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Cooling system using LN_2 and compressed air mixture: An experimental study on machining of Nickel based super alloy

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Abstract : A major problem in machining industry during machining process is increased temperature which affect quality and production cost. Increase in cutting temperature causes not only affects surface integrity, nucleate sub-surface micro cracks but accelerates rapid oxidation and corrosion. It also reduces the life of a cutting tool. To control the temperature at the cutting edge, machining industries use many fluids and lubricating oils, but usage of these conventional coolants are not effective in reducing temperature and tool wear. Further it has limitations in terms pollution and increase in handling and disposal cost. In this context, cryogenic machining has become one of the alternative methods to control the cutting temperature and tool wear. This research paper tried its best to use LN_2 as coolant during machining of Inconel 718 Nickel based superalloy material and comparative study on influence of lead level (H_1 and H_2) of cryogen in cryocan on cut edge temperature by varying cutting speed and depth of cut is done.
Keywords : cryogen, cryocan, surface integrity, rapid oxidation, corrosion, Inconel 718, cut edge temperature.

1. Introduction

The cutting force and cut edge temperature generated at the tool-chip interface during high speed machining of difficult to cut material have influence on tool performance. The energy released at the time of metal cutting is transformed into heat near the cutting edge of the tool. The dimensional accuracy of the workpiece is affected by the localized heat in the contact area and leads to tool damage and breakage[1].

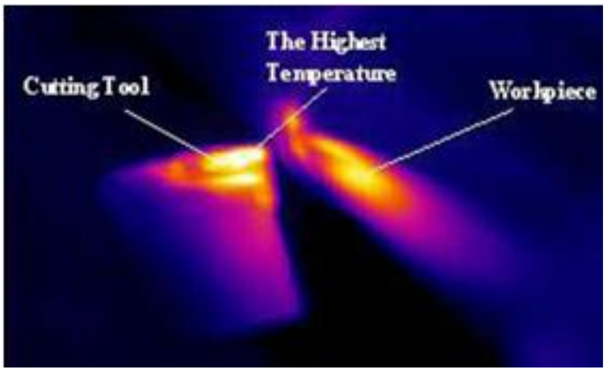


Figure 1. Thermal camera view consisting of the metal cutting process

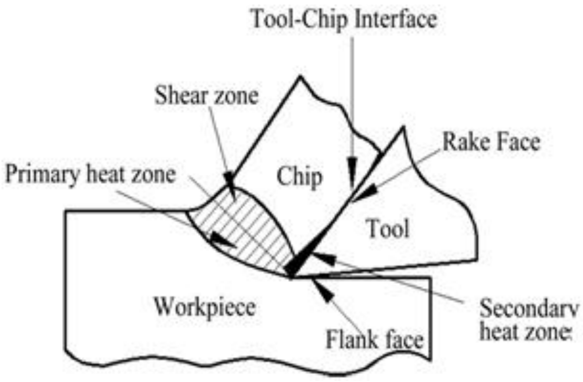


Figure 2. Regions of heat generation in machining

Figure 1 exposed the cutting zone during metal removal process[2]. There are three main sources of heat namely, the primary shear zone the secondary shear zone and the tertiary zone (Fig. 2) in metal cutting process, also the chip is moving onto the toolrakeface in the primary zone. The transformation of friction to heat energy is certainly increasing the temperature. The corresponding heat generation rate per unit surface was estimated by G.List et. al.,[3] and is given as:

$q_f = \eta\tau_f\gamma_s$ (1)

where γ_S is the incremental slip rate and η is the conversion of mechanical energy into thermal energy($\eta \approx 1$). The heat generation rate (q_f) is decomposed into two terms the frictional heat transmitted in the chip (q_C) and the heat transmitted into the tool(q_T).

$q_f = q_C + q_T$ (2)

Considering that the heating caused by friction, the factor R_S represents the heat fraction transmitted into the tool is given by equation (3).

