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The effect of cryogenic assistance on the machinability of Ti54M and energetic approach

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Abstract. Titanium alloys are increasingly being used in various applications due to their excellent mechanical properties and corrosion resistance. However, their machinability can be challenging due to their high strength and low thermal conductivity. Cryogenic assistance is a promising technique that can be used to improve the machinability of titanium alloys by reducing the cutting forces and improving the tool life. This study investigates the effect of cryogenic assistance on the machining of Ti54M, a high-strength titanium alloy. The results show that cryogenic assistance can significantly reduce the cutting forces and improve the tool life. However, the benefits of cryogenic assistance are limited at high cutting speeds. The study also provides insights into the mechanisms by which cryogenic assistance improves machinability.

Introduction

In the realm of advanced manufacturing and precision engineering, titanium alloys have firmly established themselves as indispensable materials. Over time, a multitude of alloys have been developed, each displaying varying degrees of machinability. Renowned for their exceptional traits of lightweightness, corrosion resistance, and mechanical robustness, these alloys have emerged as the preferred materials across a spectrum of industries, including aerospace, medical, automotive, and beyond. However, they are not without their challenges, particularly when it comes to machining them into intricate components and high-precision parts. This is where cryogenic assistance comes into play, acting as a bridge between the capabilities of titanium alloys and the mastery of their machinability.

Machinability, which encompasses the ability to effectively shape a material while maintaining high quality, is a central concern for engineers and manufacturers. Titanium alloys, renowned for their lightweight properties and high-temperature stability [1], such as Ti54M, distinguished by its composition and mechanical properties [2], have long been cherished for their exceptional characteristics. However, their machinability can pose challenges due to their dense and resilient metallic nature. This is where cryogenic assistance, a technology based on the use of extremely low temperatures, comes into play to push the boundaries of titanium alloy machinability.

In this research article, we delve into the intersection of cryogenic assistance and the machinability of titanium alloys. We will explore in detail how the application of cryogenic temperatures can influence the properties of titanium alloys. We will demonstrate how cryogenic assistance can address some of the most complex issues related to machinability, including managing heat generated during machining, extending tool life, and enhancing the quality of machined parts.

Cryogenic assistance

Cryogenic assistance involves utilizing extremely low temperatures, typically below -150°C (-238°F), across various fields to achieve specific objectives. This technology is rooted in the

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principles of cryogenics, which entail the study and manipulation of gases and liquids at these exceedingly low temperatures [3].

Cryogenic assistance relies on cooling substances to extremely low temperatures. At such frigid levels, many materials exhibit distinct behaviors and unique properties that can be harnessed for specific purposes. It finds applications in diverse fields, including scientific research, industry, medicine, aerospace, and energy, facilitating activities such as biological sample preservation, particle physics research, electronic component manufacturing, and energy production.

In addition to significantly enhancing machining efficiency and quality, cryogenic assistance also offers notable energy advantages. Employing cryogenic temperatures in machining processes reduces thermal stress on both the material and the cutting tools, resulting in decreased energy consumption compared to conventional machining methods. This energy-efficient approach aligns with global sustainability efforts and resource conservation, making it an attractive option for industries seeking eco-friendly manufacturing solutions. This article will not only explore technological advancements in titanium alloy machining but also underscore the critical role cryogenic assistance plays in achieving these advancements, with a focus on sustainability and energy efficiency.

While the benefits of cryogenic assistance on titanium alloys are well established, its impact on the cutting process remains challenging to study in detail. While such assistance may positively influence wear, it can also pose challenges in chip formation. As elucidated in Komanduri's work, based on Recht's findings, the cutting process and the creation of shear bands result from the competition between material work-hardening due to high deformation and a sharp increase in temperature leading to significant thermal softening.

The underlying question pertains to the adverse effects of cryogenic assistance in reducing thermal impact, a phenomenon that is not straightforward to characterize.

In summary, cryogenic assistance stands as a powerful technology that has revolutionized various areas of science and industry by enabling the use of extremely low temperatures for a multitude of applications. It opens doors to innovative possibilities and continues to inspire research and technological advancements. Although the behavior of materials under study may vary significantly, the objective of this article is to examine how cryogenic assistance can impact the cutting process and provide potential solutions through a comprehensive analysis.

Experimental set-up

Presentation of titanium alloys.

In this scientific work, the testes were made on Ti54M because of its good machinability. Table 1 and Table 2 exposes the chemical composition and a comprehensive overview of the mechanical and thermal properties of this alloy.

