Effect of Cryogenic Cutting Coolants on Cutting Forces and Chip Morphology in Machining Ti-6Al-4V Alloy

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Abstract
The cutting forces, form of chips and the morphology of the chip influences the productivity of any machining process. In this research work, the form of chips produced and its morphology in machining Ti-6Al-4V alloy is studied under dry, wet, and cryogenic machining conditions. The cutting force, feed force and thrust force which greatly influences the efficiency of the cutting tool is also studied. Efficiency of the cryogenic cutting coolants (Carbon dioxide and liquid nitrogen) in terms of chip morphology and cutting forces are analyzed in comparison with dry and wet machining conditions. The use of cryogenic coolants yielded chips with uniform serrated teeth with low average peak value and smaller pitch values. Cryogenic CO_2 coolant in particular reduced the cutting force in the range of 21 – 41%, feed force in the range of 11 – 39% and thrust force in the range of 14 – 43% when compared to wet machining.

Keywords: *Cryogenic machining, Chip morphology, Cutting forces*

1 Introduction

Modern machining industries face continuous pressure regarding the cost and high quality of the product. To remain in competition, an industry must identify the factors that result in the cost reduction of the process and still maintain the quality of the product. One of the major aspects which decide the above said parameters is the nature of the cutting or cooling lubricant used for metal cutting operations. A machining industry which aims for higher quality and higher productivity at low cost, will definitely face problem with elevated temperatures at the metal cutting zone during the machining process. Increase in the cutting temperatures increases the friction at the tool-chip interface region there by increasing the cutting forces [1]. Moreover, the type of chip produced in the machining process also greatly influences the product quality and life of the cutting tool [2].

2 Literature review

In metal cutting, the friction and the higher temperature existing at the cutting zone is the major problem, which always leads to a series of problems. Some of them include, increased cutting forces, poor surface finish and increased tool cost, due to the increase in tool failure and tool wear [3]. The problem of the increase in the cutting temperature is manageable with the selection of proper cutting fluids. Conventional coolants fail to provide the desirable control of the cutting temperature, as they cannot penetrate into the chip-tool interface, predominantly due to the plastic contact between the tool and the chip, especially at high cutting speeds [4, 5]. Though the conventional coolants are effective to some extent, the techno-environmental problems caused by them are more [6]. In the past, researchers had used many techniques for cooling and reducing the temperature that originated in the machining processes. One such effective technique of controlling the machining temperature, machining using cryogenic coolants is carried out and their efficiency in reducing the cutting forces and enhancing the chip breakability along with the morphology is studied here.

3 Experimental setup

The experimental conditions considered for the machining purpose is mentioned in Table 1.

Table 1: Experimental conditions

Workpiece	Ti-6Al-4V alloy (Ø 60 mm X 300 mm)
Cutting insert	PVD coated carbide insert CNMG 120404 MP 431 KC 5010 (Kennametal) Rake angle : -5° Clearance angle : 5°
Process parameters	Cutting velocity : 41, 94 and 145 m/min Feed rate : 0.051, 0.096, 0.143 and 0.191 mm/rev Depth of cut : 1 mm
Machining conditions	Dry, Wet, CO_2 and LN_2
Nozzle diameter	2 mm (for all machining conditions)

A high power rigid lathe (Nagmati – 175) was used to perform the turning operations. Cutting inserts were fixed in PCLNR 2020 K 12 tool holder to carry out the machining process. The experimental setup used for cryogenic machining is shown in figure 1 and 2. Cutting forces were measured by using a piezo-electric three component dynamometer (kistler) setup attached with an amplifier and a personal computer. To compare the chip morphology, the metal chips produced were viewed under SEM (Scanning Electron Microscope) and analyzed.

