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Technical paper

Experimental investigation of turning AISI 1045 steel using cryogenic carbon dioxide as the cutting fluid

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ABSTRACT

The intensive temperatures in high speed machining not only limit the tool life but also impair the machined surface by inducing tensile residual stresses, microcracks and thermal damage. This problem can be handled largely by reducing the cutting temperature. When the conventional coolant is applied to the cutting zone, it fails to remove the extent of the heat effectively. Hence, a cryogenic coolant is highly recommended for this purpose. In this paper, an attempt has been made to use cryogenic carbon dioxide (CO_2) as the cutting fluid. Experimental investigations are carried out by turning AISI 1045 steel in which the efficiency of cryogenic CO_2 is compared to that of dry and wet machining with respect to cutting temperature, cutting forces, chip disposal and surface roughness. The experimental results show that the application of cryogenic CO_2 as the cutting fluid is an efficient coolant for the turning operation as it reduced the cutting temperature by 5%–22% when compared with conventional machining.

It is also observed that the surface finish is improved to an appreciable amount in the finished work piece on the application of cryogenic CO_2. The surface finish is improved by 5%–25% in the cryogenic condition compared with wet machining.

1. Introduction

The machining industries are interested for high material removal rates and high product quality by using greater cutting velocity and feed rates to achieve better productivity. It becomes extremely tough to attain these properties as the high cutting temperature produced in the cutting zone causes premature failure of the cutting tools, which results in poor dimensional accuracy. It also weakens the surface integrity of the product by inducing tensile residual stresses and surface and sub-surface microcracks in addition to rapid oxidation and corrosion [1]. As a solution for this, it is essential to reduce the temperature in the cutting zone by the optimum selection of the machining parameters, coated tools and proper cutting fluids. In the conventional process, the cutting fluid, when applied in the cutting zone, fails to enter the chip–tool interface and hence fails to reduce the cutting temperature. The usage of conventional coolants is not so effective and moreover, it imposes major environmental problems due to the chemical breakdown of the cutting fluid in high temperature and it contaminates water and soil during huge disposal. It also imposes high cost for the setup of coolant system, as it has to be stored, pumped, filtered and recycled when it is used. It also has adverse effects on the parts of the machine tool and work piece causing corrosion, which leads to its failure. In recent years, machining investigations have been carried out using liquid nitrogen as the coolant. The major disadvantage of using liquid nitrogen as a coolant is, it affects the physical properties of the work piece due to its extreme low temperature (−196 °C). Alternatively, cryogenic CO_2 may be used as the cutting fluid as it is cheaper and available in vast amount. In previous works, researchers had hardly used CO_2 in turning operations. Hence, in this work a high pressure jet of CO_2 is used to reduce the cutting temperature and increase the cutting tool life to a nominal extent. Carbon dioxide, a cryogenic fluid is an effective and eco-friendly coolant with extreme low temperature which also shows better surface finish dimensional accuracy when compared to other conventional coolants. It is a slightly toxic, odorless, colorless gas with a slightly pungent, acid taste. The properties of CO_2 are given below.

Physical properties:

a. Melting point: −78 °C
b. Boiling point: −56 °C
c. Density: 1.977 kg/m^3.

Although carbon dioxide, generally speaking, is considered to have an adverse impact with respect to the greenhouse effect, it can be produced as waste material from power plant combustion and thus provide an environmentally neutral product [2].