Table 1: chemical composition and Ti54M [1].

	Al	**Mo**	**V**	**Fe**	**O**
Ti54M	5	0.8	4	0.5	0.16

Table 2 mechanical properties of Ti54M [1].

Proprieties	Ti54M
Modulus of elasticity E (GPa)	115
Tensile strength Re (MPa)	920
Yield strength Rp (MPa)	839
Thermal conductivity λ (W/m.K)	6 - 7
Specific heat capacity Cp (J/kg.K)	532
Temperature transus Tβ (°C)	965

Based on the experimental setup depicted in Fig. 1, a three-axis lathe, CNC SOMAB, was utilized, and a coated carbide tool CCMX 12 04 08 was selected, resulting in a rake angle of α = 15°.

Orthogonal cutting tests were conducted, during which the cutting force Fc and the feed force Ft were measured using a three-component piezoelectric dynamometer.

To achieve an orthogonal configuration, a groove was machined so that the nose radius does not cut. The edge inclination angle is set to 90°.

Experiments were carried out at various cutting speeds VC and feed rates f. The mean values of the machining forces, representing the average behavior of the respective force components in the steady state, were extracted. All cutting conditions were repeated three times, and the values presented in this article are the means of these three tests.

Regarding cryogenic assistance, Ln2 was consistently applied at the tool chip interface at the same flood rate.

Metallographic analysis was performed to comprehend the phenomena. This analysis allows for the examination of the distribution and configuration of phases, grains, and other microstructural features present in the alloy. The analysis consists of several steps: First, the chips are embedded with a thermosetting resin or polymer at elevated temperatures, then polished using SiC and CHem papers to achieve a perfectly flat, scratch-free surface, and finally etched in hydrofluoric acid to reveal the microstructure.

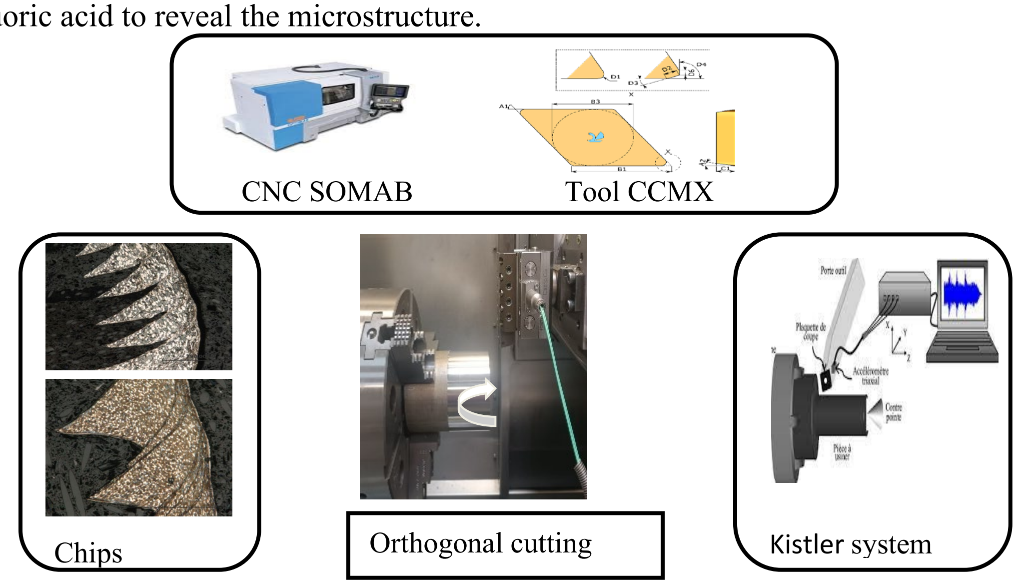

Figure 1: the experimental set up during the orthogonal cutting.

Table 3: conditions of orthogonal cutting tests performed for Ti54M.

Test	V_c (m/min)	f (mm)	A_p (mm)	α (°)
1	30	0.15	2	15
2	40	0.1	2	15
3	40	0.15	2	15
4	40	0.2	2	15
5	40	0.25	2	15
6	40	0.3	2	15
7	60	0.15	2	15
8	80	0.15	2	15
9	100	0.15	2	15

Experimental results

As shown in Figure 2, cutting forces with cryogenic assistance are lower than with dry machining, since cryogenic assistance involves the use of cryogenic liquids to actively cool the cutting zone. Concerning the dry cutting tests, cryogenic assistance seems ta have a greater impact on cutting forces at lower cutting speeds. This effect is higher for the Fc cutting force component. This can be explained by the highest temperatures got when the cutting speed increase.

