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ORIGINAL ARTICLE

Sustainability Evaluation of Machining Ti6Al4V with Graphene Inclusion

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ABSTRACT – Ti6Al4V has wide applications but is generally considered to belong to the "difficult to machine" category. The present work aims at evaluating sustainability while machining Ti6Al4V with inclusion of graphene. Graphene is included using two methods in this work. In method one, graphene is included as a dispersant in cutting fluid and applied as minimum quantity lubrication (MQL). In the other method, graphene is filled in microholes on tools to form self-lubricating tools. Experiments are performed, and results are used to evaluate carbon footprint of the operation on the environment. Economic analysis is also performed—application of graphene as dispersant as well as in solid form enhanced machining capability of Ti6Al4V. Application of 0.3 wt.% graphene dispersed cutting fluid is found to be the most economic. The use of graphene in both forms could improve the machinability of Ti6Al4V and is also found to be economical but has enhanced carbon emission to the environment.

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NOMENCLATURE

CF_{prod}	carbon footprint during manufacturing a product (kg CO_2eq)
CF_p	carbon footprint due to the generation of power utilized during machining (kg CO_2eq)
CF_{co}	carbon footprint due to making of coolant and scrapping after usage (kg CO_2eq)
CF_t	carbon footprint due to the production of cemented carbide tools utilized (kg CO_2eq)
CF_{Tial}	carbon footprint of Ti6Al4V chips developed while converting Ti6Al4Vrod to the final product (kg CO_2eq)
CF_{chip}	carbon footprint due to reprocessing of chips (kg CO_2eq)
CF_{Gr}	carbon footprint due to graphene fabrication (kg CO_2eq)
E_{tot}	total energy consumed (in kW)
E_m	energy consumed during machining = $F_t v$
t	time taken for machining
E_i	energy consumed during idle period of machine (kW).
t_i	time for which the machine is idle
E_{comp}	energy utilized by compressor (kW)
t_{comp}	time for which compressor is in operation
E_{mql}	energy utilized by MQL system (kW)
E_{soni}	energy utilized by sonicator
t_{soni}	sonication time (sec)
N	number of holes drilled on the cutting tools
E_{hdr}	energy utilized by laser for making a hole (kW)
t_{hdr}	time taken for hole drilling using laser (sec)
T_{co}	coolant life
CF_{copr}	carbon footprint for coolant production (kg CO_2eq)
CF_{codi}	carbon footprint for coolant disposal (kg CO_2eq)
CO_i	quantity of coolant initially used.
CO_{ad}	quantity of coolant additionally used
δ	amount of concentrate cutting oil
T_{tool}	cutting tool life
m_t	mass of cutting tool
m_c	mass of material removed in form of chip
ρ	density of workpiece material in g/cm^3
MRR	metal removal rate in mm^3/sec

where P_c is expenses on consumables

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P_{co}	expenses on coolant
P_{w}	expenses on water
P_{Gr}	expenses on graphene
P_{Tx}	expenses on TritonX100
P_{pow}	expenses on power utilization
P_{i}	expenses on power utilized when the machine is idle per month
P_{m}	expenses on power utilized during machining per month
P_{comp}	expenses on power utilized by compressor per month
P_{mql}	expenses on power utilized by MQL system per month
P_{soni}	expenses on power utilized by sonicator
P_{hdr}	expenses on power utilized by laser equipment for drilling holes per month
P_{tool}	expenses on cutting tools utilized per year
P_{insert}	price of one cemented carbide insert
n	cutting ends per tool (n= 4 for CNMG tool, 8 for SNMG tool)

INTRODUCTION

Ti6Al4V has vast applications in the oil industry, offshore, subsea oil, and gas due to its excellent corrosion-resistant property [1]. Its ability to osseointegrate with human bone led to its wide use in the biomedical field [1]. But low modulus, high strength at elevated temperatures, low thermal conductivity, and high chemical reactivity with the cutting tool make them difficult to machine [2]. Optimum cutting velocity was found to be 60m/min with the use of PVD coated cemented carbide inserts [3, 4, 5], and with uncoated cemented carbide insert is less than 50 m/min at 0.5 mm/rev feed [6]. Research is being done to improve the machinability of Ti6Al4V. Mishra et al. [7] created microchannels on coated cemented carbide tools and used them for machining Ti6Al4V. Texturing reduced cutting forces, friction coefficient, and curl radius. Shah et al. [8] drilled Ti6Al4V using flood coolant and cryogenic coolants – liquid nitrogen and carbon dioxide. Cryogenic machining with liquid carbon dioxide showed the least wear, followed by cryogenic machining with liquid nitrogen. Muhammad et al. [9] compared the influence of two sustainable methods: cryogenic application and minimum quantity lubrication (MQL) application of hybrid nanofluids while machining Ti6Al4V. Alumina and multi-walled carbon nanotubes were used in hybrid nanofluids. Hybrid nanofluids led to a reduction in surface roughness, cutting forces, and tool wear over cryogenic machining, while the latter led to a reduction in cutting temperature over MQL of hybrid nanofluids. Bai et al. [10] used six types of nanoparticles dispersed in cottonseed oil while machining Ti6Al4V to evaluate their lubricating properties. Alumina nanoparticles showed lubricating properties followed by silicon dioxide nanoparticles, as they showed lesser machining forces and reduced surface roughness compared to the use of other nanoparticles. Kishawy et al. [11] machined Ti6Al4V at varying levels of design variables using MQL - nanofluid and predicted design variables for sustainability assessment. Cutting speed: 170 m/min, feed rate: 0.1 mm/rev, and 2 wt. % Al_2O_3 were found to be the most sustainable parameters. Zheng et al. [12] formed line textures and hexagonal textures on the rake face of cemented carbide tool and used it while machining Ti6Al4V. Texturing reduced cutting forces, and line texturing showed a higher reduction in cutting forces. Texturing position and parameters have to be studied carefully, as it influences tool strength.