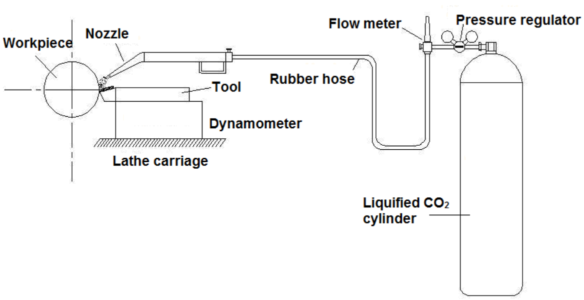


Figure 1: Schematic view of cryogenic CO_2 machining setup

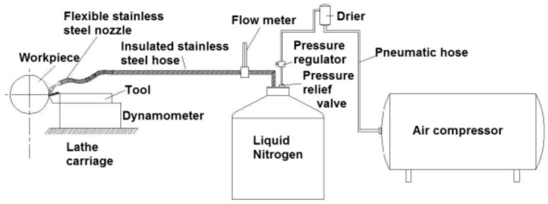


Figure 2: Schematic view of cryogenic LN_2 machining setup

4 Results and discussion

4.1 *Effect of cryogenic coolants on cutting forces*

The cutting force decreased with the increase in the cutting speed, due to the decrease in the shearing area under cryogenic cooling conditions. And also, when the cutting speed was increased, the cutting temperature also increased considerably, thereby softening the work piece. Moreover, when the cryogenic coolant was applied, the temperature in the cutting zone was reduced substantially, thereby reducing the stickiness of the metal chip with the tool rake. Better lubrication is obtained when the cryogenic coolant enters properly into the cutting zone, forming a boundary lubrication layer which reduces the friction [1]. Kalyan Kumar and Choudhury [7] also reported that the cutting force decreases with an increasing cutting speed and increases with an increasing feed rate. When the feed rate was taken as the parameter, it was observed that as the feed rate increased the cutting force also increased, due to the increase in the chip load. It is also observed that the cutting force, feed force and thrust force obtained in the cryogenic CO_2 condition are much less than those of wet and dry cutting conditions. The reduction in the cutting force was more significant at a higher cutting velocity, because of the absence of built up edges or weakened joints of the work material with the tool, on the application of low temperature cryogenic fluids. The CO_2 coolant in particular, performed better in comparison with the LN_2 coolant, as it was in the form of a pressurized jet and managed to enter deep into the cutting zone chip-tool interface, thereby reducing the friction significantly. The application of the LN_2 coolant also increases the work material surface hardness, due to its extreme low temperature which could be the other reason for a slight increase in the cutting force, when compared to the application of the CO_2 coolant. Also, the reduction in the cutting force due to cryogenic machining, results in the reduction of the cutting temperature, helps to maintain the strength and hardness of the cutting tool, thereby reducing the tool wear and adhesion between the interacting surfaces. The cutting forces were reduced in the range of about 21 – 41% and 9 – 22% in cryogenic CO_2 and LN_2 machining respectively, when compared to wet machining. Cryogenic CO_2 produced an advantage in the range of about 7 – 24% reduction in the cutting force, when compared to cryogenic LN_2 machining. This is because, the low temperature cryogenic LN_2 removes the heat in the cutting zone drastically, making the work piece brittle, which certainly increases the cutting forces. Figure 3 shows the variation of the cutting force with feed rate in different machining environments at various cutting velocities.

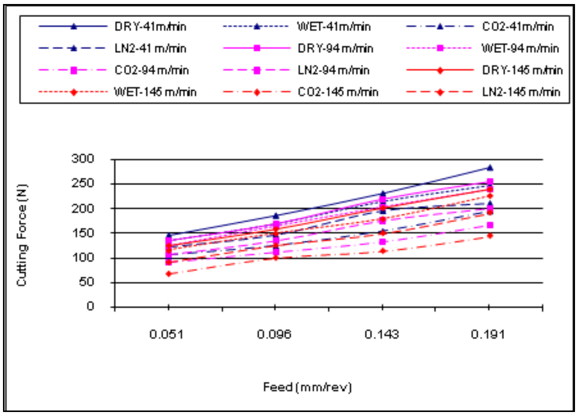


Figure 3: Variation of cutting force with feed rate

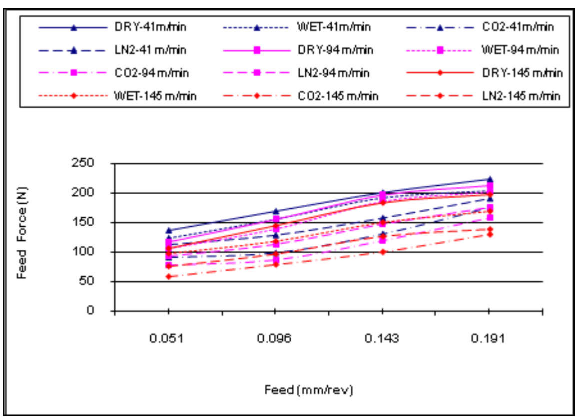


Figure 4: Variation of feed force with feed rate

In Figure 4, it can be clearly seen that the feed force increases with the increase in the feed rate, and decreases with the increase in the cutting velocity. The feed force was reduced in the range of about 21 – 46% and 11 – 39% when cryogenic CO_2 was used as the coolant, while a reduction of the feed force in the range of 15 – 33% and 6 – 22% was obtained with the cryogenic LN_2 coolant when compared to dry and wet machining respectively. The cryogenic CO_2 coolant reduced the feed force in the range of about 7 – 24% when compared to the cryogenic LN_2 coolant.

