Evaluation of machinability based sustainability indicators in the eco-benign turning of Ti3Al2.5V alloy with textured tools

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Abstract: The recent step towards "Sustainable Manufacturing (SM)" and efforts to reduce the consumption of cutting fluids have become the hot topic of research these days. Various efforts and strategies have been employed in the modern manufacturing sector to control the environmental pollutions generated from the application of cutting fluids. Therefore, in this holistic work, one such effort of reducing the consumption of cutting fluid is employed with the application of minimum quantity lubrication (MQL) and tool texturing. The turning trials were made on titanium alloy: Ti3Al2.5V alloy under dry and MQL conditions using textured and non-textured tools. The tool life, average surface roughness, specific cutting energy, air quality, and chip morphology were studied with the aid of the above-subjected conditions. In the end, the socio-economic aspects of all cooling conditions were studied and analyzed in the context of sustainable manufacturing. The outcomes of this study reveal that the combination of textured tools and minimum quantity lubrication considerably enhance the machining and sustainability performance as contended with other conditions. However, the air quality factor i.e., PM2.5 particle generation was less in the case of a non-textured tool with MQL conditions. Overall, it is worthy to mention that the combination of tool texturing and MQL cooling conditions have been considered as one the potential combination in the area of green machining.

Keywords: Air Quality; Cutting fluids; Specific cutting energy; Sustainability; Textured tool; Titanium

1. Introduction

In today's developing scenario the notion of sustainable machining has mushroomed throughout the world. The uprising of awareness about eco-friendly nature and the strict environmental laws has been forced the researchers to search for sustainable/green manufacturing alternatives [1]. According to Indian Energy Statistics in 2019, the industrial sector registered the largest energy consumption shares (41.48%) out of the total electricity consumption during 2017-2018, and escalate swiftly with compound annual growth rates (CAGR) of 8.39% respectively [2]. Fig. 1 shows that energy consumed (petajoules) with the use of Coal and Lignite was at the top in comparison to other sources. Because the resources of electrical energy are overwhelmingly produced by consuming fossil fuels, therefore the utilization of electric energy in manufacturing sector creates carbon emissions. India stands at third position after China and America in terms of greenhouse gases (GHGs) emissions. But as per the Paris protocol it guaranteed a 33-35% drop in the carbon emissions by 2030, in contrast to 2005 measures.

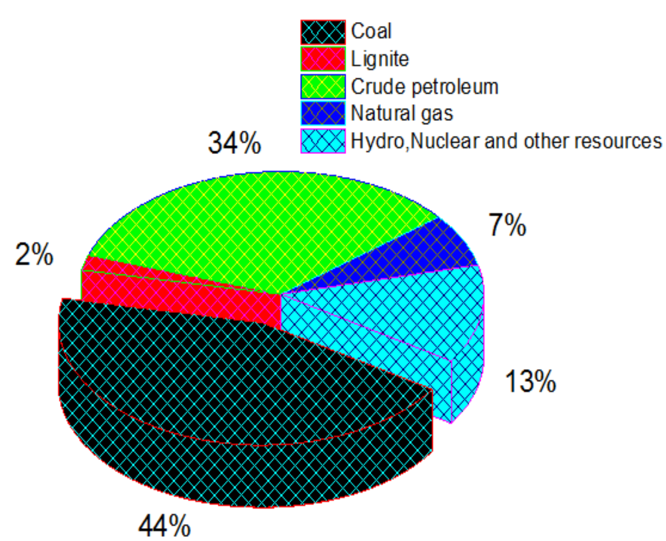


Fig. 1: Source-wise energy consumption in India during 2017-2018 [2]