Graphene is the thinnest, strongest, and most conductive material of heat and electricity [13]. These properties led to research utilizing graphene in various applications: thermal, sensors, storage, coatings, and batteries [13]. Graphene is also tested by a few researchers while machining Ti6Al4V. Li et al. [14] performed milling of Ti6Al4V and tested the performance of graphene dispersed in vegetable oil. Milling forces, temperature, tool wear, and surface integrity were drastically reduced with the use of graphene dispersed vegetable oil. García Martínez et al. [15] reviewed the works of many researchers on sustainable lubrication methods while machining Ti6Al4V. Sustainable lubrication methods like cryogenic lubrication, minimum quantity lubrication, minimum quantity cooling lubrication, use of textured tools and laser beam assisted machining were used by many authors while turning, milling, and drilling, and parameters like cutting forces, surface roughness and tool wear are evaluated. The use of graphene dispersed cutting fluid as an MQL application is not mentioned in this review. Kong et al. [16] investigated the performance of graphene mixed lubricant in hot rolling of titanium alloy sheets. Friction coefficient decreased by 30-35% compared to dry friction condition and resulted in crack-free surface and reduced debris. Patel et al. [17] investigated the tribological behavior of liquid lubricant and semi-liquid lubricant by adding graphene platelets and titanium dioxide. In the case of liquid lubricant, the use of 0.05wt% of graphene showed a good reduction in coefficient of friction, while the use of 0.1 wt.% of titanium dioxide showed more wear resistance. The combined use of graphene platelets and titanium dioxide helps in tailoring the friction and wear behavior of the lubricant. In the case of semi-solid lubricants, the addition of both nanoparticles reduced the coefficient of friction. At 20 N, high graphene concentration and low titanium dioxide concentration indicated a higher reduction in coefficient of friction. Yi et al. [18] performed turning of Ti6Al4V rod using PCBN cutting tool and maintained a very low depth of cut of 0.1 mm using varying concentrations of graphene-based nanofluids. Nearly 50% reduction in cutting forces was identified with the use of graphene oxide nanoplatelets in cutting fluid. Flank wear was reduced by almost 78% with the use of 0.3 wt.% graphenes dispersed cutting fluid. Fewer vibrations are reported at lower feed, and high coolant pressure with the use of graphene dispersed cutting fluid.

In manufacturing, any process or a product is said to be sustainable if it satisfies the three E's: employee, environment and economy, i.e., the process or the product should be employee-friendly, environmentally safe, and is economical to manufacturers. Thus, any new product has to be checked for sustainability. Abdul Rashid et al. [19] reviewed and compared four strategies of sustainable manufacturing, i.e., the efficiency of materials and resources, minimization of waste, and economic efficiency. The waste minimization strategy is found to be simpler, but its coverage is found to be narrow, while the economic efficiency strategy is found to be complex with wide coverage. Li et al. [20] proposed a method to analyze carbon emission while machining on a computer numerical control (CNC) machine. In this, the total process is broken down into smaller processes, and carbon emission during each process is evaluated and is used to find overall carbon emission quantitatively. The process is explained in detail, providing two case studies. Khan et al. [21] used alumina–graphene hybrid nanofluid in machining Haynes 25 alloy and evaluated carbon emission, energy consumption, and production cost. Khanna et al. [22] evaluated the sustainability of conventional flood machining, cryogenic machining, and minimum quantity lubrication while machining Ti6Al4V and found cryogenic machining to be the most sustainable. Karim et al. [23] evaluated the sustainability of MQL machining Al-based alloy using the PCD tool by evaluating environmental, economic and machining performance. MQL application consumed less energy and achieved higher metal removal with lesser tool changes. Shang et al. [24] devised a novel procedure for sustainability evaluation in industries by integrating energy consumption with the virtual manufacturing process. Carbon footprint and cost evaluation were also performed.

Though researchers worked on improving the machinability of Ti6Al4V using textured tools/cryogenic machining/MQL nanofluid application/graphene, not much work is done on evaluating environmental effects using carbon footprint analysis and economic analysis, which is a must to determine the sustainability of any product/ process. The present work investigates the influence of using graphene in two ways: as a solid lubricant and as a dispersant in cutting fluid while machining Ti6Al4V. The sustainability of use of graphene in machining Ti6Al4V is evaluated by investigating machining performance and environmental effects using carbon footprint analysis and by performing economic analysis.

MATERIALS AND METHODS:

Experimentation

Graphene is a very good solid lubricant and has high thermal conductivity. Graphene nanoplatelets C500, purchased from XG Sciences USA, are used while machining Ti6Al4V. Ti6Al4V rods of 150 mm long and 30 mm diameter were purchased from South Asia Metals and Alloys, Mumbai. Graphene is applied in two forms while machining Ti6Al4V. In the first case, it is applied in solid form. Microholes are drilled on the rake face of cutting tools using femtosecond laser and filled with graphene to form G1 tool, G3 tool, and G5 tool. G1 tool, G3 tool and, G5 tool have 1, 3, 5 holes drilled respectively on them. Figure 1(a) shows the table set-up to place the cutting tool on which hole is drilled using the laser. Figure 1 also shows the dimensions of holes drilled on cutting tools for (b) G1 tool (c) G3 tool (d) G5 tool; inserts with holes drilled for (e) G1 tool (f) G3 tool (g) G5 tool. In the second case, graphene is dispersed in cutting fluid to enhance the property of base cutting fluid, i.e., water-soluble oil. Water-soluble oil is widely used in industries as a cutting fluid due to its good cooling properties. Graphene dispersed cutting fluids (SO 0.1, SO 0.3, SO 0.5) are prepared by dispersing 0.1 wt. %, 0.3 wt. % and 0.5 wt. % of graphene in water-soluble oil. Triton X 100 is added as a surfactant to ensure proper dispersion of graphene in water-soluble oil during sonication using a probe sonicator.

Figure 2 shows the dispersion stability of graphene dispersed cutting fluids. Due to the addition of surfactant, hydrophobic graphene dispersed stably in cutting fluid. Graphene dispersed cutting fluid is applied as minimum quantity lubrication (MQL). The nozzle is placed in such a way that the cutting fluid strikes the back of the chip. Cutting tools used are diamond-shaped PVD AlTiN coated cemented carbide inserts of grade KC5010, Kennametal makes. Turning is performed on Ti6Al4V by maintaining the depth of cut and feed as constant at 0.5 mm and 0.13 mm/rev, respectively, and by varying cutting velocities as 67 m/min, 74 m/min, 87 m/min and 112 m/min. Turning is performed on CDL6236 lathe (230V, 50A, Power factor: 0.75). As per Shokrani et al. [3], the optimum cutting velocity while machining Ti6Al4V with coated cemented carbide tool is 60m/min. To have more tool wear, higher cutting velocities are selected and chosen velocities are based on available spindle speeds on a 5hp CDL6236 lathe. Figure 3 shows the experimental set-up. Turning of Ti6Al4V rod is performed at all four cutting velocities using (a) dry machining with (i) G0 tool, (ii) G1 tool, (iii) G3 tool and (iv) G5 tool, and (b) MQL application of (i) SO0 (ii) SO0.1 (iii) SO0.3 (iv) SO0.5 cutting fluids. G0 tool is a cutting tool with no hole, and hence no graphene and SO0 is a water-soluble cutting fluid with no graphene.

Tangential cutting force (F_t) influences energy consumed during machining, which in turn influences carbon emissions and expenses during production. Tangential cutting force is measured using dynamometer 9257B, Kistler make. Tool wear decides the number of tools utilized and hence influences the carbon footprint and economic analysis. Metzer tool maker's microscope with camera for image acquisition is used to measure tool wear. Figure 3 also shows the toolmakers microscope. For all cases, each experiment is performed thrice and the average of the results is used for further analysis. Figure 4 shows the SEM images of the cutting tool surface after machining with dry condition and MQL application of SO0.3. Darker shades in image (b) is due to the presence of graphene.

