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Sustainable Machining for Titanium Alloy Ti-6Al-4V

Imran Masood

Abstract

Sustainability achievement of difficult-to-machine materials is a major concern nowadays. Titanium alloy Ti-6Al-4V machined for dry, conventional and cryogenic cooling and surface finish is selected as response to assess machining sustainability through variables: cutting power, machining time, machining cost, material removal rate and cutting tool life. Results indicate that cryogenic cooling is more sustainable than dry and conventional cooling.

Keywords: cryogenic cooling, sustainable machining, Ti-6Al-4V

1. Introduction

In recent years, attention has made on achieving comprehensive strategy over sustainable manufacturing due to increased emission of CO₂ in environment and waste. This ultimately will improve industry's economy [1]. Machining technology is referring to implement the sustainability, which has potential to improve environmental performance and save money. The problem in implementing sustainability in production companies is due to short-term financial planning. However, long-term strategy is necessary for sustainable manufacturing.

The initiatives for the sustainable development are established at different levels, e.g., UN, OECD and National level, and are well positioned on macro level of production [2] but are lacking in implementation at shop-floor level.

Conventional machining processes using mineral-based cutting fluids tend to increase environmental problems. Attempts are in focus to attain sustainable products and processes that will eliminate the bad effects of mineral-based cutting fluids. Alternative technique of cooling by using liquid nitrogen is in focus to eliminate the adverse effects of mineral oils. The cost of machining is a major element of a mechanical industry. Cutting tools having long tool life are preferred over those with short tool life in order to reduce overall machining cost and increase productivity.

In aerospace industry, the components are usually made from superalloys. These alloys can withstand the high operating temperatures and extreme physical stresses. Out of these alloys, titanium is the most commonly used alloy. Ti-6Al-4V shows good results in application where high strength-to-weight ratio along with excellent corrosion resistance is required. This alloy is used in aircraft turbine engine components, structural parts of aircrafts, aerospace fasteners, high-performance automotive parts, marine applications, medical devices and sports equipment.

Milling is one of the mostly used machining operations in manufacturing industry. The situation becomes very difficult to handle when hard materials are required to go through milling process. The probability of tool wearing and damaging of surface roughness increases when high cutting forces and high temperatures are involved at interface of cutting tool and work material.

Much energy is utilized in a machining operation along with the wastage of chips in material removal process. Operational safety and environmental friendliness of any machining process play a vital role in sustainability of process. It is estimated that machining process contributes to the gross domestic product (GDP) of developed countries by about 5% of total the GDP [3].

The present trend is to create new and smaller products of higher quality in a shorter time and at a lower cost. There are many materials, which can be classified as 'difficult-to-machine'. Machining of such materials requires special cutting tools. Cutting parameters affect directly on the surface roughness, tool wear and machining time.

The world has now become energy conscious, and every industry is going to follow the health and safety requirements at all levels. The concept of sustainable manufacturing has now become the key focus, which deals with the economic, social, safety and environmental issues. Proper selection of cutting tool, coolant and process type is important for efficient and economic machining. Alternative solutions of dissipating the heat generated at chip-tool interface and cutting tool materials is in exploration since the last few years. Titanium alloys and other materials used in aerospace industry need special attention for their machining as these are difficult-to-machine materials.

Experimental data shows that cryogenic cooling is more sustainable than dry and conventional cooling process, and it gives the best results for tool life, surface finish of machined part, productivity with least impact on the environment, least energy cost and machining cost.

1.1 Problem related with conventional machining

Difficult-to-machine materials are heat resistant; therefore, in machining of such materials, huge amount of cutting tools and coolants is used. The cost of a machined part mainly involves the cost of tools used, electrical energy and coolant cost.

In conventional methodology, the parts are machined using mineral-based coolants. These coolants have disadvantages in worker's health and environment where it is disposed of. Titanium alloys and other nickel-based alloys are difficult-to-machine, and therefore a number of cutting tools are wasted in their machining increasing the overall cost of the product. Conventionally used coolants have many problems associated with the health of workers and environmental impact.

