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Enhancing Cooling Efficiency in Dual Nozzle CO_2-Based Vortex Tube Systems for Machining Titanium Alloys: Implications for Polymer and Composite Processing

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Abstract

In machining of Titanium alloys, the cutting temperature plays a vital role that directly influences the performance and it is required to maintain as low as possible. In this study, a dual nozzle Vortex Tube Cooling System (VTCS) that supplies cool compressed CO_2 gas is developed to reduce the cutting temperature in Ti-6Al-4V machining. The experiments were conducted at constant cutting and flow parameters during turning at different levels of nozzle angle, nozzle position from the cutting edge (tool tip distance) and at particular diameter of the nozzle. From the results, cutting force was found to improve with a greater nozzle angle and decrease with a greater nozzle tip, due to strain hardening effect on the Ti-6Al-4V and the high-pressure CO_2 gas jet on the cutting tool. Cutting temperature reduced at higher nozzle angle, however it is first decreased and then increased with tip nozzle distance because of high heat transfer coefficient of cold compressed CO_2 gas, and more heat removal from the machining zone. Surface roughness increased with the nozzle angle, it is first decreased and then increased with tip nozzle distance due to reduced coefficient of friction that CO2 gas provides at interfaces. The results demonstrate the effectiveness of the dual nozzle VTCS in improving machinability and surface quality for polymer and composite materials through efficient cooling and lubrication.

Keywords: Ti-6Al-4V, Vortex tube, CO_2 gas, Dry machining, Compressed air cooling, Sustainable machining, composite material.

INTRODUCTION

One of the most common titanium alloys is Ti-6Al-4V, which has a great strength-to-weight ratio, improved corrosion resistance, and superior weldability. Its applications mainly include aerospace (Air frame components, rotor hubs for helicopters, compressor blades, jet engine- rings, pressure vessels, rocket engine cases) which require a high strength-to-weight ratio, marine which requires high corrosion resistance and strength and bio-medical fields (1). In machining titanium alloy almost 80% of heat is directed towards the tool because its lower thermal conductivity doesn't allow the heat to pass through it. Due to this, high temperature is concentrated in the machining zone near the tool tip which tends to rapid tool wear. The large chemical affinity of titanium alloy also leads to rapid tool wear during machining with any kind of tool material, especially wear rate is higher at elevated temperatures (2). The heat generated must be minimized for effective machining and the cutting fluids are being used for this purpose for

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decades. But their usage leads to environmental pollution and affects the workers' health (causing skin deceases and breathing problems). This needs an alternative solution to prevent these effects and this can be done by minimizing the usage of cutting fluids or by providing an eco-friendly cooling medium (3). Shane et al. (4) developed a setup with two micro nozzles in which LN_2 was used as a cooling medium during the machining of Ti-6Al-4V. This technique improved the tool life and reduced the cutting temperature compared to emulsion cooling.

Taha et al. (5) studied cutting temperature, surface roughness, and power consumption during machining of mild steel under ambient and vortex tube cooling conditions. The lower cutting temperature was recorded in machining under vortex tube conditions. Munish Kumar Gupta et al. (6) used MQL in turning grade-2 titanium considering cutting forces, tool wear, and surface quality as responses at different levels of inputs. It was observed that lower cutting speeds, lower feed rates, and higher angles of approach give better outcomes. Khirod Kumar et al. (7) performed a turning operation by supplying cold CO_2 gas to the machining zone and the cooling effect was generated by using the Joule Thomson effect. Lower cutting temperature, surface roughness, and tool wear were reported compared to dry machining. Khirod Kumar et al. (6) developed a vortex tube-based cooling system in which CO_2 gas was used as a working fluid. The turning operation was performed by varying flow parameters like cold fraction and pressure at constant cutting conditions. It was found that the cutting temperature was being greatly influenced by coolant pressure. The cutting force is influenced by coolant pressure and cold fraction, whereas, the surface roughness was influenced by all three flow parameters.

