AN ANALYSIS OF CRYOGENIC MACHINING OF TITANIUM ALLOY (TI-6AL-4V): A REVIEW

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Abstract

Titanium alloys have been classified as `difficult-to-machine' materials. These alloys are extensively used in applications where the ratio of strength to weight and resistance to corrosion are of paramount significance. Titanium has mostly been used in the aerospace and automobile industries. An inherent limitation of these alloys is their poor machinability.The titanium alloy Ti-6Al-4V is a challenging material to process due to its limited tool life. In order to address this issue, a method known as cryogenic cooling is used. In cryogenic cooling, nitrogen is the preferred choice for dissipating heat created in the cutting zone during machining. This is due to its cost-effectiveness, safety, non-flammability, and environmental friendliness. Additionally, nitrogen does not contaminate the workpiece and does not need a separate disposal system. This paper conducts a review on the process of machining titanium alloys under cryogenic conditions.After reviewing the research findings; the optimal set of process parameters were selected. The taguchi experimental plan has been designed to conduct turning operations of titanium alloy material using carbide inserts in cryogenic cooling conditions.

Key words: Cryogenic, titanium alloy, Turning, liquid nitrogen coolant

1. Introduction

Titanium alloys have received considerable interest due to their wide range of applications in the aerospace, automotive, chemical, and medical industries. The most common titanium alloy is Ti6Al4V, which accounts for more than 50% of the titanium alloy production [1]. Titanium alloys are categorized as materials that are challenging to process. These alloys are extensively used in applications where the ratio of strength to weight and resistance to corrosion are of paramount significance. The machinability of titanium and its alloys is generally considered to be poor owing to several inherent properties of materials. Titanium and titanium alloys have low thermal conductivity and high chemical reactivity with many cutting tool materials. Its low thermal conductivity increases the temperature at the cutting edge of the tool. Hence, on machining, the cutting tools wear off very rapidly due to high cutting temperature and strong adhesion between tool and workpiece material. Past studies have extensively examined the machinability of titanium alloys. According to their suggestion, the most optimal performance was achieved by using straight tungsten carbides (WC-Co) with a cobalt (Co) concentration of 6 wt. % and a tungsten carbide (WC) grain size ranging between 0.8 and 1.4 µm [2]. Virtually all types of machining operations, such as turning, milling, drilling, reaming, tapping, sawing, and grinding, are employed in producing aerospace components. For the manufacture of gas turbine engines, turning and drilling are the major machining operations, whilst in airframe production; end milling and drilling are amongst the most important machining operations [3]. Progress in cutting tool materials and tool coatings has enhanced the speed at which metal is removed from titanium and its alloys. However, none of these methods are efficient owing to their chemical affinities. The reduced thermal conductivity of the coating inhibits the dissipation of heat under conditions of high stress and high temperatures. The use of cryogenic machining, which reduces cutting temperature and improves chemical stability, is anticipated to promote productivity in the machining of titanium and its alloys [26, 27].Prior research [8-15] on cryogenic machining of titanium and its alloys has consistently shown enhanced machinability when either the work piece is frozen or the tool is cooled using a cryogenic coolant. Cryogenic machining is a process in which the traditional cooling liquid (an emulsion of oil and water) is substituted with a stream of liquid nitrogen.Cryogenic machining enhances tool life in rough machining operations and preserves surface integrity and quality in finish machining operations [12, 14].Researchers have conducted cryogenic machining tests for several decades, but commercial applications are limited to few companies. Machinability studies on Titanium alloy (Ti-6Al-4V) under cryogenic and water-based coolants were conducted, revealing superior results for cryogenic coolant compared to water-based coolant, affecting MRR, cutting forces, and surface roughness values [4].