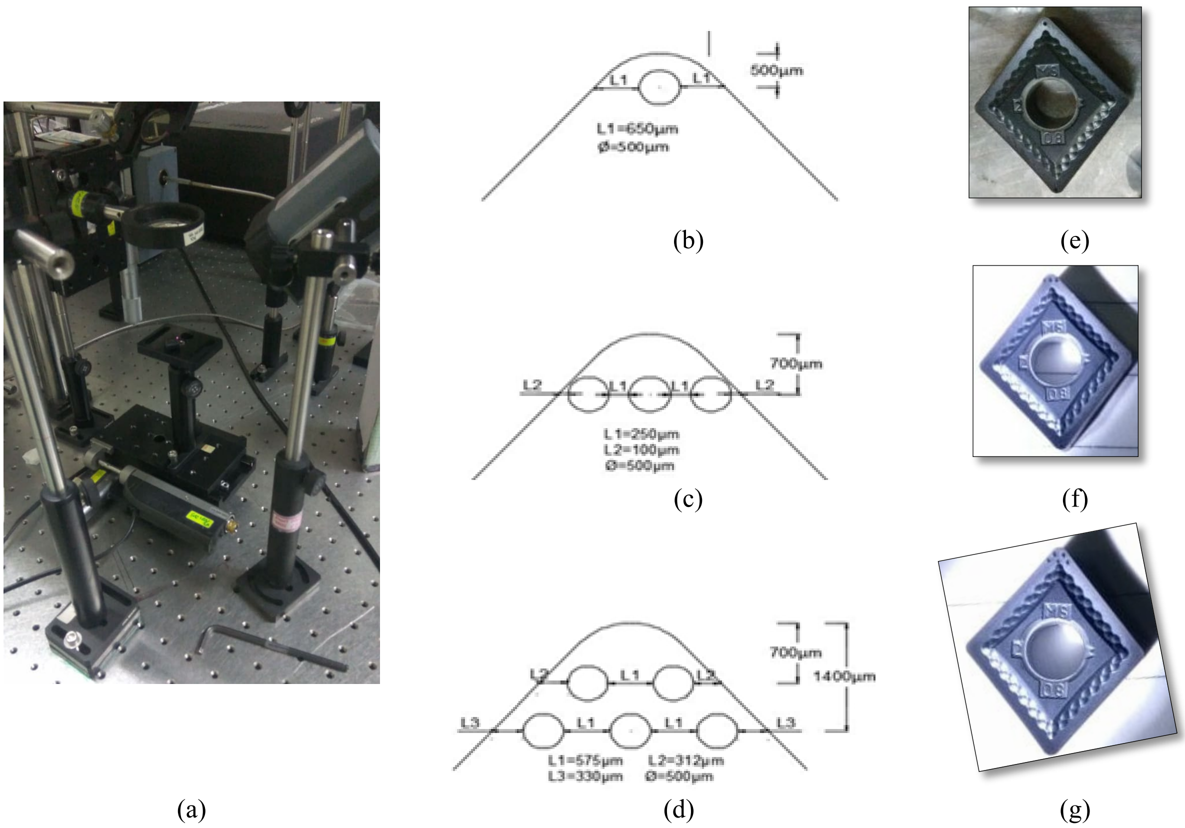


Figure 1. (a) Table set-up to place cutting tool for hole drilling, hole dimensions for (b) G1 tool (c) G3 tool (d) G5 tool, and inserts with holes drilled for (e) G1 tool (f) G3 tool (g) G5 tool.

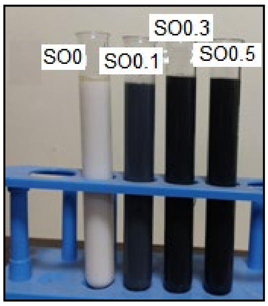


Figure 2. Dispersion stability of graphene dispersed cutting fluids.

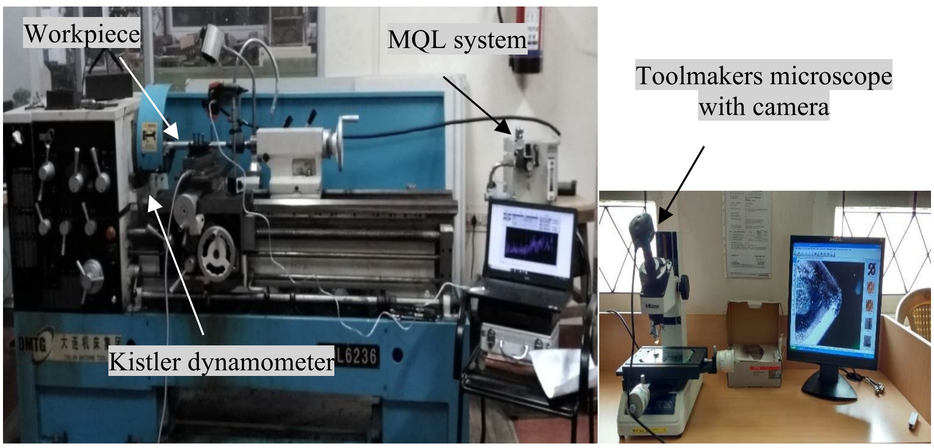
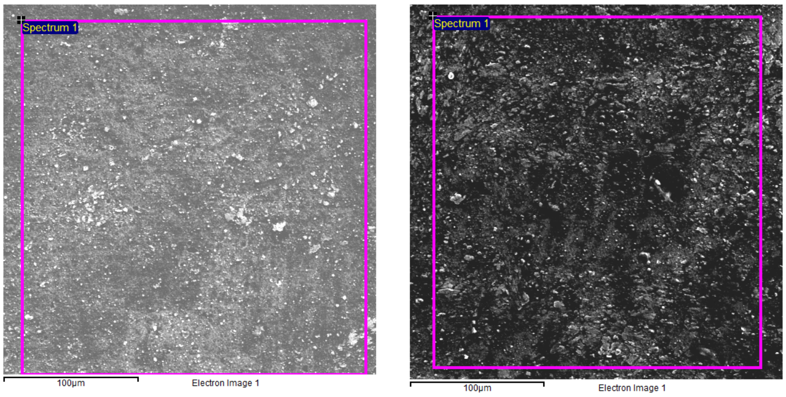


Figure 3. Experimental set-up used in the present study.



(a) (b)

Figure 4. SEM images of cutting tool surface after machining with (a) dry condition and (b) MQL application of SO0.3.

Carbon Footprint Analysis

The effect of any process on the environment can be determined by performing life cycle analysis (LCA) or carbon footprint analysis. Carbon footprint analysis from cradle to the grave was performed for all experiments. Cradle to grave analysis determines the quantity of carbon dioxide released during the entire life cycle of the generated product, which includes carbon dioxide released (a) during the production of materials utilized, (b) due to energy consumed during pre-machining operations, (c) due to energy consumed during machining operations and (d) during disposal of waste generated. Table 1 contains components considered to perform cradle to grave analysis.