The problem becomes more critical when machining the difficult-to-machine materials where high temperatures are built at the tool-chip interface. Using of conventional mineral-based coolant to reduce the temperatures and frictions is creating other environmental problems because disposition of these lubricants is not only harmful for human life but also creating issues for aquatic organisms. Social impact of conventional lubricant and coolants is increasing health and safety problems of workers due to exposure to toxic chemicals. The working environments are being polluted increasing both the mist and noise levels. Industrial setups are required to adopt the sustainability principles in order to avoid increasing cost and environmental and safety issues. Alternative coolants are in exploration phase to replace with the conventional mineral-based coolants.

2. Sustainable manufacturing

Sustainability is defined as the ability to preserve, to keep or to maintain something. When something is sustainable it means that it is able to be kept and continued [4]. The three dimensions of sustainability (**Figure 1**) are environmental, social and economic, sometimes adding technology as the fourth one [5]. Initially sustainable development defined by Brundtland is reported in 1987 as ‘the way for improving the well-being and quality of life for the present and future generation’. More precisely it was defined as ‘to meet the needs of the present without compromising the ability of future generations to meet their own needs’ [6].

Manufacturing contributes by about 22% of Europe’s GDP, while 70% of jobs in Europe are directly related with manufacturing [7]. Energy consumption is a major factor in manufacturing industry which is based on electrical energy and oil. According to the action plan for energy efficiency, industrial production is responsible for about 18% of the total energy consumption of Europe [8].

Sustainable manufacturing is important for the manufacturing industry as it helps to cope with the increasing environmental regulations, meeting the customer requirements for better environmental performance, lowering the material and energy costs resulting to greener products. Sustainable manufacturing is the creation of products using such processes that minimize the environmental impacts, conserving natural resources and energy, are safe for the communities, employees and customers and are economically sound. It has become a business imperative as companies across the world are facing increased costs of energy and materials coupled with higher expectations of customers, communities and investors.

In sustainable manufacturing, the things are created in such a way (**Figure 2**) that is economically, environmentally, socially and safety wise feasible for both the manufacturer and user. Greater emphasis is over the environmental issue followed



Figure 1.
Sustainability basic dimensions.

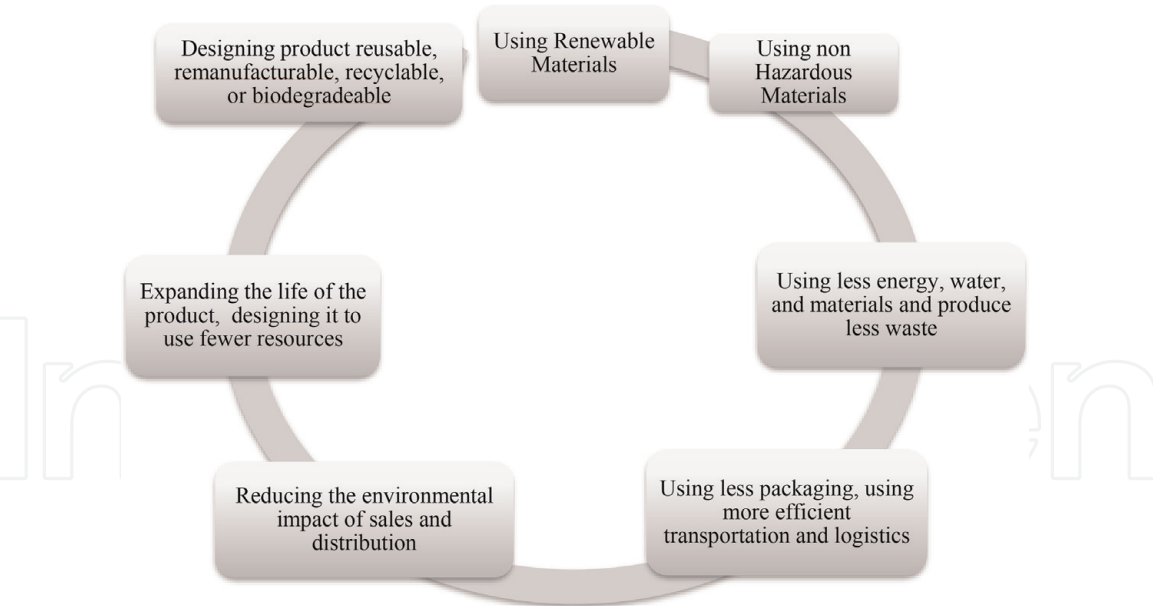


Figure 2.
Sustainable manufacturing aspects.

