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ORIGINAL ARTICLE

Machinability Study in Turning of Ti-6Al-4V under CO_2-based Vortex Tube Cooling System

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ABSTRACT – The study on the machinability of titanium alloys provides new ways to minimize the difficulty levels of machining the alloys due to substantial heat accumulation. To improve machinability, pivotal factors such as heat accumulation and cutting temperature must be regulated. In this study, a turning operation was performed on Ti-6Al-4V and the cutting temperature was reduced by supplying cooled CO_2 gas through a vortex tube connected with two nozzles. Variations in cutting force, cutting temperature, and surface roughness with cutting speed, feed, and depth of cut were recorded. Subsequently, responses were compared for single nozzle vortex tube, dry, and compressed air environments at different cutting speeds. Cutting force and surface roughness followed a similar trend which increased with decreasing speed, and increasing feed and depth of cut. The cutting temperature increased with all three variables. The proposed cooling system provided better results in terms of cutting temperature and surface roughness, while a marginally higher cutting force was observed compared to dry cutting.

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Machinability

INTRODUCTION

The alloys of titanium are widely used in the aerospace industry because of their lightweight and retaining strength at high temperatures, in the marine industry because of their resistance against corrosion and erosion in seawater, and in the automobile industry due to their specific strength. Ti-6Al-4V is a highly popular alloy of titanium because of its properties like high specific strength and corrosion resistance. Machining Ti6-Al-4V is difficult because of its low thermal conductivity and high strength. Controlling cutting temperature in Ti-6Al-4V machining is a major challenge faced by industries because of high heat generation. Cutting fluids have been used for this purpose from the beginning, but their use needs to be minimized because of drawbacks like environmental pollution and hazards for human and aqua life. To overcome these problems, different cooling approaches have been developed as a substitute for cutting fluids, such as dry cutting, near dry cutting, pressurized air cooling, and cryogenic cooling like LN2 (liquid nitrogen) [1].

Arauzo et al. [2] used a vapor compression refrigeration system to supply cool compressed air in SAE 1045 steel machining, and better tool life and surface roughness were observed compared to dry conditions. Sartori et al. [3] used CO_2 and LN2 as coolants in MQL in Ti-6Al-4V machining and found higher tool life in using CO_2 gas. Sadik et al.[4] used liquid CO_2 gas in the face milling of Ti alloy and compared the responses with wet conditions. CO_2 gas cooling provided better tool life, and it enhanced with an increase in gas flow rate. Dong-Won Kim et al. [5] used cryogenic LN2 as a coolant and compared the responses with traditional coolants in titanium machining. A reduction of 54% in cutting force and an improvement of tool life by 90% was recorded with cryogenic LN2. Suarez et al. [6] used high-pressure coolants in turning IN718 and found that this method reduced the cutting force and flank wear, whereas marginally higher notch wear was obtained compared to conventional cooling.

Sartori et al. [7] used nitrogen gas as a coolant in the range of 0 °C to -150 °C in Ti-6Al-4V machining. It was found that nitrogen at -150 °C performed better compared to LN2 and wet cooling in terms of surface finish and tool wear. Shokrani et al. [8] used LN2 in the milling of Ti-6Al-4V and compared the responses with flood conditions. Improvement in tool life by three times and reduction in surface roughness by 40% was achieved with LN2. Christian Machai et al.[9] used CO_2 snow as a coolant in turning Ti-10V-2Fe-3Al and found that tool life doubled using this coolant compared to flood emulsion. Burr formation and notch wear were also reduced significantly in the process. Gonzalez et al. developed a new method to inject CO_2 gas with MQL in the machining of integral blade rotors (IBRs) made of Ti-6Al-4V to prevent the formation of dry ice [10]. Salaam et al. [11] used a vortex tube to supply chilled air as a coolant in turning mild steel. Surface quality improved, and cutting temperature was reduced with vortex tube cooling compared to ambient conditions. The use of CO_2 leads to environmental neutrality through the use of gas obtained as a waste product in industrial and chemical processes [12].

Gupta et al. [13] used dry, N_2 cooling, N_2MQL, and RHVT-N_2MQL cooling environment in Al 7075-T6 turning. RHVT-N_2MQL provided improved surface quality and tool life compared to other conditions. Rahman Rashid et al. [14] machined Ti-6Cr-5Mo-5V-4Al by attaching it to a laser source. It was seen that lower cutting force and higher metal removal rate were achieved by this technique compared with conventional methods. Rotella et al. [15] analyzed the microstructure, grain refinement, and surface quality under dry, MQL, and cryogenic environments at various speeds, *v*,

*CORRESPONDING AUTHOR | M. Khirod | ✉ khirodmech@gmail.com and feeds, *f,* in Ti-6Al-4V machining. The study revealed improvement in outcomes under a cryogenic environment. Shokrani et al. [16] used hybrid cryogenic MQL in end milling of Ti-6Al-4V by varying *v* values and compared the responses with conventional techniques. The technique improved the tool life by 30 times and productivity by 50%. Mahapatro et al. [17] developed a cooling system based on the vortex tube principle and compared the outcomes with dry cutting in Ti-6Al-4V machining. It came through that vortex tube cooling system (VTCS) lowered cutting temperature and surface roughness. But cutting forces were significantly reduced with VTCS in turning. Mahapatro et al. [18] studied the influence of flow variables on cutting force, *Fz*, cutting temperature, *Tc*, and surface roughness, *Ra* and derived the optimum combination of flow parameters.