The carbon emission factor (F) for various operations gives the quantity of carbon dioxide equivalent in kg released per unit quantity of the operation. Carbon emission factor during production of electricity, F_e= 0.82 kgCO_2 eq./kWh [25], for emulsifier oil, F_{co} = 2.85 kgCO_2 eq./lit [20], workpiece Ti6Al4V, F_{TiAl} = 46.5 kg CO_2eq./kg [26], Ti6Al4V chips recycling, F_{chip} = 5.2 kg CO_2eq./kg [26], graphene, F_{Gr} = 137 kg CO_2eq./kg [27], tungsten carbide tool, F_t = 29.6 kg CO_2eq./kg [20], during disposal of waste coolant, F_{cow} = 0 for dry machining and MQL application, as no coolant is disposed off as waste.

Table 1. Components considered for cradle to grave analysis.

Materials utilized (a)	Energy consumption pre-machining (b)	Energy consumption during machining (c)	Disposal of waste generated (d)
Workpiece Ti6Al4V (CF_{Tial})	By sonicator for dispersion nanoparticles in cutting fluid	By Machine tool during turning operation	Chip recycling
Graphene nanoparticles	By laser for drilling holes on inserts	By Machine tool during stand by period	Cutting fluid treatment and disposal
Coolant		By compressor which supplies compressed air for MQL application	
Water		By MQL system: to supply the cutting fluid as MQL.	
Cutting tool (cemented carbide)			

Detailed carbon footprint analysis is performed as mentioned by Le et al. [19]. The quantity of carbon emitted, i.e. carbon footprint (CF_{prod}) during manufacturing a product is given by Eq. (1) [19].

$$CF_{prod} = CF_p + CF_{co} + CF_t + CF_{TiAl} + CF_{chip} + CF_{Gr} \tag{1}$$

$$CF_p = F_e E_{tot} = F_e((E_m + E_{mql})t + E_i t_i + E_{comp} t_{comp} + E_{soni} t_{soni} + NE_{hdr} t_{hdr}) \tag{2}$$

where, CF_{prod} is carbon footprint during manufacturing a product (kg CO_2eq), CF_p is carbon footprint due to the generation of power utilized during machining (kg CO_2eq), CF_{co} is carbon footprint due to making of coolant and scrapping after usage (kg CO_2eq), CF_t is carbon footprint due to the production of cemented carbide tools utilized (kg CO_2eq), CF_{Tial} is the carbon footprint of Ti6Al4V chips developed while converting Ti6Al4Vrod to the final product (kg CO_2eq), $CF_{chip}$is carbon footprint due to reprocessing of chips (kg CO_2eq), and CF_{Gr} is carbon footprint due to graphene fabrication (kg CO_2eq).

$$CF_{co} = \frac{(t_i + t)}{T_{co}}(CF_{copr} + CF_{codi}) \quad (3)$$

where,

$CF_{copr} = F_{co}(CO_i + CO_{ad})$

$CF_{codi} = F_{cow}\left(\frac{CO_i + CO_{ad}}{\delta}\right)$

$$CF_t = \frac{t}{T_{tool}}(F_t m_t) \quad (4)$$

$$CF_{TiAl} = F_{TiAl} \times m_c \quad (5)$$

where,

$m_c = \frac{Density \times MRR \times t}{10^6}$ kg

$MRR = \frac{1000 \times f \times d \times v}{60}$

$$CF_{chip} = F_{chip} \times m_c \quad (6)$$

$$CF_{Gr} = F_{Gr} \times m_{Gr} \quad (7)$$

where, $m_{Gr} = Q_{Gr} \times co_{fr} \times t$

Q_{Gr} is graphene utilized per ml of coolant. For 0.1 wt.%: 0.00105g, 0.3 wt.% : 0.00315 g, 0.5 wt.%: 0.00525 g

co_{fr} is rate of coolant flow = 10 ml/min

Economic Analysis

A third key point in evaluating the sustainability of any process is to check its economic feasibility. The incorporation of any new process or product should improve the quality without compromising much on the economic terms. Economic analysis for machining of Ti6Al4V at varying cutting velocities considering varying cutting environments, i.e. dry machining, MQL application of water-soluble oil without graphene (SO), MQL application of graphene dispersed water-soluble oil (SO0.1,SO0.3,SO0.5), dry machining using graphene filled self-lubricating tools (G1 tool, G3 tool, and G5 tool) was performed. It is assumed that machining is done on one machine for a period of 1 year containing 52 weeks with six working days per week and eight working hours per day. Price of consumables is emulsifier oil concentrate: \$1.61/liter [28], water: \$3.59/5kl [29], graphene nanoparticles from XG science USA: \$0.55/g (from quotation in 2019), surfactant Triton X 100: \$26.05/liter (from quotation in 2019), cutting tool: \$8.77/tool (from quotation in 2019) and price of power consumption in Andhra Pradesh, India: \$0.079/kWh [30]. Economic analysis is performed as mentioned by Amrita et al. [31]. Overall price spent (OP) in machining per year is calculated using Eq. (8)

$$OP = P_c + P_{pow} + P_{tool} \quad (8)$$

$$P_c = P_{co} + P_w + P_{Gr} + P_{Tx} \quad (9)$$

$$P_{pow} = (P_i + P_m + P_{comp} + P_{mql} + P_{soni} + P_{hdr}) \times 12 \quad (10)$$

$$P_{tool} = \frac{t_m \text{per year}}{T_{tool}} \times \frac{P_{insert}}{n} \quad (11)$$

RESULTS AND DISCUSSION

Machining Performance

Effect on tangential cutting forces

Feed force (F_y), radial force (F_x) and tangential cutting force (F_z) are three components of force acting on the cutting tool, which are measured using the Kistler dynamometer. Power consumed during machining operation depends on tangential cutting force, which in turn contributes to carbon footprint and economic analysis. Tangential cutting forces are compared for all cases and presented in Figure 5. Tangential cutting forces are found to increase with the increase in cutting velocity showing a peak at 74 m/min, and then decrease with an increase in cutting velocities. Forces are found to be highest with dry machining. Dry machining with one hole filled with graphene tool, i.e. G1 tool showed reduced forces at all velocities. G1 tool has a single hole on the rake face filled with graphene. During machining operation, the chip slides over the rake face of the cutting tool. Graphene in the holes of the rake face gets smeared over the rake surface due to friction extrusion [32]. The presence of graphene between the chip and the tool reduces the sliding friction and thereby reducing the resultant cutting force and hence the tangential component of the cutting force. Similar results were viewed by Song et al. [33].