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2. Literature review

Rowe and Smart [3] used oxygen as the cutting fluid in the machining and observed that the application of oxygen reduced the contact length of chip cutting tool. Williams and Tabor [4] examined oxygen gas effect as a lubricant. It was noticed that the use of oxygen reduced cutting forces. As a result better surface finish occurred. The study also recommended the higher pressure of oxygen to be applied to obtained lower frictional values. Wang and Rajurkar [5] used liquid N_2 (LN_2) cooled PCBN tool for machining hard-to-cut materials such as advanced ceramics and had studied that with LN_2 cooling, the cutting temperature was reduced to a lower range thereby improving the tool life and surface finish to a greater extent. Paul et al. [6] has studied the effectiveness of cryogenic cooling by liquid nitrogen jet on tool wear and surface finish in plain turning of AISI 1060 using two types of carbide inserts in different geometry. Hong et al. [7] used a specially designed micro nozzle to inject a minimum quantity of LN_2 on to the chip–tool interface at the point of highest temperature for machining titanium alloy Ti–6Al–4V. In order to cool the rake area an additional micro nozzle was used and concluded that when the two nozzles used together, the consumption of LN_2 was reduced acknowledging with better cooling effect and tool life. Dhar et al. [8] has carried out experimental machining work by machining AISI 1040 and E4340C steels using coated carbide inserts with two different geometries under cryogenic LN_2 environment and concluded that the cutting temperature reduced around 34% which in turn reduced the tool wear rate, dimensional inaccuracy and surface roughness. Akir et al. [9] has studied the effects of cutting fluid, some gases applications and dry cutting on cutting forces, thrust forces, surface roughness, friction coefficient and shear angle. Machining of AISI 1040 steel material was carried out using nitrogen, oxygen and carbon dioxide gases and concluded that the gases application is the most favorable when compared with the results obtained by using conventional fluids. On the comparison amongst the gases, carbon dioxide proved to be the better cutting fluid. Junyan Liu et al. [10] has machined C45 steel in different conditions under compressed air, oil water emulsion, water vapor as the cutting fluids. They have concluded that the water vapor when used as the cutting fluid produced the advantageous results. Clarens et al. [11] proposed a new method to lubricate, cool and evacuate chip in metal working operations using super critical carbon dioxide. Their investigations indicated that the super critical carbon dioxide Metal Working Fluids (MWF) perform significantly better than straight oil soybean and petroleum MWFs, and are better than water-based MWF emulsions based on these oils. De Chiffre et al. [2] have carried out experimental investigations by comparing the efficiency of CO_2 with the commercial water-based product as the coolant on threading and parting/grooving stainless steel. Tool life, cutting force, chip disposal and work piece surface finish were analyzed and concluded that the efficiency of CO_2 was as high as 173% relative to water-based product in terms of the tool life. It was found that CO_2 when applied at a rate of 6 g/s is an efficient coolant for threading and parting/grooving stainless steels. Dhar and Kamruzzaman [12] have carried out experimental investigation in the role of cryogenic cooling by applying LN_2 jet on cutting temperature, tool wear, surface finish and the dimensional deviation in turning of AISI 4037 steel at industrial speed and feed combination by coated carbide insert. It was observed that the conventional coolant failed to show any significant improvement in the tool life. Junyan Liu et al. [13] applied water vapor, gases (carbon dioxide and oxygen), water vapor and gas mix as coolants and lubricants and analyzed that the application of water vapor, gases and water vapor with gas reduced the main cutting force and the cutting temperature than the other lubricating conditions. It is also observed that the tool life increased on the application of water vapor and water vapor with gas mix considerably when compared with dry cutting. Kalyan Kumar and Choudhury [14] found out that around 14.83% advantage on reduction of cutting forces in cryogenic condition was present and around 37.39% advantage on flank wear which was attributed by the reduction of cutting temperature on machining stainless steel SS202 using carbide insert. LN_2 was used as the cryogenic coolant and the consumption was high which increased the overall machining cost. Vishal et al. [15] presented the advances in techniques as minimum quantity lubricant, high pressure coolant, cryogenic cooling, compressed air cooling and use of solid lubricants. Their experiments resulted in reduction in friction and heat at the cutting zone, hence improving the overall productivity. Liu Junyan et al. [16] used water vapor as the cutting fluid and studied the lubrication action in cutting ANSI 304 stainless steel. They reported that the cutting force and the tool flank wear are reduced about 50%–75% compared with dry machining.