1.1 Literature Review

Many experiments have been conducted to investigate the machining characteristics of different materials under Cryogenic condition in various machining operations, such as turning, milling, drilling, and grinding, are employed in producing aerospace components.Benfredj N. et al. [22] examined the process of grinding AISI 304 stainless steel utilizing cryogenic cooling. They discovered that injecting liquid nitrogen (LN2) into the interface between the grinding wheel and workpiece resulted in a significant decrease in the temperature of the grinding zone.Govindaraju N. et al. [23] performed drilling tests with cryogenic LN2 cooling, resulting in a notable decrease in cutting temperature for AISI 1045 steel material. Ravi S. et al. [24] conducted a study on cryogenic cooling during end milling operations. They observed a drop in cutting zone temperature of 43-48% and 26-35% for the hardened AISI D3 tool steel material when compared to dry and wet machining, respectively. Dhananchezian M et al. [25] investigated the effect of using a modified cutting tool insert on the turning process of AISI 304 stainless steel. The results showed that using LN2 as a coolant led to a significant decrease of 44-51% in cutting temperature compared to traditional coolant. Ke Y. (28) examined the use of Cryogenic cooling in high speed milling of Ti–6Al–4V material. They used a TiAlN coated carbide tool and achieved a significant 32.7% decrease in cutting force. Dhananchezian M. et at. [29] conducted turning experiment on Ti–6Al–4V workpiece material with a modified carbide tool insert; examined the use of cryogenic and wet coolant. A decrease of 38% in cutting force was seen while using cryogenic machining compared to wet machining. In a study conducted by Hong S Y. [30], it was shown that regardless of the cooling method used, both the thrust and primary cutting forces increase during cryogenic machining of Ti-6Al-4V. Furthermore, it was seen that further cooling of the workpiece led to an increase in the cutting forces. Antonio Festas et at. [16] Found that the use of Minimum Quantity Lubrication to address machining issues in titanium alloys used in medical devices manufacturing. The main challenge is extracting or dissipating high heat during machining. To improve machining performance of titanium alloys, use appropriate cutting tools, choose appropriate cutting parameters, use cutting fluids, and use proper cooling methods.Mehdi Hourmand et at. [17] Found that during machining of Ti-alloy high cutting temperatures, dynamic loads, and mechanical pressures in Ti alloy cutting cause rapid plastic deformation and tool wear. Traditional cooling methods improve tool life and reduce machining force, but high heat transfer results in chipping and thermal cracks. Modern cooling methods like HPWJA, ACF spray system, cryogenic method, MQL, and MQLN improve titanium alloys' machinability compared to traditional methods.Burri Srinivasa Reddy et al. [18] investigated the machining of commercially pure titanium under cryogenic conditions at high speeds, using a Taguchi orthogonal array to determine cutting parameters. Results show that cryogenic liquid significantly lowers cutting temperatures, producing chips with favorable serrations.Bejjani R. et at. [19] Investigated the combination of cryogenic and ultrasonic-assisted machining for machining difficult-to-machine materials like titanium alloy Ti-6Al-4V. Using FEM and CFD models, the study found a 22% reduction in cutting forces and decreased tool wear compared to conventional turning.

The objective of this study was to examine the process of machining titanium alloys under cryogenic conditions. After reviewing the research findings, we have chosen the optimal set of process parameters. Subsequently, a Taguchi experimental plan has been designed to carry out turning operations on titanium alloy Ti-6Al-4V (Grade5) material. This will be done utilizing carbide inserts under cryogenic chilling circumstances.

2. Materials Properties

2. 2.1 Titanium Alloy

The specific material considered in this work is Titanium alloy, Ti-6Al-4V (Grade5) bar with an initial diameter of 30mm. Ti-6Al-4V has following nominal composition (in wt %); Al:6.0; V: 4.0; Fe(max):0.3; Si(max): 0.15; C(max): 0.1; N(max): 0.05; H(max): 0.015; O(max): 0.15 Ti: remainder

2.2 Tool Material

Tungsten carbide (WC-Co) inserts are used for machining experiments. The inserts were composed of 94 weight percent tungsten carbide with 6 weight percent cobalt serving as the binder. The tool used for carrying out the tests.