In metal cutting manufacturing processes, the raw materials are transformed into finished components using electrical energy while simultaneously generating wastes and emissions. Further due to the rise in electricity charges, the proper understanding regarding lower energy consumption along with minimum emission of carbon particles during machining of titanium alloys has become a hot topic among researchers' community. Ti-3Al-2.5V (Grade-9) because of its high strength to weight ratio are used in hydraulic tubing of aircraft aerospace and connecting rods of racing cars, etc. Generally, this grade of Ti alloys is ideal for higher temperature, because it keeps their mechanical as well as creep resistance properties. But, due to poor thermal conductivity, high chemical affinity, and generation of high stresses during turning at the tool cutting edge Ti3Al2.5V lies under the group of hard-to-cut materials. Furthermore, because of poorer thermal conductivity, a large amount of cutting temperature is produced at the cutting zone which weakens the cutting tool and worsens the surface quality of the machined part [3]. To enhance the turning performance various types of synthetic-based coolants with the use of flood cooling are used by machinists [4]. Although due to their anti-environment nature (disposal issue, health problems) various eco-benign alternatives have been searched by the researchers [5, 6]. Nowadays, minimum quantity lubrication (MQL) has been a widely used and accepted eco-friendly technique within the researcher's community [7]. With the application of this process little quantity (50-200 ml/hr) of biodegradable cutting fluid along with compressed air supplies to the cutting zone [8]. Cutting fluid in the form of misting covers a large surface area of the tool-chip/tool-workpiece region and provides cooling/lubrication tasks resulted in less friction, lower temperature generation, reduced cutting forces, increased tool life, and improved surface roughness of machined component [6]. Recently, the surface texture technique has been arisen as an excellent sustainable alternative to enhance the machining performance [9, 10]. The generation of texture patterns on the tool surface helps in easily storing cutting fluid within the recesses and under the influence of hydrodynamic lift, force supplies the fluid on the rake surface of the cutting tool during turning. Therefore, with the aid of surface textured tool friction at the contact surface reduced and resulted in low cutting temperature along with minimum cutting forces and enhanced the tool life. The creation of less cutting force during turning under the influence of textured tools under the influence of MQL also helps in low energy consumption. The finding discovered that the use of surface textured tool/MQL technique or combination of texture-MQL is an excellent sustainable alternative to enhance the turning performance along with lower energy consumption as well as carbon emissions during machining. Ge et al. [11] explored the performance of fabricated micro-grooves on the rake face of carbide tools while turning H13 steel. Their results revealed that maximum wear at the rake face of textured tools was lowered by 63.8%-83.2% in contrast to un-textured tools due to the high shear angle and minimum friction coefficient. Singh et al. [3] found that during turning of Ti3Al2.5V with carbide cutting inserts under the influence of MQL environment tool life increased by 145% to 266% along with the excellent surface finish, whereas poor air quality (150 mg/m^3–305 mg/m^3) under MQL condition and maximum energy consumption under dry turning was measured. In another study done by Sing et al. [12], the investigators observed that textured tools under MQL environment enhanced the overall turning performance w.r.t. dry turning in terms of reduced tool wear, good surface finish, lowest chip curl diameter of chips resulted in large shear angle and low coefficient of friction. Gupta et al. [13] in their study established that textured tools with MQL conditions can be used sustainably without textured tools about reduced tool wear, excellent finish, and minimum temperature generation at the cutting zone while turning of titanium alloy. Orra and Chaudhary [14] compared the experimental results of machining with textured and un-textured tools. The authors observed that at a cutting speed of 150 m/min and feed 0.1 mm/rev, the reduction coefficient of the chip was 1.5 for surface textured tool resulted in high shear angle as well as low energy consumption in contrast to un-textured cutting tools. Arulkirubakaran et al. [15] done experiments for turning grade-5 titanium alloys using textured tools. They observed that fabricated texture tools produced minimum cutting forces, low cutting temperature as well as less wear of the cutting tool. Jianxin et al. [16] explained that development of lubricating layer with low shear strength helps in decreasing the contact area amid tool and chip surface while machining resulted in 5-15% reduction in cutting temperature, minimum cutting force (15-25%) in comparison to non-textured tool. Niketh and Samuel [17] studied the performance of micro-texture process for reducing of friction in tool-workpiece interface and the applications of textures on drilling tools for sustainable drilling of Ti6Al4V alloy. The researchers found that micro texturing of cutting tool is a viable technique to reduce energy consumption due to the reduction in frictional force in the machining process when drilling of Ti6Al4V alloy. Paras et al. [10] explored the tool life, and power consumption and surface roughness in cutting operation of AISI 1018 with textured tools under nano-cutting fluids. They concluded that the utilizing of textured tools with nano-cutting fluids has had an effect that reduces cutting tool wear, improves surface quality, lowers spindle load, and increases the efficiency of milling operations.

When the literature search is considered, it has been noticed that textured tools are significantly improved machining performance in terms of surface roughness, tool life, cutting force and cutting temperature, etc. However, it has been found that there is no comprehensive study taking into account the economic, environmental, and health aspects of machining using textured and non-textured tools under sustainable conditions. By considering these issues, this study explored tool life, surface roughness, and chip formation to meet economic sustainability. For environmental sustainability research, specific cutting energy consumption was considered and explored. Finally, to measure the extent of aerosols particles near the machining zone and make a comment about clean production, the air quality measurement concerning PM2.5 under various conditions was conducted in the machining process of Ti-3Al-2.5V alloy. More detailed information about the framework of the study, experimental process, and results can be found in the following sections.

2. Materials and methods

Experiments were conducted on a precision conventional lathe machine. For experimentation grade-9, Titanium alloy: Ti3Al2.5V is selected as base material. Due to the low strength to weight ratio and high hardness (32 HRC), Ti-3Al-2.5V is largely used in aerospace, hydraulic engine tubing, and for manufacturing connecting rods for high-speed racing cars. Table 1 indicates the elements that exist in the chosen material. The workpiece was 150 mm long and 32 mm in diameter. For turning trials, the properties of the selected cutting insert were as follows: ISO description: TNMA160408THM (Produced by WIDIA); tool geometry: nose radius of 0.8 mm, rake angle of 5° (negative), clearance angle of 5°, the inclination angle of 6°, major cutting edge angle of 90°. For generating patterns on the rake surface of insert femtosecond laser was used. Dimple textures (diameter =80μm, depth=50μm, center to center distance= 150μm) were chosen. To find more information about the manufacturing of texture patterns and optimization of texture parameters refer to the author's previous works [18]. Turning trials were performed under two different sustainable cutting modes such as dry and MQL as illustrated in Table 2. All parameters used in the machine tool during turning experiments are also presented in Table 3. In the selection of these mentioned parameters for turning experiments, literature information and the recommendations of the cutting tool manufacturer were taken into account. For tool wear analyzes, maximum flank wear was considered based on ISO-3685 and the tool maker's microscope (Produced by Mitutoyo) was utilized for measurements. The tests were terminated when the VB_{max} approached 0.3 mm. For this reason, it is assumed that the cutting tool life is over when VB_{max} reaches 0.3 mm. For measuring the quality of air surrounding the working area (PM2.5), advanced air quality (Smile drive) instrument was used during experimentation and for power measurements, the energy analyzer made by Fluke was employed on machine tools. The experimental setup and measurement procedures are presented in Fig. 2.