Previous researchers used different cooling system alternatives to conventional cutting fluids, but the use of vortex tubes as a cooling source was limited. Previous studies focused on applying chilled CO_2 as a coolant in machining. The current work deals with the study of CO_2-based VTCS attachment in Ti-6Al-4V turning. Hence, the need for understanding the proposed cooling strategy in titanium machining is very important as this is one of the viable alternatives for conventional cutting fluids. CO_2 gas generated from different processes can be used in a pressurized form to produce a cooling effect. Previously, the effect of flow variables on the machinability of Ti-6Al-4V was studied [18]. This study compares dry, compressed air, single nozzle VTCS, and dual nozzle VTCS at different *v* values. Then, the influence of machining variables on responses is discussed in detail.

EXPERIMENTAL WORKS

The ti-6Al-4V workpiece was machined in turning operation on the lathe machine with an uncoated carbide tool insert (CNMG120408 THM) and PCLNR2525M12 tool holder. Initially, turning was carried out under dry and compressed air cooling (7 bar) environments; VTCS single nozzle [17] and dual nozzle setup [18] were attached to the lathe machine and turning operation was performed at 20% cold fraction and inlet pressure of 7 bar. The responses were measured at different *v* values given in Table 1 by keeping the *f* value at 0.25 mm/rev and the depth of cut, *d* at 1 mm. The experimental setup of the dual nozzle VTCS is shown in Figure 1 and the responses were measured at different levels of machining parameters as in Table 1 under dual nozzle VTCS. The flow parameters cold fraction, coolant pressure, and tooltip-nozzle distances were maintained constant throughout the experiment [18]. The response parameters and respective measuring instruments are presented in Table 2. Each experiment was conducted thrice, and the mean value of individual responses was considered as the final result. Initially, the influence of different cooling environments on the responses was analyzed at various *v* values. Further, the effects of input parameters on responses were investigated experimentally.

Table 1. Input conditions for VTCS-assisted turning

Parameter	Values
Coolant pressure (bar)	7 bar
Cold fraction (%)	20%
Nozzle diameter (mm)	6 mm
v (m/min),	60, 70, 80, 90, 100.
f (mm/rev)	0.21, 0.25, 0.27,
d (mm)	0.8, 1, 1.2
Nozzle angle (θ)	45°
Tooltip nozzle distance	3.5 cm

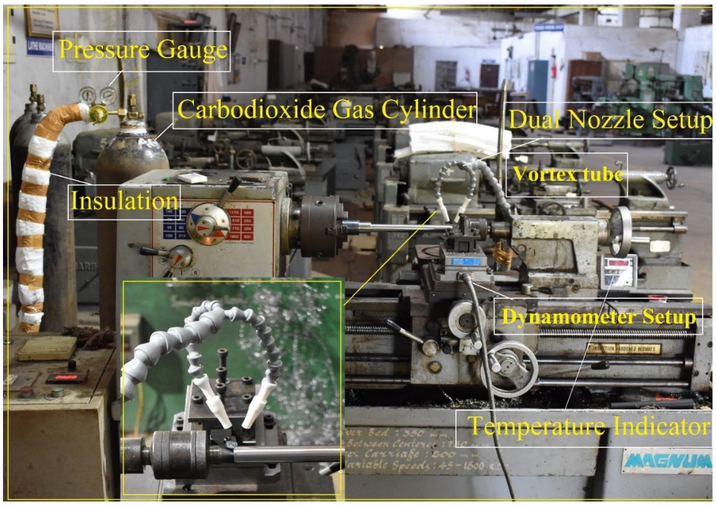


Figure 1. Experimental setup of the dual nozzle VTCS

Table 2. Response parameters and measuring instruments

Variable	Measuring instruments & specifications
Cutting force	Kistler dynamometer ,model- 5070
Cutting temperature	Fluke thermal imager, model -TI400
Surface roughness	Surtronic roughness tester, model -S128

RESULTS AND DISCUSSION

Cutting Force

The cutting force is a vital parameter in machining which helps to analyze power consumption, tool life, and rigidity requirement. The *Fz* value measured at different *v* values under different cooling media is presented in Figure 2. The minimum *Fz* value was observed under dry-cutting conditions, while the maximum *Fz* value occurred under compressed gas cooling conditions. In Ti-6Al-4V machining under dry cutting, the heat generated accumulated in the machining zone, and the low thermal conductivity of the material prevented the heat conduction to the atmosphere. This led to high temperatures in the machining zone, and the workpiece was subjected to thermal softening. Hence, low energy was required to perform the machining operation, and a low *Fz* value acted on the cutting tool. In the case of compressed air cooling, the heat generated was carried away by the pressurized gas and minimized the thermal softening effect. Along with this, the gas focused from the nozzle applied external impulse force on the cutting tool and further increased the *Fz* value. The impulse force acting due to high-velocity gas is given by $\rho a V^2$, where ρ is the density, a is the area of the nozzle outlet and V is the velocity of the gas leaving from the nozzle. The impulse force mainly depends on the flow rate and velocity of the coolant.