The major objective of this work is to study especially the effect of cryogenic CO_2 as the cutting fluid in machining AISI 1045 steel and to compare the parameters like cutting temperature, cutting forces, chip thickness, shear angle and surface roughness with wet and dry machining. Cryogenic CO_2 with high cooling potential was expected to remove ample heat from the cutting zone and this will also result in the improvement of mechanics of chip formation. Discontinuous chips were formed which would be easy to remove and dispose.

3. Experimental setup

The experimental work is carried out by turning a medium carbon steel AISI 1045 which is highly usable in the industry manufacturing various machine parts which is also cheaply available. The dimensions of the work piece considered are Ø 60 mm and length 300 mm. Machining is carried in a rigid and powerful lathe (NAGMATI - 175) using multi-coated carbide insert (CNMG 120412-5 TN2000). The machining process is carried out in 3 different speeds and 4 feed rates. For each environment (cryogenic, wet and dry conditions) separate work piece is used. These work pieces are taken from the same parent raw material as there should not be any deviations in the results obtained in the experiments due to the property change of the material although it is negligible. Similarly for every combination of speed and feed a new cutting insert in used for machining purpose. A tool holder PCLNR 2020 K 12 is used to hold the cutting insert. Kistler type 9257B piezo-electric three component dynamometer, a Kistler type 5070A12100 multichannel charge amplifier and a PC based data acquisition system (Dynoware) is used to measure the cutting forces. The average surface roughness value *Ra*, for the finished part along the job axis is found by using a talysurf surface roughness tester with gauge range ± 150 μm, resolution – 0.014 μm, Stylus - 112/1502 diamond tip radius 5 μm and the cut off value considered is 0.8. In the cryogenic condition, CO_2 gas is supplied from the cylinder through a nozzle whose outlet tip having Ø 2 mm. The nozzle is fixed at a distance of 50 mm from the cutting zone. A CO_2 regulator is attached to the cylinder for maintaining the pressure in the flow of CO_2. A CO_2 flow meter is also attached in the circuit for maintaining the flow rate of the gas. In the wet machining, an oil based conventional coolant is used which is supplied by the same nozzle that is used for the cryogenic CO_2 supply. A coolant pump with the coolant tank setup is used for this purpose.

The results obtained in cryogenic cutting with respect to the cutting temperature, chip thickness, cutting force, surface roughness and shear angle are compared with wet and dry cutting for evaluation. The experimental setup for cryogenic machining is shown in Fig. 1.