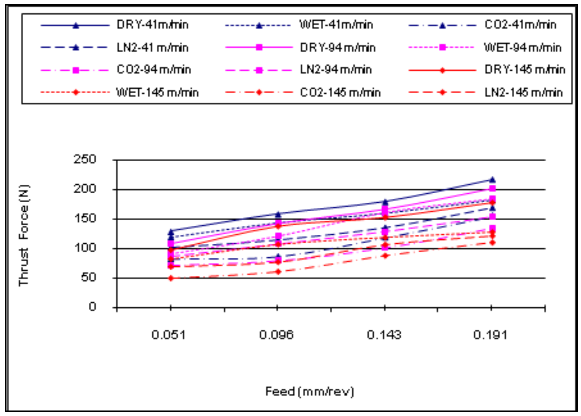


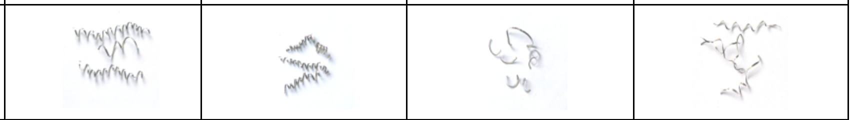
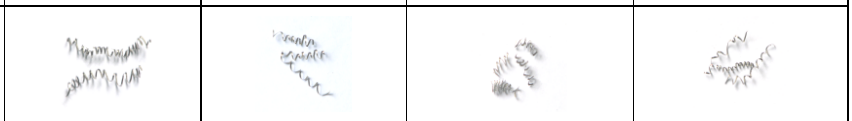
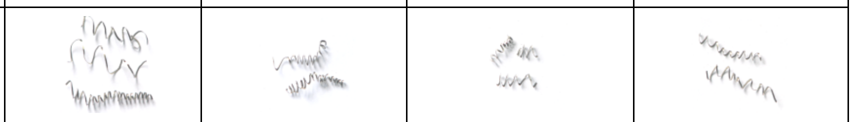
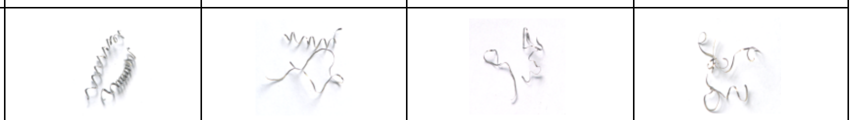
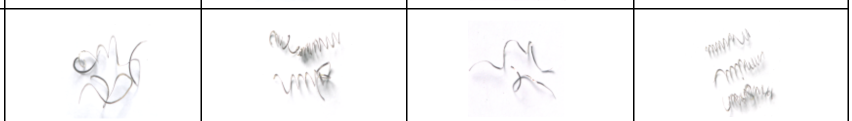
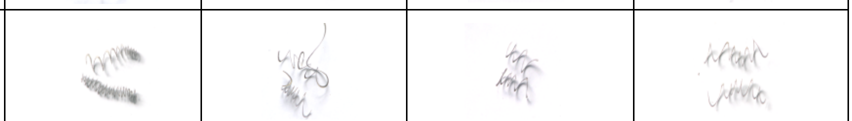
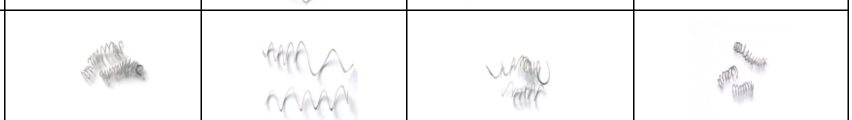
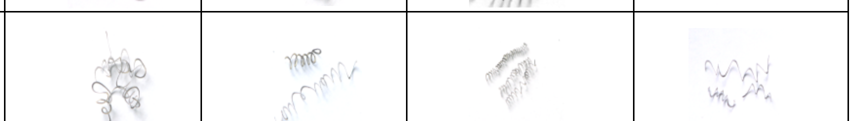
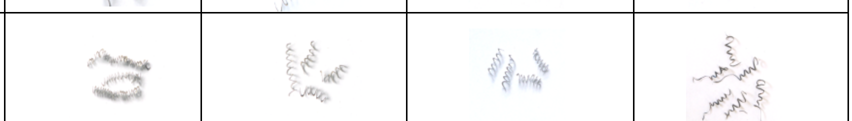
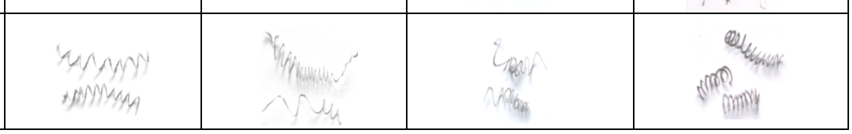
Figure 5: Variation of cutting force with feed rate

