THE EFFECT OF CRYOGENIC COOLING ON SURFACE ROUGHNESS OF TITANIUM ALLOY: A REVIEW

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ABSTRACT: Titanium alloy is a unique material that can maintain its high strength–weight ratio during elevated temperatures. It is one of the important metal parts of the engine components and aircraft structural. Surface roughness is one of the important parameters used in evaluating the quality of finish machined surfaces because of these parts of components in aerospace industry are manufactured to reach high consistency level. To improve the surface roughness of the work materials, the use of coolant in manufacturing operations such as turning process must be considered properly. The application of cryogenic coolant in machining process was analyzed in details in this review. The study was based on the application methods in machining operations which is the turning process on titanium alloy and the condition of work materials by looking at surface roughness values when using the coolant. The findings showed the most constructive method for machining operations was cryogenic cooling. This is because of its capability in producing better surface finishes by reducing the cutting temperature during machining operation, subsequently, enhancing the quality and function of the products or components.

KEYWORDS: *Cryogenic Cooling; Titanium Alloy; Surface Roughness; Turning process*

1.0 INTRODUCTION

Over the last decade, the interest for titanium alloys, especially in the aerospace, commerce has essentially extended because of their high strength to weight ratio, decreasing the formation of corrosion and capability in maintaining the strength at high temperatures [1–4]. On the other hand, titanium and its alloys are extremely hard to change their shape as they represent a more challenge to machining processes due to the temperatures and stresses produced are higher during machining operations [5–8]. There are many types of titanium alloys. One of them is the Ti-6Al-4V ELI alloy. ELI represents extra low interstitial which has a more grade of pureness compared to the ATI Ti-6Al-4V alloy. This alloy compromises in high strength and its depth hardening ability which contains low oxygen, carbon and iron [9–11].

Turing process is a machine operation in which the materials will be removed from the workpieces to create a cylindrical shape or a difficult surface profile using a single-edge cutting tool [12]. High speed machining is used in the machining operation with a specific end goal to increase the productivity and at the same time, improve product quality and decrease manufacturing cost. High-speed machining (HSM) is one of the more current advances and is known as a metal removing process for the most part generally utilized in an industry to develop various machine parts [13–15]. An excellent surface finish of the product can be achieved using this machining process. It is also valuable due to higher removal rates and low cutting forces while at the same time it decreases costs and machining time in comparison with conventional cutting [11, 16, 17]. The tool life will diminish quickly due to high cutting temperature in the cutting zone generated by the machining. Besides, the machining also produces a bad surface finish which has high value in surface roughness and severe microstructure alterations that are caused by the quick tool failure and fragment at the cutting edge [6, 9].

Titanium alloys are often used in components that require high reliability, hence, maintaining their surface roughness is necessary, yet their surface is easily damaged during the machining process. This is due to titanium alloys have poor machinability characteristics. The damage often occurs in the form of microcracks, phase transformations, plastic deformations and residual stress effects. As the heat that is generated during machining operation is a major cause in damaging the machined surface, the surface metallurgy of the finished product must be prioritized [5–6, 9, 18].

The effectiveness of the cooling/lubrication provided must be considered to make sure that surface roughness values or surface quality are improved during machining titanium alloys [16]. The main function of cutting fluid is to lubricate or cool the heat generation zone, which occurs during the machining process by reducing the friction among the cutting tool, chip, and work material interface. The application of cutting fluid has three techniques which are flooded machining, semi-dry machining and cryogenic machining [19–20]. The health and environmental problems will arise if the conventional cutting fluid is used in an industrial, mainly with regard to their degradation and final disposal [21–22].

Besides, the clearance of the remaining cutting fluid must be done because it is an environmental contaminant and the government has taken serious action on its implementation [23–24]. Hence, the cryogenic machining is better compared with the machining that use conventional cutting fluid because the liquid gas that is used in cryogenic machining will vaporise into the surroundings and become a part of the atmosphere [25–27].

