holder, ADCLNL 16-4D is used to conduct experiments using cutting fluid along with regular flood coolant system available in the existing machine tool setup. Fig. 2.2 shows the double jet stream type of tool holder. This double Jetstream tool holder deliver cutting fluids effectively through the dual openings at the optimum position close to the cutting tip. This jet lifts the chip away from the rake face and carry away the heat produced during machining thereby reducing the heat load and imparting better tool life.

Experimental conditions used for Inconel 718 and Stellite 6 are shown in Table 3.

2.4 Measurement Systems

2.4.1 Measurement of tool wear

Measurement of flank wear was done using a Mitutoyo Tool Maker's Microscope (TM 505/510), which has a magnification of 15X and least count of 0.005mm, after each machining cut. Machining passes were carried out till the flank wear reached 0.4mm as per ISO 3685 standard[11].

2.4.2 Measurement of cutting tool vibrations

The cutting tool vibrations were measured using a triaxial accelerometer (Model 65-10 Isotron® By Meggit) online. The accelerometer was mounted on the tool holder, so as to obtain the vibrations signals in x, y and z directions; i.e along the direction of depth of cut, speed and feed directions (refer fig. 2.1). The sensed vibration signals, at a sampling frequency of 10 kHz were sent to a DNA-PPCx, Power DNA cube (UEI make). The most sensitive and significant vibration signals was along speed direction (V_y) and were only considered in this study.

2.4.3 Measurement of surface roughness

Surface roughness was measured offline using a stylus type instrument, Taylor Hobson Talysurf 50. The surface roughness parameters measured are R_a and R_t. Surface roughness was measured considering a sampling length of 2.5 mm. Surface roughness was measured at three different locations on the circumference of the work piece and average value has been taken. The surface roughness measurement setup is shown in Fig. 2.3.

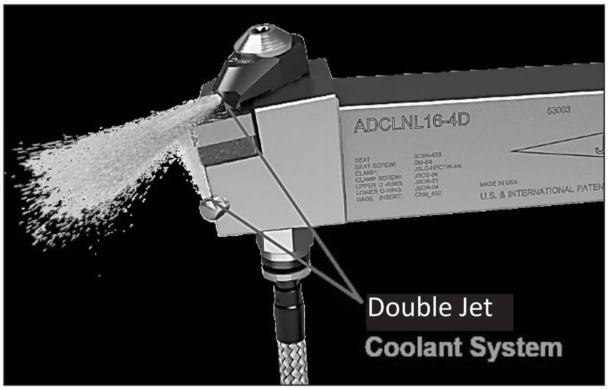

Fig 2.2 Double jet stream type of tool holder (SECO)

Fig 2.3 Surface roughness measurement setup

Table 3: Experimental parameters

Parameters	Cutting speed(m/min)	Feed rate (mm/rev)	Depth of cut (mm)
Conditions	40	0.10	0.5 (constant)
	60	0.15	
	80	0.20	

2.4.4 Measurement of temperature

The temperature at tool–work piece interface was measured using 30” Dual Laser Infrared Ray Thermometer (By Extech Instruments). The temperature was measured for every 10 mm distance over a length of 50 mm machining pass. Temperature readings were noted down and the average value is calculated for every machining pass.

3. RESULTS AND DISCUSSION

Experimental results on turning of Inconel 718 and Stellite 6 and their inferences with regard to the output parameters i.e. tool flank wear, cutting temperature, surface finish and cutting vibrations have been discussed in this section. Average values of the output parameters obtained at different machining passes were considered for analyzing the effect of cutting conditions on them. Further, comparison of results is made considering dry machining, use of jet cooling and flood cooling techniques.

3.1 Inconel 718

3.1.1 Tool flank wear

As illustrated in Fig. 3.1, feed rate has an inverse influence on tool flank wear, as feed increases, tool wear decreases. Further as speed increases, tool wear increases. T higher cutting speeds, tool gets worn faster at faster rate, with tool failure patterns like heavy notching [12]. But as the feed rate increases, tool wear rate are reduced at low speed and higher speed machining conditions; whereas, at medium cutting speed of 60 m/min it shows an increasing trend.