Table1. wt% chemical composition of elements

Al	V	Fe	O	C	N	H	Ti
3.3	2.4	0.24	0.12	0.05	0.02	0.012	Balance

Table 2: Machining experiment conditions

Code	**Conditions**
C1	Dry cutting condition with non-textured insert
C2	Dry cutting condition with textured insert
C3	MQL cooling condition with textured insert
C4	MQL cooling condition with non-textured insert

Table 3. Details of the parameters used in the turning tests and MQL system

Parameters	**Description**
V_c(m/min)	100 m/min and 150 m/min
F (mm/rev)	0.15 mm/rev
a_p (mm)	0.3 mm
MQL conditions	Cutting oil= canola oil, Flow rate = 120 ml/hr, Pressure = 6bar, nozzle distance(30mm) and nozzle angle with horizontal (45°)

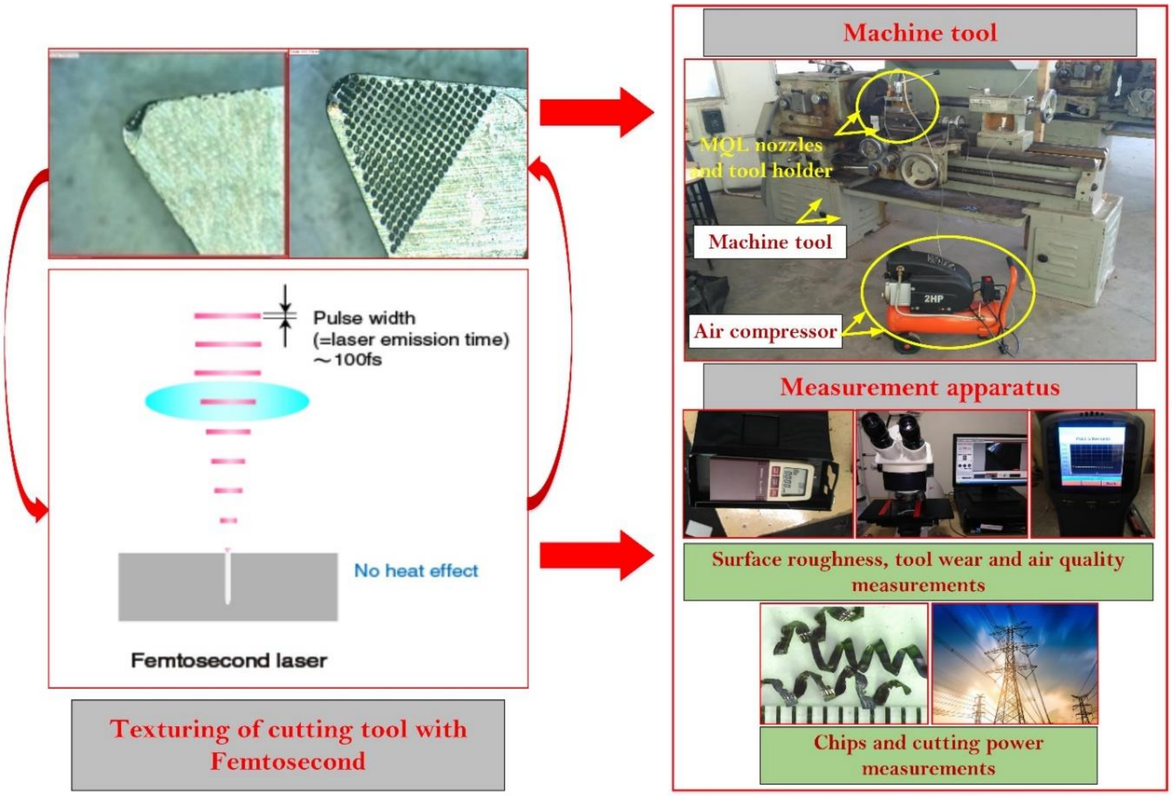


Fig. 2: The experimental setup and measurement procedures

3. Results and Discussion

3.1 Tool life

The concept of sustainability has been very effective in revising the targets in the field of machining in recent years. From a sustainability perspective, the primary performance measures of a manufacturing process are product quality, process cost, total energy consumption, employee health, environmental pollution, waste management, and process efficiency. However, in the process leading to sustainable manufacturing, trying to optimize all indicators at the same time complicates the process. It is, therefore, necessary to focus on the main factors that have a direct impact on sustainability measures. In this regard, it is unquestionable that tool wear or tool life is one of the most important of these factors since it has played a highly important role in controlling the sustainability measures especially such as workpiece quality, cost, and energy consumption [19]. Taking into account all these, in this section, tool life was explored during the turning of Ti3Al2.5V alloy with textured tools and without textured tools under several cutting modes such as dry and MQL, and outcomes are presented in Fig. 3. In addition, Fig. 4 shows worn tools under dry and MQL modes. Accordingly, it is possible to evaluate the results in Fig. 3 from three different aspects. These are the cutting speed effect, cooling condition effect, and tool effect. According to Taylor's well-known traditional equation ($V_c \times T^n = C$) [20], the most influential parameters of tool life are the cutting speed and n and c constants that are the particular combination of tool/workpiece material pair. As seen in Fig. 3, the tool life decreased by 50% in textured tools and 42.86% in non-textured tools with the increase of cutting speed during turning of Ti-3Al-2.5V under a dry environment. Similarly, the tool life decreased by 17.24% and 27.27% in textured tools and non-textured tools, respectively, under the MQL cutting environment. This situation is directly related to the increase in the metal removal rate per unit time and the temperature in the cutting zone. Increasing temperatures weaken the mechanical properties of the tool, causing it to wear faster [21]. Metal cutting fluids, which are applied more or less in the chip