In VTCS single nozzle, at 20% of cold fraction, *Fz* value was lower compared to compressed air because only 20% of the total flow rate was available. However, the low-temperature coolant from the vortex tube produced a strain-hardening effect in the workpiece to a high *Fz* value compared to dry cutting. When the coolant was supplied using dual nozzle VTCS, the only vertical component of the impulse force ($2\rho a V^2 \sin 2\theta$) acted on the cutting tool. Hence, *Fz* value was lower on dual nozzle VTCS compared to single nozzle VTCS [18]. The influence of *v* on cutting force is shown in Figure 2; it was observed that the *Fz* value decreased with an increase in velocity. It decreased in the range of 9-12 % based on *d* values when *v* value increased from 60 to 10 m/min. The material removal rate increased with an increase in *v* values which required more energy for machining. This energy was transformed into heat and increased the temperature in the machining zone which led to thermal softening. In Ti-6Al-4V, beyond 25 m/min of *v* value, the thermal softening phenomena dominate and reduce the cutting force [14]. Figure 4 shows the variation of cutting force with *d* value. It increased in the range of 4-7% based on *v* values when *f* value increased from 0.21 to 0.29 mm/ rev. The increase in *f* value increased the friction coefficient at the cutting zone, which raised the rubbing force (friction force) and led to higher *Fz* value. A high *f* value increases MRR and requires more energy, thereby requiring more force for shearing. The cutting force increased in the range of 6-10 % based on the cutting velocity when *d* value increased from 0.8 to 1.2 mm. MRR increased as *d* value increased, and hence higher energy was required for machining which led to an increase in *Fz* value.

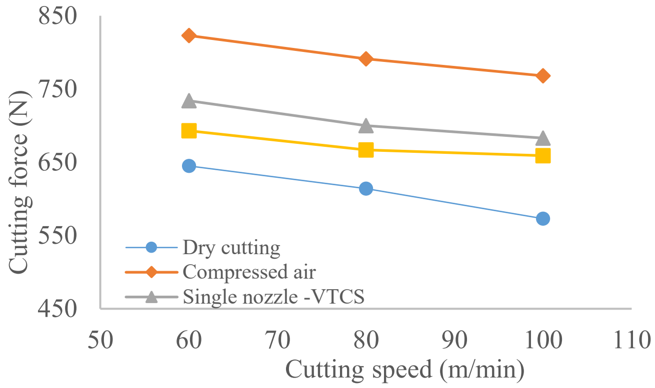


Figure 2. Influence of different cooling environments on *Fz* value

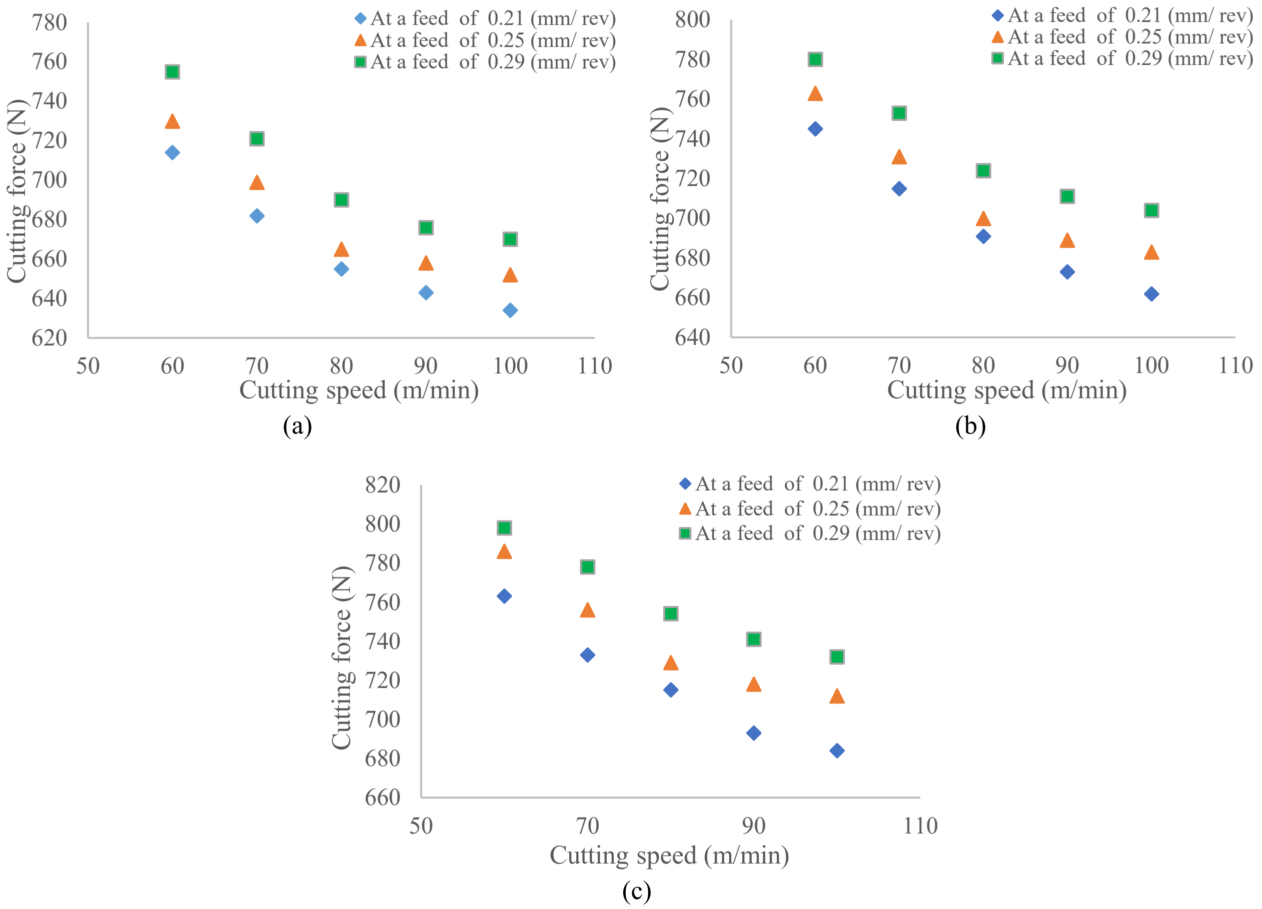


Figure 3. Variation of *Fz* value with *v* and *f* values at *d* value of (a) 0.8 mm (b) 1 mm and (c) 1.2 mm

