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# Machining of Nimonic 90 Alloy Under Dry and $LN_2$ Environment Using AlTiN Coated and Uncoated Tungsten Carbide Inserts

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## Abstract

Over the last few decades, sustainable techniques have been developed at increased pace in order to encourage and improve the efficiency of dry machining process. Among the sustainable techniques, the use of coated tools and application of Liquid nitrogen ($LN_2$) can be helpful in eliminating the cutting fluids for machining aerospace grade alloys. In this research work, dry environment machining is performed with AlTiN coated inserts. The performance of the coated inserts under dry mode has been compared with uncoated inserts under $LN_2$ environment for machining of Nimonic 90 alloy. For the short duration tests, the use of $LN_2$ reduced the cutting forces as compared to the dry machining. This is mostly attributed to the lower plastic deformation over the tool rake face under $LN_2$ mode. From the SEM micrographs of flank wear, fracture and notch formation have been observed for the tool under dry environment. On the other hand, the effective cooling capacity of $LN_2$ prevented these wear phenomenon. The evidence of excessive plastic deformation can also be seen at sticking and sliding zone over cutting tool during dry machining. Application of $LN_2$ also prevented the excessive deformation the sticking of chip fragments at the rake face.

Keywords: Cryogenic, Carbide tool, Coating, Dry machining, Nickel alloy, Wear.

## 1. INTRODUCTION

Nickel (Ni) based alloys such as Nimonic 90 has become one of the widely used materials for aerospace application due to its ability to retain high strength at elevated temperature [1]. Further due to its properties such as good corrosion resistance, high thermal stability and high wear resistance, this Ni based alloy is widely considered for chemical and nuclear engineering applications [2]. However, the inherent properties such as low thermal conductivity, high chemical affinity and high strain hardening considerably lowers the machinability rating of Nimonic 90 alloy [3]. The low thermal conductivity of this alloy results in excessively high cutting temperature over the tool tip during the machining. This temperature can easily go up to 1000 °C during machining [3]. The high chemical affinity of nickel present in Nimonic 90 can cause the chip adhesion and BUE (built up edge) formation over the tool rake face [4]. During machining, the BUE gets detached from the rake face and results in abrasion wear. The detached BUE causes surface defects over the machined material. High strain hardening during the machining of nickel based alloy also results in excessively high tool wear. Notch wear, chipping and frittering are the most common wear occurring over the cutting insert during the machining of Nimonic alloy [1].

In the past, flood cooling method was the most common approach to control the problems associated with the machining of difficult to machine materials. However, excessively high cost of preparation, maintenance and disposal of the fluids used during flood cooling is a matter of concern [5]. The cutting fluids are considered as the ideal environment for the bacterial growth. These bacteria can change the PH value of the cutting fluid thereby increase the risk of machine tool and work piece corrosion. The chemical additives which are used to control the bacterial growth are highly reactive to skin and cause skin cancer to the operators [6]. The mist produced due to the vaporization of cutting fluids could also be inhaled by the operators. This could deteriorate their health by causing lung diseases, asthma and esophagus cancer.

Dry machining is considered as the best approach to eradicate the cutting fluids during the machining. The adoption of dry machining can bring several benefits as shown in Fig.1 [7]. It can also eliminate the risk of health hazards amongst the workers such as skin and respiratory related diseases. However, the reduction in tool life, high cutting temperature, high contact friction, poor surface integrity, loss of geometric forms and accuracy, reduced production rate and low machinability rating are still the major problems encountered during dry machining process [5]. Therefore, it is essential to explore the alternative approaches which can enhance the effectiveness of dry machining process.

Coating deposited on the cutting inserts is a major strategy to improve the contact friction and wear resistance during the machining [3]. In this regard , de Paiva, et al. [8] used the TiCN, AlTiN and $TiCN+Al_2O_3$ hard coatings over the carbide inserts for the machining of super duplex steel. The formation of alumina ceramic tribofilm with AlTiN coating during the machining doubled the tool life as compared to other coatings. In another work various nitride coatings were deposited over the M2 tool steel [9]. The use of nitride coating improved the performance of tool steel in terms of wear during ball on flat specimen test (ASTM G133). In another research work nitride coatings over carbide inserts was used to machine the O2 cold steel [10]. As compared to uncoated inserts the use of coated inserts significantly improved the tool wear and surface finish.