2.3 Properties of Titanium Alloy

The key properties of titanium Alloy (Ti-6Al-4V) are:

Table 1. Properties of Titanium alloy (Ti6al4v) [3]

Properties	Unit	Typical values
Density	g/cm^3	4.42
Melting point	°C	1649 ±15
YS	MPa	900
UTS	MPa	1000
Elongation	%	18
Hardness	HB±5	241

3. Development of Cryogenic Machining

The development of low-temperature method has been ongoing since the mid-19th century. Between 1850 and 1900, significant advancements were made in the field of thermodynamics, which laid the foundation for cryogenic science. During this period, the first pioneers in cryogenic science conducted their research. The first obstacles was identifying methods to achieve sufficiently low temperatures for the liquefaction of gases such as oxygen, nitrogen, hydrogen, and helium. The transmission of the liquefaction technique occurred throughout the early decades of the 20th century. In 1961, W.S. Hollis claimed that the lifespan of carbide tools might be extended by using CO2 as a coolant during the process of machining titanium alloys [5]. In the 1960s, researchers at Grumman Aircraft Manufacturing documented a rise in material removal rates while machining titanium using liquid nitrogen (LN2) and carbon dioxide (CO2) [9]. In 1970, Uehara and Kumagai conducted an experiment on the machining of a titanium alloy and stainless steels. It has been shown that the behavior of different metals has varying impacts on tool life, surface roughness, and flank wear [26]. CO2 and LN2 are the primary cryogenic liquids utilized for machining

4. Cryogenic Cooling Liquid for Machine Tools

Friction while cutting causes the generation of heat between the cutting tool and work-piece. The heat created will be conducted via chips, while the remaining heat will be dispersed into the workpiece and cutting tool.

The heat absorbed will cause the cutting tool to become less effective, leading to either deformation, the production of a built-up edge, or the failure of the cutting tool. These issues result in surface imperfections on the machined surface [8]. In order to address this issue, cryogenic liquid is delivered to the cutting area using several methods and equipment. The liquid is contained in tanks that have either a cylindrical or spherical form, and these tanks are equipped with pressure control and vaporizer systems. During the cryogenic liquid spraying procedure for cooling, the pressure inside the tank propels the coolant towards the cutting zone, eliminating the need for any further energy for the application as shown in figure 1.

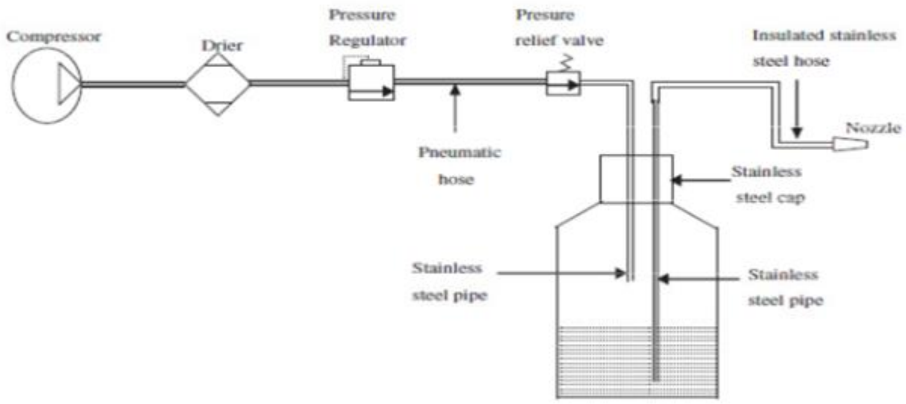

Figure1. Cryogenic cooling setup

Figure 2. Cryogenic Machining Setup [20]

4.1. Discharge Process of Liquid Nitrogen (LN2)

The objective is to provide liquid nitrogen to the cutting zone while preventing evaporation. ICEFLY Cryogenic Machining Technology, as a licensee of Air Products' liquid nitrogen technology, collaborates with Advanced Research Systems to enhance tool longevity and accelerate cutting speeds in machining processes.