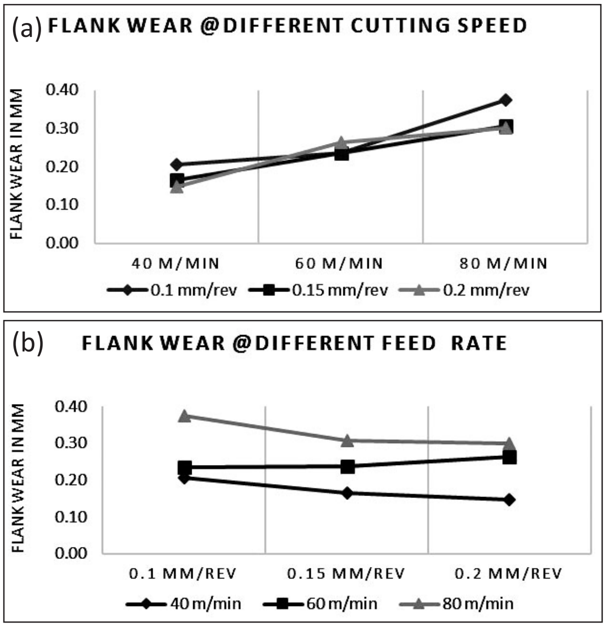

Fig 3.1 Influence of cutting parameters on tool flank wear, a) Cutting speed b) Feed rate

Also rapid wear was observed after only three machining passes in case of higher speed of 80m/min and higher feed rate of 0.2 mm/rev with a value of 0.35 mm.

3.1.2 Cutting temperature

Heat generated at the tool chip interface is the result of friction between tool tip and sheared chip. Among the cutting conditions considered in the machining process, increase in the cutting speed is found to be more contributing to the generation of heat, when compared to increase in the feed rate as shown in Fig. 3.2 a) and b). However, temperature of around 100^0C has been observed at the highest feed rate of 0.2mm/rev. It is possibly due to the higher cutting speeds imparting higher metal shearing rate. Similarly, higher feed rate imparts higher friction and very less time is allowed for the heat dissipation on to chip. Therefore, the heat accumulation at the interface leads to higher