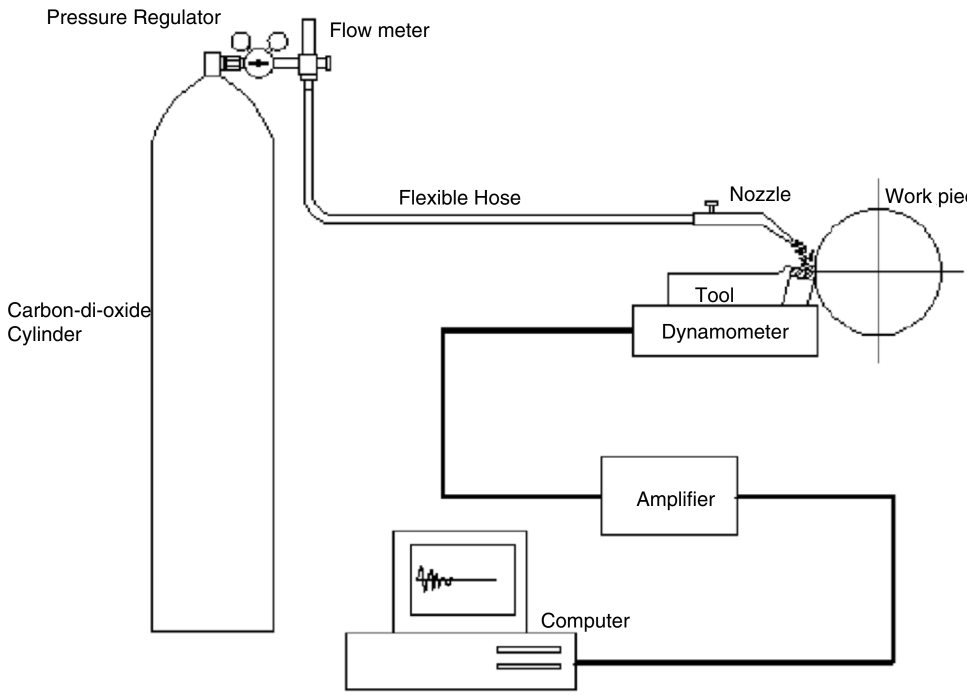


Fig. 1. Experimental setup for cryogenic machining.

4. Experimental conditions

Work specimen: AISI 1045 steel (Ø 60 mm X 300 mm)

Cutting insert: Multi-coated carbide insert (CNMG 120412-5 TN2000)
Rake angle: −5°
Clearance angle: 5°

Process parameters
Cutting speed: 40.51, 94.2, 145.1 m/min
Feed rate: 0.051, 0.096, 0.143 and 0.191 mm/rev
Depth of cut: 1 mm

Machining environments: Dry, Wet and Cryogenic conditions

Nozzle diameter: 2 mm (Used for both conventional coolant and CO_2)

CO_2 **Flow rate**: 3 g/s

5. Experimental results and discussion

5.1. Cutting temperature

The CO_2 gas jets at a temperature of −78 °C is supposed to cool the hot cutting zone, but its effect is less reasonable as the high flow speed cryogenic jet cannot penetrate the chip–tool interface fully. However, the temperature is considerably reduced as the CO_2 jet stream nears the cutting zone area. The cutting temperature is measured in the chip–tool interface area (rake) in different cutting environments using a noncontact type IR-thermometer (Accuracy ±1.0 °C) which can measure a temperature range of 50–1000 °C. The cutting zone temperature is measured by making the IR ray from the IR-thermometer to impinge exactly on the tool–chip interface (cutting zone) during the machining process and the maximum temperature attained is recorded. Here it is assumed that the surface of the work piece is a gray body, with constant emissivity (ε). Assuming no other energy source, the radiance received by the instrument detector is independent of distance from the target.

Fig. 2 shows the variation of the cutting temperature obtained in different speeds and feed rates.

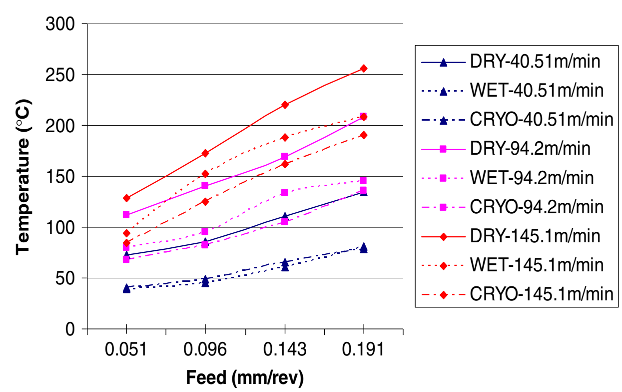


Fig. 2. Variation of cutting temperature in different machining environments.

It is observed that the cutting temperature increases with the increase in feed and speed. It is also observed that when the speed is kept constant with varying feeds the temperature increased considerably. This is observed similarly with constant feed and variable speeds.

The results indicate that there is a reduction in the cutting temperature in cryogenic condition of around 5%–22% when compared to wet cutting, which depends on the other machining parameters like cutting speed and feed rate. The temperature values obtained in wet condition in low speeds is favorable for machining than the cryogenic condition as the conventional coolant entered most of the cutting area in the low speeds there by reducing the cutting temperature largely. When the higher speeds and feeds are applied, the cryogenic condition yielded the less temperature values than the conventional machining, as the coolant is unable to enter the cutting zone at high speeds. It is also observed that the percentage of reduction in temperature is less in low speed than the high speed machining, as the cutting temperature produced originally is less. Where as in high speeds, favorable percentage of reduction in temperature is obtained as the cutting temperature produced in the cutting zone is comparatively high which favor for the high speed machining.