Many researchers focused on the application of high pressure coolants and their impact on cutting temperature, surface roughness, and tool wear. Focus on the position and angle of impingement was seldom found while supplying coolant in the high pressure coolant system. Air and LN_2 were used as a working fluid in many works, however, usage of CO_2 gas is limited. The present work focuses on developing VTCS in which CO_2 gas was supplied using two nozzles during the machining of Ti-6Al-4V, and suggesting that this system could be applied to a broader range of materials beyond titanium alloys.

Polymers and composites, are often used in aerospace, automotive, and biomedical applications, benefit from the incorporation of bark fibers to create lightweight materials (9, 10). Leveraging these properties in applications such as paint and powder coatings, cosmetics, food, ceramics, and textiles can lead to advanced composite materials. For example, microcrystalline cellulose (MCC) extracted from citrus peel cellulose can be utilized as a reinforcing filler in polymer composites due to its unique physicochemical properties, biodegradability, and compatibility (11). These natural fibers possess antimicrobial properties, enhancing their suitability for composites and nanofillers, which can significantly impact strength retention and reduce crack initiation around holes in composites during machining (12, 13). Effective cooling during machining can prevent thermal degradation and improve the durability of polymer composites. This is crucial for maintaining the mechanical integrity and long-term performance of composite parts.

This current study focused on developing a dual nozzle VTCS and the effects of nozzle angle and tip nozzle distance, and nozzle diameter on responses by performing the experiments at various input parameter combinations. This research underscores the potential for improved cooling efficiency and eco-friendly machining practices across various industries.

EXPERIMENTATION

In this study, Ti-6Al-4V was used as a workpiece for analysis, and turning operation was performed on the lathe machine by attaching a VTCS set up to find the effect of different parameters such as nozzle angle and nozzle position from the cutting edge on the responses. PCLNR2525M12 was used as the tool holder and CNMG120408 THM was used as the cutting insert which is having a rake angle of $+10^0$, a clearance angle of $5^{0,}$ and a nose radius of 0.8 mm. CO_2 gas was selected as a working fluid due to its stability at atmospheric pressure, positive Joule Thomson coefficient, and less coefficient of friction between the mating surfaces. Along with this, CO_2 can be cooled down to the required temperature in less time compared to LN_2 (8). The effect of flow parameters in VTCS on responses were studied in the previous work (14). The Schematic of the VTCS is shown in Figure 1.

In the VTCS, two nozzles were utilized to introduce cold CO_2 into the cutting zone, maintaining the necessary pressure. The maximum cooling capacity of a vortex tube can provide depends on multiple factors, including the input compressed air pressure and flow rate, the cold fraction setting, and the type of gas used.

The cooling capacity of vortex tube per unit time is given as equation 1. (15)

$$Q_c = \dot{m}_c C_p (T_i - T_c) = \alpha \dot{m}_i C_p (T_i - T_c) \quad (1)$$

where, cold fraction $\alpha = \frac{\dot{m}_c}{\dot{m}_i}$
$\dot{m}_i$ = mass flow rate of the vortex tube inlet [kg s^{-1}]
$\dot{m}_c$ = mass flow rate of cold outlet [kg s^{-1}]
C_p = specific heat at constant pressure [J kg^{-1} °C^{-1}] cold air
T_i = temperature at inlet [°C]
T_c = temperature at cold outlet [°C]

In this study the maximum cooling capacity provided by the vortex tube, based on the parameters chosen, is approximately 1352 watts (1.352 kW).