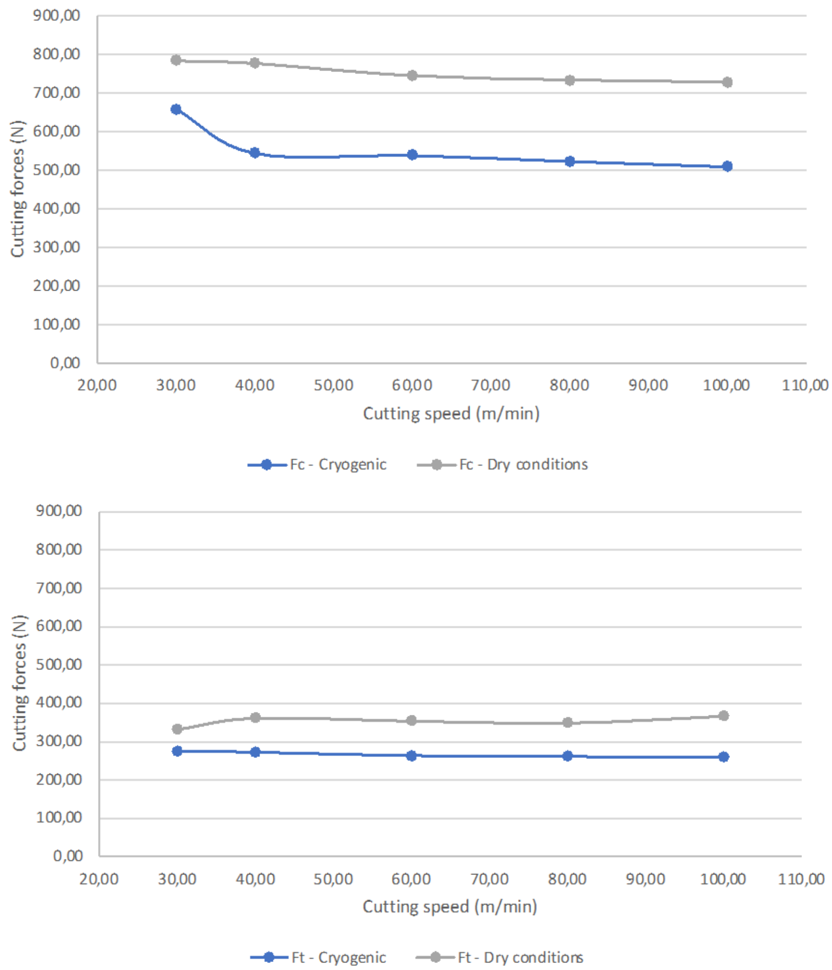

Figure 2: Effect of cryogenic assist on cutting forces

These results may not suffice to fully define the effect of cryogenic assistance on these titanium alloys, prompting a deeper exploration of other parameters. These parameters not only investigate the influence of cryogenic assistance but also aid in analyzing the cutting process. Parameters such as friction coefficient, shear plane stress, and shear angles warrant consideration.

The cutting process yields shear zones, which are categorized into three zones: the primary ZCP zone (plasticity), the secondary ZCS zone (friction), and the tertiary zone (elastic return) [4], as illustrated in Figure 3.

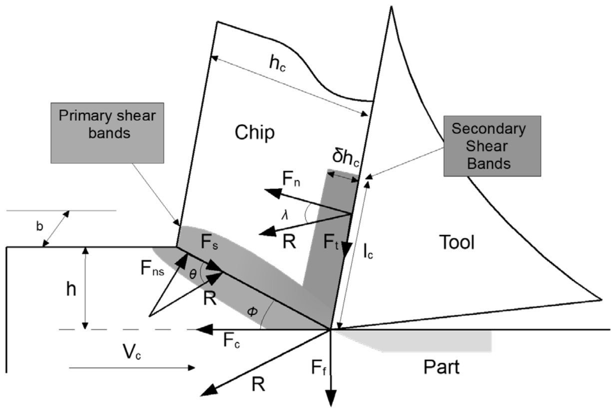

Figure 3: Deformation zones in orthogonal cutting

The coefficient of friction in machining is a parameter that measures the resistance to sliding between two surfaces in contact during the machining process. It represents the force of friction between the cutting tool and the workpiece being machined, and can have a significant impact on machining performance, finished part quality and tool life.