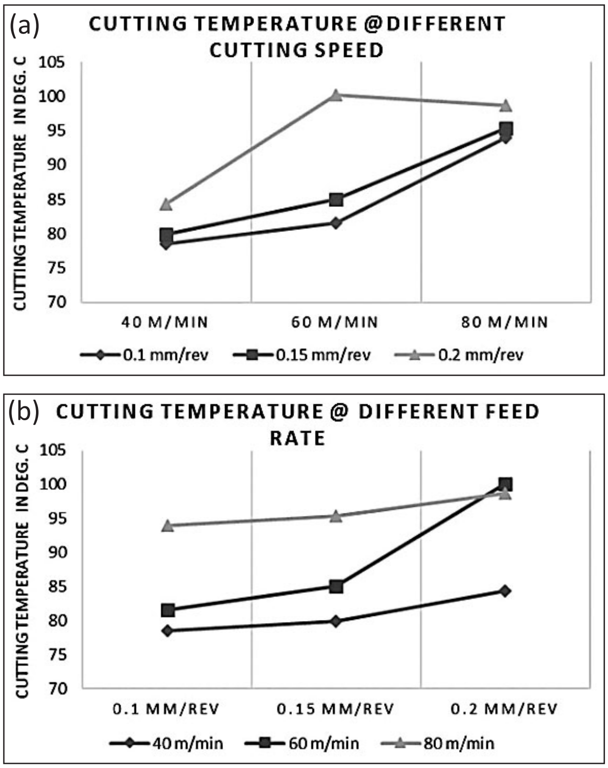

Fig. 3.2 Variation of cutting temperature with, a) Cutting speed b) Feed rate

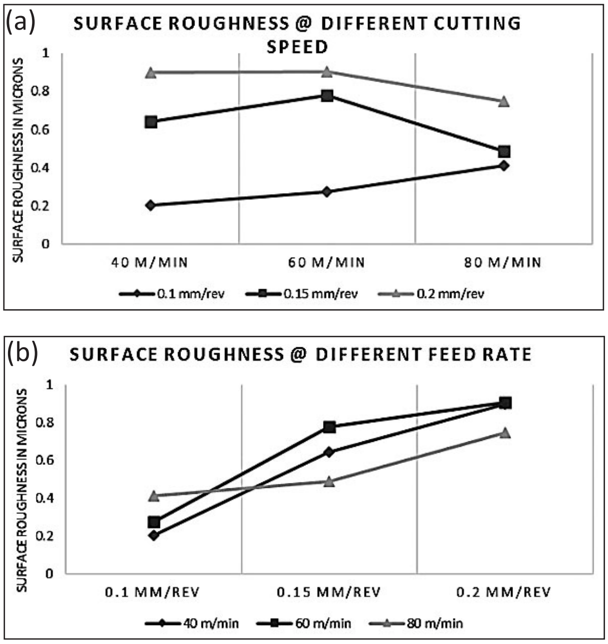

Fig. 3.3 Variation of surface roughness with, a) Cutting speed b) Feed rate

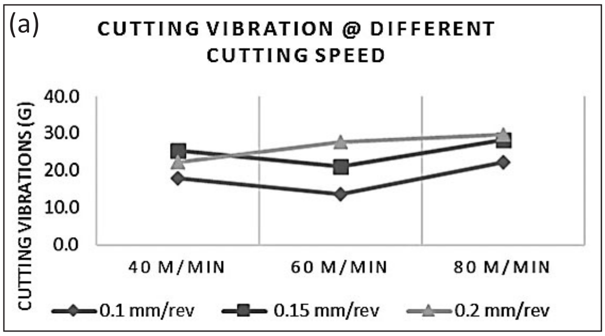

Fig 3.4 a) Influence of cutting parameters on cutting vibrations cutting speed

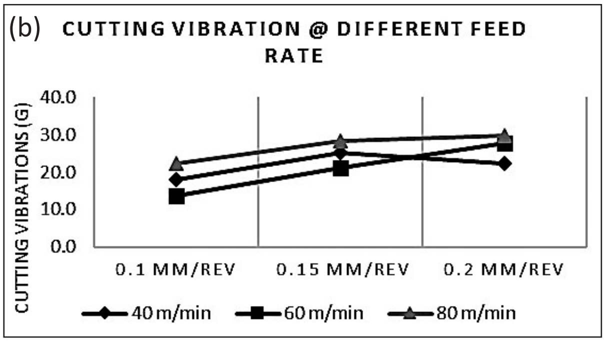

Fig 3.4 b) Influence of cutting parameters on cutting vibrations feed rate

temperature. This effect is clearly reflected on the tool life also, as flank wear reaches 0.48 mm in only 3 cuts.

3.1.3 Surface Roughness

Higher cutting speed and lower feed rate generally yield improved surface finish as shown in Fig. 3.3 a). At higher speeds, there may be thermal softening of material and there is also a possibility that surface flaws may get removed [12]. Increasing the cutting speed for getting a better surface roughness is a preferred method. As the feed rate increases, surface roughness value increases causing deterioration of the surface quality as shown in Fig. 3.3 b). As per the literature, increasing feed rate negatively affects the surface quality [25]. A very good surface roughness has been obtained at the lowest feed rate and lowest speed which can be attributed to very low tool wear rate.

3.1.4 Cutting vibrations

The shearing forces experienced by the work piece leads to cutting tool vibrations and more the feed rate, more is the cutting forces and hence the cutting tool vibrations. As shown in the Fig. 3.4 a), there is no clear correlation between the feed rate and tool vibrations at lower and medium cutting speeds of 40 m/min and 60 m/min. High speed and feed rate cause increased tool vibrations as shown in both fig. 3.4 a) and b).

3.1.5 Dry, flood and jet cooling condition

High cutting speed of 80m/min and feed rate of 0.2mm/rev have been found to be detrimental to tool life, under dry machining condition, with tool wear of 0.4 mm reaching in minimum number of passes. Hence, these cutting parameters have been considered to compare the effect of Flood and Jet cooling techniques on various output parameters like flank wear, cutting temperature, surface finish and cutting vibrations.