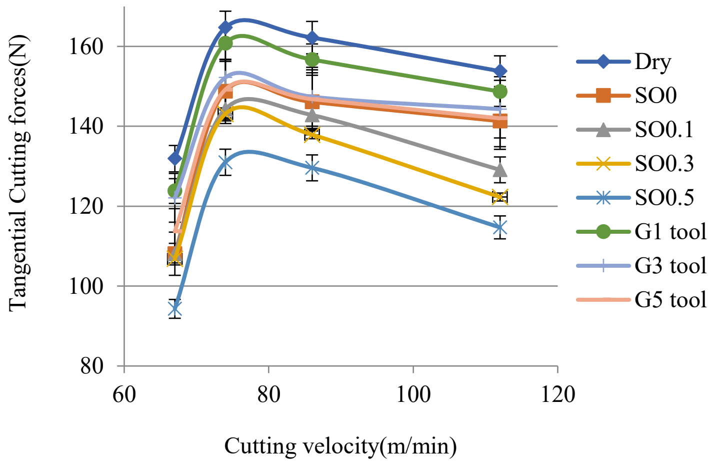


Figure 5. Variation of tangential cutting force with cutting velocity.

Tangential cutting force was further reduced with the G3 and G5 tool. The quantity of graphene increased with an increase in the number of holes on the rake face, thereby reducing the friction more and hence reducing the machining forces. Tangential cutting forces obtained with G5 tool are almost the same as that obtained with MQL application of soluble oil without graphene. In the case of MQL application, small droplets of cutting fluids are formed which has increased surface area. Effective entry of these droplets at heat generating zones, at primary, secondary, and tertiary zones, helps to effectively remove heat and provide lubrication, thereby reducing cutting forces. Tangential cutting forces are found to further decrease with the use of graphene in cutting fluid. Cutting forces are found to decrease with an increase in the quantity of graphene in water-soluble oil, with SO0.5 showing the least tangential cutting forces at all velocities. The percentage reduction in tangential cutting force is shown in Table 2. SO0.5 showed maximum reduction in tangential cutting forces at all velocities. The inclusion of graphene in water-soluble oil increased its thermal conductivity and lubricating properties. This has helped in reducing cutting forces.

Table 2. Percentage reduction in tangential cutting force w.r.t dry machining

	67	74	86	112
Dry	-	-	-	-
SO0	18.04	9.65	9.93	8.13
SO0.1	18.12	12.39	11.96	16.06
SO0.3	19.03	13.11	14.98	20.48
SO0.5	28.51	20.46	20.10	25.42
G1 tool	6.14	2.37	3.39	3.32
G3 tool	7.43	7.59	9.12	6.18
G5 tool	13.80	9.41	9.49	7.67

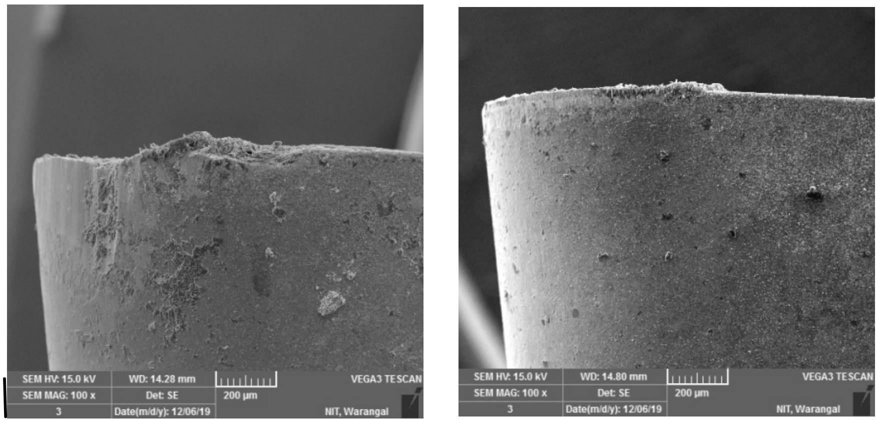
Effect on flank wear

Table 3 shows the variation of flank wear at varying velocities for all machining conditions. Maximum flank wear is seen in dry machining with the G0 tool. Graphene-filled tools showed reduced flank wear. G5 tool showed the lowest flank wear among all cases of dry machining with a maximum of 35% reduction in flank wear at 112 m/min w.r.t dry machining with the G0 tool. Ti6Al4V has a very low thermal conductivity (≈ 6.7 W/mK), and in such a case, the dissipation of heat from the heat zone is a cause of concern. Graphene has a very high thermal conductivity of order 3000-4000 W/mK.

Table 3. Variation of flank wear.

	67	74	86	112
Dry (G0)	139.87	177.39	159.57	208.11
SO0	110.56	121.05	115.60	126.56
SO0.1	97.69	108.02	102.67	115.82
SO0.3	71.25	78.94	73.73	84.61
SO0.5	89.63	94.77	92.11	97.37
G1 tool	136.87	142.21	139.47	173.76
G3 tool	134.21	139.57	136.97	144.83
G5 tool	115.82	131.68	121.31	134.85

Graphene added in solid form on the rake face of the tool helped in reducing friction at the chip-tool interface and also helped in quicker heat dissipation, leading to decreased tool wear and hence increased tool life. G1 and G3 tools show almost similar flank wear, but the G5 tool showed much-reduced flank wear. A higher amount of graphene in the G5 tool may have enabled a continuous supply of graphene from holes leading to its uniform distribution on the rake face, which has caused good lubrication and acted as a layer for heat dissipation. Amrita et al. [34] found that with Triton X 100 as surfactant added in the same ratio as graphene, SO0.3 has the highest thermal conductivity, followed by SO0.5, SO0.1, and SO0. The addition of graphene in soluble oil increased the thermal conductivity. But increase in the quantity of surfactant Triton X100 reduced thermal conductivity causing SO0.5 to show lesser thermal conductivity than SO0.3. A similar trend can be seen in the variation of flank wear, with SO0.3 showing the least flank wear and SO0 showing the highest flank wear among all MQL applications. The higher quantity of graphene and TritonX100 in SO0.5 led to increased viscosity than SO0.3, which led to a bigger droplet size during MQL application. This may have led to the insufficient entry of droplets in the cutting zone leading to higher flank wear with SO0.5 compared to SO0.3. Abrasion and adhesion are found to be the mode of failure in all cases. Figure 6 shows SEM images of flank wear with dry machining and SO0.3 machining at 112 m/min. A decrease in flank wear can be visualized from the SEM images.



(a) (b)

Figure 6. Flank wear with (a) dry machining and (b) SO0.3 machining at 112 m/min.

Carbon Footprint Analysis

In order to determine the effect of machining on the environment, a carbon footprint analysis was performed. Carbon footprint analysis gives the total amount of carbon dioxide released into the atmosphere during the machining process. Assuming that the Ti6Al4V workpiece of dimensions Ø30 mm × 150 mm is completely machined. The total carbon dioxide emitted carbon footprint during production (CF_{prod}) is calculated using Eq. (1).

