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Cryogenic Machining of Super Alloys used in Aerospace Industry: A Review

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Abstract: A super alloy has advantages like mechanical strength, resistance to creep at high temperatures, good surface stability, and corrosion resistance. Although these properties make them very useful in the aerospace application, but it also makes them very difficult to machine. Difficulties faced in machining of these alloys include high tool wear, high cutting forces, and poor chip breakability. A cryogenic machining technique is applied to overcome these problems for machining of super alloys.Depending upon the machining conditions like cutting speeds, feed rate, depth of cut etc. different machining techniques have different effects on tool life. This report studies the effect of cryogenic machining technique for different machining conditions and compares the result with other machining techniques to achieve greater tool life which leads to lesser production cost.
Keywords: Cryogenics, cryogenic machining, super alloys

1. Introduction

A super alloy, or a high performance alloy, is an alloy that exhibits several key characteristics like excellent mechanical strength, resistance to thermal creep deformation, good surface stability, and resistance to corrosion and oxidation. Super alloys are heat-resisting alloys based on nickel, nickel-iron, or cobalt that exhibit a combination of mechanical strength and resistance to surface degradation. they have unique combination of properties like high strength at elevated temperatures, resistance to chemical degradation and wear resistance. Ability to maintain these properties at elevated temperatures severely hinders the machinability of these alloys, thus they are generally referred to as difficult-to-cut alloys. Super alloys are of 4 types used in aerospace industry, viz. Nickel-based, Titanium alloys, Cobalt based alloys and iron based alloys.

The high performance characteristics of super alloy at elevated temperature severly hinders the machinability of these alloys. Machinability of a material is assessed by measuring the tool life, surface finish generated and component forces during machining. These alloys show high strength even at cutting temperatures which causes high cutting forces and generates more heat at the tool tip. The heat generated softens the tool material resulting in increased tool wear.

2. Objectives

To achieve

- Increased tool life
- Reduction in tool wear
- Lowering surafce roughness
- Cutting costs to improve competitiveness
- Reducing resource consumption
- Have less environmental and social impact

3. Literature Survey

The properties of superalloys make them difficult to machine and thus advanced techniques need to be used in their machining. Patel R. R. et al. mentioned in their paper that the superalloys have unique combination of properties like high strength at elevated temperatures, resistance to chemical degradation and wear resistance & ability to maintain these properties at elevated temperatures severely hinders the machinability of these alloys, thus they are generally referred to as difficult-to-cut alloys. Improvements achieved from research and development activities in this area have particularly enhanced the machining of difficult to cut nickel base and titanium superalloys that have exhibited low machinability due to their peculiar characteristics such as poor thermal conductivity, high strength at elevated temperature, resistance to wear and chemical degradation, etc. Patel R. R. et al. in their paper highlights an overview of major advances in machining techniques that have resulted to step increase in machinability. Hence lower manufacturing cost, without adverse effect on the surface finish, surface intergrity, circularity and hardness variation of machined component.[3]

Cryogenic treatment of tools has been reported to improve the wear resistance of tools. Oppenkowski A. et al in their paper addresses about the factors influencing the deep cryogenic treatment that affect the mechanical properties of tool steels. Factors investigated were the austenitizing temperature, cooling rate, holding time, heating rate, and tempering temperature. The results show that the most significant factors influencing the properties of tool steels are the austenitizing and tempering temperatures.[1]

Cooling approach has significant impact on the cooling of tool and thus the tool life. Hong S. et al in their paper study the different types of cooling approaches in the cryogenic machining. This paper addresses different types of cooling approaches like rake cooling, flank cooling, toolback cooling, precooling the workpiece etc. It also studies their effect on tool temperature and cutting forces generated at the tool.[6]