Figure 5 show that the thrust force increases with the increase in the feed rate, and decreases with the increase in the cutting velocity. The thrust force obtained in dry, wet, cryogenic CO_2 and LN_2 cooling conditions at a cutting velocity 145 m/min and a feed rate of 0.191 mm/rev are 177 N, 128 N, 110 N and 122 N respectively. The cryogenic CO_2 coolant reduced the thrust force for the same cutting conditions by about 37.85% and 14.06% when compared with dry and wet machining respectively. The cryogenic LN_2 coolant reduced the thrust force by about 31.07% when compared to dry machining condition. Only 4.69% reduction of the thrust force was observed in the cryogenic LN_2 cooling condition when compared to wet machining. The cryogenic CO_2 coolant offered a reduction in the thrust force in the range of about 28 – 55% and 14 – 43%, while the cryogenic LN_2 coolant offered a reduction in the thrust force in the range of about 20 – 44% and 4 – 28% when compared to dry and wet machining respectively. The cryogenic CO_2 coolant was advantageous in the range of about 9 – 27% in reducing the thrust force when compared to the cryogenic LN_2 coolant.

4.2 *Effect of cryogenic coolants on chip form*

The chip images in machining Titanium alloy under different machining environments are shown in the Table 2.

Table 2: Chip images in machining Titanium alloy under different machining environments

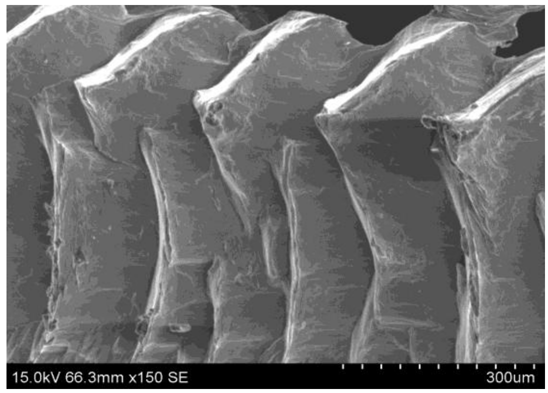
Speed (m/min)	Feed (mm/rev)	Dry Machining	Wet Machining	Cryogenic CO_2 Machining	Cryogenic LN_2 Machining
41	0.051				
	0.096				
	0.143				
	0.191				
94	0.051				
	0.096				
	0.143				
	0.191				
145	0.051				
	0.096				
	0.143				
	0.191				

The form of chip produced greatly influences the productivity of any machining industry. The formation of chips and their breaking aspect is very important in machining, as it affects the surface finish, work piece accuracy and tool life. Hence, the production of an acceptable form of chips with good chip control is essential in metal machining. The images of the chips given in Table 2, visualizes that there is a reduction in chip thickness and better chip breakability, especially when cryogenic CO_2 was used as the cutting fluid.