$$\mu = {F_f}/{F_t} \quad (1)$$

F_N and F_f are the normal and friction forces in the measurement frame [5]:

$$F_f = F_C sin\alpha + F_T \cos\alpha \quad (2)$$

$$F_N = F_C cos\alpha - F_T \sin\alpha \quad (3)$$

Shear angles, also known as plastic deformation angle, is a parameter used to describe the deformation of a material when subjected to shear stress. It measures the angle between the direction of the applied shear stress and the direction of the resulting deformation in the material. It is given by [5]:

$$\phi = tan^{-1}\left(\frac{\frac{tu}{tc}\cos(\alpha)}{1-\frac{tu}{tc}\sin(\alpha)}\right) \quad (4)$$

The shear band stress is the resultant stress generated in the zone AB, shown in Figure 3, of plastic deformation and is given by equation [5]:

$$\bar{\sigma}_{AB} = \sqrt{3}k_{AB} \ \ where \qquad k_{AB} = \frac{F_S sin\phi}{t_u w} \quad (5)$$

With the aid of these equations and the cutting forces measured by Kistler, the calculations of these parameters can be carried out as depicted in Figure 4. This progression is notably intriguing. Despite the evolving nature of the cutting forces, there exists a distinct contrast in the coefficients of friction, with cryogenic assistance markedly reducing this coefficient. This disparity can be elucidated by the contact phenomena at the tool-chip interface. With cryogenic assistance, it appears that the contacts are no longer adhesive.

Regarding stress, the trends exhibit variation. Below 60 m/min, the stress in the primary shear plane is lowest in the dry condition. However, this trend reverses above 60 m/min. This inflection point may be attributed to the heightened temperature in the shear plane due to the increased cutting speed and the limited effect of cryogenic assistance.

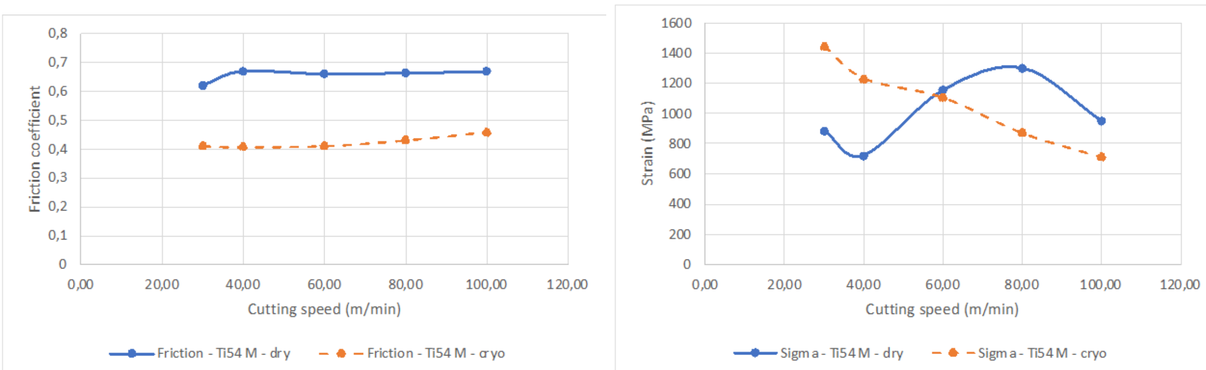

Figure 4 : Evolution of strain in primary shear bands and friction coefficient according to cutting conditions for Ti54M

The fundamental question revolves around how cryogenic assistance can affect the cutting process to varying degrees. As illustrated in Figure 4, it appears that the assistance can impact both the secondary and primary zones. However, discerning the proportion of the assistance's effect and its influence in these two zones proves challenging. To address this, we have differentiated the energy consumed during cutting for each zone.

The energy supplied (Wext), primarily transformed into temperature, is the product of cutting force and cutting speed. Consequently, by disregarding the energy in the tertiary zone, this energy can be divided into two components: the energy in the primary zone (W1) and the energy in the secondary zone (W2). Recognizing that temperature influences forces through thermal softening, a cooling source can alter this energy balance. This forms the focus of the subsequent stage of analysis. Furthermore, it is feasible to discern the phenomena by analyzing the energy in both shear zones.

$$W_{ext} = F_c V_c \tag{6}$$
$$W_1 = F_s V_s \tag{7}$$
$$W_2 = F_n V_{chip} \tag{8}$$

Where V_{chip} is the chip velocity and V_s the shearing velocity.