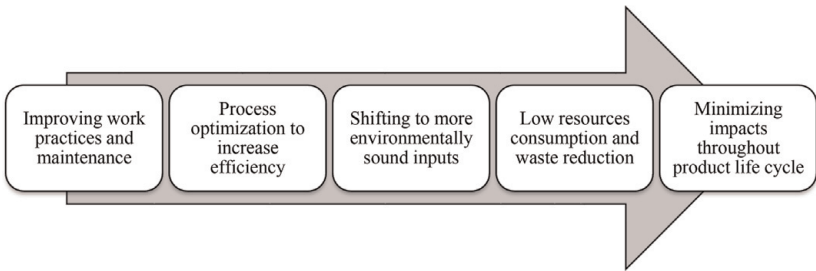


Figure 3.
Implementing sustainable manufacturing.

by the safety of workers and then economically. It leads the industry proactively to cleaner products and processes.

A process is said to be sustainable only when it has the lowest impact to the environment, is beneficial for society and is sound economically [9]. Hallmarks for the sustainable manufacturing are environmental friendly, lower machining costs, minimum energy consumption, personnel health, waste reduction and operational safety [10]. Globally the industries are striving for sustainable manufacturing by adopting advanced lubrication and cooling techniques, using vegetable oils or other environment-friendly cutting oils, selecting advanced tooling and accomplishment of advanced hybrid manufacturing processes, etc. [11]. Manufacturing industries of the USA, EU and other international countries are facing challenges to reduce the emissions of carbon dioxide and improve the efficiency of energy by making revolutions in technologies and processes [12].

The environment, social development, education, natural resources, poverty and inequality are examined for sustainable developments [13]. Sustainability has no destination or limits, but it has continuous improvement making the constant advances in company’s overall sustainable performance. However spectrum of efforts can be followed as given by the United Nations Environment Programme [14] and OECD [15]. Sustainability is implemented by improving the work practices, optimizing processes, reducing resource consumption and minimizing impacts throughout the product life cycle (**Figure 3**).

2.1 Sustainable machining

Industrial trends are shifting from conventional to sustainable manufacturing principles. Such revolutions are outcome of diseases found in workers at shop floor, requirement of cost reduction for manufacturing and Government policies for environmental protection [16]. There is a need to make the machining systems sustainable in which processes are non-polluted, conserving both energy and natural resources, and economically sound and safe for employees [17]. Growing global competition and energy costs demand for such machining processes which are cheaper, using better utilization of resources and efficient usage of energy [18].

In the process of transforming inputs to outputs, the consumption of resources must be reduced to achieve sustainability. Refining the processes and machine tools are major factors for reducing the resources and energy consumption. The production systems are designed to support the continuous waste reduction, elimination or recycling. This can be achieved by less generation of waste; increasing recycling or re-usage; efficient usage of water, materials and energy; avoiding metal working fluids; and improving the management of lubricating oils, swarf and hydraulic oils. Sustainability will be gained by using the alternatives of cooling and lubrication fluids (CLFs) and dry machining using the coated cutting tools [19].

In a sustainable machining process, the tool life, productivity and effective utilization of resources will be increased, while the machining cost, machine cutting power and adverse effect of cooling and lubrication fluids will be decreased. The model of sustainable machining is presented in **Figure 4**.

Alternative cutting oils such as vegetable oils are renewable, environment-friendly and non-toxic in nature [20].

2.2 Conventional machining

Present investigations show that the cutting fluids are creating severe problems to health and environment [21]. The conventional fluids are considered very dangerous to the health and are rated out of top five hazardous to health [22]. Bulk use of conventional coolant in machining industries is causing increase in environmental damage [23].

Machining process contributes to worldwide economy, and it tends to become unsustainable when using such cooling and lubrication fluids which are oil based. These are made from mineral oils extracted from crude oil which is highly non-sustainable. Extract of crude oil is used to formulate the mineral oil which is converted to CLF. Although the vegetable oils are naturally derived, these are not used as CLF due to higher costs and reduced performance [24].