$R_S = q_C/q_C$ (3)

Sun et al.,[4] have studied the gaseous refrigeration systems on machining of difficult to cut materials which was compared with the cooling systems based on cold compressed air. These systems are not commonly used in manufacturing industry where commercial cold compressed air (CCA) systems exist and it is a new and effective technique for reducing friction and heat in the cutting zone.

CCA systems are easy to install and requires minimum maintenance and electrical energy. Moreover, it is more ecological, safer for the operators and provides better results against any conventional cooling systems. The CCA system as an alternative to the traditionally lubrication/cooling systems used in machining of materials and analyzed. The experimental results revealed that reduction in friction, cutting forces and temperature increased the tool life by chip breaking and its evacuation were the main reason for increasing surface finish and productivity[5].

1.1 LN_2 as coolant and its properties

Many researchers have made attempt to improve the machining performance of inconel 718 with TiAlN coated carbide as cutting tool using liquid nitrogen as coolant. This paper explicitly discussed the influence of LN_2 (cryogenic) coolant on the cut edge temperature of cutting zone during machining of Inconel 718 Nickel based super alloy using TiAlN coated carbide as cutting tool.

When the liquid nitrogen comes into contact with any surface it starts to boil and vaporize rapidly thereby brings an interesting effect called "Leidenfrost Effect". The Leidenfrost effect occurs when a liquid comes into contact with a surface at a higher temperature than its boiling point and forms a layer of insulating vapor between liquid and the surface. This means that a cryogenic liquid (or any light porous material soaked with it) will lift itself up from the floor and start to hover. The mere act of spilling some on a smooth surface floor will cause to move about with virtually zero friction, it moves and changes shape like an amoeba and smokes slightly [6].

Since liquid nitrogen warms up from its liquefaction temperature of -196°C to room temperature (25°C), it undergoes a phase change from liquid to gas causing an expansion of 174.6 times the original volume of liquid. The resulting nitrogen gas is than warmed by 221°C expanding 3.7 times higher. The net expansion of liquid nitrogen is (174.6 x 3.7) 645.3 times the original volume when heated to room temperature. This means that 1 liter of liquid nitrogen will occupy 645.3 liters as a gas once it has all vaporized. Due to this dramatic expansion, when liquid nitrogen is placed in a closed container and allowed to vaporize, the pressure in the container will rise quickly, and if it is not allowed to escape, the container is very likely to burst [7].

Liquid nitrogen is potentially very dangerous since it can cause instant frostbite. Never allow it to come into contact with bare skin. Objects should be lowered into the liquid nitrogen and removed with tongs and it should not splash into the eyes. Gloves and protective eyewear must be worn during machining [8].

1.2 Cryogenic storage tanks

Liquid nitrogen normally stored in several types of containers like the dewar, cryogenic liquid cylinder and cryogenic storage tank. Storage quantities vary from a few liters to many thousands of gallons. Since heat leak is always present, vaporization takes place continuously. Rates of vaporization vary, depending on the design of the container and the volume of stored product. Figure (3) shows a typical cylindrical cryogenic storage tank used in this experimental set up. It includes a tank, air compressor, and pressure control manifold. Tanks are equipped with various circuits to control product fill, pressure buildup, pressure relief, product withdrawal, and tank vacuum[9].

