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Sustainability Analysis of Machining Inconel 718 Using Graphene-Based Nanofluids and Self-Lubricating Tools

Reference

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ABSTRACT

Inconel 718 has wide application due to its excellent strength at high temperatures and corrosion resistance. But because of the problems associated with machining, it is categorized as "hard-to-machine" material. The present work aims at identifying a sustainable method to machine Inconel 718 with the application of graphene. Sustainability evaluation consists of evaluating a product or process for the satisfaction of three E's: employee, environment, and economy. In the present work, the effect of graphene-based cutting fluid and graphene-based self-lubricating tools on cutting forces and tool wear is evaluated while machining Inconel 718. In addition, economic analysis and carbon footprint analysis are carried out to verify the advantage and feasibility of using the formulated cutting fluids and self-lubricating tools. Furthermore, minimum quantity application of conventional cutting fluid and graphene-based nanofluids and dry machining using graphene-based self-lubricating tools are compared to estimate the best conditions for environmental impact. Minimum quantity application of 0.5 weight percent (wt %) graphene-based nanofluid showed the least tangential cutting forces, while 0.3 wt % showed the least tool wear. Tool wear decreased by ≈70–84 % with 0.3 wt % graphene-based nanofluid compared with dry machining over the velocity range of 65–115 m/min. At 112 m/min, the minimum quantity application of 0.3 wt % graphene-based nanofluid reduced carbon emission by 3,334 kg carbon dioxide compared with dry machining per machine tool per year. Minimum quantity application of 0.3 wt % graphene-based nanofluid is also found to be most economical compared with other environments at all cutting velocities showing ≈70–80 % reduction in expenditure compared with dry machining.

Keywords

carbon footprint, economic analysis, machining performance, graphene, Inconel 718, minimum quantity application, sustainability