Shape memory alloys are the alloys that remebers their original shape and when deformed returns to its pre-deformed shape when heated. Beacause of this property shape memory alloys are used in aerospace industry. But machining of these alloys is a difficult task because og high cutting forces, high tool wear etc. Kaynak Y. et al studies the effect of cryogenic machining on the tool life for machining of these shape memory alloys. The paper also compares the results obtained for cryogenic machining with wet and preheated machining conditions and presents the results for the effective method or machining process for the shape memory alloys.[4]

Co-based super alloys are employed widely in some fields. These alloys have significant amount of cobalt, nickel, chrome and tungsten. In this group, Stellite, Haynes 188 and Haynes 25 are the most commonly used Cobased super alloys. Co-based Haynes 25 super alloy unites many excellent properties such as: high-temperature strength with good resistance to oxidizing environments up to 980°C for prolonged exposures, and excellent resistance to sulfidation. Sarikaya Murat et al in their paper presents the effect of dry wet and cryogenic machining conditions on Co-based super alloys.[5]

The properties of titanium alloys that make them desirable engineering materials also make them difficult to process into components. In particular, titanium's high chemical reactivity, high strength, high hardness and low thermal conductivity translate into large cutting forces and frictional heat which rapidly degenerates tools even under modest machining conditions. The use of liquid nitrogen as a coolant has received great recent interest due to the inherent environmental benefits that it carries. Also the high pressure coolant pumps are nowadays available commercially. Bermingham J. et al studies both these processes in their work and their effect on the machining of super alloys for tool life and tool wear.[2]

4. Case Study

4.1 Effect of cooling approach on machining

Selection of appropriate cooling approach towards the tool and the workpiece is necessary while using cryogenic machining. Many aspects of machining get affected while using cryogenic cooling like cutting temperature, cutting forces, tool wear and tool life etc. The different types of cooling approaches may be listed as:

- Pre-cooling the workpiece
- Indirect cryogenic cooling
- cryogenic spraying with jet
- Direct cryogenic cooling

Hong S. et al during turning of Ti-6Al-4V observed that the cutting temperature for dry machining at the speed of 1.5m/s can easily reach 1000°C which causes to softening of the tool and leads to tool failure. Tool crater wear increases drastically above the 500 ^{o}C. For the conventional emulsion cooling, the effect of coolant on tool rake can make a significant difference in tool temperatures. Proper application of coolant results into much lower temperature, but it is still more than 500 ^{o}C (743 ^{o}C). Cryogenic cooling approaches reduces the tool-chip interface temperature significantly, except for cryogenic tool back cooling. Cryogenic tool back cooling reduces the tool temperature to about 787 ^{o}C which is still higher that what we get with conventional emulsion cooling. Cryogenic rake or flank cooling alone can reduce the temperature up to 359 ^{o}C and 420 ^{o}C respectively. If both the cooling approach are applied simultaneously the tool temperature reduces to about 232

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°C. The similar tool temperature measurements were taken for different cutting speeds at the cutting speeds vs temperature plot is as shown in fig 1

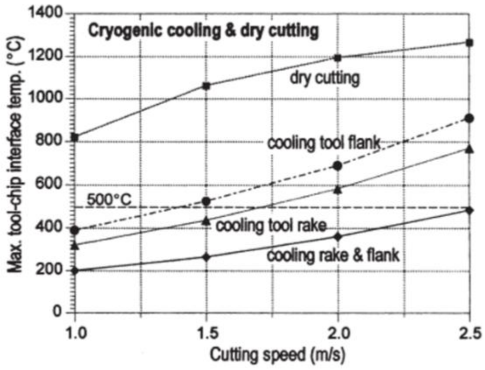


Fig 1: Tool temperatures versus cutting speed predicted by FEM study[6]

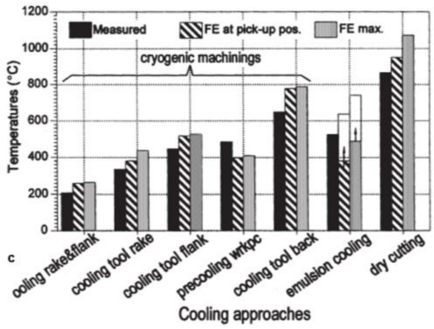


Fig 2: Measured and predicted tool temperature for different cooling approaches[6]