It is clearly evident from Fig. 3.5 a) that, flank wear rate has decreased considerably for jet cooling and flood cooling technique compared to dry machining. Flank wear of 0.325mm is attained after 80mm of cutting length in dry machining, whereas with aid of either of the cooling methods, same amount of tool flank wear was attained after 160mm length of cut, achieving a 100% increase in tool life. However, the two methods do not seem to show any significant difference in their effect as shown in Fig. 3.5. a), except at the second pass.

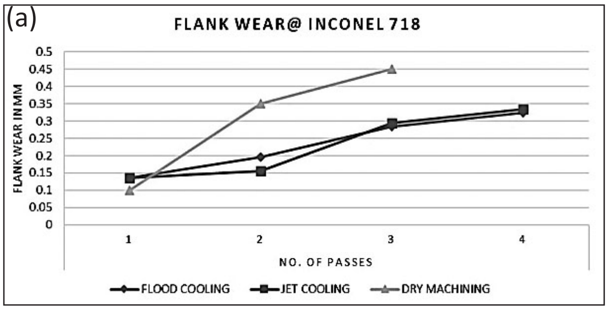

Fig 3.5 a) Influence of cooling conditions on flank wear

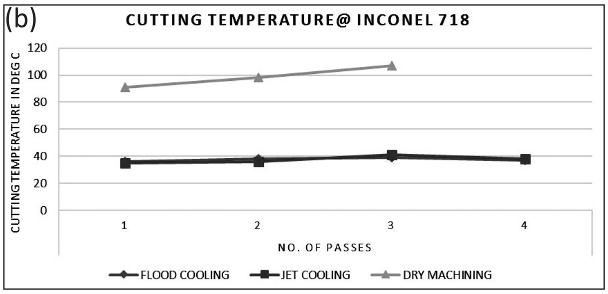

Fig. 3.5 b) Influence of cooling conditions on cutting temperature

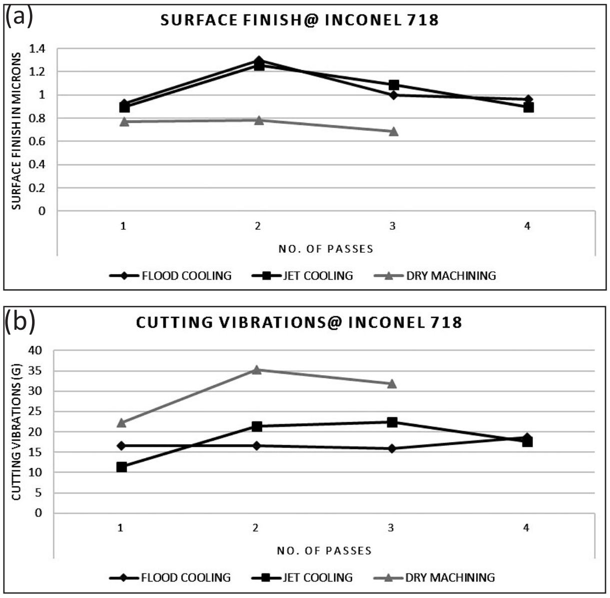

Fig 3.6 Influence of cooling conditions on, a) Surface roughness b) Cutting vibrations

Fig. 3.5 b) shows the effect on cutting tool temperature. Interestingly, cutting temperature is almost constant for different machining passes under both cooling conditions, but in dry machining it shows an increasing trend; which can also be considered as one of the potential reasons for increase in the tool wear rate and 50% reduction in tool life. There is a drastic reduction in cutting temperature of more than 100 %, when using both the cooling techniques.

The improved tool life has not contributed in the improvement of surface finish obtained during flood or jet cooled machining operations as shown in Fig.3.6 a). Average surface roughness value R_a, is about 30% lower in dry machining compared to the use of cooling technique. In dry machining, increased wear rate has resulted in larger tool nose radius which has possibly contributed in improved surface finish in comparison with coolant assisted machining [13]. Cutting tool vibrations have also been reduced in coolant aided machining conditions.