removal process, provide an opportunity to reduce both the friction on the surfaces in contact with each other and the temperature by accelerating the heat transfer in the relevant area. The MQL method (also called near-dry) delivers very small amounts of oil and compressed air to the cutting zone in a pulverized way, providing an effective performance and minimizing environmental concerns arising from excessive cutting oil employment. As shown in Fig. 3, the MQL method depending on the tool type achieved an improvement of between about 107% and 220% in tool life compared to dry cutting. This result is very important in terms of meeting the various criteria of sustainable machining with environmental approaches such as MQL. Although the efficiency of the cutting process is tried to be increased by using a little or too much cutting fluids, alternative efforts except for the use of cutting fluids are continuing to increase tool performance under both dry conditions and other cutting conditions [9]. One of these efforts is the textured tools that are the subject of this study. In this study, tool life was improved by textured tools in different percentages as per changing cutting conditions. Namely, while tool life improved between 40 and 60 percent in a dry environment thanks to texture tools, this improvement was realized as 31.8 to 50 percent in the MQL environment. Tool surface texturing is one of the promising ways to allow sustainable machining by improving tribological properties [22]. In the literature, the contribution of textured tools to the cutting process has been based on more than one reason. For example, the creation of micro-scale surface textures in cutting tools improves the lubrication capacity and reduces adhesion, and provides significant improvements in friction coefficient by reducing the contact length between the chip–tool interface and consequently tool wear [23]. It was stated that the textured surfaces prevent the hard particles belonging to the tool and the workpiece from being trapped in the textured surfaces, thus preventing them from acting as abrasive between the tool and the workpiece [24, 25]. In addition, Gupta et al. [13] also emphasized that as the channels produced by textured expands the surface area of the tool, the heat dissipates better, which reduces tool wear. It was claimed that by Arslan et al. [24] textured grooves act as a reservoir, ensuring a continuous supply of oil on the tool-chip surface. Therefore, this allows an improvement in machining output parameters which increases tool life. It is thought that although special machine types are required for the production of textured tools, which are considered both as a sustainable technique and as an alternative to the use of cutting fluids if they are adopted during the production phase of the cutting tools, it can be very beneficial in terms of environmentally friendly production [9].

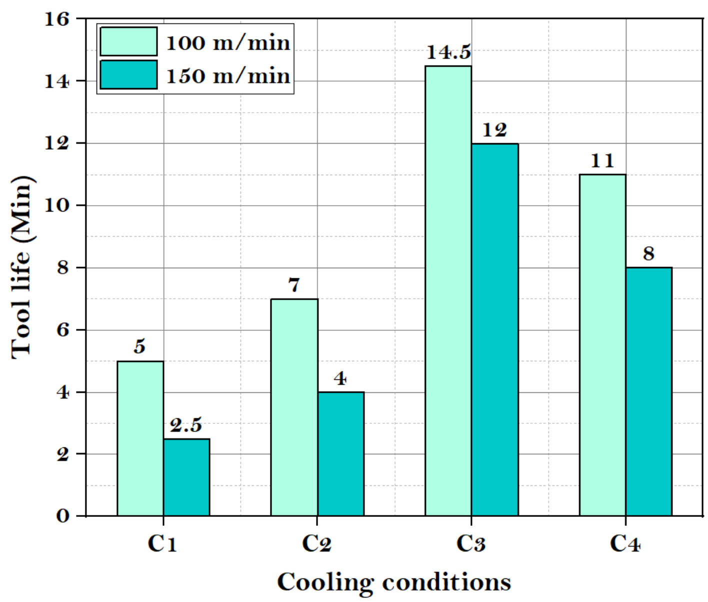


Fig. 3: The effect of machining conditions on tool life while turning titanium alloy