These results are indeed intriguing, shedding light on the challenge of analyzing results solely based on stresses, strains, or friction coefficients. Initially, the external energy increases linearly and seems to remain consistent with or without assistance. This phenomenon can be attributed to the rise in cutting speed.

Secondly, it becomes apparent that in dry tests, the energy in the primary bands consistently remains lower. There are two plausible interpretations. The first suggests that the temperature generated by cutting constrains forces and consequently energy. This interpretation aligns with Komanduri's findings, illustrating the role of temperature in shear band formation. Alternatively, the cooling effect of the assistance appears to be efficacious. The separation of material in the primary band demands more energy and is thus less susceptible to temperature effects.

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Figure 5 : Evolution of energies when cutting speed increase

When the feed rate increases, the outcomes diverge (Figure 6). Indeed, the escalation in feed and thus in exertion inherently results in a significant surge in energy consumption. In this scenario, the energy consumed by the primary zone increases linearly with the feed rate in dry tests. Conversely, with cryogenic assistance, the energy remains stable. Regarding the secondary zone, the results also deviate from those obtained previously. Irrespective of the feed rate, the energy remains constant.

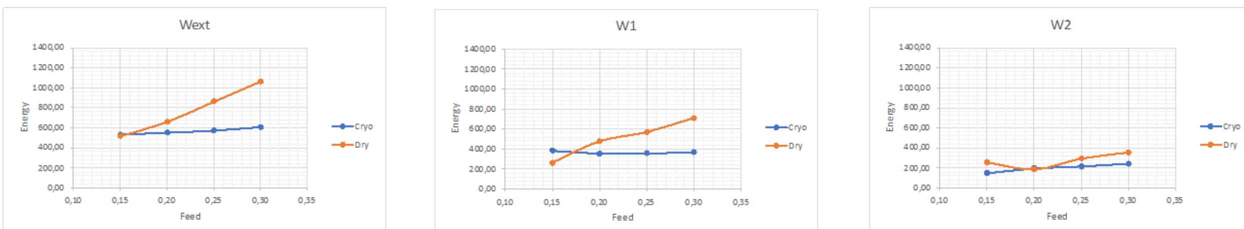
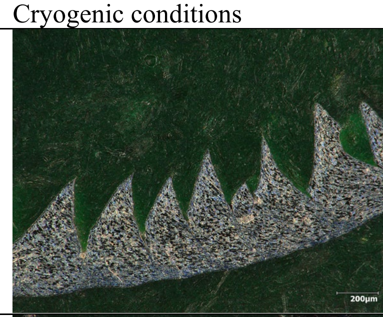


Figure 6 : Evolution of energies in different cutting zones when feed increases

Lastly, another avenue for elucidating the evolution of the cutting process is chip analysis. Such analysis reveals all the thermomechanical stresses, including deformation and temperature. Drawing from the insights of the article in [6], the progression of the cutting process and the distribution of stresses in the zones can be deduced by analyzing the volumes of deformed material.

In this regard, it is observed that the volume in the primary shear bands remains constant regardless of the reshaping conditions. Conversely, the size of the secondary zone diminishes, along with its energy consumption (Figure 6).

	Dry conditions	Cryogenic conditions
Vc=30 m/min		
Vc=40 m/min		

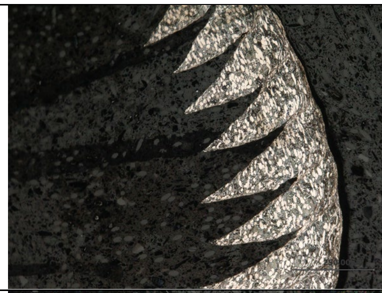
Vc=60 m/min		
Vc=100 m/min		

Figure 7 : Chip morphologies according cutting conditions

Conclusion

This article investigates the influence of cryogenic techniques on the machining of Ti54M, a material gaining increasing popularity. Through an experimental campaign, we have delineated the constraints of cryogenic assistance particularly evident as cutting speeds escalate. It becomes apparent that at excessively high cutting speeds, the rise in temperature surpasses the compensatory capacity of the assistance. Conversely, and notably concerning wear, the stresses, and more significantly, the energies imparted in the secondary zone diminish with cryogenic assistance, despite higher temperatures prevailing in this zone. This variance may be elucidated by the specific application zone of the liquid nitrogen.

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