Another strategy that is implemented to improve the dry machining is the use of liquid nitrogen ($LN_2$) as a coolant during the cutting process. The proper application of $LN_2$ over the rake face can reduce the tool-chip friction condition by forming a gaseous cushion [11]. Due to this reason the use of cryogenic coolant reduced the flank wear by 38% during machining of stainless steel [12]. The profound effect of cryogenic cooling in terms of reduced tool wear was also observed during the machining of NiTi shape memory alloy as compared to dry and MQL machining [13].

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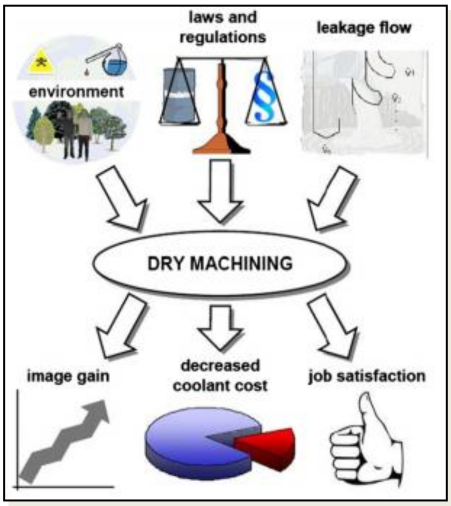

**Fig. 1.Benefits of dry machining [7].**

The use of coated inserts and cryogenic cooling are promising strategies to enhance the capability of dry machining. These strategies can further be used to impart sustainability during the machining of nickel based alloys. Therefore, in this research work the performance of the AlTiN coated carbide inserts under dry mode has been compared with uncoated inserts under $LN_2$ environment for the machining of Nimonic 90 alloy.

## 2. MATERIALS AND METHODS

### 2.1 Workpiece and tool material

Nimonic 90 round bar of 60 mm diameter and 300 mm length was used for the machining. The main constituents of Nimonic 90 are Ni (57.58%), Cr (19.32%), Co (17.62%), Ti (2.21%) and Al (1.32%). For the cutting purpose S grade AlTiN coated (KC5525) and uncoated (K313) tungsten carbide inserts made by Kennametal were used.

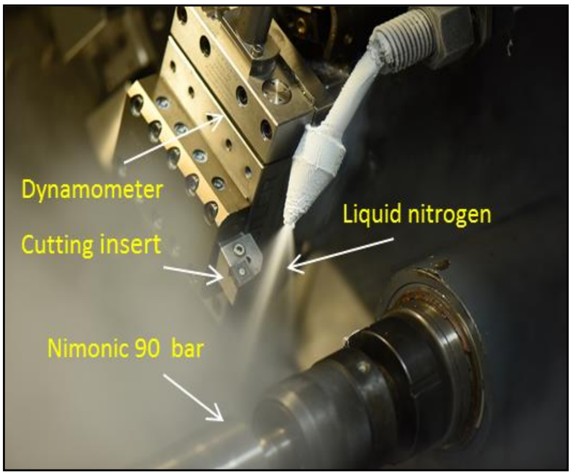

**Fig. 2.Leadwell T-6 turning center for carrying out dry and cryogenic machining.**

### 2.2 Measuring devices

Kistler dynamometer (9257B) mounted on the tool post of Leadwell T-6 turning center has been employed for the cutting force measurement. The charge produced at the dynamometer during the cutting was amplified using the Kistler charge amplifier (5070A). Further, Taylor Hobson talysurf was used to measure the surface roughness during the cutting. Wear analysis of the cutting inserts after the machining has been carried out using the Ziess EVO 50 scanning electron microscope (SEM).

### 2.3 Experimental details

All the experiments were carried out on a Leadwell T6 turning center. The setup used for experiments is shown in Fig. 2. Each experiment is repeated thrice to minimize the measurement error. Different levels of cutting speed (20, 60, and 100 m/min), feed rate (0.04, 0.12, and 0.2 mm/rev) and nose radius (0.2, 0.8, and 1.6 mm) were chosen as the cutting parameters.