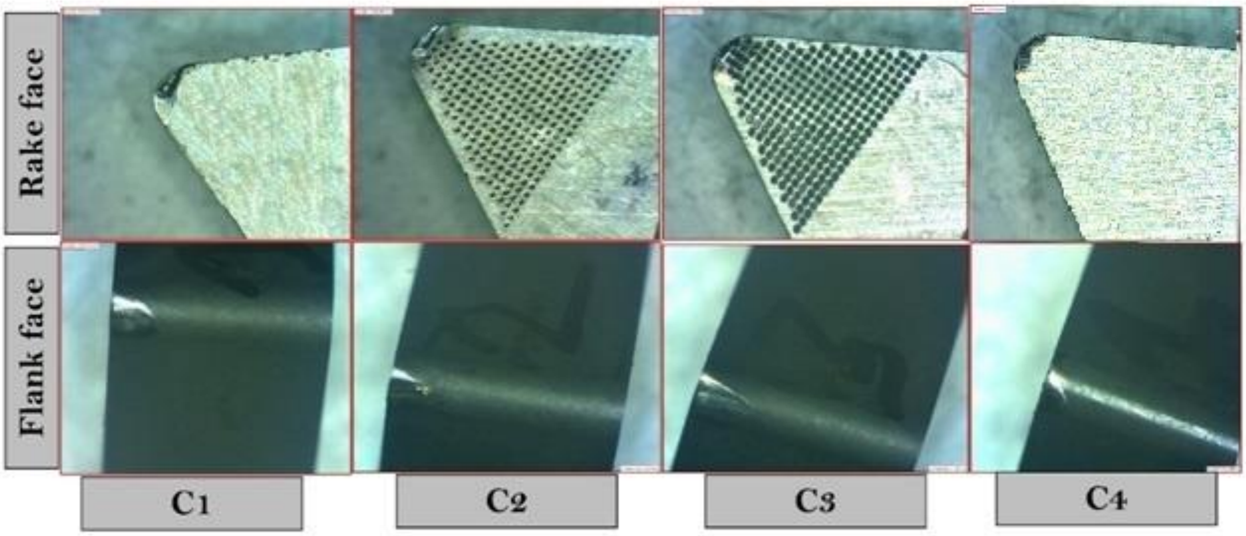


Fig. 4: Worn cutting inserts under various turning conditions at cutting speed of 100 m/min

3.2 Surface roughness

The quality of the machined surfaces is one of the most important criteria of sustainable production. Because a low surface roughness significantly develops the fatigue strength, corrosion resistance, and friction life of the surface. Surface roughness also affects some functional features of parts viz., contact, wear, heat conduction, ability to hold and distribute the oil film, coating and resistance life, etc [26]. For this reason, process parameters should be chosen appropriately to accomplish the desired surface characteristics. Moreover, it is a very important issue that this process is carried out by the sustainable product concept. In the current research, the surface roughness of the workpieces was measured after turning the Ti alloy with different types of inserts under dry and MQL conditions, and the results are shown in Fig. 5. According to the average surface roughness (Ra) equation ($Ra=f^2/32\times r$), the two known most effective parameters on roughness are feed rate (f) and nose radius of the insert (r). Therefore, in this study, both parameters are taken as constant and the effect of other inputs i.e., insert type (textured and non-textured tools), cutting environments (dry and MQL), and cutting speed (100 and 150 m/min) on roughness has been investigated. Accordingly, there is a clear increase in surface roughness with increasing cutting speed as seen in Fig. 5. This percentage increase varied between 4.88% and 13.23% depending on the tool type and cutting environment. The reasons for this increase were thought to be the acceleration of tool wear with increasing cutting speed as mentioned in the previous section. When turning with textured tools under a dry environment, the highest surface roughness was measured as 0.97

μm. Later, with the incorporation of the MQL system into the cutting process, the surface roughness was also significantly reduced. Through MQL, this decrease was calculated as 37.1% and 35.1 for 100 m/min and 150 m/min cutting speed, in non-textured tools respectively, and 39.7% and 44.2% in textured tools compared to dry turning environment. The superiority of the MQL method over dry cutting has often been mentioned in the literature [7, 27, 28]. The fact that the MQL method reduces friction by creating a thin oil layer on the tool-chip surface decreases the cutting temperature, prevents the workpiece distortion due to high temperature, and easy evacuation of the chips from the cutting area can be counted among the important factors in reducing the surface roughness [6]. Although surface quality can be improved by setting the cutting parameters to lower levels and by using cutting fluids, this raises concerns such as environmental pollution, health, productivity, and machining economy. Hence, researchers have applied texturing to tools as an alternative method to improve process performance in both dry environments and sustainable cutting environments such as MQL [12]. In this study, the textured tools reduced the surface roughness in both dry and MQL environments (refer to Fig. 5). While the surface roughness with textured tools has improved by up to 23.6% tools under dry environment, it has improved up to 31.8% under the MQL environment as compared to conventional tools. The main purpose of the development of textured tools was to improve tribological properties during machining [29]. The main mechanisms for improving the tribological properties of these tools are debris compaction, decrease in contact length, development in lubrication capacity, greater thermal dissipation area; this ultimately helps to reduce the machining force tool wear and consequently the surface roughness of the workpiece [22].

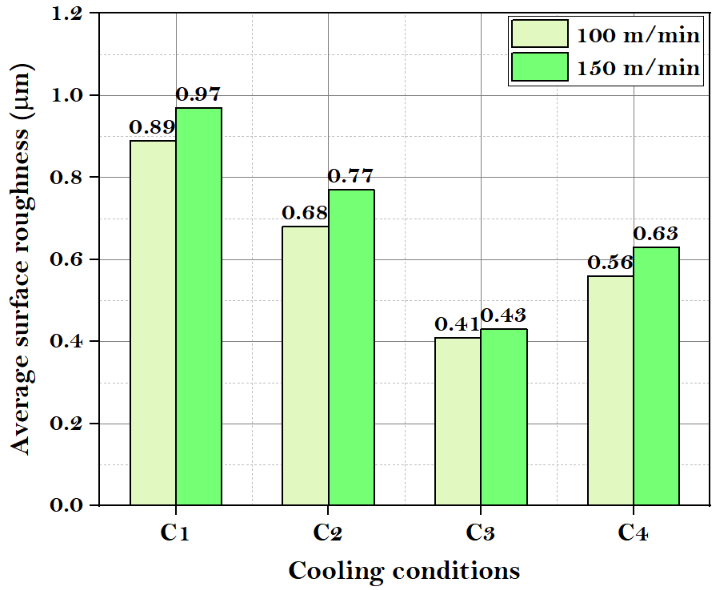


Fig. 5: The effect of machining conditions on surface roughness while turning titanium alloy