Cryogenics is the field related to technology at deep freezing temperatures, which begin at lowest temperatures below -120 K (-150 °C) [25]. Elshwain et al. [7] also stated in their study that cryogenic uses materials at lowest temperatures which do not exceed -150°C. However, typical boiling points of permanent gasses, for example, helium, hydrogen, nitrogen, oxygen and normal air as cryogens do not exceed -180°C. Liquid nitrogen (LN2) or liquid carbon dioxide (CO2) is generally used in cryogenic machining as a coolant due to its properties which have lowest melting temperatures that will decrease the temperature at the cutting zone. Although pressure above 50 kPa is needed to maintain it in liquid form, carbon dioxide is usually added to the list. Several potential advantages of cryogenic cooling have been mentioned before which include sustainable manufacturing; being a cleaner, safer and environmentally friendly solution [28]. Besides, the material removal rate and tool life will increase better surface quality which has lower surface roughness value of the machined part [25]. The main disadvantage of cryogenic cooling is the high cost of liquid nitrogen. The liquid also cannot be reused unlike conventional cutting fluids, thus, it is very important to choose a suitable cryogenic cooling plan to decrease the usage and increase the performance [28]. Natasha et al. [20] reviewed the cryogenics' application effect on surface integrity of workpiece in general processes. However, reviews have yet to be done on the consequence of cryogenic cooling on surface roughness of titanium alloy in turning process. Hence, this paper focused on a review of the use of cryogenic liquid as a coolant in turning titanium alloy and its effect on surface roughness. Table 1 shows the common assessment of this review.

Table 1: The assessment of surface roughness under cryogenic cooling

Authors	Work materials	Type of cryogenic	Investigation topic
Dhananchezian and Kumar [23]	Titanium (Ti–6Al–4V) alloy	Liquid nitrogen	Surface roughness, tool wear, cutting force and cutting temperature
Venugopal et al. [40]	Titanium (Ti-5Al-5Mo-2Sn-V) alloy	Liquid nitrogen jets	Surface quality, surface roughness, tool wear and cutting force
Wang and Rajurkar [45]	Titanium (Ti–6Al–4V 6%) alloy, Inconel alloy, Tantalum	Liquid nitrogen	Surface roughness value, tool wear and cutting force
Rajurkar and Wang, [46]	Titanium alloy, Tantalum and Aluminum	Liquid nitrogen	Surface roughness, tool wear
Sun et al. [42]	Ti-5553 alloy	Liquid nitrogen	Surface finish, tool wear and cutting force
Sun et al. [41]	Ti-6Al-7Nb alloy	Liquid nitrogen	Surface roughness, hardness, microstructure
Rotella et al. [47]	Ti6Al4V alloy	Liquid nitrogen	Surface roughness, Surface and subsurface hardness, Microstructure, Phase changes—XRD analysis
Bordin et al. [44]	Titanium alloy Ti6Al4V	Liquid nitrogen	Surface integrity, Tool wear mechanisms and modes
Tirelli et al. [43]	Titanium alloys Ti6Al4V	Liquid nitrogen	Surface quality, tool wear, and cutting force

2.0 CRYOGENIC COOLING EFFECT ON SURFACE ROUGHNESS

Surface roughness values basically show the performance and quality of finished product. Thus, the relationship between surface roughness and its usability has been given attention in the field of manufacturing. Surface finish is an important part in machinability that is generally analyzed because it represents the quality and performance of the product, as well as the residual stresses and the existence of surface and subsurface microcracks [29]. On the other hand, Yazid et al. [30] stated that one of indicators quality of machined surface of the workpiece is surface roughness.

2.1 Constraint in Producing Better Surface Finish

Nowadays, estimates on preliminary design surface roughness become the main focus in research field when it comes to metal cutting [31]. The main factors affecting the surface roughness are caused by the built-up edge. According to Che Haron et al. [32], failure modes of the tool are the cause of the surface roughness. Surface roughness decreases are approved for the reduction of auxiliary flank wear where the tool hardness is maintained by the lower cutting temperature [33–34]. On the other hand, the surface roughness values are also affected by parameters of the tool namely shape of tool insert, the nose radius; type of insert rake and selection of coolant [35]. A cryogenic coolant is selected in this process. The value of surface roughness, Ra, improves when using cryogenic cooling matched to the dry and wet machining [36–39]. If the cutting velocity increases, the surface roughness value will decrease. Smaller values of surface roughness represent better surface finish. Figure 1 represents the improvement of the surface roughness against wet and dry machining.