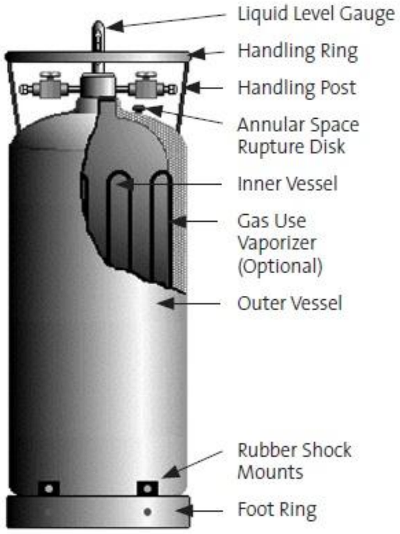
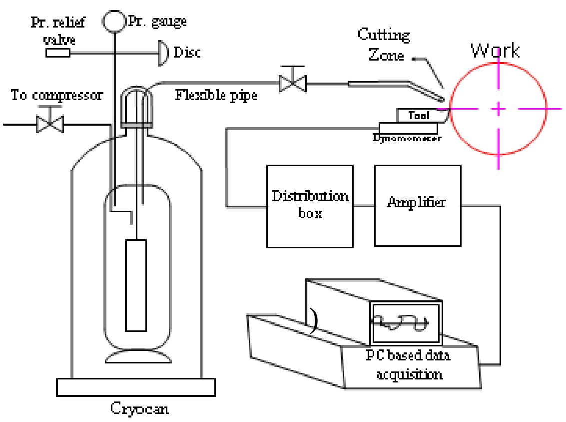


Figure 3. Cross sectional view of typical Cryogenic Liquid Cylinder (Yihuan et al,[9])

2. Methodology

2.1. Machine tool with cryogenic cooling system

In this research study, a high powered universal lathe was used to machine the workpiece. Figures 4(a) and 4(b) illustrate the experimental set up used for this research work.



(a) **(b)**

Figure 4. Experimental set up with cryogenic cooling system

2.2. Workpiece and Cutting tool

Now-a-days nickel-based super alloys are gaining significance, as it finds extensive applications in aerospace, marine, nuclear reactor and chemical industries. Several characteristics including superior mechanical and chemical properties at elevated temperature, high toughness and ductility, high melting point, excellent resistance to corrosion, thermal shocks, thermal fatigue and erosion are the reason for wide domain of application[10,11].

In this research study, Inconel 718 Nickel-based superalloy was chosen as work material as it possessed excellent mechanical properties at low and intermediate temperatures (−250°C to 700 °C)[12]. The head level (H) in the LN_2 storage tank (cryocan)was maintained at 0.6 m, and 0.9 m during the experiments, and the compressed air was admitted into the cryocan to maintain constant pressure using pressure regulator mounted on the top of the cryocan. The chemical properties of Inconel 718 work material obtained from the test results were compared and the values are presented in Table 2. The physical properties of the work material are given in Table 3 [13].

Table 2. Comparison of chemical composition of Inconel 718 work material

Elements	C	Si	Mn	S	P	Cr	Fe	Mo	Co	Nb	Cu	V	Al	Ti	W	Ni
Aerospace Material Specification %	0.08 max	0.35 max	0.35 max	0.015 max	0.015 max	17.0-21.0	Balance *	2.80-3.30	1.00 max	4.75-5.50	0.30 max	-	0.20-0.80	0.65-1.15	-	50.0-55.0
Report %	0.059	0.036	3.120	0.005	0.011	19.045	17.297	3.120	0.448	4.788	0.037	0.026	0.536	1.023	0.247	53.101

Table 3. Physical properties of the Inconel 718 workmaterials

Density (ρ) Annealed Annealed and Aged	**kg/m^3** 8193 8221
Melting Range, °F (°C)	2300-2437 (1260-1336)
Specific Heat @ 21°C, J/kg °C	435
Curie Temperature Annealed Material Annealed and Aged Material	**°F (°C)** <-320 (<-196) -170 (-112)
Permeability Annealed Material Annealed and Aged Material	at 200 oersted and 70°F 1.0013 1.0011

3. Result and Discussion

The cut edge temperature and the percentage of reduction in the cut edge temperature measured during the machining of Inconel 718 material are given in Table 4.