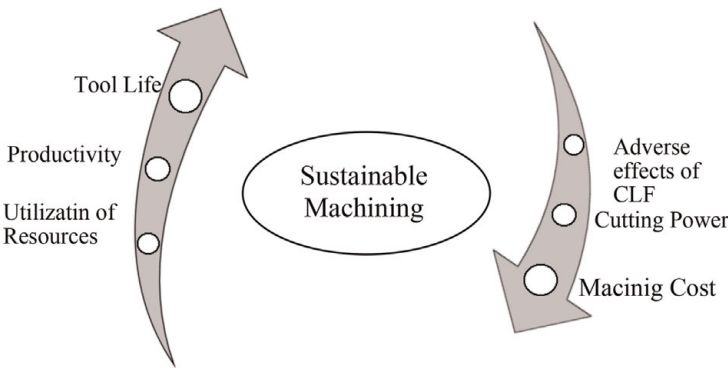


Figure 4.
Sustainable machining model.

CLFs are widely being used in metal cutting industry to counter the heat generated by machining besides that they have disadvantage of hazardous to health and environment. One of the most unsustainable elements in machining process is the use of cooling/lubrication fluid which is extracted from crude oils [25].

Cutting fluids are dangerous for health. In a report it is stated that about 80% of the skin diseases are due to the use of cutting fluids [26]. The machinists are facing the problem of skin and respiratory diseases due to metal working fluids [27]. Among the machinist over 1 million workers all over the world are facing toxic effects of cutting fluids, and majority of the cases are related to chest bronchitis [28]. According to a report [29], about 640 million gallon of coolant and lubrication fluid is used annually throughout the world. European Union estimated for metal working fluid and found that 3,20,000 tons is annually used and 66% of which is disposed-off after usage [30]. Used coolant in conventional machining has its adverse effects on the environment [31].

2.3 Cryogenic machining

Cryogenic machining is much safer than the conventional lubrication and coolants. Nitrogen gas has no hazards on life as about 79% of this already exist in air. Liquid nitrogen at cooling temperature is effective for cooling the cutting edge during machining of hard materials as cutting temperature exceeds 200°C [32]. It is a new technique of cooling the cutting zone and part during the machining at high speed and temperatures with cryogenic CLF. The coolant is nitrogen which is liquefied at -196°C and is safe, non-corrosive and non-combustible gas. This gas evaporates leaving no contaminates with part, operator, machine tool, and chips; thus disposal cost is eliminated. Mostly cryogenic CLFs are applied in the machining of superalloys.

The cryogenic machining process is more beneficial and more sustainable in terms of safety, clean and environment-friendly machining. Due to minimization in changeover time, productivity also increases. Tool life is increased due to low abrasion rate and chemical wear. Improvement is observed in the surface quality without the degradation in its mechanical/chemical properties.

For implementation of cryogenic machining at industrial level, investigations are required about the tool wear and tool life using cryogenic cooling [33]. Application of cryogenic machining at shop-floor level will be transitioning towards the sustainable machining and will promote the development of optimization for cryogenic fluid delivery with mass flow and controlled pressure.

In cryogenic machining the cryogenic fluid is directly applied on the cutting tip of the tool. This flow is manageable to be controlled against flow and pressure which makes it more economic than conventional fluids. N_2 gas is used as a cooling medium in cryogenic machining and is harmless to the health. This process increases the tool life and helps in productivity improvement, surface integrity improvement, chip breakability enhancement, reduction in built-up edge and burr formation [34–37].

In comparison of cryogenic cooling with conventional cooling and lubrication process, it is clear that the cost of power required for pumping of cooling and lubrication fluid is eliminated. The cost of cleaning CLF from the machined part becomes zero. Alternates of cutting fluid like N_2 , O_2 and CO_2 have been used and compared to wet and dry machining and found that fine surface finish obtained with increased flow rates and pressure of gases [38].

Compressed air as coolant was used for machining of optical glass and found that low cutting forces are observed as compared with diamond drilling [39].

Experiments performed using liquid nitrogen in turning process of titanium alloy with modified tools resulted in improved tool life, surface finish and reduced

cutting temperature of 65% and reduced cutting forces [40]. Experiments were also performed to check the machinability by considering the surface roughness. Ti-6Al-4V was machined in dry, wet and cryogenic conditions to observe the surface roughness. Surface finish is found consistently better with cryogenic than with dry and wet [41].

Different gases have been used as a coolant like CO₂, air, argon and nitrogen [42]. Experimental results conducted on Steel AISI 1040 using CO₂, O₂ and N₂ show that best surface finish is achieved using CO₂ then oxygen and nitrogen. Cryogenically compressed air was used for investigating the chip temperature, cutting force and the chip formation during the turning of Ti-6Al-4V [43].