3.2 Stellite 6

The heat generated during machining of Cobalt alloys will be mostly transferred to the cutting tool due to the lower thermal conductivity of the work piece. This phenomenon subsequently leads to increase in tool tip temperatures and causes excessive tool wear, which results in reduced tool life. The presence of hard, abrasive intermetallic compounds and carbides in the alloy causes severe abrasive wear on the cutting edge. The experimental findings of machining Stellite -6, in dry, flood cooled and jet cooled conditions have been discussed in this section.

3.2.1 Flank wear

The tool wear shows an increasing trend with increase in the cutting speed and feed rate [15]. A drastic increase in tool wear at the high speed of 80 m/min and high feed rate of 0.2mm/rev is observed and tool wears to 0.52 mm quickly at the end of third cut for a total machining length of 120mm. The main failure mode was excessive flank wear and modes like abrasion, adhesion, diffusion and chemical wear was observed [22].

Cutting speed seems to be a dominant factor, as at higher speeds irrespective of feed rate, the tool wears beyond the failure criteria of 0.4 mm well within 4 cuts of total length of 160mm. However, low speed and low feed rate is the safest cutting conditon as far as the useful life of the tool is concerned. About 10% rise in tool wear rate is observed during each cut at low speed of 40m/min and feed rate of 0.1mm/rev.

Cutting Temperature

Fig. 3.8 a) and b) show the variation of cutting

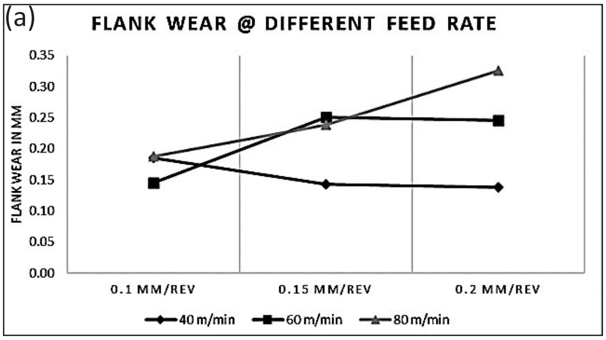

Fig. 3.7 a) Influence of cutting parameters on tool flank wear

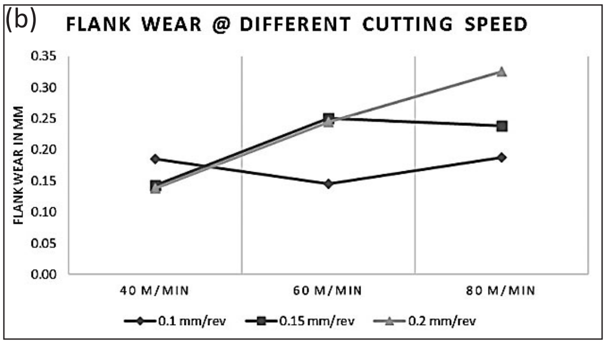

Fig. 3.7 b) Influence of cutting parameters on tool flank wear

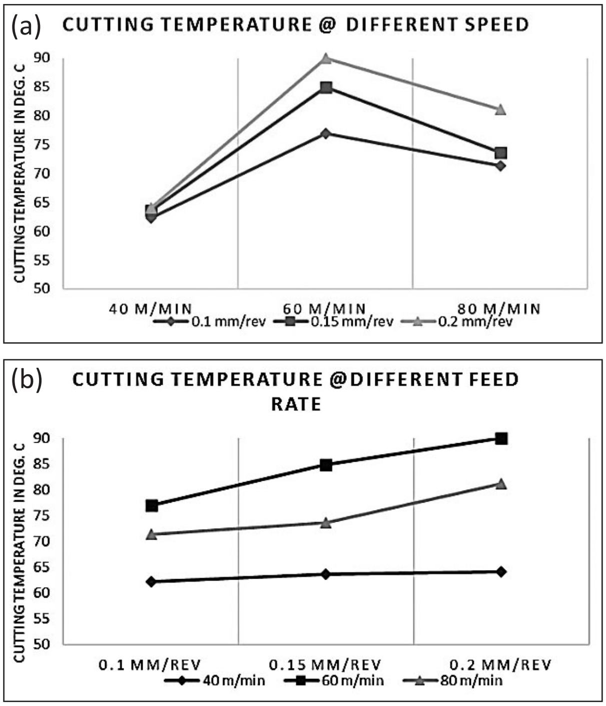

Fig. 3.8 Variation in cutting temperature with respect to, a) Cutting speed b) Feed rate