## 3. RESULT AND DISCUSSION

### 3.1 Cutting force

Variation of the main cutting force under dry and cryogenic cooling condition has been in Fig. 3. At lower cutting speed of 20 m/min, the use of coated tool under dry mode produced the main cutting force of 244.2 N. While, for the same cutting speed, the use of cryogenic cooling with uncoated tools produced a cutting force of 231 N. Similarly, for higher cutting speed of 60 m/in and 100 m/min, the use of $LN_2$ reduced the cutting force by 14 N and 11 N respectively as compared to dry machining mode. The slight relative advantage of the cryogenic cooling over the dry machining in terms of cutting forces is due to the formation of nitrogen cushion between the chip and tool during the machining [11]. The formation of such cushion reduced the plastic deformation of the rake face [12]. It also reduced the chances of welding between the chip and rake during the cutting process. Similarly, the variation of the feed rate also led to a marginal reduction in the cutting force with cryogenic cooling as shown in Fig. 3b. It is interesting to note that the increase in feed rate from 0.04 mm/rev to 0.2 mm/rev, increased the main cutting force approximately by 100 N for both dry and cryogenic cooling conditions. The significant increase in the cutting force may be attributed to an enhanced shear and normal stress over the rake face with increase feed [3].

### 3.2 Analysis of the wear on the flank face

Flank wear has been examined through scanning electron micrographs after 30 mm of machining. Fig. 4 shows the flank wear for both the environments at 60 m/min of cutting speed. It is clear from the SEM micrograph that the high temperature generated at the cutting zone under dry condition caused the excessive notch wear and edge fracture of cutting insert. However, during cryogenic environment, the boiling heat transfer mechanism introduced a high heat flux between tool rake face and liquid nitrogen [14]. Due to this the superior cooling capacity of $LN_2$ prevented the excessive flank wear.

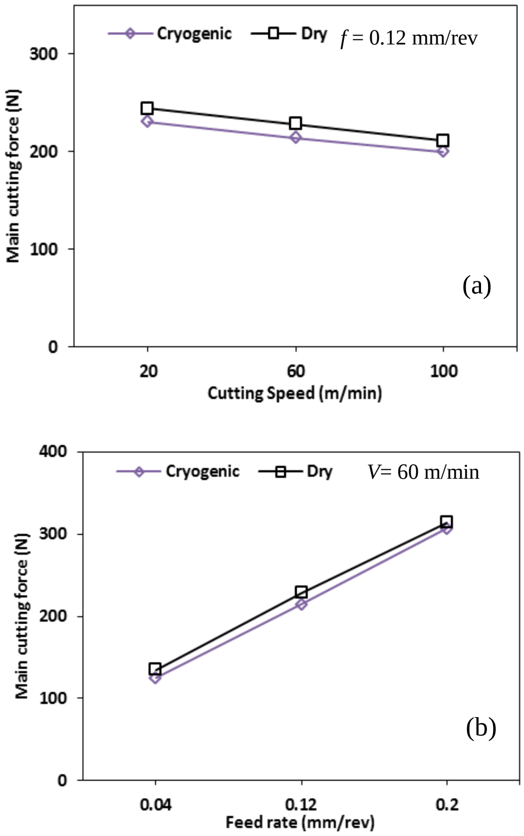

**Fig. 3. Variation of main cutting force under dry and cryogenic mode with different (a) cutting speeds and (b) feed rates.**

### 3.3 Analysis of rake face after machining

The condition of rake face after machining at 60 m/min under dry and LN$_2$ environment is given by Fig. 5. It is clear from the SEM micrograph that machining under dry condition resulted in adhesion and edge fracturing at sticking zone of the rake face. In addition to this the coating peeling off was also observed. This happened possibly due to the continuous flow of hardened chip over the rake face in case of dry machining.