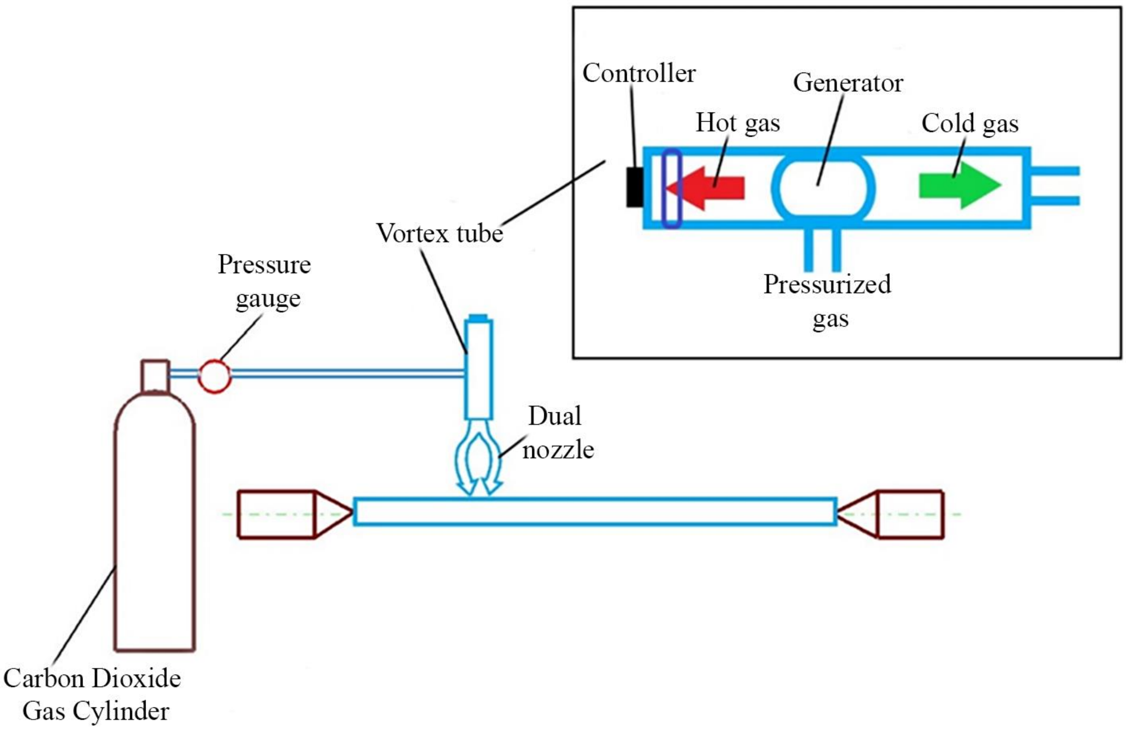

Figure 1. Schematic of CO_2 based VTCS.

This study mainly deals with the nozzle configuration of VTCS which includes the study of the influence of the nozzle angle and tool tip distance on the response parameters. The experiments are performed at different combinations of input variables and the outcomes are measured by respective devices at a constant speed (80 m/min), feed (0.25 mm/rev), depth of cut (1 mm), pressure (7 bar), and cold fraction (20%) as listed in Table 1.

Table 1. Experimental conditions.

Category	Specification
Machine	Precision Lathe (Make: Magnum Tools)
Cutting speed, Feed, Depth of cut	80 m/min, 0.25 mm/rev, 1 mm.
Cooling environment	Dry cutting, Compressed air, Compressed CO_2 gas, Air-VTCS, and CO_2 -VTCS
Pressure	7 bar
Cold fraction	20%
Nozzle angle	30^0,45^0,60^0
Tool tip nozzle distance	2.5 cm, 3.5 cm, 4.5 cm
Nozzle diameter	6 mm

RESULTS AND DISCUSSION

The VTCS assisted turning was performed for Ti-6Al-4V alloy at different nozzle angles, and tip nozzle distance and their effects on responses were discussed in the following sections.

Cutting Force

Minimizing cutting force is crucial as it directly impacts the specific cutting energy and power consumption, making it an important response parameter in the cutting process. Cutting force occurs mainly because of two major sources of which one is due to the resistance offered by deformation of Ti-6Al-4V and the other is due to the force generated by impulse-momentum of high speed stream of gas coming from the nozzle to the machining zone in VTCS assisted turning. The force caused due to impulse-momentum of coolant is given by

$$F = \rho a v^2 \tag{2}$$

Where 'ρ' is the density of the coolant, 'a' is the area of the cross-section of the nozzle outlet and 'v' is the velocity of the coolant. The axis of the nozzle is maintained at an angle of θ to the horizontal plane.