3.3 Specific cutting energy

In the manufacturing industry, the share of machine tools in energy consumption is considerably high [30]. Because of the growing worries about the depletion of fossil fuel resources and the environmental pollution and climate change-related use of mentioned resources for electricity generation, there is serious pressure on the energy waste of machine tools to reduce the negativities associated with the excessive use of energy to produce a product [31]. Therefore, it has become a necessity to ensure energy efficiency in machine tools. For this, specific cutting energy (E_{SC}) is commonly utilized to analyze the energy efficiency for machining processes.

$$E_{SC} = \frac{E_{machining}}{MRR} \quad (1)$$

Here, $E_{machining}$ is the energy consumption in J during machining and MRR is the chip volume (mm^3). So, E_{SC} in J/mm is defined as unit energy consumption during machining to remove a unit volume of work material. A lower E_{SC} is clear evidence that energy is used efficiently during cutting. In this section, the specific cutting energy in machine tools during turning of Ti-3Al-2.5V alloy under dry and MQL environments by using non-textured and textured tools were investigated and the results are provided in Figure 6. Accordingly, a clear decrease in specific energy consumption is seen with increasing cutting speed. This decrease was between approximately 28%-29.4%. On the one hand, increasing the cutting speed increases the consumption of electrical energy for the spindle to rotate faster, on the other hand, it also increases the volume of the chip removed per unit time. Since the rate of increase in the chip volume was higher than the increase in energy consumption, there was a decrease in specific cutting energy at elevated cutting speeds. It has been reported that about 30% of the world's total energy is used to overcome friction [32]. The employment of cutting fluids is often at the forefront of efforts to reduce the friction between contacting surfaces. As seen in Fig. 6, the specific cutting energy has been brought to more reasonable levels using the MQL system. Compared to dry cutting, the reduction in E_{SC} was between 8.2% and 12.8% through the MQL environment. A very small amount of lubricant with compressed air penetrates the tool-chip interface in a pulverized manner, resulting in the formation of a thin oil film layer in this area and thus a decrease in the friction coefficient between the contact surfaces [27, 33, 34]. The formation of micro-sized textures on the rake face is another method to reduce the friction between contacting surfaces and consequently energy consumption. The ability of textured tools to reduce specific cutting energy compared to non-textured tools can be also seen in Fig. 6. The improvement in specific cutting energy under dry cutting with textured tools was up to 5.5% in comparison with non-textured tools. The reduction of specific cutting energy is seen as an important result in dry cutting without any cutting fluid. Moreover, the improvement in specific cutting energy under MQL with textured tools was up to 8.9%. The basic factors behind the reduction in specific cutting energy are the trapping of hard and abrasive micro-sized particles, which lead to friction and wear, inside the micro-grooves, and the improvement of tribological characteristics [22]. In general, it can be said that the positive effect of textured tools on friction and wear in the machining process helps to improve energy efficiency and tool life and product life, and quality.

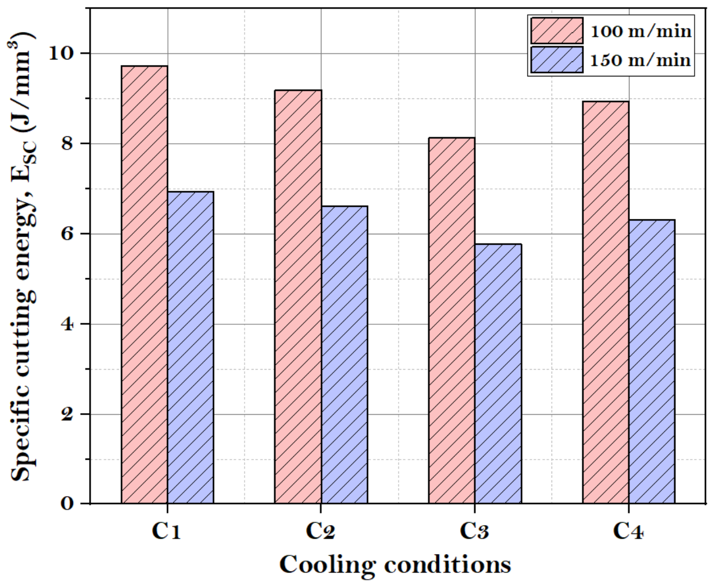


Fig. 6: Influence of machining conditions on specific cutting energy while turning titanium alloy

3.4 Air pollution

Nowadays air pollution surrounding the machining zone has been a major concern among the machinist community. During turning various type of factors generates poor air quality like dust in case of dry machining and formation of aerosols in MQL machining. To measure the extent of aerosols particles near the machining zone, air quality measurements concerning PM2.5 under various conditions (Table 2), were conducted. Aerosols (PM2.5 or <PM2.5) easily enters the extreme regions of the lungs and generates various health issues like occupational asthma, bronchitis, and pneumonia, etc. Therefore, efforts are required to investigate the quality of air surrounding the working area to mitigate dangerous health issues. Fig. 7 shows the generation of PM2.5 under various conditions at varying speeds. As the speed increases from 100 m/min to 150 m/min, the aerosol generation also increases. However, the maximum PM2.5 particles were generated under C4 conditions followed by C3, C1, and C2 at both tested speeds. The application of textured tools creates fewer PM2.5 particles under MQL as well as dry turning. Texture tools help in retaining liquid particles in case of MQL and debris under dry turning. When pressurized fluid hits the cutting tool surface then due to irregular tool surface area low amount of PM2.5 is generated under the MQL environment. At the highest cutting speed, the use of textured tools under the MQL environment (C3) generates 22 % less

PM2.5 in comparison to non-textured tools under MQL (C4) conditions. Fig. 8 also shows the actual measurement of PM2.5 particles surrounding the machining region under MQL environment at highest cutting speed. Similarly, the formation of PM2.5 particles with the use of textured tools under dry state (C2) was 24 % less than turning with non-textured tools under dry conditions (C1). With the rise in speed the generation of PM2.5 particles increases in the range of 12% (C1), 13% (C2), 5.1% (C3), and 8.6% (C4) under varying conditions. Next, under dry turning the generation of PM 2.5 particles were between 50%-128% lower than the MQL turning at maximum speed.