Carbon footprint due to power utilization

The emission factor for the production of electricity, $F_{e,}$ is considered as 0.82 kgCO_2eq./kWh [25]. Carbon footprint due to power utilized (CF_p) is evaluated using Eq. (2). It is the least for dry machining. MQL application of water-soluble oil (SO) uses additional accessories like an air compressor and MQL system, which consumes power. Thus, the carbon footprint due to power consumption with MQL application of SO is higher than dry machining. With the use of nanofluids, a sonicator is used to disperse nanoparticles in emulsifier oil; hence, more power is consumed with the use of nanofluids. But with an increase in the concentration of nanoparticles from SO0.1 to SO0.5, tangential cutting forces (F_t) acting on the cutting tool during machining Ti6Al4V decreased. This in turn, decreased the power consumption during the actual machining process given by $F_t \times v$ at a particular velocity. Hence, with MQL application of nanographene cutting fluid, the carbon emitted due to power consumption increased and then decreased with an increase in the concentration of graphene. For graphene-filled self-lubricating tools, holes are produced by using laser, which consumes power. Power consumed for making holes is proportional to the number of holes; hence power consumption increased in order G1tool, G3tool, and G5tool. Tangential cutting force decreased with an increase in graphene-filled holes, but the reduction in power consumption due to this is less compared to the increase in power consumed in hole making. Figure 7 shows the variation in carbon footprint due to the utilization of power (CF_p) for all conditions.

Carbon footprint due to cutting tools utilized

The emission factor for the production of carbide tool, $F_{t,}$ is considered as 29.6 kg CO_2eq./kg [20]. Carbon footprint due to utilization of cutting tools (CF_t) is proportional to tool wear. Higher is the tool wear, more will be quantity of tools used and more will be carbon released during production. CF_t is calculated using Eq. (4). Dry machining showed maximum tool wear and hence more carbon release. The use of graphene-filled self-lubricating tools reduced tool wear. Tool wear slightly decreased with an increase in the number of graphene-filled holes. But not much reduction in tool utilization was noticed. Hence, carbon released in all cases of graphene-filled self-lubricating tools remained almost the same. While at a higher velocity of 112 m/min, there is a slight decrease in carbon released with the use of G5 tool. MQL application of SO and graphene dispersed SO showed a reduction in tool wear. But, since there is less reduction in the tool wear, the quantity of cutting tools consumed remained almost the same and hence the carbon footprint due to the utilization of tools. SO0.3 showed the lowest tool wear and thus a slight reduction in carbon footprint due to the utilization of tools. Figure 7 shows the variation in carbon footprint due to the utilization of cutting tools (CF_t) for all conditions.

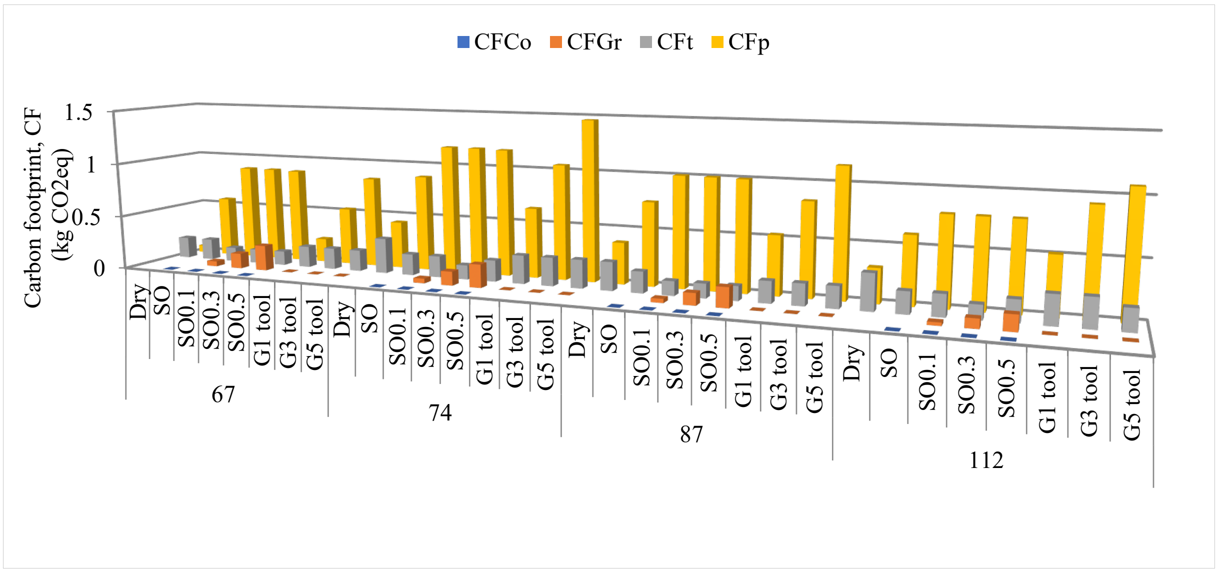


Figure 7. Carbon footprint due to utilization of power (CF_p), coolant (CF_{co}), nanoparticles (CF_{Gr}) and cutting tool (CF_t).

Carbon footprint due to material utilized and chip recycling

Emission factor during the production of workpiece Ti6Al4V, F_{TiAl} is considered as 46.5 kg CO_2eq./kg [26], and emission factor for Ti6Al4V chips recycling, F_{chip} is considered as 5.2 kg CO_2eq./kg [26]. Carbon footprint due to quantity of material (Ti6Al4V) machined (CF_{TiAl}) and recycling of chips obtained (CF_{chip}) are the same for all cases, as they depend on the shape of raw material and finished product and is independent of the type of coolant or tools used. CF_{TiAl} for all cases is found to be 29.10kgCO_2eq and CF_{chip} is found to be 3.25kgCO_2eq obtained by using Eq. (5) and Eq. (6), respectively.

Carbon footprint due to nanoparticles utilized

The emission factor for the production of graphene, F_{Gr} is considered as 137 kg CO_2eq./kg [27]. The carbon footprint during the production of nanoparticles utilized (CF_{Gr}) in the machining process is calculated using Eq. (7). It increased with an increase of graphene concentration in emulsifier oil and also with the increase in the number of graphene filled holes in self-lubricating tools. As less graphene is used in microholes in self-lubricating tools compared to graphene dispersed in cutting fluids, the carbon footprint is more for graphene dispersed cutting fluid. Figure 7 shows the variation in carbon footprint due to the utilization of power (CF_{Gr}) for all conditions.

Carbon footprint due to coolant utilized

The emission factor for the production of emulsifier oil, $F_{co,}$ is considered as 2.85 kgCO_2eq./lit [20], and emission factor for disposal of waste coolant, F_{cow} is considered as 0 for dry machining and MQL application, as no coolant is disposed off as waste. The carbon footprint due to the production of coolant utilized (CF_{co}) is calculated using Eq. (3). It is found to be constant for all MQL applications, at a particular velocity, as fluid is supplied at a constant rate. With the increase in cutting velocity, machining time reduces and hence the utilization of coolant also. Figure 7 shows the variation in carbon footprint due to the utilization of coolant (CF_{co}) for all conditions.