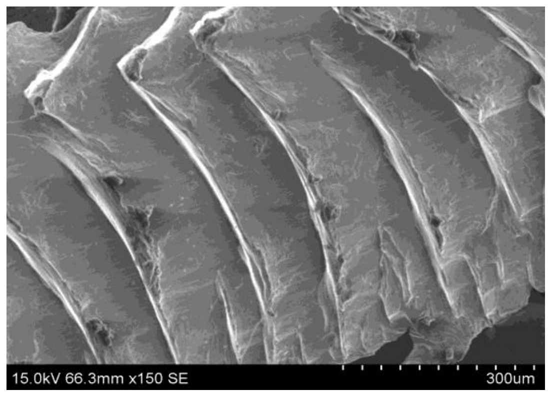
When the cryogenic coolants are applied the chip breakability was better, compared to wet machining, due to the reduced friction and cutting force, as the cryogenic coolants especially cryogenic CO_2 penetrates efficiently into the tool-chip interface. The application of cryogenic fluids produces a better cushioning effect, and a reduction in adhesion and friction is obtained, leading to the reduced thickness of the chips. Moreover, the nature of the chip material will change from ductile to brittle, when the cryogenic fluids get directly in contact with the chips formed, that helps better chip breakability. It was observed in general, that the chip thickness increased with an increase in the feed rate for all machining conditions and cutting speeds. During dry and wet machining, at a low cutting velocity of 41 m/min, long and thick tubular chips were produced, and got accumulated near the cutting zone, causing a hindrance to the machining process. When cryogenic coolants were applied, the transition of the chip material from ductile to brittle took place near the cutting zone, which helped in better chip breakability and reduced chip thickness. At a cutting velocity of 94 m/min, closely curled long tubular chips were produced during dry and wet machining, and at the same cutting velocity, short tubular and closely curled chips were obtained through cryogenic cooling which is favorable for metal machining with better chip breakability. At a high cutting velocity of 145 m/min and feed rate of 0.051 and 0.096 mm/rev, long snarled chips were produced and got accumulated near the cutting zone, causing poor surface finish on the workpiece and more wear on the cutting insert. When cryogenic fluids were used, short fine tubular chips with less thickness, especially at high feed rates of 0.143 and 0.191 mm/rev were obtained. The use of cryogenic CO_2 and LN_2 coolants also helped in washing away the metal chips from the cutting zone effectively, thereby causing appreciable improvement of up to 63% and 35% respectively in the surface finish, when compared to wet machining.

4.3 *Effect of cryogenic coolants on chip morphology*

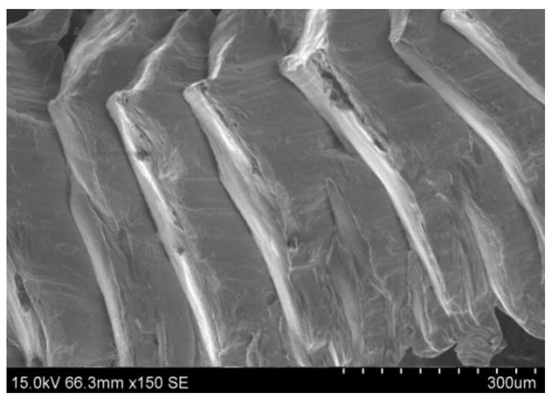
The SEM images of the chips with primary serrations and saw tooth profile obtained in machining Titanium alloy under different machining environments at a cutting speed of 145 m/min and feed of 0.191 mm/rev, are shown in Figures 6(a-d) and 7(a-d) respectively.