Table 4. Cut edge temperature and percentage of reduction in machining Inconel 718

Sl No	Cutting speed	Depth of cut	Cut edge temperature		Percentage of reduction in cut edge temperature, LN_2 Head H_1 vs H_2
			LN_2 Head $H_1 = 0.6$ m	LN_2 Head $H_2 = 0.9$ m	
1	44	0.5	79	52	34.18
2		1.0	105	55	47.62
3		1.5	180	85	52.78
4	73	0.5	105	65	38.10
5		1.0	130	80	38.46

6		1.5	160	20	87.50
7	102	0.5	130	78	40.00
8		1.0	125	63	49.60
9		1.5	150	72	52.00

The variation of cut edge temperature under LN_2 head level H_1 and H_2 in machining Inconel 718 material at different cutting speeds and depth of cuts were presented in Figure 6 and Figure 7.

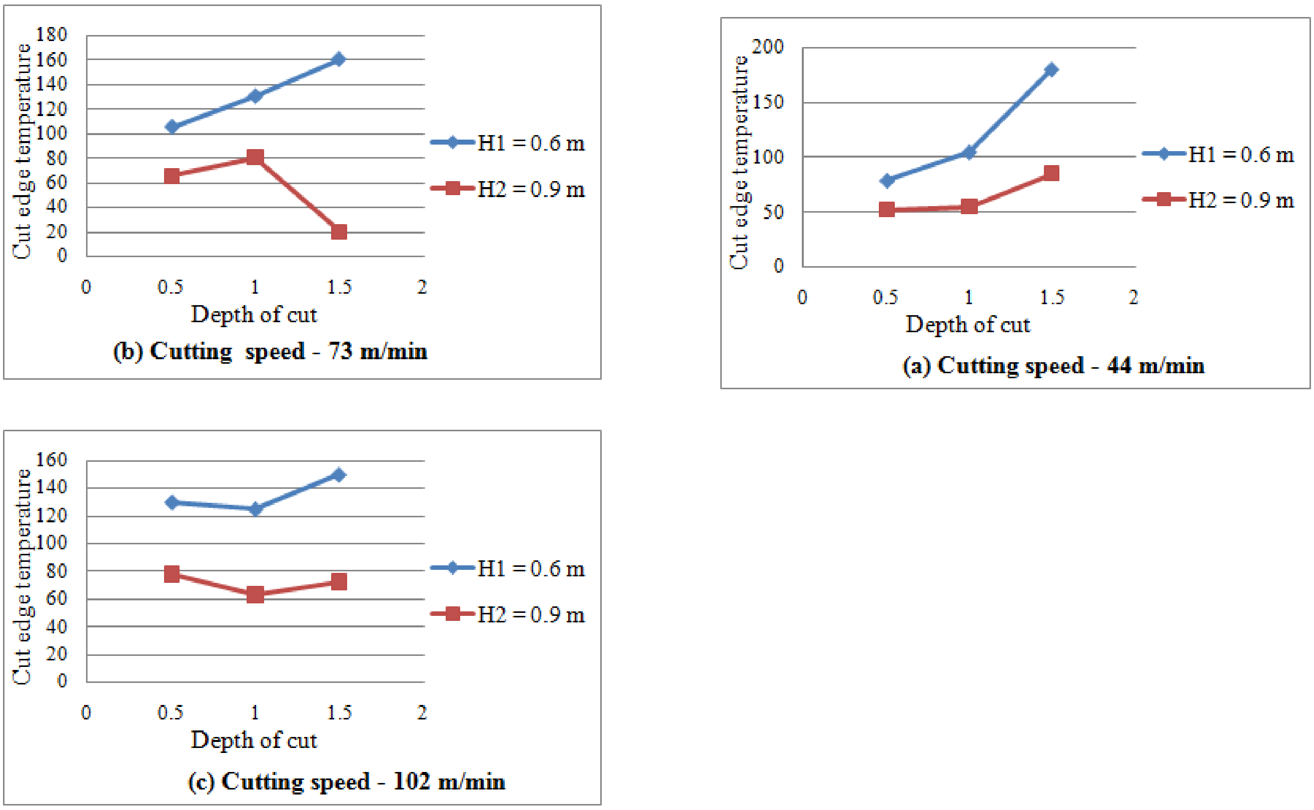
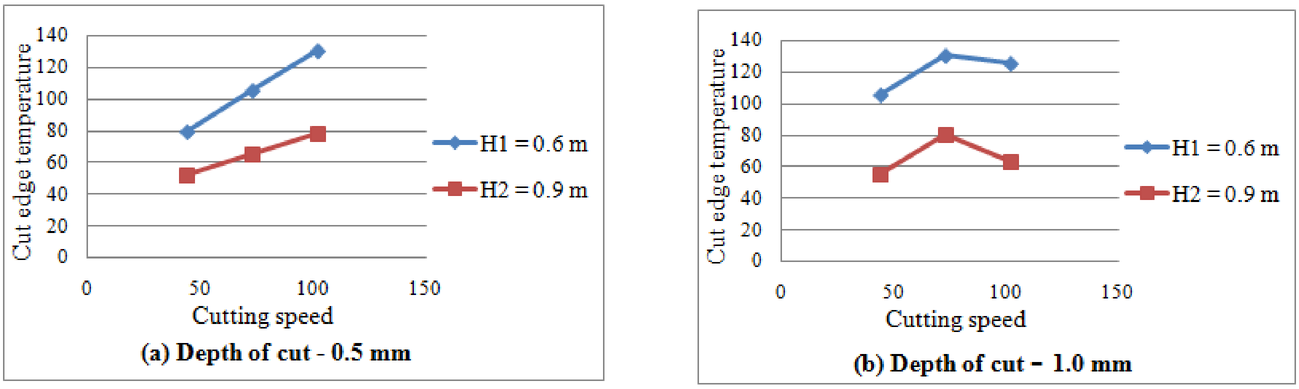