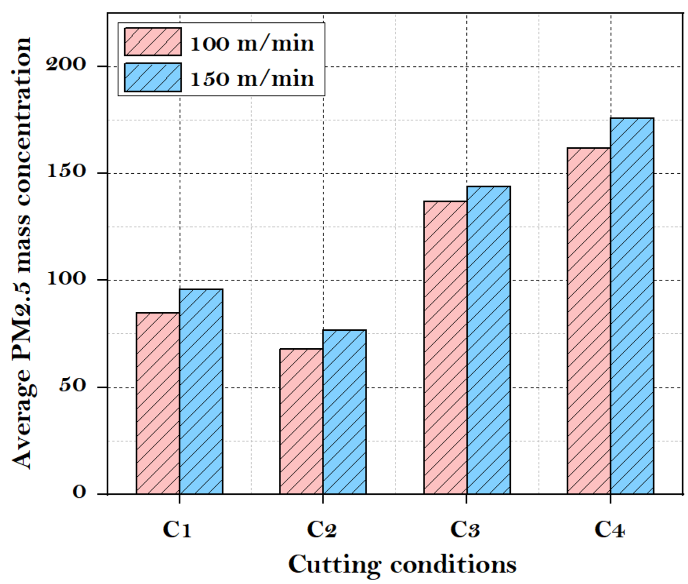
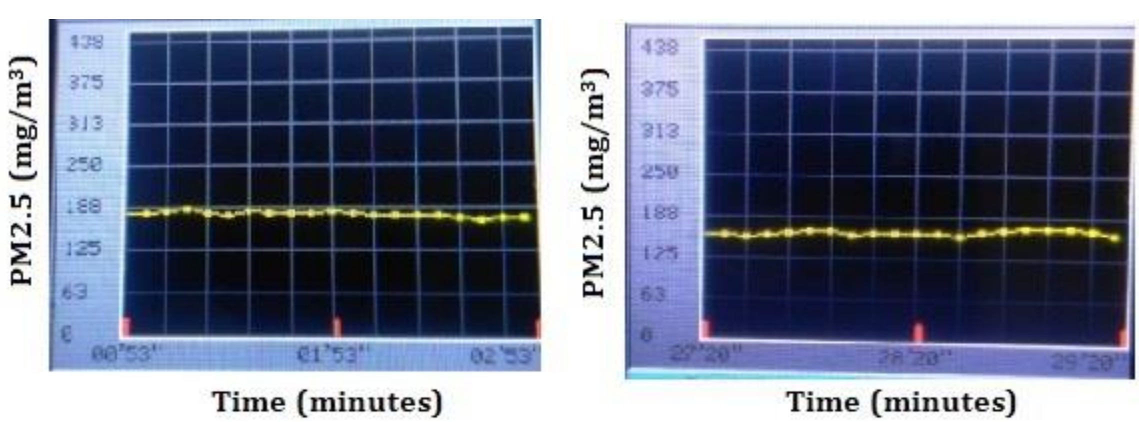


Fig. 7: PM2.5 particles generation under various machining conditions



(a) (b)

Fig. 8. PM2.5 aerosols formation under (a) C3 and (b) C4, conditions at 150 m/min

3.5 Chip morphology

Fabrication of textured patterns significantly affects the chip's morphology. These patterns reduced the area of contact between chips and tool rake surface in comparison to non-textured tools. The analysis of chip morphology at the highest cutting speed depicted that texture geometry along with MQL supply reduced the chip curl diameter, as indicated in Fig. 9. The curling of chips or curl diameter lies in the order of C1>C2>C4>C3. Under dry state machining with a non-textured tool (C1) creates more chip curl radius in contrast to dry turning with a textured tool (C2). This was mainly due to the reduced contact area between sliding chips and tool rake face with the application of textured tools resulted in enhanced chip breakability. Another reason for less chip curl diameter under C2 than C1 is trapped debris within the texture pockets. This trapped debris in the form of dry dust formed an uneven surface on the rake face of the cutting tool due to which high friction generated and resulted in discontinued chips along with reduced chip-curl diameter. Further, under the MQL environment, both cooling, as well as lubrication action provided by MQL fluid, helps in minimum curling of chips than dry turning. The pressurized fluid also enhanced the chip's breakability. It is visible from Fig. 9 (C3 and C4) that with the use of textured tools under the MQL environment chips are disintegrated into very small particles in comparison to turning without a textured tool (C4). Under C4 condition, the contact area of sliding chips on the top surface of the tool was large, therefore, more curling has been seen in contrast to the C3-MQL environment. So, in nutshell textured tools with MQL provide better lubrication and cooling at the tool-chip interface along with reducing the contact length (low chip-curl diameter) and resulted in better surface finish and less tool wear.