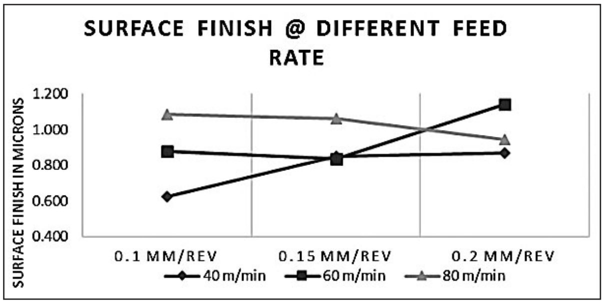

Fig. 3.9 a) Variation in surface finish with respect to cutting speed

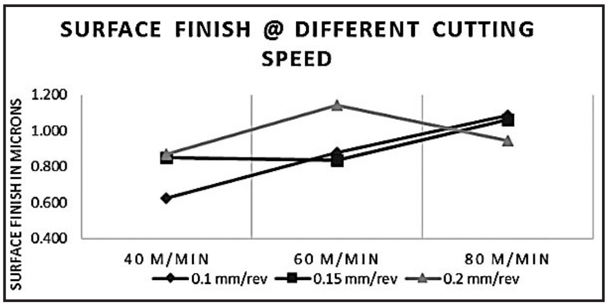

Fig. 3.9 b) Variation in surface finish with respect to feed rate

temperature with respect to cutting speed and feed. The moderate speed of 60m/min is causing the maximum temperature of 92^{0}C. Cutting temperature linearly increases with feed rate and for highest feed rate the temperature recorded was 93^{0}C. The abrasion of the tool surface with the hard constituents of the alloy increases friction leading to significant rise in the cutting temperature. At lower feed rates the tool-workpiece surface rubbing is not so significant and hence the heat generated is less and that improves the tool life, as seen in Fig.3.7 b). For a given feed rate, variation of cutting speed has a significant influence on tool flank wear and cutting tool temperature, whereas for a given cutting speed, variation of feed rate does not have a significant influence on tool flank wear and temperature, as shown in the Fig. 3.7 a) & 3.8 a).

3.2.2 Surface roughness

Generally, high speed and low feed rate is suggested for better surface quality. As shown in Fig. 3.9. a) and b), high speed of 80m/min and high feed rate of 0.2mm/rev are yielding lower average surface finish values. Neveretheless, lowest cutting speed has obtained the finest surface finish which is due to least tool wear rate.

3.2.3 Cutting vibrations

Cutting vibrations are the result of tool wear or vice versa. Hard particle abrasion is what casues the tool wear, while machining

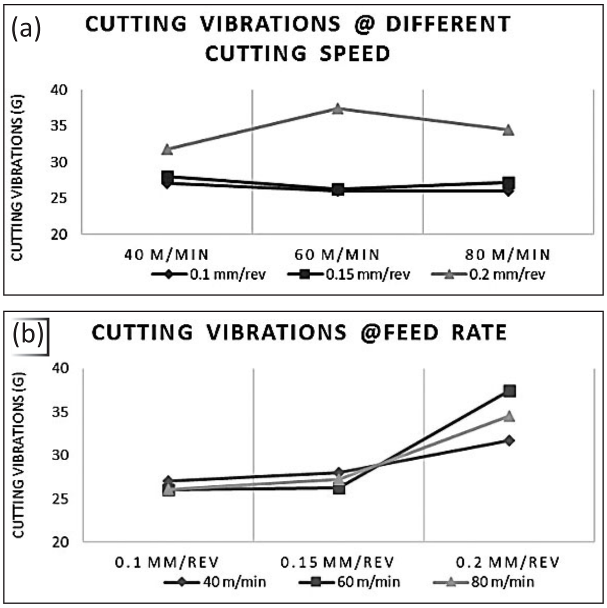

Fig 3.10 Influence of cutting parameters on cutting vibrations, a) Cutting speed, b) Feed rate