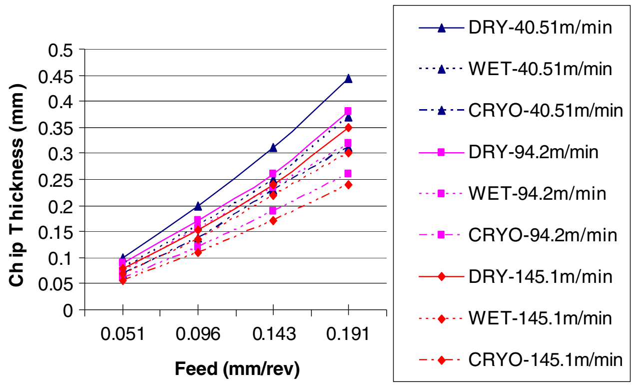


Fig. 3. Variation of chip thickness with feed rate.

5.2. *Chip thickness*

Hagiwara et al. [17] has stated that the chip shape and size are the major factors in chip breakability. The chip thickness for the chips obtained in machining the work piece in different cutting conditions is measured by using a precision micrometer. Analyzing the chip thickness, with the increase in the feed rate, the chip thickness considerably increases. It is also observed that at higher speeds the chip thickness decreases. In general the cutting fluid mainly depends on heat convection to reduce the cutting temperature. CO_2 can reduce the contact friction in the tool–chip interface with the high efficiency lubricating action, cooling effect as the temperature of cryogenic CO_2 is much lesser than the cutting temperature. The variation of the chip thickness with cutting speed and feed is shown in Fig. 3.

In cryogenic machining, the chip breakability is good when compared with wet and dry machining. The cutting temperature is reduced on application of CO_2 gas better than the application of the conventional coolant. This is because CO_2 in the gas form penetrates better in the cutting zone than any conventional liquid coolant. As a result it reduces the adhesion and friction between the tool and the chip effectively, resulting in the reduction of the chip thickness. Reduction in chip thickness is about 8%–23% on cryogenic machining when compared to wet machining.

The images of the chips obtained in dry, wet and cryogenic environments are shown in Table 1, which obviously proves that there is a reduction in chip thickness and better chip breakability.

The measured values of the chip thickness are mentioned in Table 2.

At low speed (40.51 m/min), when the feed rate is increased, size of the curl obtained in the chip gets increased and at constant speed and feed the chip breakability is improved and the chips snarled with few turns or small pieces are obtained in the cryogenic condition compared to wet and dry condition. In dry and wet machining, the thickness of the chips obtained is more than that of cryogenic and it is hard to break as it is closely curled. At high speeds discontinuous chips are obtained with less thickness in cryogenic machining where as in dry and wet machining continuous chips are obtained which will result in poor surface finish of the product and less tool life.

5.3. *Surface roughness*

The average surface roughness value R_a, for the finished work piece is found by using a talysurf surface roughness tester. Fig. 4 shows the variation of surface roughness values with different speeds and feeds.

It is observed that the surface finish is increased to a nominal amount in the finished part, which is turned under cryogenic conditions when compared to wet and dry conditions. The surface finish is found to be better in cryogenic condition because the chip breakability is better during machining and less accumulation of chips near the cutting zone and thereby frictional contact of the chips with the finished work piece is avoided. It is also noticed that as the cutting speed increases the surface finish gets better as there is a reduction in the cutting force that leads to the minimal vibration during machining and there is an increase in surface roughness values when the feed is increased. The surface finish gets better by around 5%–25% in cryogenic conditions when compared to wet condition. The least appreciable results occurred at high speeds, which are around 4%–16% in cryogenic condition. This is because at high speeds, due to the high generated cutting temperature the chips formed always try to get stuck to the tool tip, hence leaving the rough surface on machining.