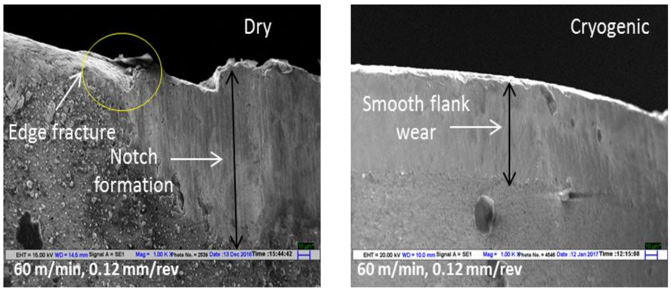

**Fig. 4. Variation of main cutting force under dry and cryogenic mode with different (a) cutting speeds and (b) feed rates.**

Excessive deposition of chip fragments over the rake face has been also observed under dry condition. The supply of LN$_2$ at -196 °C has resulted in effective suppression of the adhesion and fracturing at the sticking zone of the rake face. The gaseous cushion provided by the cryogenic fluid also prevented the adhesion of the chip fragments over the rake face.

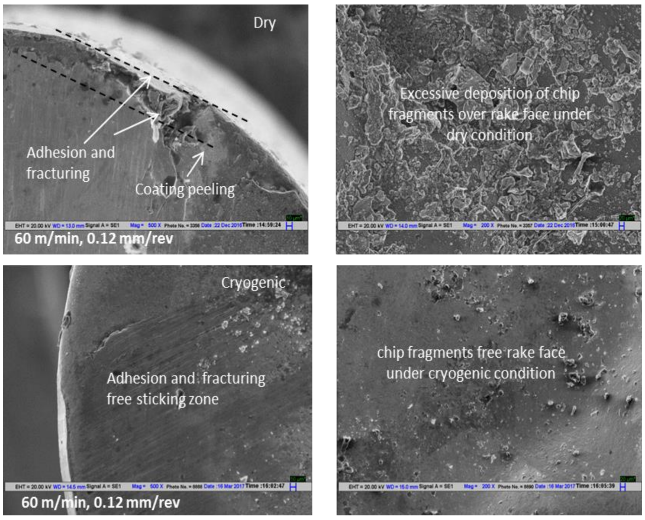

**Fig. 5. SEM micrographs of rake face after machining at 60 m/min under dry and LN$_2$ enviornment**

### 3.4 Effect on surface finish

It can be seen from Fig. 6 that the use of cryogenic coolant resulted in relatively high surface roughness at low cutting speed as compared to dry machining. The absence of effective lubrication for cryogenic cooling might have resulted in such increase of surface roughness at low speed [15]. On the other hand the reduction in coefficient of friction caused by the presence of coating over the cutting tool has significantly reduced the surface roughness at lower cutting speed [1].

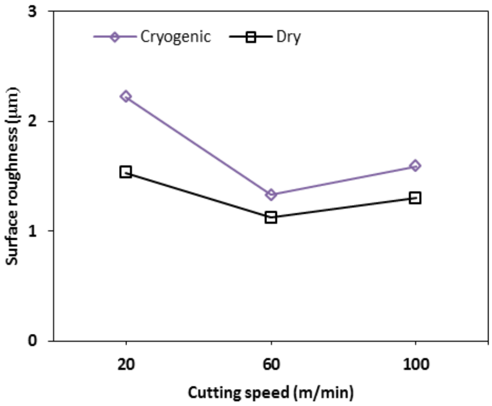

**Fig. 6. Variation of surface finish with cutting speeds under dry and cryogenic condition.**

## 4. CONCLUSIONS

Machining of Nimonic 90 alloy has been conducted using AlTiN coated carbide inserts under dry mode and uncoated inserts under cryogenic environment. Upon machining experiments the following conclusions can be drawn from this research work.

- The combination LN$_2$ and uncoated tool has reduced the main cutting force as compared to the combination of dry cutting and coated tools. The formation of liquid nitrogen cushion between the tool and chip could be the possible reason for such reduction.

- The superior cooling capacity of $LN_2$ due to high heat flux has suppressed the notch wear and edge fracture for the uncoated tools during the machining.

- The application of $LN_2$ also prevented the excessive adhesion of chip fragments over the rake face of uncoated tools. On the other hand the presence of protective coating was not able to prevent the adhesion of chip fragments under dry condition as coating peel off happened at an early stage of machining.

- The absence of effective lubrication especially at low cutting speed increased the surface roughness under $LN_2$ cooling regime.

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