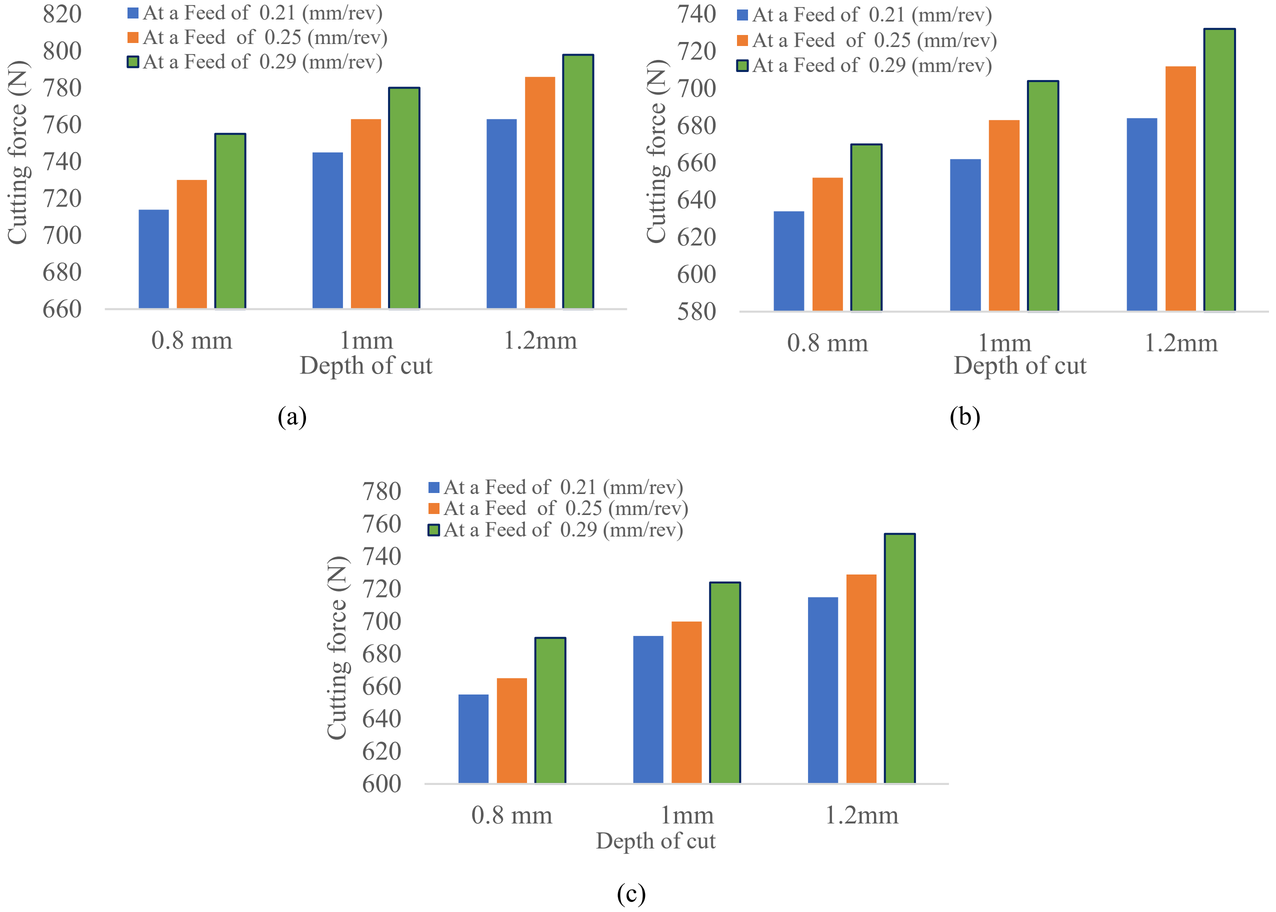


Figure 4. Variation of *Fz* value with *d* and *f* values at *v* value of (a) 60 m/min, (b) 80 m/min and (c) 100 m/min

Cutting Temperature

Cutting temperature is a crucial parameter in machining that directly influences tool wear, surface quality, and friction coefficient at the cutting zone. In the machining of Ti-6Al-4V, higher heat generation, which needs to provide an effective heat removal mechanism to minimize tool failure and ensure better surface finish, creates a necessity to study *Tc* values [19]. The *Tc* value was measured by varying *v* value under different cooling media in VTCS-assisted turning, as presented in Figure 5. The maximum *Tc* value was obtained under a dry environment because the heat energy accumulation in the machining zone was not carried away by any external means that raised temperature due to lack of coolant. Along with this, a higher coefficient of friction between chip tool interfaces due to lack of lubricant in dry cutting increased the *Tc* value. In compressed air cooling, pressurized air as a coolant increases the heat transfer rate. It depends on the heat transfer coefficient, *h,* of the cooling medium and the temperature of the coolant. Supplying compressed air at a higher velocity enhances the *h* value and minimizes the *Tc* value for all values of *v*. In the case of a single nozzle VTCS, cold CO_2 gas is supplied, which means the coolant temperature attains sub-zero value in the machining zone which increases the rate of heat transfer rate. Along with this, the positive Joule-Thomson coefficient of CO_2 gas generates refrigeration effect while expanding to lower pressures and minimizing the heat that leads to lower temperature compared to dry and compressed air cooling. In dual nozzle VTCS, the minimum temperature obtained was slightly lower than *Tc* value obtained in single nozzle VTCS because of the effective penetration of coolant while supplying coolant using two nozzles compared to a single nozzle.