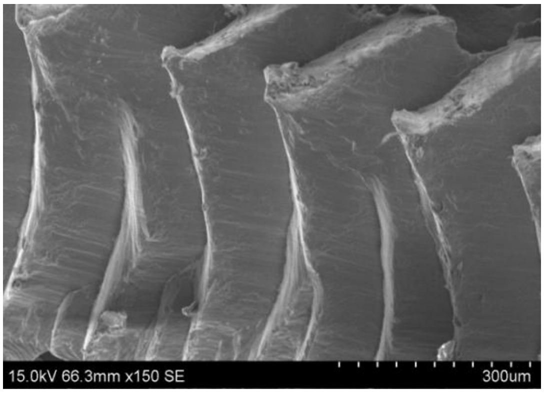
(a) Dry machining



(b) Wet machining



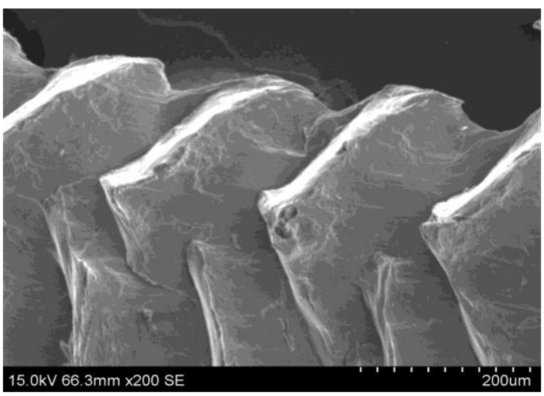
(c) Cryogenic CO_2 machining



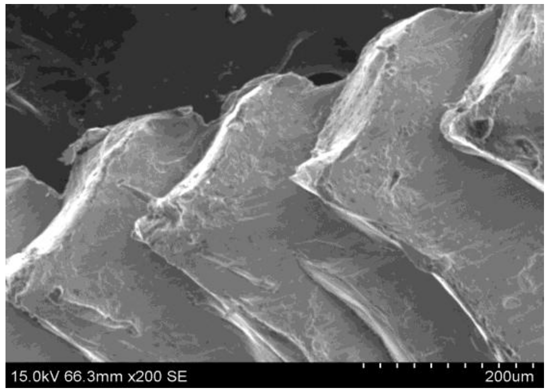
(d) Cryogenic LN2 machining

Figure 6: SEM views of the chip with primary serrations for Titanium alloy

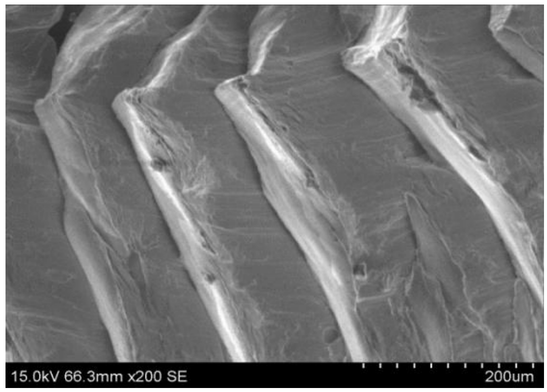
Generally, in machining titanium and its alloys, serrated and segmented chips are observed, since these materials have a low thermal conductivity. Segmented chips promote rapid tool wear and low material removal rates. Smaller sized alternative serrations were also found in the chips obtained from dry and wet machining. Cryogenic cooling resulted in uniform and smaller serrations, when compared to dry and wet machining. The average pitch values measured from the chips at a cutting speed of 145 m/min and feed rate of 0.191 mm/rev, are 187µm, 175µm, 112µm and 170µm in dry, wet, cryogenic CO_2 and cryogenic LN_2 machining respectively. The average peak values measured from the chips obtained in machining Titanium alloy under dry, wet, cryogenic CO_2 and cryogenic LN_2, are 88µm, 71µm, 61µm and 70µm respectively.



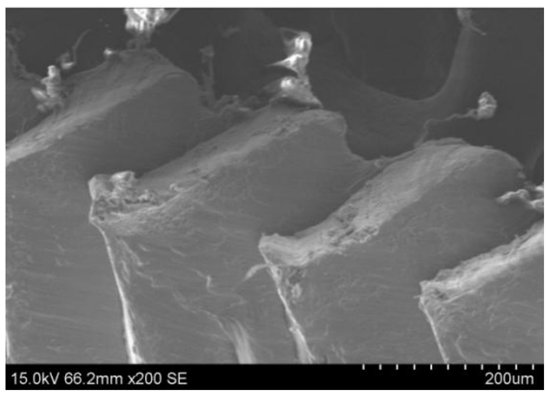
(a) Dry machining



(b) Wet machining



(c) Cryogenic CO_2 machining



(d) Cryogenic LN_2 machining

Figure 7: SEM views of the chip with saw tooth profile in machining Titanium alloy

5 Conclusions

The turning of the Titanium alloy workpiece was carried out, using a PVD coated carbide insert CNMG 120404 MP 431 KC 5010 at different speed-feed combinations under different cutting environments. The major conclusions of this investigation are:

1. The cutting forces were reduced in the range of about 21 – 41% and 9 – 22% in cryogenic CO_2 and cryogenic LN_2 machining respectively, when compared to wet machining.
2. Feed force and radial force reduced in the range of about 14 – 40% and 14 – 43% with the cryogenic CO_2 coolant, and in the range of about 6 – 22% and 5 – 28% with the cryogenic LN_2 coolant, when compared to the wet machining process.
3. Better chip breakability was observed and acceptable forms of fine chips were produced in both cryogenic CO_2 and LN_2 machining with reduced chip thickness.
4. The use of cryogenic coolants produced uniform and smaller size serrations in the metal chips obtained.

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