Sustainability in machining can be assured by reduction in energy consumption for machining processes, minimizing waste (less generation of waste and increasing the recycling of waste).

Benefits of using the sustainable machining cover increasing MRR without increasing wear rate of the cutting tool, decreasing the tool changeover time increasing productivity and improving the machined surface without degradation which results in the presence of chemical coolants.

2.4 Machining issues of Ti-6Al-4V alloy

The most commonly used materials in aerospace industry are nickel alloys, titanium alloys and Co-Cr alloys [44]. Thermal conductivity of such materials is low, and therefore temperature observed at the cutting zone is extremely high. These facts have called for sustainability in machining and finding the alternate to conventional oil-based CLF as cooling and lubrication [45–48].

Higher temperatures are observed in the high-speed machining (HSM) that result in high temperatures at cutting tool and part interface. In the reports it is given that tooling cost is about 4% of the total machining costs and coolant/lubrication cost is about 15% of total machining cost [49]; therefore huge sustainability gain is possible by avoiding CLF and using high-performance coated cutting tools [50]. Titanium alloy (Ti-6Al-4V) is referred to as difficult-to-machine material. It has low thermal conductivity due to which very high temperatures occur during the machining at the cutting point. Its mechanical properties are very good for load-carrying applications due to which it is mostly used in the commercial and military aircrafts. **Figure 5** shows the comparison of machining difficulty level with other common materials.

This alloy, also called Grade 5 titanium, shows good results when used in applications where good mechanical and thermal properties along with good strength-to-weight ratio are the primary objectives. Due to its good results in strong environments and resistance to corrosion, it is also used in petroleum industries, nuclear reactors, turbine blades, marine applications and medical implants. Demand of

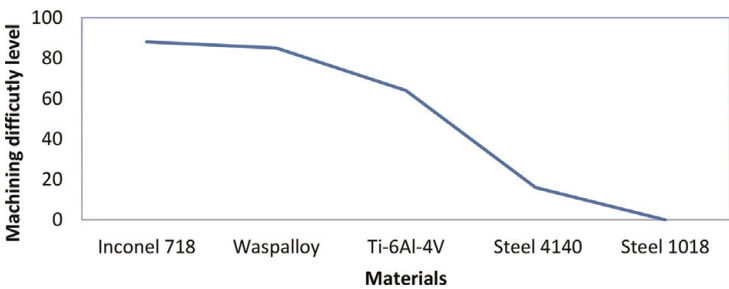


Figure 5.
Machining difficulty level of Ti-6Al-4V.

titanium parts is extensively increasing for industry of aircrafts such as Boeing 787. Preparation of titanium parts requires much cost for machining operations.

Due to low thermal conductivity, titanium has poor machinability. Titanium alloys can be used at temperature of 600°C. Titanium is related to a group of hard materials like nickel alloys, ceramics and cobalt-chromium alloys. It is important to cool down the cutting tool temperature in order to improve the cutting tool life, especially in the case when machining the materials with low thermal conductivity like Ti-6Al-4V alloy [51].

Coolant in conventional machining is harmful to aquatic organism and may cause long-term adverse effects in the aquatic environment. It is harmful to the respiratory system and can cause slight irritation making the environment contaminant. Repeated exposure may cause skin dryness. Nitrogen gas is harmless to environment and worker's health. Therefore, cryogenic machining nullifies the exposure to toxic chemicals making it safer for both workers and environment.

2.5 Machining problems of difficult-to-machine materials

In machining of difficult-to-machine materials like Ti-6Al-4V, excessive tool wear and heat are produced making the surface quality poor [52]. Alternative solutions of dissipating the heat generated at chip-tool interface and cutting tool materials are in exploration since the last few years. The main reasons for rapid tool wear are building of high cutting temperatures. In machining of hard and difficult-to-machine materials, the conventional CLF (oil-based) does not effectively decrease the cutting temperatures, and therefore tool life is not increased. It is due to the fact that the coolants do not access the chip-tool interface which is under high cutting temperature and vaporize close to the cutting edge. Due to this phenomenon, the conventional CLF becomes ineffective for machining the materials with low thermal conductivity and high shear strength.

Dry machining is not recommended at high-speed machining of difficult-to-machine materials. Such materials are used in aerospace industry and are capable of bearing high operating temperature like in jet engines.