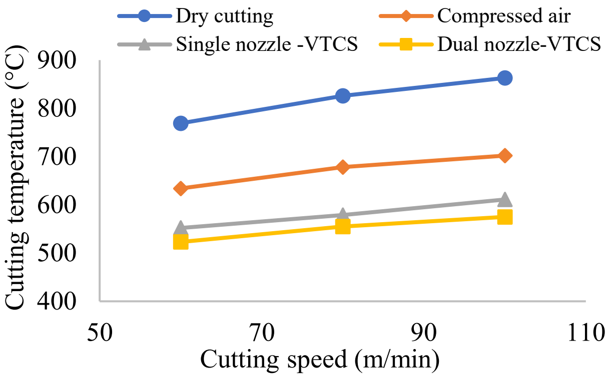


Figure 5. Influence of different cooling environments on *Tc* value

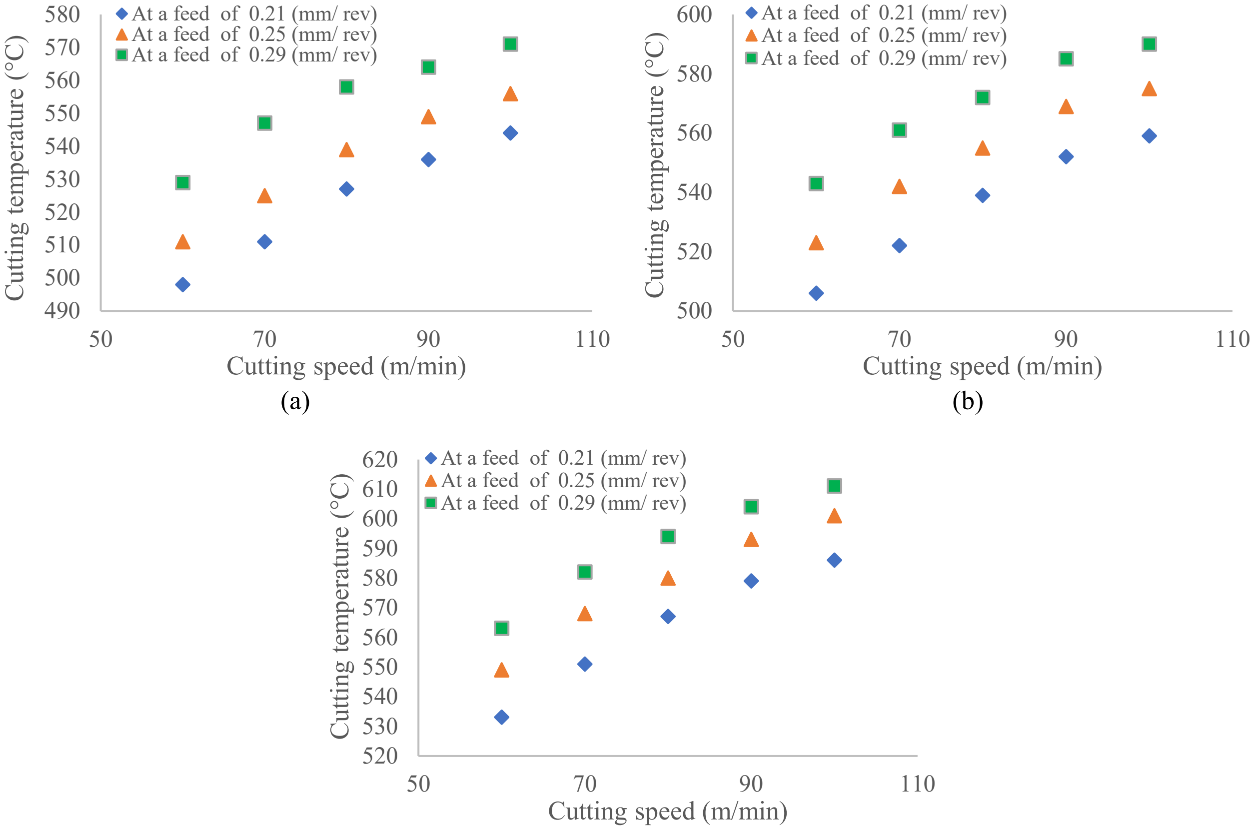
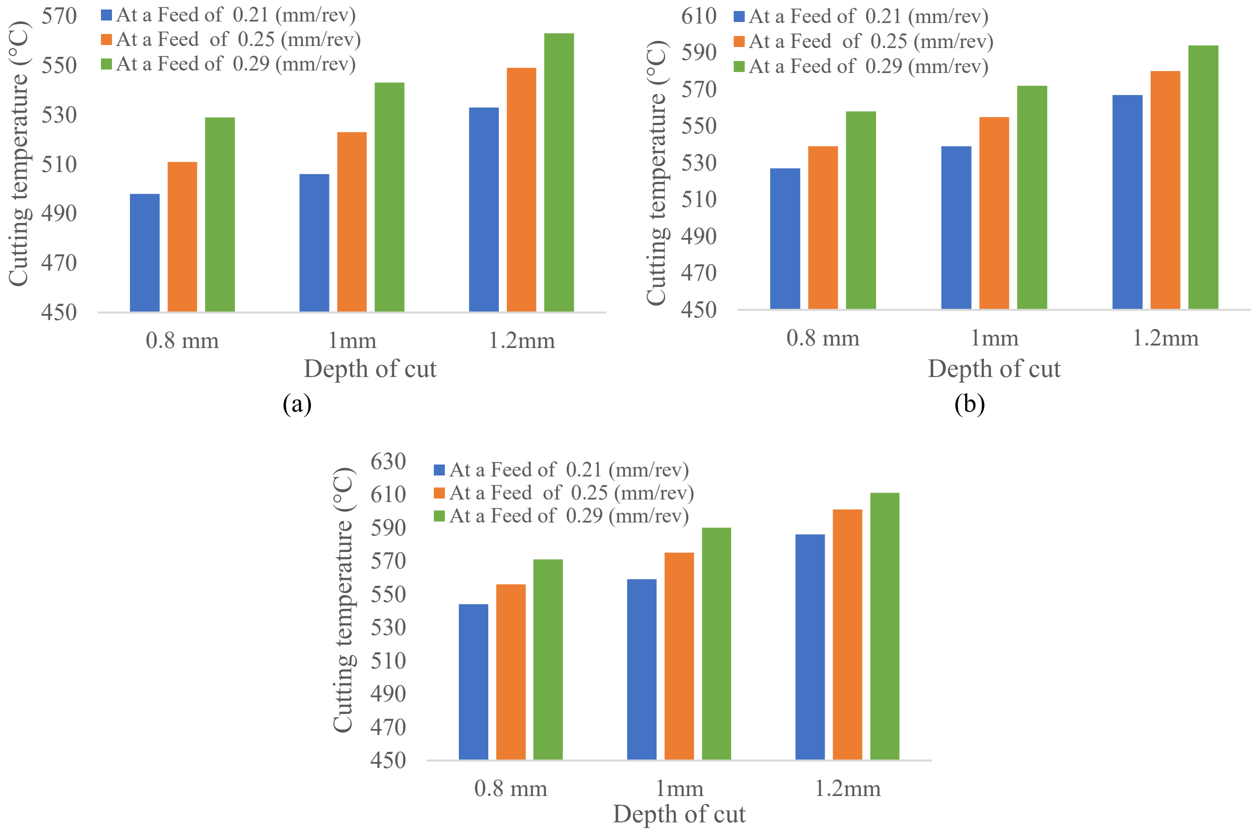