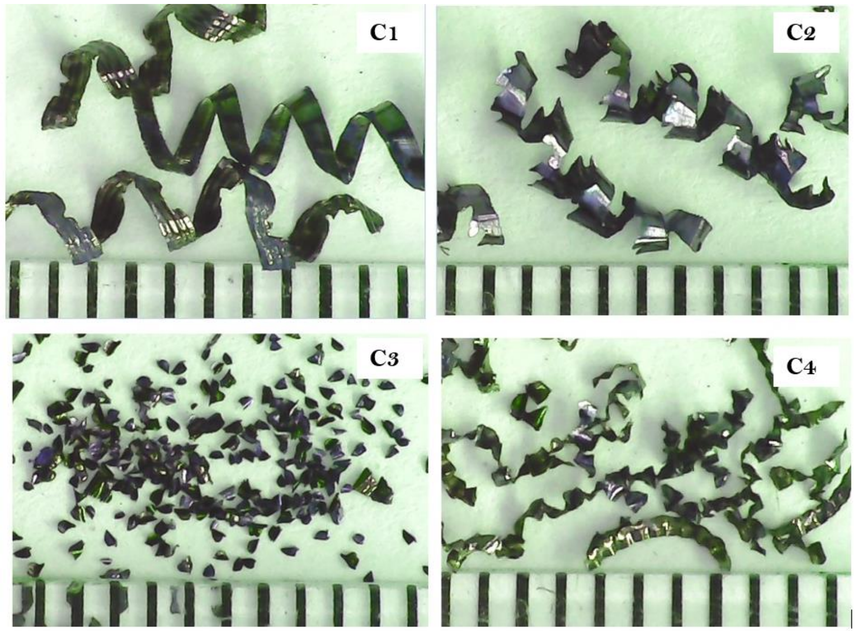


Fig. 9: Chips morphology under different conditions (C1, C2, C3, C4) at 150 m/min

3.6 Overall evaluation of sustainability indicators

The present work comprises two investigations (1) Machinability studies and (2) environmental studies. In the machinability studies, tool wear and tool life, surface roughness, and chip morphology were evaluated, whereas the novel indicator air quality and specific cutting energy during machining operation were considered in environmental studies. In this section, the social, economic, and environmental factors related to the employed machining conditions are deliberately discussed in Table 4. Based on these observations it has been noticed that the cooling conditions considerably affect the machining efficiency and environmental aspects.

Table 4. Performance indicators under different cooling conditions

Sr. No.	Indicator	Cooling conditions	Remarks
1.	*Social*	Dry without textured	The employed cooling condition i.e., a textured tool under MQL condition provides good results. It also produces fewer emissions and their effect is less on humans and operators during machining operations.
		Dry with textured	
		MQL cooling with textured	
		MQL cooling without textured	
2.	*Economic*	Dry without textured	Textured tool under MQL environment enhanced tool life
		Dry with textured	

		MQL cooling with textured	along with excellent surface finish helps in reducing manufacturing cost.
		MQL cooling without textured	
3.	*Environment*	Dry without textured	With the application of textured tools the air quality surrounding the machining zone improved.
		Dry with textured	
		MQL cooling with textured	
		MQL cooling without textured	

4. Conclusions

In the current investigation, the experimental trials were carried out on titanium alloy under different cutting conditions. The various indices such as tool life, surface roughness, specific cutting energy, air quality, and chip formation were studied. Based on the experimental findings, the following conclusions were drawn:

1. The tool life is highly influenced by the combination of textured tools and MQL cooling conditions. This combination provides a higher tool life while machining difficult-to-cut titanium alloy. The reason is that the MQL cooling and tool texturing provides both lubrication and cooling effect during the machining operation. This mechanism results in the low value of cutting temperature at the tool-chip interface and therefore, good tool life was observed.
2. The surface roughness values were drastically reduced with the application of MQL conditions and tool texturing. Through MQL, this decrease was calculated as 37.1% and 35.1 for 100 m/min and 150 m/min cutting speed, in non-textured tools respectively, and 39.7% and 44.2% in textured tools compared to dry turning environment.
3. The specific cutting energy values were decreased with an increase in cutting speed values. The cutting speed increases the consumption of electrical energy for the spindle to rotate faster, and it also increases the volume of the chip removed per unit time. Since the rate of increase in the chip volume was higher than the increase in energy consumption, there was a decrease in specific cutting energy at elevated cutting speeds. When the comparison between cooling conditions was made, the MQL and textured tools also provide the minimum specific cutting energy values.
4. The air quality during machining was measured in this work. The minimum values were noticed under dry conditions because, at dry conditions, very few fumes were produced during the machining operation.

5. Lastly, the chips were observed under all cutting conditions. Dry state machining with a non-textured tool creates more chip curl radius in contrast to dry turning with the textured tool. This was mainly due to the reduced contact area between sliding chips and tool rake face with the application of textured tools resulted in enhanced chip breakability. Further, under the MQL environment, both cooling, as well as lubrication action provided by MQL fluid, helps in minimum curling of chips than dry turning. The pressurized fluid also enhanced the chip's breakability.

Ethics approval and consent to participate

Not applicable

Consent for publication

The consent to submit this paper has been received explicitly from all co-authors.

Availability of data and materials

Not applicable

Competing interests

The authors declare that they have no competing interests.

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Conceptualization: Rupinder Singh and Munish Kumar Gupta**; Methodology:** Rupinder Singh and Munish Kumar Gupta**; Investigations:** Rupinder Singh and Munish Kumar Gupta**; Writing original draft: All the authors; Writing, review, and editing: All the authors.**

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