From Figure 2, it can be observed that the cutting force was increased with nozzle angle (θ). The cold compressed gas with high velocity was focused on the cutting tool that creates an impulse force equal to $\rho a v^2$ in the direction of the nozzle axis as shown in Figure 2. The force can be resolved in two components, the vertical component of this force ($2\rho a v^2 \sin\theta$) opposes the tool movement, resulting in an increment in cutting force. The horizontal components of force ($\rho a v^2 \cos\theta$) of the two nozzles doesn't show any significant effect as they act opposite to each other. Consequently, when the nozzle angle is increased, the vertical component of the force also increases, causing a corresponding rise in the cutting force.

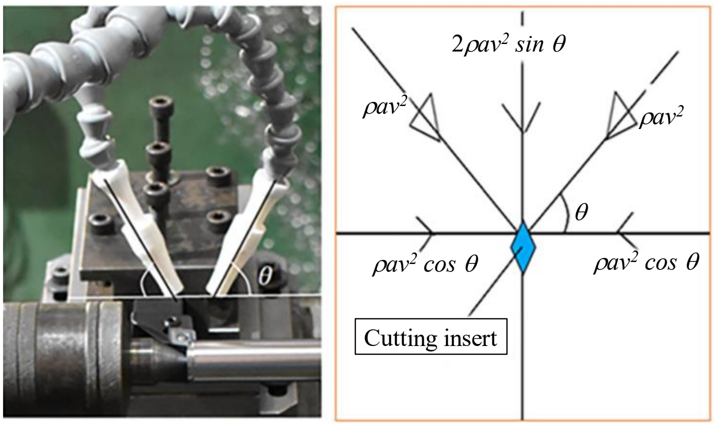

Figure 2. Nozzle setup and external forces on cutting insert.

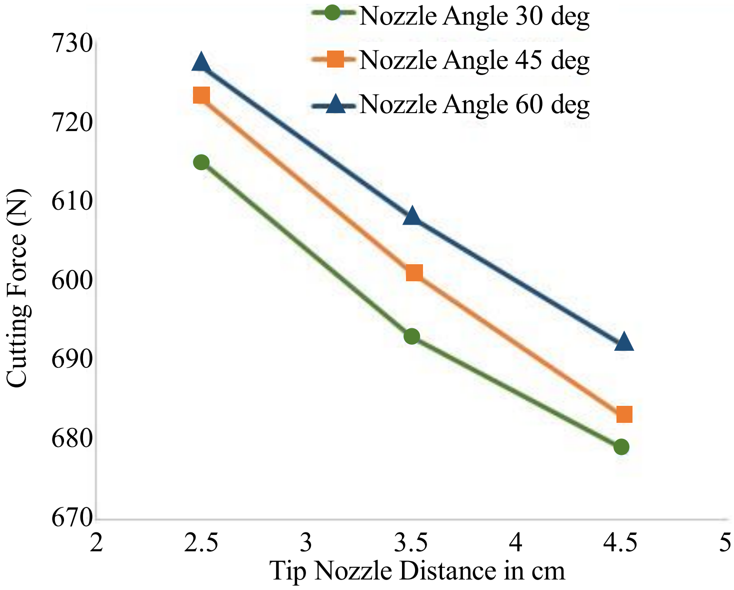

Figure 3. Variation of cutting force with tip nozzle distance at 6 mm of nozzle diameter.

Figure 3 represents that the cutting force is mostly affected by the tip-nozzle distance i.e. increasing the tip-nozzle distance decreased the cutting force. This is because at higher distances the time of travel for the impact is more which reduces the acceleration ($a = \frac{\Delta v}{\Delta t}$) of the coolant and thereby reduces the cutting force exerted on the cutting tool. In Addition to the fluid leaving the nozzle with particular kinetic energy mainly depends on the velocity and the amount of coolant and that is diminished during traveling from the nozzle exit to the machining zone. Hence, the transfer of lower energy to the cutting tool while impact causes lower cutting force at higher tip nozzle distances (16).