2.6 Surface finish for metals

The quality of machined parts can be ensured by measuring the surface roughness. The quality of a surface with low roughness value is good over the surface having greater value of roughness. Surface finish is the important characteristic of precise devices as poor surface finish results in the problems of malfunctioning, geometric inaccuracy and excessive wear [53]. Surface finish and dimensional accuracy of a part greatly affect during its useful service life. Obtaining better surface finish of microstructures is in focus nowadays [54]. Failure of components commonly occurs as a result of poor surface of parts; therefore getting good surface finish is too much important. Researchers paid much attention towards getting good surface-finished parts using optimization techniques.

Surface roughness is mostly influenced by the feed rate, tool geometry, tool wear, chatter, tool deflection, cutting fluids and properties of working material. Other different kinds of factors (**Figure 6**) can affect the surface roughness.

Most of the researchers have used the machining parameters in their work to find the response over the surface roughness. For example, the large nose radius of cutting tool will produce better surface finish than the small nose radius [55]. The feed rate plays also its role in surface finish that the smaller feed rate yields better surface finish.

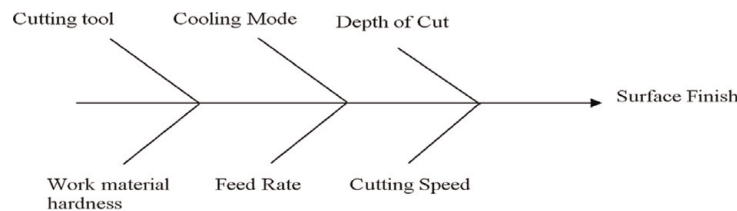


Figure 6.
Parameters that affect surface roughness.

2.7 Machining cost

Cost of a machined part mainly involves the cost of cutting tools, electrical energy and labour and coolant cost. High machining cost of titanium alloy Ti-6Al-4V has made it important to ensure longer tool life by selecting the favourable cutting conditions [56]. Present competitive trends of manufacturing are focused on generating the products with low cost and high quality. The cost of machining was computed based on the machining time, while total cost was calculated adding the machine cost, setup cost, material cost and non-productive costs [57].

A cost estimation model has been proposed in [58] for optimization of machining cost which includes material cost, tool cost and overhead and labour cost. In this proposed model, if the desired cost-effective results are not achieved, then the feedback is given to a designer for modifications. The feasible process parameters including cutting speed, feed rate and depth of cut are selected to attain optimum results. Constraints of cutting tool specification, tolerances, cost, time, machining sequence and required surface finish are taken into consideration.

3. Sustainability assessment for machining of Ti-6Al-4V

Sustainability of a machining process refers to the impact on environment, power consumption and safe for operator, which were satisfied in the experimental works as the cost of tool was reduced in the cryogenic cooling and it also impact on time saving for tool changing and setup time, which result in increasing productivity. An advantage of cutting in cryogenic process is evaporating back of cooling gas (Nitrogen) into air, which ensures the healthy environment for workers.

In experimental work [59], face milling of hardened Ti-6Al-4V at 55 HRC was carried for dry, conventional and cryogenic cooling conditions. Experiment model was designed using software design expert and technique of central composite design (CCD) was selected. Surface finish as response was checked and compared for each scenario of cooling. Resulting values of surface finish were compared based on iso-response technique, and the cutting power, cutting time, material removal rate, machining cost and cutting tool life were calculated as given in following sustainability parameters:

Cutting power: it was found that the cutting power required in cryogenic machining is 61.9% less than cutting power required in dry machining.

Machining cost: it is found that electricity cost is 47.55% less than dry machining and 14.22% less than conventional machining.

Adverse effects of CLF: the adverse effects of conventional coolants are reduced by replacing the coolant with N₂ gas. Corresponding cutting power and machining cost are also reduced.

Machining time: machining time for cryogenic machining is 15.12% less and for conventional machining it is 12.51% less than dry machining.

Material removal rate: the material removal rate is 81.12% more for cryogenic than dry machining.

Tool life: cutting tool's life is 5.2 times more for cryogenic cooling which indicates that the waste in the form of damaged tools is reduced.

4. Conclusions

From the experimental results, it is concluded that cryogenic machining is recommended for Ti-6Al-4V. Results are satisfying sustainability for eco-friendly impact on the environment, reducing tooling and energy cost. Efforts can be made to switch from conventional machining to cryogenic machining which would be beneficial in reducing machining costs, health risks along with fine surface surface.