Carbon footprint during overall production

The total carbon footprint during overall production (CF_{prod}) is calculated using Eq. (1). Table 4 shows all components and total carbon footprint at 74m/min. Ranking based on the lowest to the highest quantity of total carbon released during production, CF_{prod} (in kgCO_2eq) at 74m/min is shown in the last row of Table 4 with dry machining with conventional tool emitting the lowest carbon followed by dry machining with self-lubricating tool G1tool. Carbon footprint increased with the quantity of graphene in water-soluble oil. With MQL application of graphene dispersed cutting fluid, though power consumption during machining has reduced due to a reduction in tangential cutting force and also there is a reduction in the quantity of tools utilized due to reduced tool wear, which in turn reduced carbon emission due to graphene cutting fluid, but this reduction is less compared to carbon emission due to increase in power utilized for sonication and carbon emission due to nanoparticles utilized, leading to increase in overall carbon footprint. Since the quantity of graphene used in self-lubricating tools is less compared to that used in graphene dispersed cutting fluid, the carbon footprint is less with graphene-based self-lubrication tools compared to graphene dispersed cutting oil. Figure 8 illustrates the total carbon footprint during production for all machining conditions at all velocities of experimentation.

Table 4. All components and total carbon footprint at 74 m/min.

	Dry	SO	SO0.1	SO0.3	SO0.5	G1tool	G3 tool	G5 tool
CF_p	0.4330	0.8822	1.1726	1.1720	1.1659	0.6410	1.0517	1.4652
CF_t	0.3226	0.1936	0.1936	0.1291	0.1936	0.2581	0.2581	0.2581
CF_{TiAl}	29.1005	29.1005	29.1005	29.1005	29.1005	29.1005	29.1005	29.1005
CF_{chip}	3.2543	3.2543	3.2543	3.2543	3.2543	3.2543	3.2543	3.2543
CF_{Gr}	0	0	0.0423	0.1268	0.2113	0.0002	0.0007	0.0012
CF_{co}	0	0.8372	0.8372	0.8372	0.8372	0	0	0
CF_{prod}	33.1105	33.4309	33.7635	33.7829	33.9259	33.2541	33.6653	34.0793
Rank	1	3	5	6	7	2	4	8

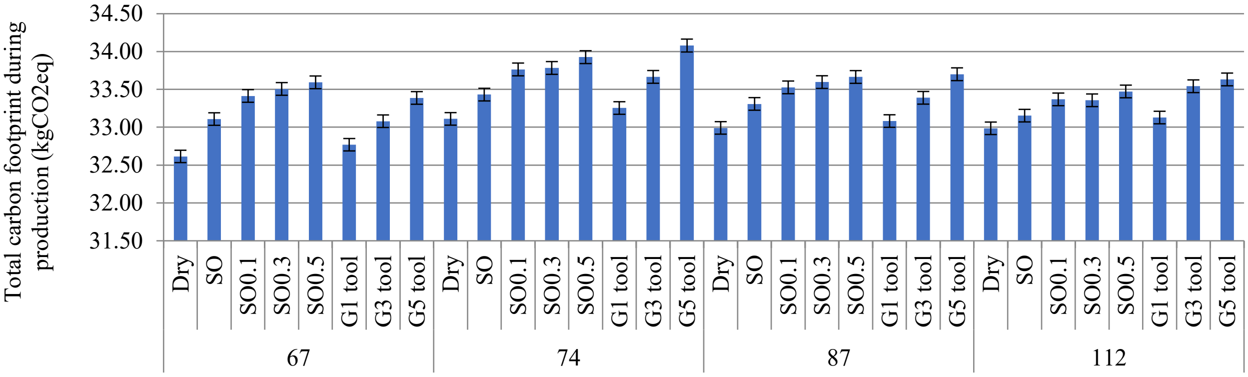


Figure 8. Total carbon footprint during production for all machining conditions.

At all velocities, graphene dispersed emulsifier oil, and graphene filled cutting tools increased the burden on the environment leading to the emission of more carbon to the atmosphere compared to dry machining with the conventional cutting tools and MQL application of water-soluble oil.

Economic Analysis

Economic analysis is performed to determine the total amount spent on machining Ti6Al4V. Overall price spent (OP) in machining per year is obtained using Eq. (8).

Expenses on consumables

Consumables utilized during machining include coolant, water, nanoparticles, graphene, and cutting tools. For dry machining, as no cutting fluid and graphene are used, no amount is spent on consumables. With dry machining using graphene-filled self-lubricated inserts (G1 tool, G3 tool, G5 tool), the consumable used is graphene, whose quantity is proportional to the number of holes in the inserts. Hence the cost of consumables increased from G1 tool to G5 tool. MQL application of water-soluble oil (SO) uses concentrated emulsifier oil, water and MQL application of graphene dispersed soluble oil (SO0.1, SO0.3, SO0.5) uses graphene as well as surfactant Triton X100 along with concentrated emulsifier oil and water. Thus amount spent on consumables increased from SO to graphene-filled cutting fluids. Amount spent on consumables also increased from SO0.1 to SO0.5 due to an increase in the quantity of graphene consumed. Figure 9 shows the variation of expenses on consumables/year (P_c) at varying velocities and all machining conditions.

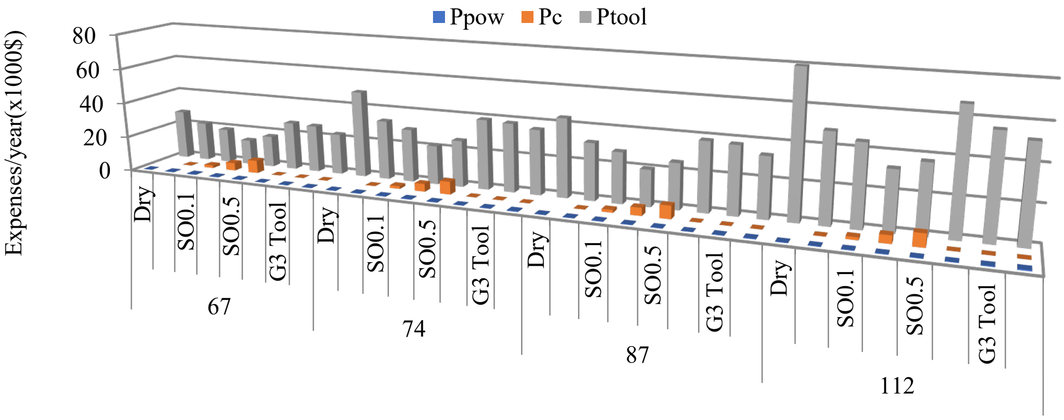


Figure 9. Variation of expenses P_c, P_{pow}, P_{tool} at varying velocities and all machining conditions.