Figure 6. Variation of *Tc* value with *v* and *f* values at *d* value of (a) 0.8 mm, (b) 1 mm and (c) 1.2 mm

Figure 6 shows the influence of *v* value on *Tc* value. From the figure, it was identified that the *Tc* value increased as velocity increased. The *Tc* value increased in the range of 8-10 % based on the *d* value when cutting velocity increased from 60 to 100 m/min. This is because higher speed led to higher MRR and consumed more energy in machining. All consumed energy was converted into heat and increased the *Tc* value. Along with this, the time of exposure of the machining zone to the coolant was lower at higher speeds which caused ineffective heat transfer that resulted in increased cutting temperature.

Figure 7 shows the variation of *Tc* value with *f* and *d* values. The *Fz* value increased in the range of 5-8% based on the cutting velocity when *f* value increased from 0.21 to 0.29 mm/ rev. The *Tc* value increased in the range of 7-8 % based on the cutting velocity when *d* value increased from 0.8 to 1.2 mm. The *Tc* value increased with *f* and *d* values at a particular speed. This was due to an increase in material removal rate at higher *f* and *d* values and higher energy required for the machining. This energy which is converted into heat in the machining zone led to a rise in *Tc* value.



(a) (b)

(c)

Figure 7. Variation of *Tc* value with *d* and *f* values at *v* value of (a) 60 m/min, (b)80 m/min and (c) 100 m/min

Surface Roughness

Surface roughness influences the quality and indirectly influences the fatigue life of the finished component. In this study, average roughness, *Rz* was considered, which is a widely accepted parameter to evaluate surface roughness. *Rz* value was measured by varying *v* value under different cooling media in VTCS-assisted turning and is presented in Figure 8. The maximum *Rz* value was observed under a dry environment because of the lack of coolant or lubricant, which causes larger heat accumulation in the cutting zone and leads to rapid tool wear and deterioration in surface finish. A higher friction coefficient was observed at a higher *Tc* value that further spoiled the finish. In compressed air cooling, the pressurized gas as a coolant removes heat accumulation to some extent. Along with this, high-pressure air can be penetrated into the machining zone and provides a lubricating effect, which minimizes the friction coefficient, and reduce *Rz* value, compared to a dry environment. In the case of a single nozzle VTCS, heat removal is effective, and the friction coefficient is lower at the cutting zone due to CO_2 gas. This improvement in the surface finish is significant compared to compressed air cooling. The penetrating ability of cold CO_2 gas and the effective chip removal of high-pressure coolant further improved the surface finish. Dual nozzle VTCS results in minimum *Rz* value, and it was slightly lower than the *Rz* value obtained in single nozzle VTCS because of the effective penetration of coolant using two nozzles compared to a single nozzle.