Cutting Temperature

The cutting temperature stands out as the most influential parameter while the machining of titanium alloy, impacting both the tool life and the surface finish of the machined component. The generation and transfer of heat in the machining zone mainly influence the cutting temperature. As shown in the Figure 4 that the cutting temperature decreased as the nozzle angle increased. This may be due to the increment in the area focused by the coolant on rake face at higher angles. An increase in the area for the same velocity and same amount of coolant increases the rate of heat transfer from the machining zone which leads to decrease in cutting temperature at higher nozzle angles.

The heat transfer rate from the machining zone is given by the equation

$$Q=hA(T_m-T_g) \qquad (3)$$

Where h is the heat transfer coefficient, A is the surface area of the heat-affected zone, Tm is the generated temperature generated in the machining, and T_g is the temperature of coolant supplied to the machining zone. The heat transfer coefficient is derived from the Nusselt number correlation which is given in the following equation 4.

$$Nu = K\,(Re^a\,Pr^b) \qquad (4)$$

Where Nu= Nusselt number, Re= Reynolds number, Pr= Prandtl number given by

$$Nu = \frac{hL}{k},\ Re = \frac{\rho v L}{\mu},\ Pr = \frac{\mu c_p}{k}$$

K, a, b are the constants depending upon the type of flow and Re and Pr values, ‘k’ is the thermal conductivity of the fluid, ‘L’ is the characteristic length, and ‘μ’ is the dynamic viscosity of the fluid. To minimize the cutting temperature, it is required to transfer more amount of heat and from the equation, it is clear that Q can be increased either by increasing 'h' value or by decreasing 'T_g' value. The value of 'h' depends upon the velocity of the fluid molecular weight and the specific heat of the fluid.

From Figure 4 it can be observed that cutting temperature first decreased then increased with tip nozzle distance. A higher cutting temperature is observed at a lower tip nozzle distance even though there is a higher rate of heat transfer. This may be because of the chips that are adhering to the tool and workpiece in the machining zone which causes heat accumulation. The lower thermal conductivity of the chip material doesn't allow the heat to transfer and leads to a rise in the temperature. At higher tip-nozzle distances, the rate of heat transfer diminishes because the kinetic energy of the coolant is progressively lost over distance, resulting in a reduction in velocity for a given coolant quantity. The velocity is directly interlinked with the heat transfer coefficient and decreases the heat removal from the machining zone. So, there is a compromise between heat accumulation and heat transfer coefficient at lower and higher tip-nozzle distances leading to a minimum cutting temperature at a medium value of tip nozzle distances.

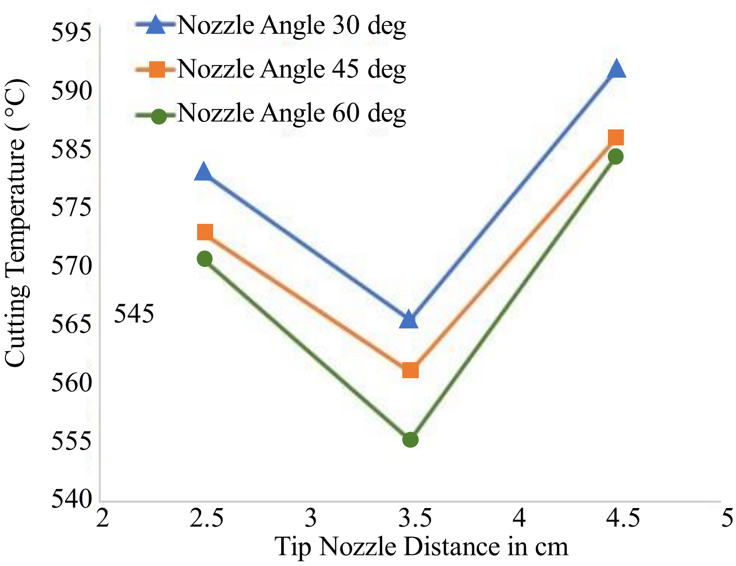

Figure 4. Variation of cutting Temperature with tip nozzle distance at 6 mm diameter.