The method utilizes a coaxial tube-in-tube arrangement, in which high-pressure LN2 is circulated through the inner tube, while the outer jacket tube carries low-pressure LN2, resulting in less heat dissipation inside the inner tube. This ensures that the liquid reaches the farthest end of the tube, where it may be forcibly expelled onto the cutter.

The ICEFLY system offers a range of rigs for delivering LN2. One example of a programmable coolant nozzle system available for mills is the Cryo-SpiderCool system [9]. As shown in Figure 2 and 3.

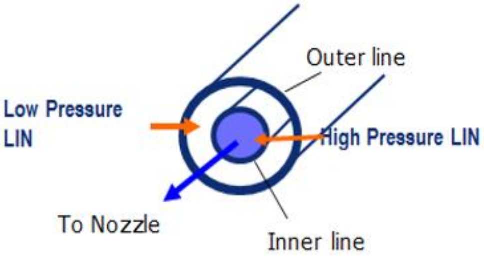

Figure 3. Discharge Process of Liquid Nitrogen (LN_2) [20]

*LN2 indicates Liquid Nitrogen

5. Advantages of Cryogenic Machining

Table 2 demonstrates that machining Titanium alloy under cryogenic temperatures is superior than cutting with aqueous coolants. The scientists have found some advantages [20, 29]:
(i) The use of cleaner, safer, and environmentally friendly alternatives may help remove the various expenses related to traditional cutting fluids and clean-up procedures. (ii) Enhancing the rate at which material is removed without incurring additional expenses for worn-out tools and tool replacement. (iii) augmentation of production rate (iv) enhancement of cutting speeds and prolongation of cutting tool lifespan (v) It reduces the friction and corrosion caused by abrasion and chemicals. (vi) The hard alloy components are now easily machinable, but in the past, it was challenging to manufacture such alloys. (vii) Enhancements in the smoothness and precision of machined surfaces (ix) Potential cost savings in investment owing to a decrease in the number of required machine tools. (x) Enhanced manufacturing flexibility resulting from decreased production times and increased production rates.

Table 2. Comparison with other coolants [29]

Category	Mineral oil	Anionic Surfactant	Nonionic surfactant	Liquid nitrogen
Energy use (Mega-jule)	5.94	60.20	51.50	1.80
Global warming potential (GWP) (Kg Co2-Eq)	3.56	3.00	5.60	0.00
Water use (Kg)	0.00	6.00	0.00	*50.00
Acidification (g SO2-eq)	3.83	25.00	15.80	0.00
Solid waste (g)	5.19	64.20	27.10	0.00

6. Process Parameters of Machining

Proper selections of Process parameters during machining are very important to improve machining performance. In order to improve machining performance, the process parameters must be optimized.

6.1 Flow Rate and Pressure of Cryogenic Supply

Proper selection of Flow Rate and Pressure of Cryogenic liquid supply can improve the machining performance. The flow rate of externally supplied LN2 in turning operations has been documented in various combinations, ranging from 0.5 kg/min to 3.36 kg/min, at pressures of 1.4 - 24 bars. The most typical combination involves a flow rate of less than 1 kg/min and a pressure of 7.5 - 15 bars [11, 12, 13].

6.2 Process Parameters of Lathe Machine Tool

Selection of the process parameters (speed, feed and depth of cut) and the levels for each condition is important to understand the significance of each parameter and its impact on the machining performance. The cutting speed was typically evaluated within the range of 70 to 150 m/min, with a feed rate of 0.10 to 0.25 mm/rev [1,16]. The depth of cut varied between 0.30 and 2.00 mm [17].