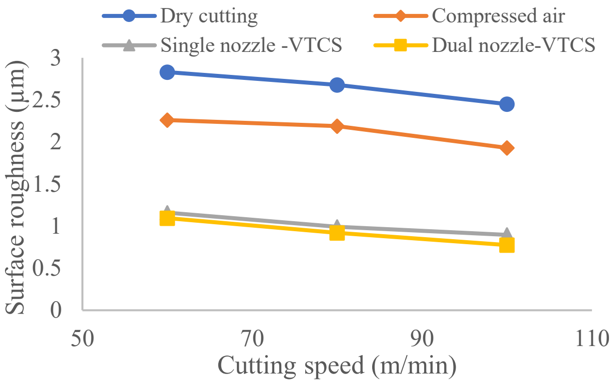
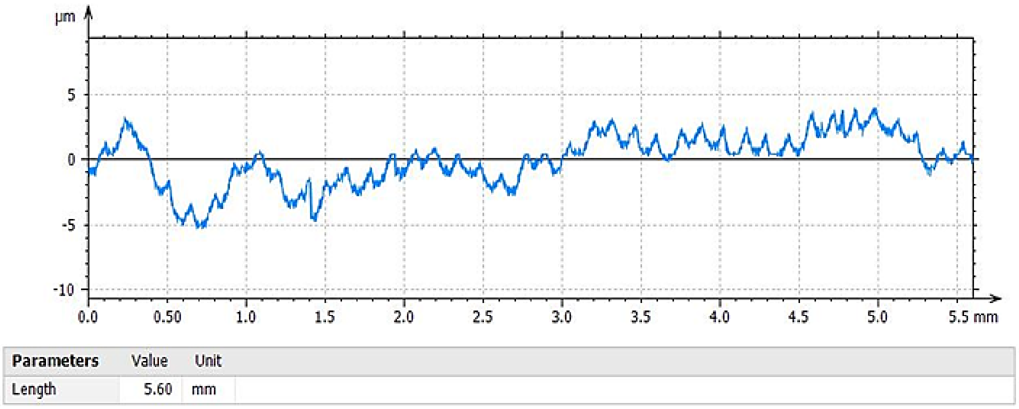


Figure 8. Influence of different cooling environments on 'Rz' values

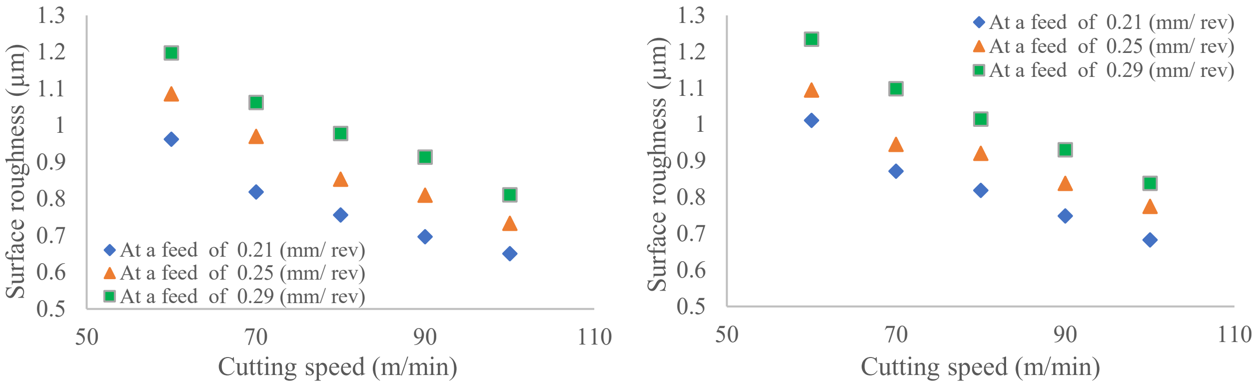
The *Rz* value measured by varying *v* values under different cooling media in VTCS-assisted turning is shown in Figure 8. The maximum *Rz* value was observed under the dry environment due to the lack of coolant or lubricant in dry cutting, causing large heat accumulation in the cutting zone, which initiates rapid tool wear and deteriorated surface finish. A higher friction coefficient at a higher *Tc* value further spoiled the finish. In compressed air cooling, the pressurized gas as a coolant removes heat accumulation to some extent. Along with this, high-pressure air can penetrate the machining zone and provides a lubricating effect that reduces friction coefficient as well as *Rz* value compared to a dry environment. In the case of a single nozzle VTCS, the removal of heat is effective, and the friction coefficient is lower at the cutting zone due to CO_2 gas. This improved the surface finish significantly compared to compressed air cooling. The penetrating ability of cold CO_2 gas and the effective chip removal of high-pressure coolant further improved the surface finish. Dual nozzle VTCS results in a minimum *Rz* value, and it was slightly lower than *Rz* value obtained in a single nozzle VTCS because of the effective penetration of coolant using two nozzles compared to a single nozzle. The surface profile of the workpiece under VTCS at 80 m/min is shown in Figure 9, and the deviation of the surface from the mean position is lower, which indicates a better finish.

Figure 10 represents the influence of cutting velocity on *Rz* value. From the figure, it is evident that the increase in velocity leads to a decrease in the *Rz* value. It decreased in the range of 30-32 % based on the *d* value, where cutting velocity increased from 60 to 100 m/min. At higher values of *v*, the formation of chatter marks on the machined surface was few and the time for built-up edge formation was low, which improved the surface finish [20].

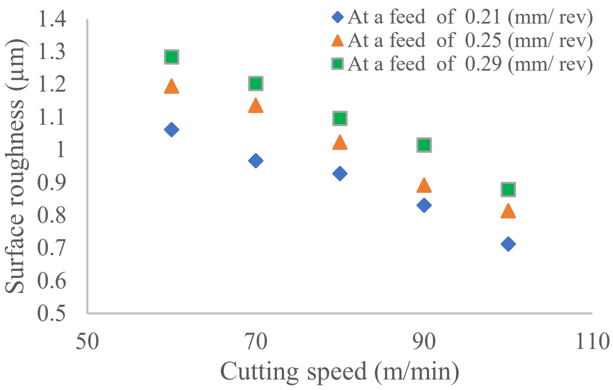


Parameters	Value	Unit
Length	5.60	mm

Figure 9. The surface profile of the Ti-6Al-4Vin VTCS assisted turning at a *v* value of 80 m/min