Surface Roughness

Surface roughness plays a pivotal role in machining since it impacts essential aspects such as fatigue strength, corrosion resistance, service life, and component reliability. A good surface finish improves the performance and durability of the component. Mostly, it relies on the penetrating ability of the coolant, the amount of fluid available, and the coefficient of friction offered by the cutting fluid in between the mating parts. From Figure 5 it is observed that surface finish was not significantly affected by nozzle angle but very minutely decreased with reduced nozzle angle. This was because of the enhanced penetration capacity of cutting fluid at a lower nozzle angle and it leads to reduction in surface roughness.

From Figure 5 it is observed that surface roughness first reduced and then improved with the tip nozzle distance. At a lower distance, the chips adhere to the surface, and evacuation of chips is difficult because there is less space available for chip disposal. Even though there is a higher penetration ability of the coolant at lower tip nozzle distances, the adhesion of chips diminishes the surface finish. Similarly, at higher nozzle distances higher surface roughness is observed due to the lack of penetration of coolant. So, there is a compromise between adhering of chips and penetration ability of coolant and therefore, the better surface finish was observed at medium ranges of tip nozzle distance of around 3.5 cm.

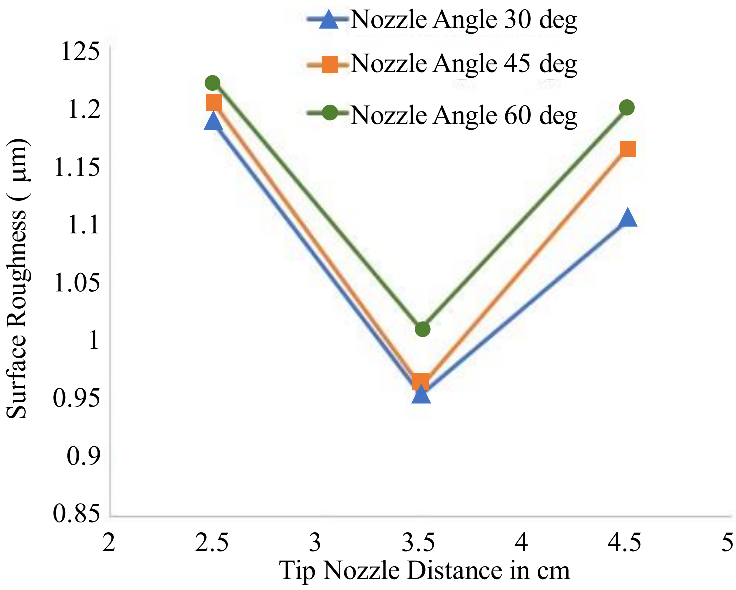

Figure 5. Variation of surface roughness with tip nozzle distance at 6 mm diameter.

CONCLUSION

In this paper, a CO_2-based Vortex Tube Cooling System (VTCS) was utilized to deliver the coolant into the machining zone using two nozzles during the turning of Ti-6Al-4V. The effects of input parameters were discussed, yielding the following conclusions with implications for polymer and composite processing:

- The cutting force rises as the nozzle angle increases but declines with a greater tip-nozzle distance.
- The cutting temperature decreased as the nozzle angle increased and exhibited an initial decrease followed by an increase with changes in the tip-nozzle distance.
- Surface roughness decreases as the nozzle angle decreases, showing an initial decrease and subsequently increasing with variations in the tip-nozzle distance.

These findings suggest that optimizing nozzle angles and distances in CO_2-based VTCS can significantly enhance machining performance, not only for titanium alloys but also for polymers and composites.

- The CO_2-based VTCS can help manage the variable thermal properties of polymer composites by providing precise and localized cooling, ensuring uniform processing and reducing the risk of thermal damage.
- By minimizing the use of traditional cutting fluids and utilizing an eco-friendly cooling medium like CO_2, the VTCS contributes to more sustainable manufacturing practices. This is beneficial for the lifecycle management of polymer composites.

Thus, the dual nozzle VTCS presents a viable eco-friendly alternative for improving cooling efficiency across diverse machining applications.

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