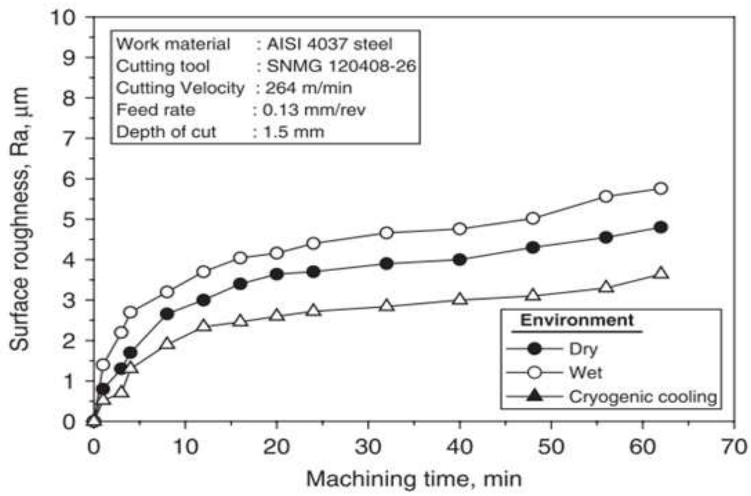

Figure 1: The comparison surface roughness value between dry, wet and cryogenic machining [33]

2.2 Benefits of Cryogenic Cooling Toward Previous Study

The value of surface roughness value, Ra, will be improved when using cryogenic cooling in machining against dry and wet machining condition, This condition has been proven by several researchers [36]. Dhananchezian and Kumar [23] used modified cutting tool inserts in examining the cryogenic machining Ti–6Al–4V alloy. From the experiment, 25-35% surface roughness parameter was reduced using cryogenic cooling compared with wet machining. This is due to the use of liquid nitrogen at the chip tool interface, assistant flank surface, recently machined work material and primary flank surface through the gaps made in the cutting tool insert. It brings about cutting temperature becomes lower, amount of adhesion between the work piece surface and tool auxiliary flank surface is reduced, and tool wear rate becomes lower. Figure 2 shows the difference in surface roughness versus cutting velocity.

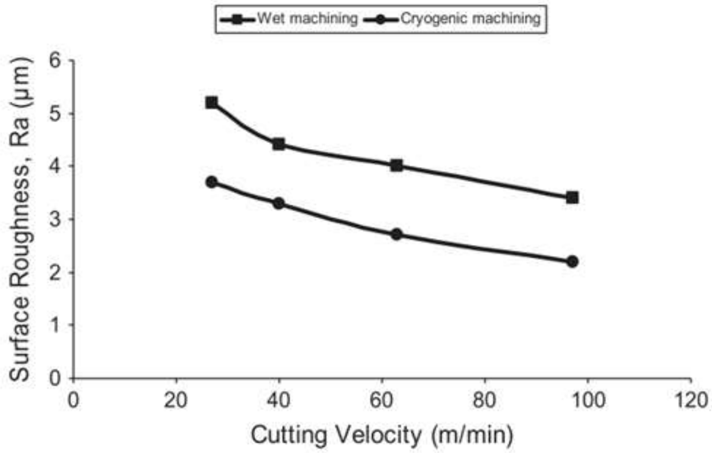

Figure 2: Difference in surface roughness versus cutting velocity [23]

In another study, Venugopal et al. [40] used TiB2-coated carbides during turning titanium alloy (Ti-5Al-5Mo-2Sn-V) under cryogenic cooling and examined surface roughness values. The results of surface roughness values were compared between cryogenic and dry machining. From the experiment, an improved surface quality which is without any plastic deformation is found under cryogenic cooling, whereas the surface undergoes glazing under dry machining process. Figure 3 shows the profile of surface roughness that is achieved under cryogenic and dry conditions at cutting velocity (V_c) of 56 m/min and 72 m/min. This is supported by Sun et al. [41] that analyzed the use of cryogenic cooling as a coolant during machining Ti-6Al-7Nb alloy in improving surface integrity for biomedical applications. It is found that, 35% and 6.6% of surface roughness are improved when using cryogenic coolant as a cooling compared with flood-coolant and dry machining. In contrast, better surface quality which has the lowest surface roughness value is produced under MQL machining to flood-cooled and cryogenic machining as higher ductility could be accomplished because of the elevated temperatures. This result was found by Sun et al. [42] in their study on improved machinability of Ti-5553 alloy from cryogenic machining and the comparison with flood-cooled and MQL machining. Besides, Tirelli et al. [43] analysed the rough turning of Ti-6Al-4V alloy using cryogenic and traditional cooling as a coolant and made comparison between these coolant. It is concluded that liquid nitrogen does not affect the surface finish of products or the chip morphology. Bordin et al. [44] also found that surface roughness value in dry machining is 20% lower than cryogenic cooling for all the cutting lengths in their analysis of tool wear in cryogenic machining of additive manufactured titanium Ti-6Al-4V alloy.