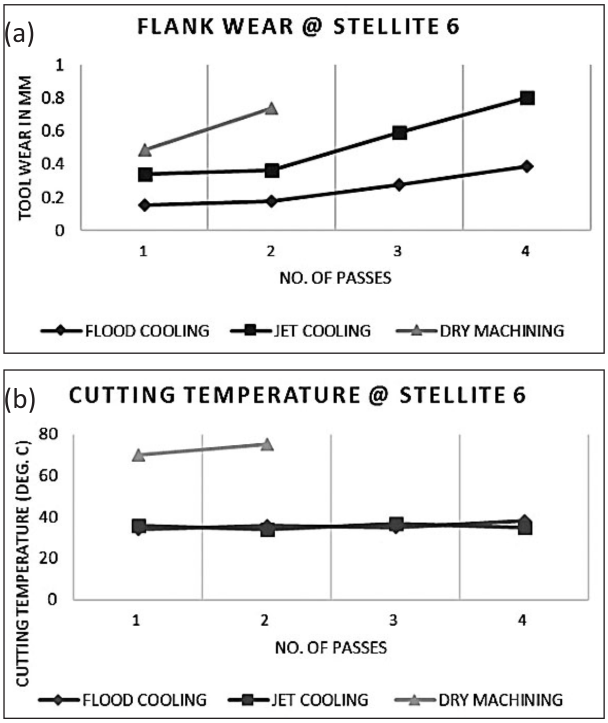

Fig 3.11 Influence of cooling condition on, a) Tool wear b) Cutting temperature

Stellite 6 material. Abrasion acclerated by excessive feed rate, leads to excessive tool wear and there by causing the tool vibration. Cutting tool vibration is also high at higher feed rate of 0.2mm/rev as shown in Fig.3.10 a). There is a decrease in cutting tool vibrations at higher speed, which is actually an advantage in high speed machining applications.

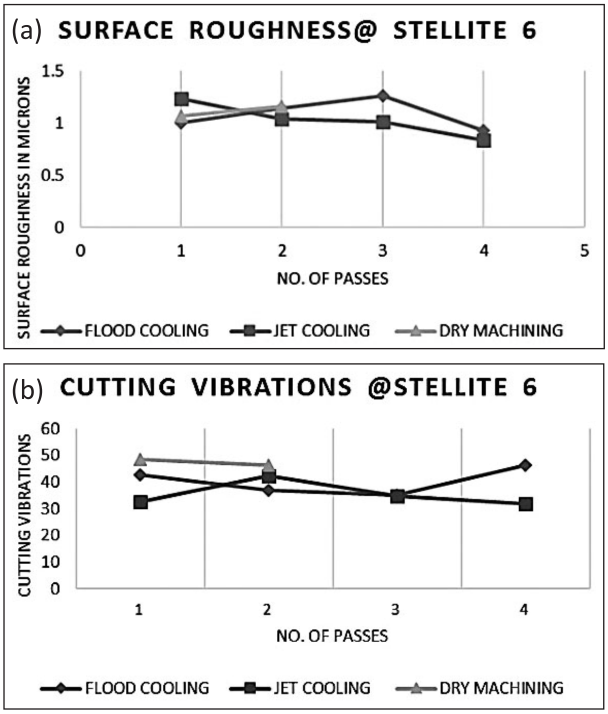

Fig 3.12 Influence of cooling conditions on, a) Surface roughness b) Cutting vibrations

3.2.4 Dry, flood and jet cooling condition

Unlike Inconel 718 alloy, Stellite doesn't show a clear behavioural difference during machining with or without the aid of cooling technique with regard to all ouput parameters considered for analysis, except flank wear and cutting tool temperature.