The average surface roughness values in the wet condition at three different speeds 40.51, 94.2, 145.1 m/min are 4.5 μm, 2.5 μm and 1.5 μm respectively. These values are comparatively high than the values obtained in cryogenic condition. The average values obtained in cryogenic condition are 3.5, 2 and 1 μm.

5.4. *Cutting force*

Fig. 5 shows the variation of cutting force with variable feeds at different speeds.

It is observed that the cutting force decreases with increase in the cutting speed. This is because when the speed increases, the cutting temperature also increases considerably thereby softening the work piece. Moreover when the cryogenic coolant is applied the temperature in the cutting zone is reduced considerably thereby reducing the stickiness of the metal chip with the tool rake.

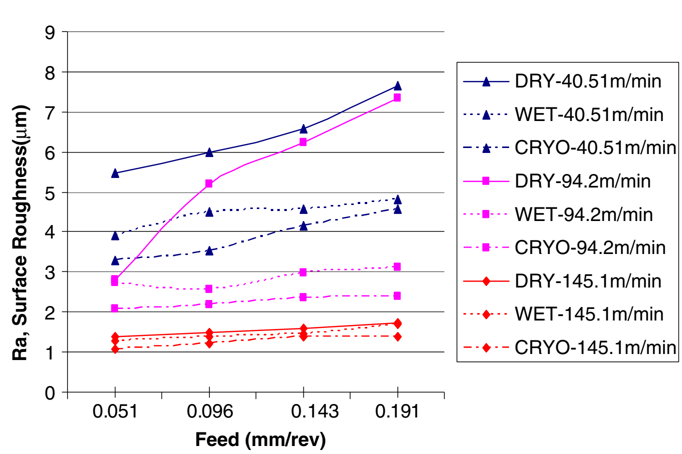


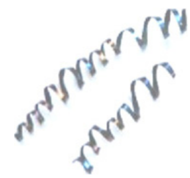
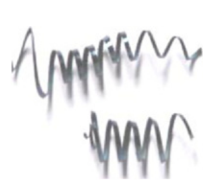
Fig. 4. Comparison of surface roughness with feed rate.

Table 1
Chip images in dry, wet and cryogenic CO_2 machining conditions.

SPEED (m/min)	FEED (mm/rev)	DRY	WET	CRYOGENIC CO_2
	0.051			
	0.096			
40.51	0.143			
	0.191			
	0.051			
	0.096			
94.2	0.143			
	0.191			

(*continued on next page*)

Table 1 (*continued*)

SPEED (m/min)	FEED (mm/rev)	DRY	WET	CRYOGENIC CO_2
145.1	0.051			
	0.096			
	0.143			
	0.191			

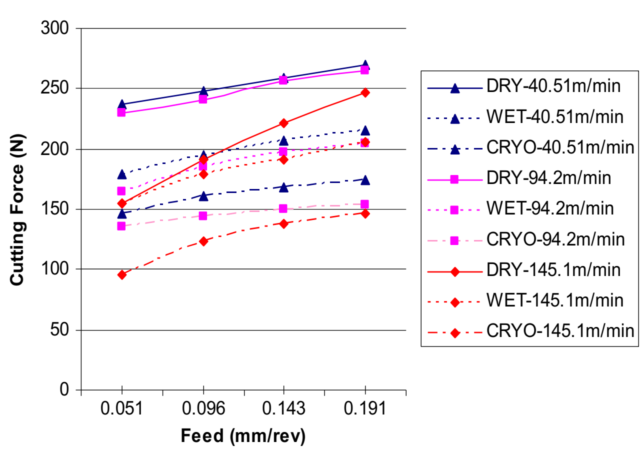


Fig. 5. Comparison of cutting force with feed rate.

The effect of speed on cutting force is advantageous to an extent of about 17%–38% in cryogenic condition when compared with wet cutting. This is due to the lubrication effect produced in the cutting zone and the work piece becomes less sticky thereby requiring less amount of force to shear the material. Better lubrication is obtained when the cryogenic coolant enters properly into the cutting zone forming a boundary lubrication layer which reduces the friction. When the feed rate is taken as the parameter, it is observed that as the feed rate increases cutting forces also is increased due to the increase in the chip load. With the values obtained for tangential and feed force, it is observed that both the forces increase with the increase in cutting speed and feed rates. It is also observed that the cutting force, tangential force and feed force values obtained in cryogenic condition is much less than that of wet and dry cutting conditions.