Economical cryogenic cooling is the concept of using minimum amount of liquid nitrogen to increase the tool life upto 5 times. It injects the liquid nitrogen through a micro nozzle between chip braker and tool rake and another one on flank face. The liquid nitrogen absorbs heat from the rake and flank face and evaporates forming a gas which forms a cushion between tool and chip that functions as lubricant. It helps to reduce flank and crater wear. In this type of delivery system the liquid nitrogen is not wasted by cooling unnecessary locations avoiding negative impact of increasing cutting forces.

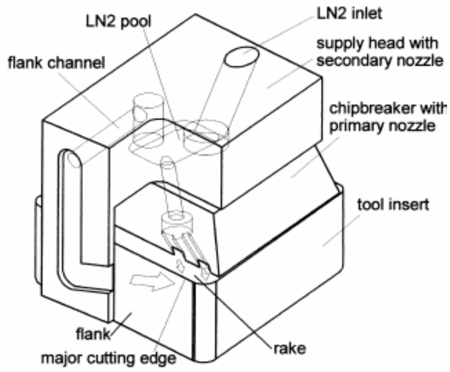
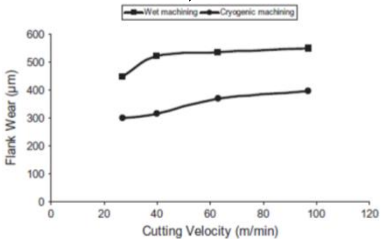


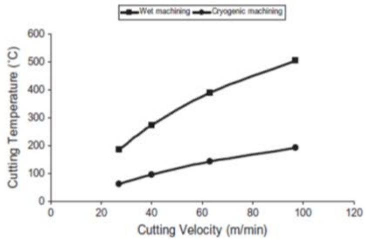
Fig 3: Two nozzle liquid nitrogen delivery system[6]

4.2 Comparison of cryogenic cooling and wet machining for Ti-6Al-4V turning

Different machining conditions gives different results for the cutting temperatures, cutting forces, surface roughness, tool wear and tool life. M. Dhananchezian et al studied the effect of cryogenic machining and wet machining on tool wear, surface roughness and cutting temperatures. In a turning of Ti-6Al-4V round bar of diameter 40mm and length 300mm, for wet machining the emulsion cutting fluid was obtained by mixing the concentrate with water at a ratio of 1:20 soluble oil. Cutting tool is modified with cutting inserts with holes on rake and flank face for cryogenic coolant application to the heat generation zone directly. The tests are performed at different cutting speeds with constant feed rate and depth of cut (depth of cut 1 mm, feed rate of 0,159 mm/rev, cutting speed of 27, 40, 63 and 97 m/min).



(a)



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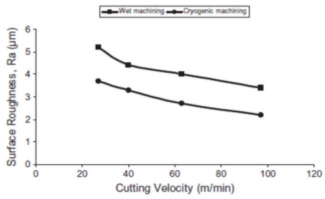


(c)

Fig 4: Effect of different machining conditions on (a) flank wear (b) cutting temperature (c) surface roughness[7]

It was observed that in cryogenic cooling the cutting temperature was reduced by 62% over wet machining due to the direct application of liquid nitrogen to the heat generation zones through holes made in the cutting insert. Fig. 4(c) shows the average surface roughness, Ra, obtained after wet and cryogenic machining. The reduction of Ra due to cryogenic cooling was about 25-35% compared to wet machining due to less adhesion between the newly generated workpiece surface and tool auxiliary flank surface and lower tool wear rate which is also evident in Fig. 4(a).