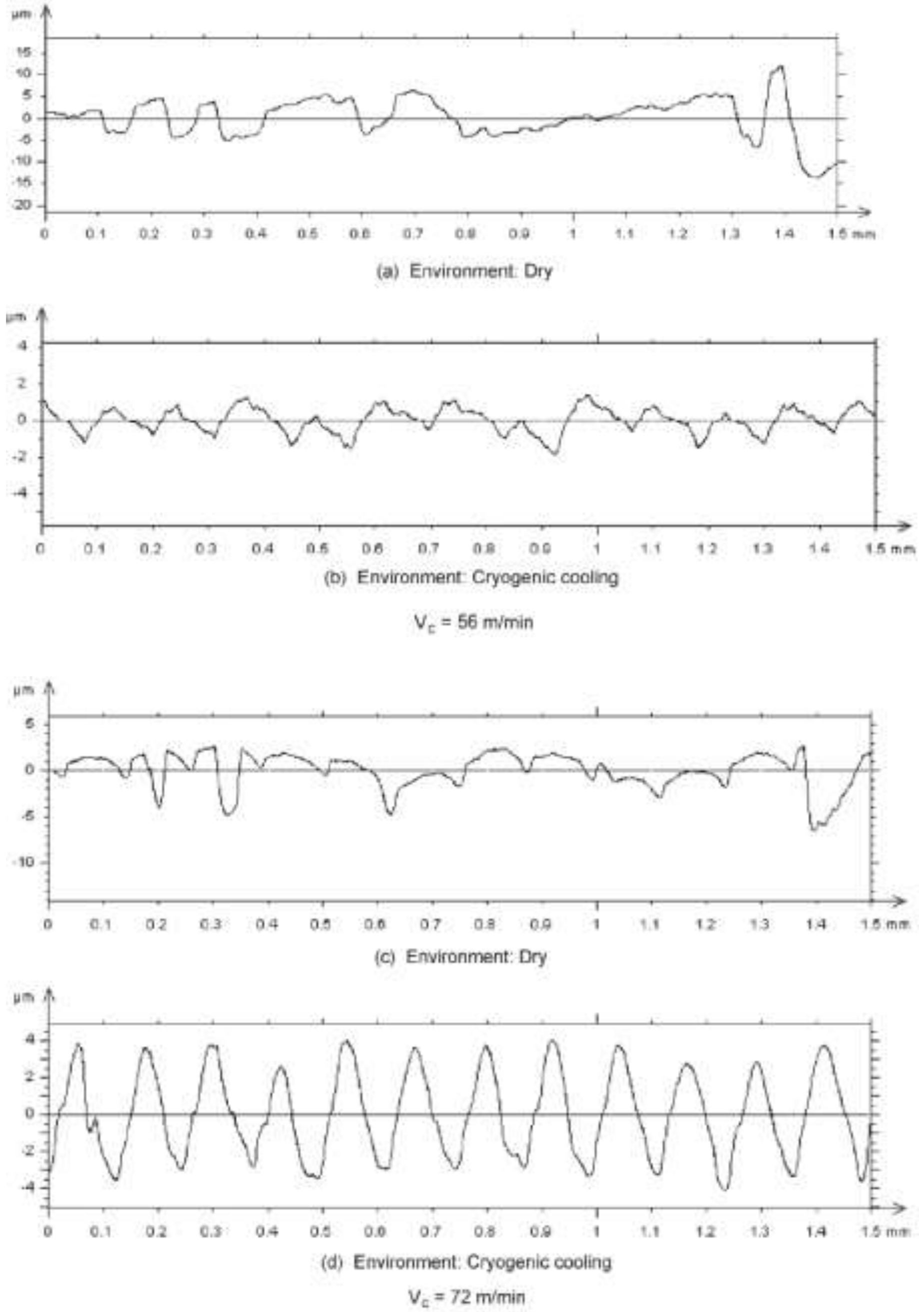

Figure 3: Surface roughness profiles on the machined surface of Ti-5Al-5Mo-2Sn-V alloy at V_c values 56 m/min and 72 m/min respectively [40]