Table 2
Chip thickness values.

Chip thickness (mm)				
SPEED m/min	FEED mm/rev.	DRY.	WET.	CRYOGENIC
40.51	0.051	0.1	0.08	0.07
	0.096	0.2	0.16	0.1375
	0.143	0.31	0.25	0.23
	0.191	0.445	0.37	0.3125
94.2	0.051	0.09	0.075	0.06
	0.096	0.172	0.155	0.12
	0.143	0.26	0.235	0.19
	0.191	0.38	0.32	0.26
145.1	0.051	0.08	0.07	0.055
	0.096	0.153	0.135	0.11
	0.143	0.24	0.22	0.17
	0.191	0.35	0.3	0.24

5.5. Shear angle

Shear angle is calculated for all the cutting conditions in different speeds and feed rates. Using the measured chip thickness, shear angle is calculated by using the formula [18]

$\tan Ø = (r \cos\gamma)/(1 - r \sin\gamma)$

Where Ø — Shear Angle

r – Chip thickness ratio = Uncut Chip thickness / Deformed Chip thickness

γ – Rake Angle

Fig. 6 shows the variation of the shear angle with different feed rates at different speeds.

Comparing the shear angle under dry, wet and cryogenic machining it is noticed that there is an increase in shear angle in cryogenic machining as there is reduction in the cutting temperature at the cutting zone by the application of cryogenic

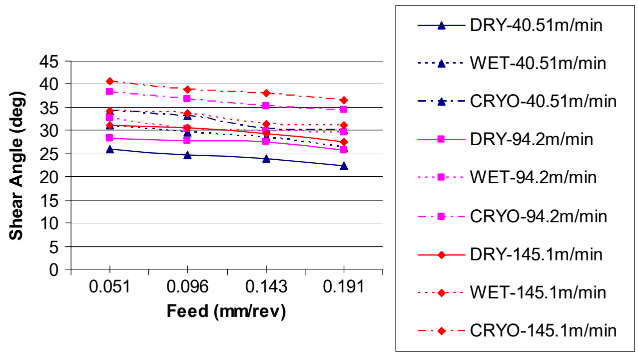


Fig. 6. Comparison of shear angle with feed rate.

coolant. The increase in shear angle will reduce the plane of shear thereby reducing the chip thickness. It is found that there is an increase of 6%–21% in shear angle for cryogenic condition when compared with the wet cutting. It is observed from the graph that at constant feed rate and increasing speeds, the shear angle is increased. The application of CO_2 in the cutting zone increased the shear angle in all the cutting parameters which will produce the low cutting forces in cryogenic conditions.

6. Conclusion

The cryogenic CO_2 is used as the cutting fluid for turning AISI 1045 steel and the major conclusions and the results of the experimental work conducted can be summarized as follows:

- The cutting temperature is reduced around 5%–22% in cryogenic condition when compared with wet cutting, which in turn increase the tool life as the adhesion between tool and chip is avoided to a considerable extent. The increase in the tool life helps in the economy of a metal cutting industry to a greater extent.
- Cutting force in cryogenic machining is observed to be less than that of wet and dry cutting. Approximately 17%–38% advantage is obtained by cryogenic machining over wet machining.
- Better chip breakability is obtained in cryogenic condition as the shear angle is increased resulting from the reduction in plane of shear thereby reducing the chip thickness.
- Surface finish of the finished part is also improved in cryogenic condition to an appreciable amount on comparison with the other two environments.

Cryogenic cooling is found to be more advantageous as far as the high speeds and feed rates are concerned. Cryogenic CO_2 is a potential alternative for other cryogenic coolants if the environmental aspects are taken care.

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