As the cutting tool used is an uncoated carbide insert, heat generated during machining would marginally affect its tool wear behaviour. The alloy is heat resistant and most of the heat generated in machining is not carried away by the chip, but transferred on to tool. Dry machining could be satisfactorily performed only for two passes of cutting length 80mm, where as it lasts longer upto 160mm cutting length by exibhiting a 100% extended tool life as shown in in Fig. 3.11 a). Jet cooling technique is better than flood cooling in reducing the flank wear. Where as, cutting temperature is drastically reduced by 50% compared to dry turning process. There is no difference in the reduction in cutting tool temperature for Jet and Flood cooling techniques.

Similar to the Inconel turning operation, surface finish doesn't seem to affected by the cooling method deployed. No clear trend of influence of flood cooling could be noticed but jet cooling technique has resulted in reduced R_a value, compared to flood cooling, with increase in number of passes as shown in Fig. 3.12 a). However, at the end of tool life, both have almost same surface roughness values. None of the cooling method show definite effect on cutting vibrations as shown in 3.12 b). During dry machining, vibrations are higher than with use of cooling techniques and hence are useful in reducing the vibrations.

4. CONCLUSIONS

Machining of both Nickel based and Cobalt-Chrome based super alloys are found to be challenging and major conclusions from the study involving use of uncoated carbide inserts in dry condition and with use of flood and jet cooling techniques are as follows.

4.1 Inconel 718

- Cutting speed has direct effect on flank wear rate and feed rate has direct influence on the cutting tool temperature. At low cutting speed of 40m/min, both low feed rate of 0.1mm/rev. and high feed rate of 0.2mm/rev. are favorable for longer tool life. However, increase in cutting speed is causing a rise in tool temperature there by increasing tool flank wear and leading to tool failure.
- Surface finish deteriorates with increase in the feed rate. High speed of 80m/min and low feed rate of 0.1mm/rev is found to be best to obtain a good surface finish.
- Higher vibration values have been noticed at higher cutting speed and feed rate.
- Both the Flood and Jet cooling methods have significantly reduced tool wear rate, cutting temperature and cutting vibrations. But the usage of coolant has a negative effect on obtaining better surface finish, since the experimental data shows that better R_a values have been achieved in dry cutting than that with use of cooling techniques.

4.2 Stellite 6

- Lowest flank wear is exhibited at low cutting speed and feed rate of 40m/min and 0.1mm/rev condition. High speed and feed rate combination leads to excessive increase of tool flank wear and eventual tool failure.
- Higher cutting temperature values are noted at medium cutting speed of 60m/min and increased feed rate leads to increase in tool tip temperature.
- Better surface finish is obtained at lower cutting speed and at higher cutting speeds, interaction with feed rate doesn’t show a clear trend in obtaining good surface finish.
- Tool vibrations are high, when the feed rate is 0.2mm/rev. Highest vibrations have been obtained at medium cutting speed of 60m/min and also leads to poor surface finish. Hence this combination needs to be avoided to get good surface finish.
- Aid of both the cooling methods utilized for turning Stellite 6 has influenced the machining in positive way. It has resulted in improved tool life, reduction in cutting temperature and vibrations. But use of cutting fluid is not effective in achieving better finish.

Overall efforts in utilizing a cutting fluid to turn the heat resistive super alloy work pieces considered for the experiments is fruitful in carrying away the heat produced during machining thereby reducing the tool tip temperature and increase tool life. But the same doesn’t bring any exhaustive improvement in surface finish of turned jobs; and in the case of Inconel 718, cutting fluid has negative effect. Jet cooling can be effectively used to reduce the various output parameters. There is a need for more detailed study using jet cooling with different flow rates and pressure to understand its influence on the output parameters.

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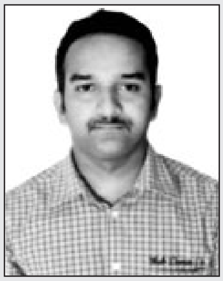

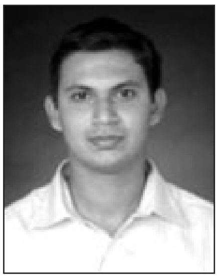

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