Expenses on power utilized

Total power utilized is the summation of power utilized by accessories like compressor, sonicator, MQL system, and laser (for drilling microholes) and power utilized during the machining process, which is the product of tangential cutting force and cutting velocity. In the case of dry machining, power is utilized only during the machining process, which is high compared to other cases as the tangential cutting force acting on the tool is high. In the case of dry machining using graphene-filled self-lubricating tools, along with power utilized during machining, power is also utilized by laser for making holes which is proportional to the number of holes. The power utilized for making holes is of order G1 tool < G3 tool < G5 tool, while power consumed during machining is of order G5 tool < G3tool < G1tool, as less tangential force is obtained with an increase in the quantity of graphene on the rake face from G1 tool to G5 tool. But as power consumed by laser is more, the total power consumed is of order G1 tool < G3 tool < G5 tool. MQL applications of cutting fluids make use of compressor and MQL system. Graphene dispersed cutting fluid requires the use of a sonicator for dispersing graphene into water-soluble oil. Thus, power consumed by accessories in MQL applications is more compared to dry machining and is of order SO < SO0.1 = SO0.3 = SO0.5. But with emulsifier oil, the tangential force acting on the cutting tool decreased. The tangential force also decreased with graphene dispersed emulsifier oil, showing the least tangential force with SO0.3. Hence, power consumed during machining is of order SO0.3 < SO0.5 < SO0.1 < SO. But, due to less difference in power consumed during machining with SO0.1, SO0.3, and SO0.5, the amount spent on overall power utilized is nearly the same for all graphene dispersed emulsifier oil applications. Figure 9 shows the variation of expenses on power utilized/year (P_{pow}) at varying velocities and all machining conditions.

Expenses on cutting tools utilized

Total expenses on cutting tools (P_{tool}) is proportional to tool wear. The more the tool wear is, the more will be the number of tool changes; hence more will be the amount spent on cutting tools. From Table 3 showing the variation in flank wear, flank wear is of order Dry > G1 tool > G3 tool > G5 tool > SO > SO0.1 > SO0.5 > SO0.3 and hence same is the order for amount spent on cutting tools. As the component of total expenses, P_{tool} is greater than the other two components, P_c and P_{pow}, total expenses in machining are dominated by P_{tool}.

Table 5 shows the expenses in all three components and the overall expenses in machining at a cutting velocity of 74 m/min. The last row in Table 5 gives the ranking based on overall expenses/m^3 of material removed during machining Ti6Al4V. MQL application is found to be economical compared to dry machining. MQL application of 0.3 wt.% water-soluble oil (SO0.3) is found to be the most economical, followed by SO0.1, SO0.5, and SO. Among dry machining, the use of graphene filled self-lubricating tool G5 tool is found to be the most economical followed by the use of G3 tool, G1 tool and conventional cutting tool. Figure 10 shows the overall expenses/volume of material removed per year for all experiments. A trend similar to that obtained at 74m/min found at all cutting velocities.

Table 5. All components and overall expenses in machining at 74 m/min.

	Dry	EO	EO0.1	EO0.3	EO0.5	DryG1 tool	DryG3 tool	DryG5 tool
P_c (×1000$)	0.00	0.12	1.54	4.40	7.25	0.00	0.01	0.02
P_{pow} (×1000$)	0.25	0.24	0.31	0.31	0.31	0.11	0.27	0.40
P_{tool} (×1000$)	49.01	33.45	29.85	21.82	26.19	39.29	38.57	36.39
Total expenditure/year (×1000$)	49.26	33.81	31.71	26.53	33.75	39.41	38.84	36.81
Total expenditure/m^3 of material removed ($)	68.39	46.94	44.01	36.82	46.85	54.71	53.92	51.10
Rank	8	4	2	1	3	7	6	5

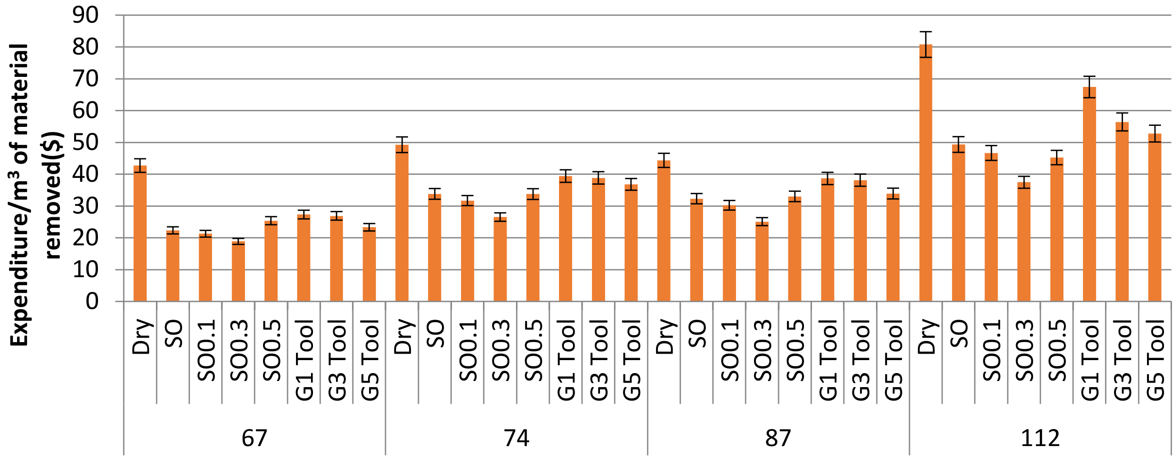


Figure 10. Overall expenses/volume of material removed per year for all experiments.

CONCLUSION

i. Graphene applied as a solid form and also as a dispersant in cutting fluid showed improved Ti6Al4V machining performance.
ii. Tangential cutting force decreased by 28.51% with MQL application of 0.5 wt.% graphene dispersed soluble oil at 67 m/min.
iii. Tool wear is found to be least with MQL application of 0.3 wt.% graphene dispersed soluble oil.
iv. At all velocities, graphene dispersed soluble oil and graphene filled cutting tools increased the burden on the environment leading to the emission of more carbon to the atmosphere compared to dry machining with the conventional cutting tools and MQL application of emulsifier cutting oil.
v. MQL application of 0.3wt% graphene dispersed soluble oil is found to be most economical in machining Ti6Al4V.
vi. The machinability of Ti6Al4V has improved with the use of graphene dispersed emulsifier oil and graphene-filled self-lubricating tool, and the process is employee-friendly and economical compared to the use of conventional emulsifier oil and dry machining but is not eco-friendly.

FUTURE SCOPE

Machining of Ti6Al4Vusing different wt% emulsifier oil can be performed at varying cutting parameters and optimum parameters can be identified. Hybrid nanofluids in combination with graphene can also be tested in machining Ti6Al4V. Graphene filled tools can be tested to identify the duration for which the lubrication lasts and a possible solution can be found to supply solid lubricant continuously.

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