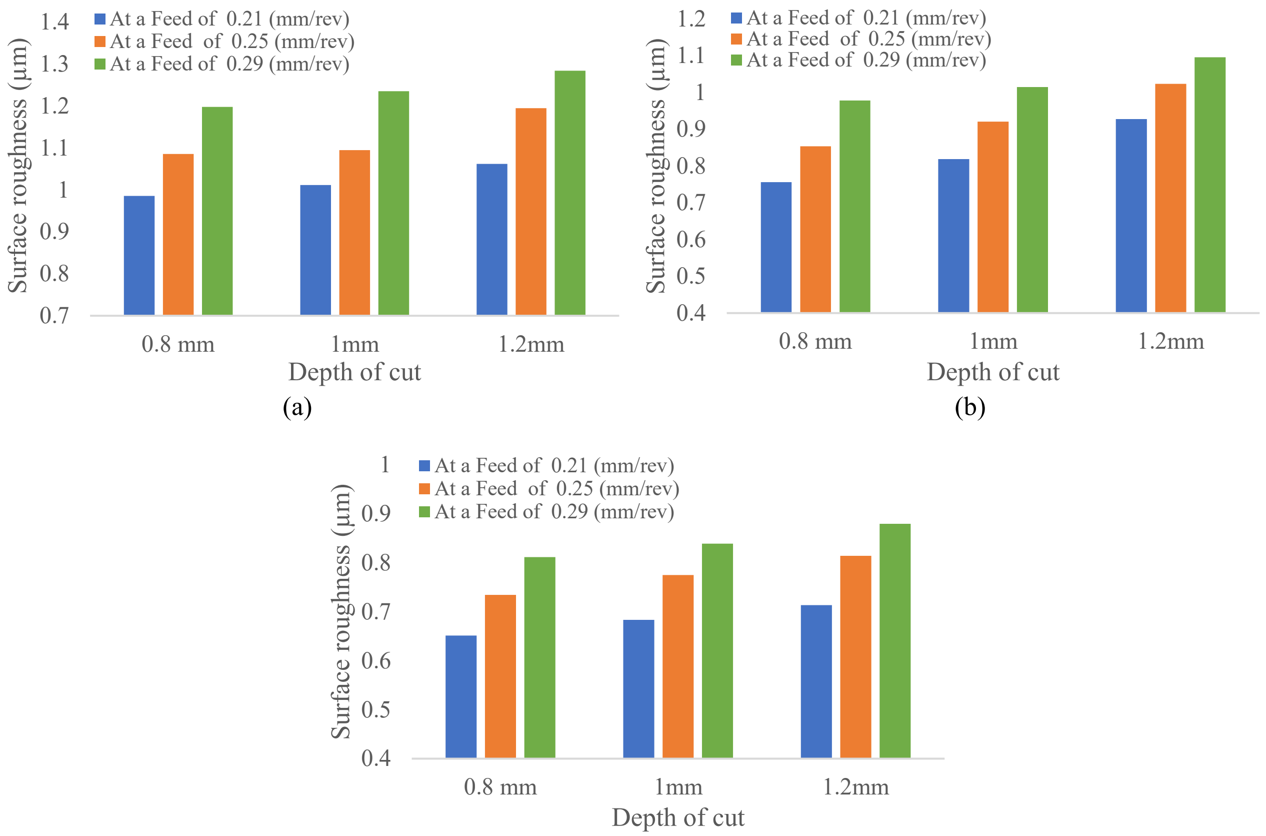


(a) (b)



(c)

Figure 10. Variation of *Rz* value with *v* at *d* value of (a) 0.8 mm, (b) 1 mm and (c) 1.2 mm



(a) (b)

(c)

Figure 11. Variation of *Rz* value with *d* and *f* values at *v* value of (a) 60 m/min, (b) 80 m/min and (c) 100 m/min

Figure 11 indicates the influence of *f* and *d* on *Rz*. It increased in the range of 11 - 24% based on the cutting velocity where *f* value increased from 0.21 to 0.29 mm/rev. This is in line with the theoretical relationship $Ra=f2/8r$ (*f* is feed rate and, *r* is nose radius). The formation of chatter marks was higher at large *f* values and distant feed marks also occurred resulting in a higher *Rz* value [21]. The *Rz* value increased in the range of 10-20 % based on the cutting velocity where *d* value increased from 0.8 to 1.2 mm; this was because of the higher heat-affected zone and a higher shear angle that increased the friction coefficient at the cutting zone and increased surface roughness [21].

CONCLUSIONS

The turning operation was performed on Ti-6Al-4V with a CO_2 gas environment assisted by dual nozzle VTCS. Initially, the responses were compared with dry cutting, compressed gas cooling, and single nozzle VTCS at various cutting speeds to observe the performance of the dual nozzle VTCS. Further, the input parameters were varied at different levels under CO_2 -based dual nozzle VTCS. The results and analyses led to the following conclusions:

i. Lower cutting force was observed during the dry cutting of TI-6AL-4V followed by dual nozzle VTCS, single nozzle VTCS, and compressed air cooling.
ii. The lower cutting temperature and surface roughness were observed in CO_2-based dual nozzle-VTCS followed by single nozzle VTCS, compressed air cooling, and dry environments.

iii. In dual nozzle VTCS assisted turning, cutting force is significantly reduced with an increase in cutting speed. The higher feed and depth of cuts produced more amount of cutting force at a particular cutting speed.
iv. The cutting temperature in dual nozzle VTCS assisted turning increased with a rise in cutting speed. The higher cutting temperature was observed at higher feeds and depth of cuts.
v. In the dual nozzle, VTCS assisted turning, surface roughness significantly reduced with a rise in cutting speed—higher feed and *d* value produced high surface roughness.

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