Figure 6. Variation of the cut edge temperature while machining Inconel 718 with different cutting speed under LN_2 head H_1 and H_2

It is obvious from the Figure 6 that the variation of cut edge temperature in turning of Inconel 718 material at a cutting speed of 44 m/min and depth of cut 0.5 mm during LN_2 head H_1=0.6m was 79°C, while for the same cutting conditions, the cut edge temperature obtained in LN_2 head H_2=0.9m was 52°C. The decrease in cut edge temperature was nearly 34.18% compared to LN_2 head (H_2) level.



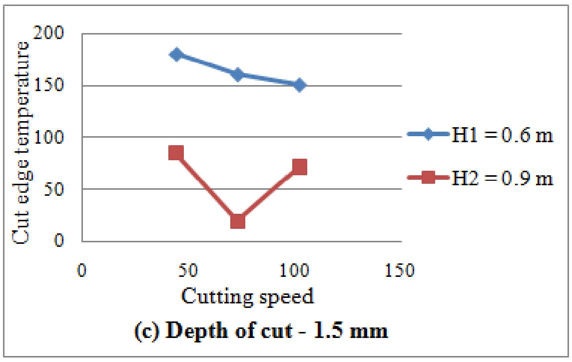


Figure 7. Variation of the cut edge temperature while machining Inconel 718 with different depth of cut under LN_2 head H_1 and H_2

Figure 7 clearly showed that the variation in cut edge temperature during the machining of Inconel 718 material keeping constant depth of cut and varying cutting speeds (44, 73 and 102 m/min). The study predicted the drastic decrease in cut edge temperature against LN_2 heads ie., H_1 and H_2 level at 0.6m and at 0.9m accordingly.

4. Conclusion

The effect of cryogenic liquid nitrogen as a cutting coolant for machining Inconel 718 Nickel based superalloy was studied with two heads of LN_2 in terms of cutting temperature. The following conclusions were drawn based on experimental study: Cryogenic LN_2 machining seemed an effective alternative method to reduce the cutting temperature raised during machining process. Cryogenic LN_2 head H_2 in cryocan gave considerable reduction in cut edge temperature during machining as compared with LN_2 head H_1.The LN_2 head H_2 level could reduce in cut edge temperature of about 34 - 87 %, compared to LN_2 head H_1 level.

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