The minimum value of surface finish can be obtained by the cryogenic machining using the coated carbide cutting tools. The cutting tool will not be damaged by cryogenic cooling ensuring both the sustainability and cost saving. Comparison of cutting power, cutting time, electricity cost, coolant cost, machine operating cost and material removal rate (Figure 7) for nearly identical response of surface finish shows that the cryogenic machining is more sustainable than others.

The results of tool life describe that cutting tool will survive for longer time in cryogenic cutting conditions than dry and conventional, resulting low cost of tool for the machining processes. Similarly, the cost evaluation resulted in low machining cost for cryogenic cooling as compared to dry and conventional. Cryogenic machining is more affordable and economic as there is no cost of pumping coolant, very low cost for cutting tool inserts and labour.

Cutting tool inserts were found damaged in dry machining, whereas very low wear was found in conventional, and no wear was found in cryogenic machining.

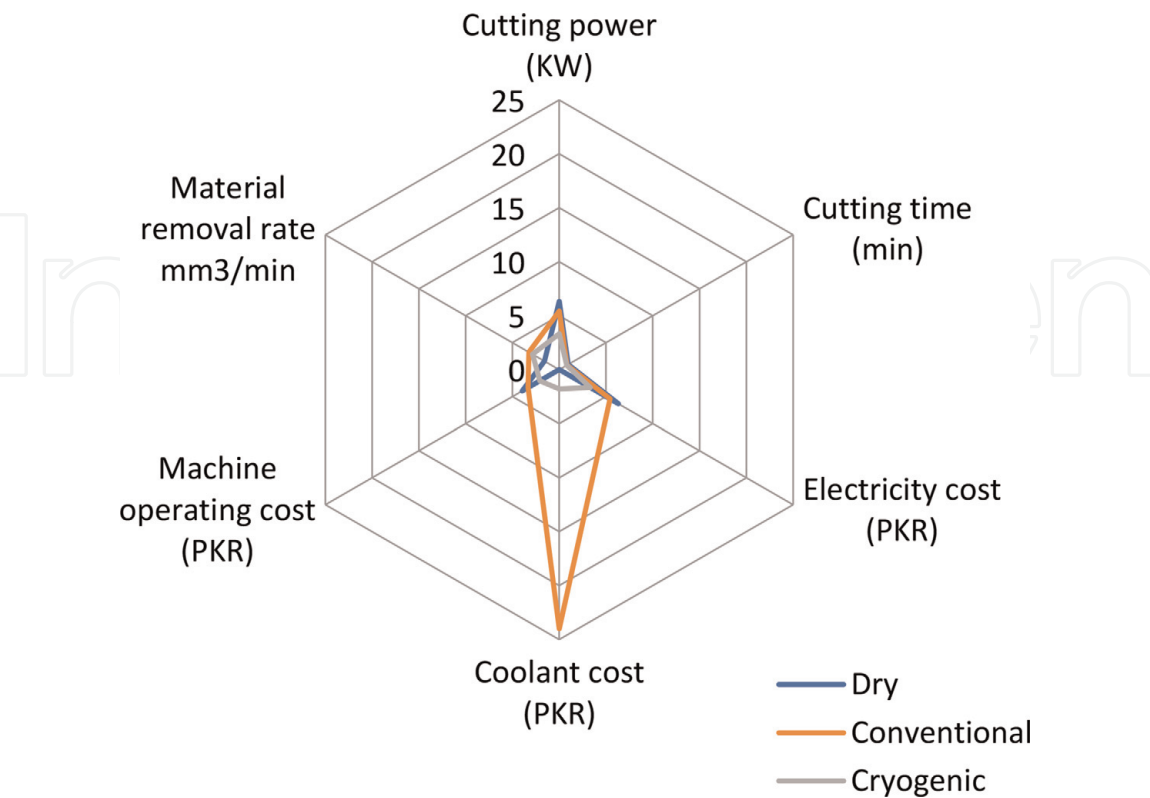


Figure 7. Average response values calculated for nearly identical surface finish.

The coolant used in conventional machining has its adverse effects on worker's health and environment, while the nitrogen gas is harmless. The tool wear rates are also high for dry and conventional. Summarizing all findings, it can be stated that cryogenic machining supports the sustainable machining.

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