4.3 Analysis of tool wear and force components for *NiTi* shape memory alloys

Application of shape memory alloys (SMAs) continue to increase as they are recognized as possible and better alternative design solutions for engineers facing new technical challenges. There are some difficulties in machining *NiTi* shape memory alloys. To avoid this problem Kaynak Y. et al performed an experiment to compare tool wear and cutting forces results for dry preheated and cryogenic machining with $Ni_{49.9}Ti_{50.1}$(at %) alloy in the form of 10mm diameter round bar. Constant feed rate of 0.1mm/rev and depth of cut 0.5mm were employed with the selected cutting speeds 12.5, 25, 50m/min.

The dominant wear observed during the machining is notch wear at the depth of cut boundary region. Notch wear at the major and minor cutting edges is measured for each cutting condition. The measured maximum notch wear is presented in Fig. 5.

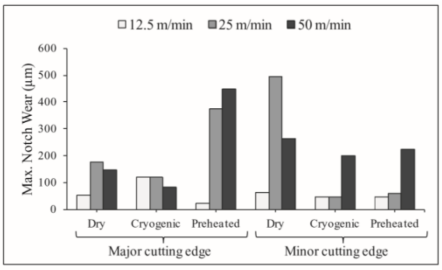
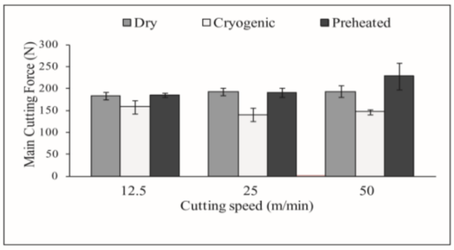


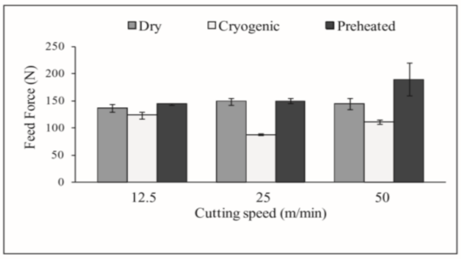
Fig. 5: Comparison of notch wear with various cutting speeds and conditions[4]

At the higher cutting speeds, cryogenic machining significantly reduces the notch wear in comparison with dry and preheated conditions. However, it must be noted that at the lowest cutting speed of 12.5 m/min, cryogenic machining produces the largest notch wear at the major cutting edge in comparison with dry and preheated conditions.

Cutting forces generated also vary with respect to cutting speeds and machining techniques. For dry and preheated machining the increasing trend was observed for increasing cutting speeds. But the main cutting force shows decreasing trend for cryogenic machining with increasing cutting speeds. Radial and feed force components slightly increase at 50 m/min cutting speed in comparison with 25 m/min cutting speed.



(a)



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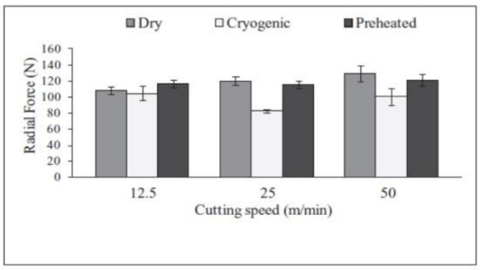

(c)

Fig 6: Variation of (a) main cutting force (b) feed force (c) radial force with cutting speeds and cooling/preheated conditions[4]

5. Summary and Conclusion

Cryogenic cooling, an environmentally safe alternative to conventional emulsion cooling, is an efficient way of maintaining the temperature at the cutting interface well below the softening temperature of the cutting tool material. It helps in increasing the tool life by decreasing the tool wear. Also the cutting forces are reduced with the help of cryogenic coolants which helps in increased tool life. An appropriate cooling approach is necessary for the effective results with tool life when using cryogenic coolants. Simultaneous rake and flank face cooling gives the best results for lowering the cutting temperatures at the interface. Surface integrity is also improved significantly(25-35%) by using cryogenic machining over dry, wet ot preheated machining. It reduces the post processing cost for the product.

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