7. Taguchi Experimental design in turning of titanium alloy (Ti-6Al-4V)

The turning experiments have been carried out on a CNC Lathe machine tool using tungsten carbide cutting tools for the machining of titanium alloy (Ti-6Al-4V) bar with a diameter of 30 mm in cryogenic cooling condition using LN2. The tool material used in the experimental work is carbide in the form of rhombohedral insert. A Kistler dynamometer has been suggested for installation on the table, with the workpiece securely fastened above it, in order to accurately measure the cutting forces. The experimental setup used in this study is shown in Table 3 and Table 4, displaying the specific cutting conditions employed.Figure 2 displays a CNC machine accompanied by a cryogenic setup.Selection of the parameters and the levels for each condition is important to understand the significance of each parameter and its impact on the machining performance. A list of the selected process parameters and their lives for this experiment is shown in Table 1.

Table 3. Process parameters for turing at three level

Symbol	Process / Cutting parameters	Unit	Level 1	Level 2	Level 3
A	Cutting speed	m/min	70	85	100
B	feed rate	mm/rev	0.1	0.2	0.25
C	depth of cut	mm	0.5	1.0	1.5
D	Flow Rate of LN2	kg/min	0.5	1.0	1.5

Table 4. Taguchi L9 Orthogonal array of experimental Plan

Experiments no.	A	B	C	D
1	70	0.1	0.5	0.5
2	70	0.2	1.0	1.0
3	70	0.25	1.5	1.5
4	85	0.1	1.0	1.5
5	85	0.2	1.5	0.5
6	85	0.25	0.5	1.0
7	90	0.1	1.5	1.0
8	90	0.2	0.5	1.5
9	90	0.25	1.0	0.5

Conventional experimental design approaches are very intricate and not user-friendly. When the number of process parameters rises, a substantial amount of experimental effort must be conducted. Taguchi employs a unique configuration of orthogonal arrays to investigate the whole parameter space with a limited number of tests [31].The Taguchi technique is a methodical approach that applies experimental design and analysis to enhance the quality of a product. In order to choose suitable orthogonal arrays, the degrees of freedom of the orthogonal array are computed. The degrees of freedom represent the number of independent comparisons required for optimizing process parameters, and it is one fewer than the number of levels of the parameters. Due to the presence of four machining input parameters, there are a total of eight degrees of freedom. Consequently, a Taguchi L9 orthogonal array, which comprises nine sets of data, was chosen [32].

8. Conclusions

Liquid nitrogen has been crucial in achieving efficient and effective cooling during machining by safeguarding the cutting tool from deformation and the production of built-up edges. Various experts have done trials that demonstrate the numerous benefits of using liquid nitrogen as a coolant for machining tough materials.These advantages include an excellent surface polish, reduced cutting forces, and higher material removal rate (MRR) compared to water-based coolant.

The use of liquid nitrogen mitigates the environmental damage caused by traditional coolant and decreases the expenses associated with coolant disposal.After reviewing the research findings, we have chosen the optimal set of cutting parameters and taguchi design ofexperiment has been proposed to conduct turning experiments on a CNC Lathe machine tool using tungsten carbide cutting tools for the machining of titanium alloy (Ti-6Al-4V) bar with a diameter of 30 mm in cryogenic cooling condition using LN2.In order to investigate the machining characteristics of turning Ti-6Al-4V, three levels of cutting parameters were examined. These parameters include speed (70, 85, 100 m/min), feed (0.1, 0.2, 0.25 mm/rev), depth of cut (0.5, 1.0, 1.5 mm), and flow rate of LN2 (5.5, 1.0, 1.5 kg/min). The study focused on analyzing cutting forces, surface roughness, and tool life.The Taguchi analysis has been employed to optimize the process parameters in turning of Titanium alloy materials for achieving higher machining performance.The current study may be expanded to conduct nine sets of experiments as per taguchi design and analyze the experimental results by S/N ratio and ANOVA to find the optimum set of cutting parameters for the cryogenic machining of Ti-alloy (Ti-6Al-4V) on a lathe machine tool.

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