A novel study by Wang and Rajurkar [45] on cryogenic cooling as a coolant in machining of difficult to machine with the same cutting length, they found that the surface quality of all materials including titanium alloys with LN2 cooling is better than without LN2 cooling. Hence, the lower surface roughness value is formed from cryogenic cooling application. Figure 4 represents the value surface roughness in turning of Reaction Bonded Silicon Nitride (RBSN) with three different types of Cubic Boron Nitride (CBN) inserts, Ti–6Al–4V alloy, tantalum with H13A inserts, and Inconel

718 alloy.

Besides, Rajurkar and Wang [46] used cemented carbide inserts under cryogenic cooling condition in machining titanium Ti-6Al-4V alloy. They found that using liquid nitrogen coolant for turning process will improve surface roughness values compared with dry machining and another cooling method.

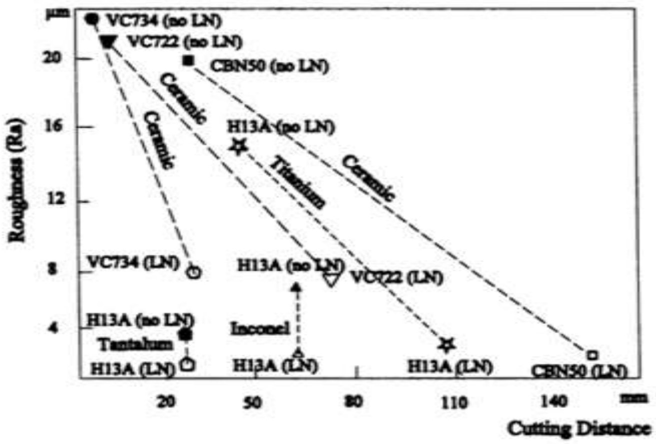

Figure 4: Surface roughness under cryogenic cooling in turning process [45]

Rotella et al. [47] reported that the surface roughness values in cryogenic machining are lower than flood and dry machining under all cutting speed/feed conditions. Kaynak et al. [48] analysed tool wear under cryogenic machining of Nickel Titanium (NiTi). Figure 5 shows the surface roughness values in three conditions increase, which present the bad surface finish quality. However, the results from cryogenic machining show better and consistent surface roughness quality over time.

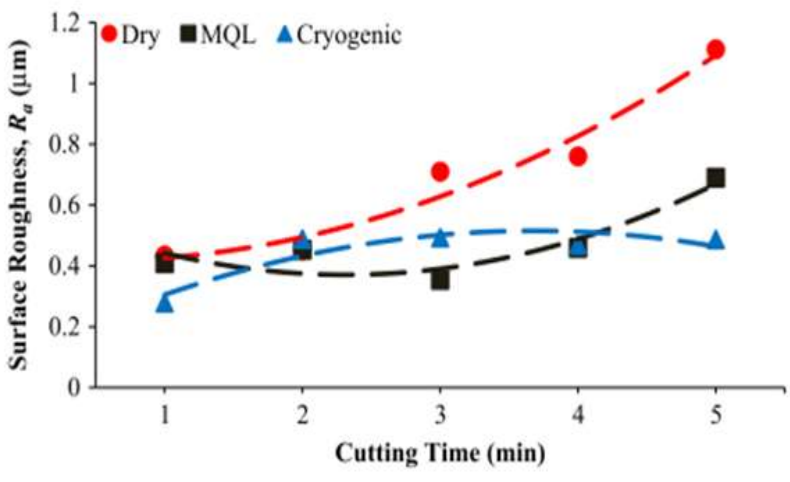

Figure 4: Surface roughness of the workpiece versus cutting time [48]

3.0 CONCLUSION

Surface roughness value of the work materials that is achieved by final manufacturing process describes the properties and quality of a component. This reviewed study provides an overview of turning process that encourages surface roughness in work material under cryogenic cooling. From this review, it can be recognized that the best coolant application during manufacturing operations is using cryogenic cooling. This is due to the improvement in surface finish of the work materials by decreasing surface roughness values. However, there are still a few gaps that can be further analyzed. For future work, further critical review regarding cryogenics' effect on surface integrity of titanium alloys can be carried out.

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