Introduction

Inconel 718, a nickel-based alloy, is widely used in steam turbines and aerospace applications because of its resistance to extreme climatic conditions such as high temperature and corrosive environments. But is it categorized under "difficult-to-machine" materials because of problems encountered during its machining. Low thermal conductivity, rapid work hardening ability, and chemical reactivity of these materials make them difficult to machine. Thus, investigations are being carried out to identify techniques that can improve their machinability and improve tool life while machining Inconel 718. Various techniques like the use of a high-pressure jet,[1] cryogenic machining,[2–4] dry machining using textured tools and self-lubricated tools,[5–7] application of nanofluids,[8–10] and combinations of these[11,12] are being investigated. Most of these works concentrated on improving the machining performance of Inconel 718. But to have a sustainable environment, the manufacturing process should be sustainable. Sustainability means "meeting the needs of the present without compromising the ability of future generations to meet their own needs."[13] It is three-dimensional: economical, environmental, and social. A sustainable manufacturing process should be employee friendly, benign to the environment, and economical. The effect of any manufacturing process on the environment can be studied by performing a "carbon footprint" analysis. Human activities like extensive use of fossil fuels in automobiles, electricity generation and consumption, etc., lead to the release of "greenhouse gases," especially carbon dioxide (CO_2), which is responsible for drastic climate changes.[13] Wiedmann and Jan[14] defined carbon footprint as the total quantity of CO_2 released either directly or indirectly during a process or stored over the life cycle of the product. Campatelli[15] analyzed the effect of turning AISI 1040 steel on the environment by performing a carbon footprint analysis. Machining was done at varying parameters, i.e., feed and depth of cut and different lubricating environments: dry, flood, and Minimum Quantity Lubrication (MQL). Energy consumed during machining is determined by measuring the cutting forces generated. Carbon emitted through power consumption and scrap treatment is determined. Carbon emissions from dry and MQL machining were similar; however, MQL gave a longer tool life compared to dry machining. Rajemi, Mativenga, and Aramcharoen[16] developed a model to determine optimum cutting velocity during turning of AISI 1040 steel under dry machining, which would minimize energy footprint and would lead to economic tool life. Fang et al.[17] applied the concept of carbon footprint during scheduling in a flow shop. A model that could minimize energy consumption and carbon footprint during scheduling in a flow shop was developed. Mativenga and Rajemi[18] performed the turning of EN8 medium carbon steel at varying cutting velocities, feed, and depth of cut and determined optimum cutting parameters that would lead to the minimum energy footprint. Optimum cutting parameters based on the minimum energy footprint led to a 64 % reduction in energy footprint compared with those recommended by suppliers and 44 % better performance compared with machining at mid values of the cutting parameter range. According to Sun and Zhang,[19] the workpiece to be machined, cutting tool, and cutting fluid used are three main important parameters in machining that influence carbon footprint. To perform carbon footprint analysis, the boundary must be set based on the production process, and different sources have to be identified that either directly or indirectly lead to carbon emission. They developed an input-process-output model that would help to plan the machining process, optimally minimizing the carbon footprint in machining. Pervaiz et al.[20] performed turning of Ti6Al4V using the uncoated tool at varying speeds and feeds at dry as well as flood environment and studied their effect on surface roughness and energy consumption. An increase in feed and hence metal removal rate led to an increase in surface roughness and a decrease in energy consumption. The optimum feed was obtained from the point of intersection of graphs of surface roughness and energy consumption. Camposeco-Negrete[21] performed the turning of AISI 6061T6 aluminum alloy using a carbide tool at varying cutting velocities, feed, and depth of cut under dry conditions. Experiments were performed using the response surface method, and optimum parameters were identified that would minimize energy consumed per unit volume and maximize the quality of the surface. The proposed method could reduce energy consumption by ≈14 % and surface roughness by 360 %. Li et al.[22] defined a boundary for Computer Numerical Control-based machining systems and gave a detailed quantitative procedure to determine the amount of carbon emitted during the machining process. Total carbon emitted during the whole manufacturing process was determined by cumulating the carbon emissions due to power consumption, the use of tool, coolant, material, and chips produced. Total carbon emitted during high-speed dry machining was found to be less than that that emitted during wet machining. Denkena, Dittrich, and Jacob[23] proposed a technique to improve the energy efficiency in machining of titanium components widely used in aircrafts. This technique is based on improving the quality of chips to an easy recyclable extent. The use of cutting fluid gave the lowest machining cost per part, followed by dry machining and cryogenic machining. The cost of recycling the chips produced was found to be the highest with those produced from cryogenic machining, followed by dry machining, and least with those produced during the use of cutting fluids. Considering both manufacturing as well as recyclable cost, cryogenic machining was found to be most economical.

Singh et al.[24] performed turning of Ti3Al2.5V at different cooling conditions and tried to identify the best sustainable cooling method. Tool wear, surface roughness, energy consumption, and carbon emissions are found to be lowest with MQL application, while the particulate concentration in the working area was found to be alarming. The use of Ranque-Hilsch vortex tube (RHVT) for cooling showed a slight increase in energy consumption with a similar performance to the MQL application. Gupta et al.[25] compared effectiveness, energy consumption, economic parameters, and carbon emissions of dry machining, cryo machining, and hybrid cryo-MQL machining. Hybrid cryo-MQL machining at lower cutting parameters showed the best sustainability index. Gupta et al.[26] compared the performance of RHVT + MQL and nitrogen + MQL while machining Ti6Al4V. The use of nitrogen + MQL showed the least specific cutting energy and surface hardness. Krolczyk et al.[27] reviewed the works of many researchers and summarized the key factors leading to sustainable production. Krolczyk et al.[28] performed turning of duplex stainless steel and observed that if the cutting tool grade is properly selected, tool life could be three times that found with the use of cutting fluids. Krolczyk et al.[29] tested machined surfaces generated during dry machining and using MQL. Machined surface with MQL showed good scatter of irregular peaks resulting in a high wear-resistant surface.

Although works are done on evaluating environmental effects by determining carbon footprint during machining, most of them are done for dry machining conditions. Most of the studies are limited to steel and aluminum alloys. Less work is found on carbon footprint evaluation while machining Inconel 718. Many works are reported to evaluate the effectiveness of the application of nanofluids to machining, but very few works are found on understanding the effect of nanofluids on the environment.

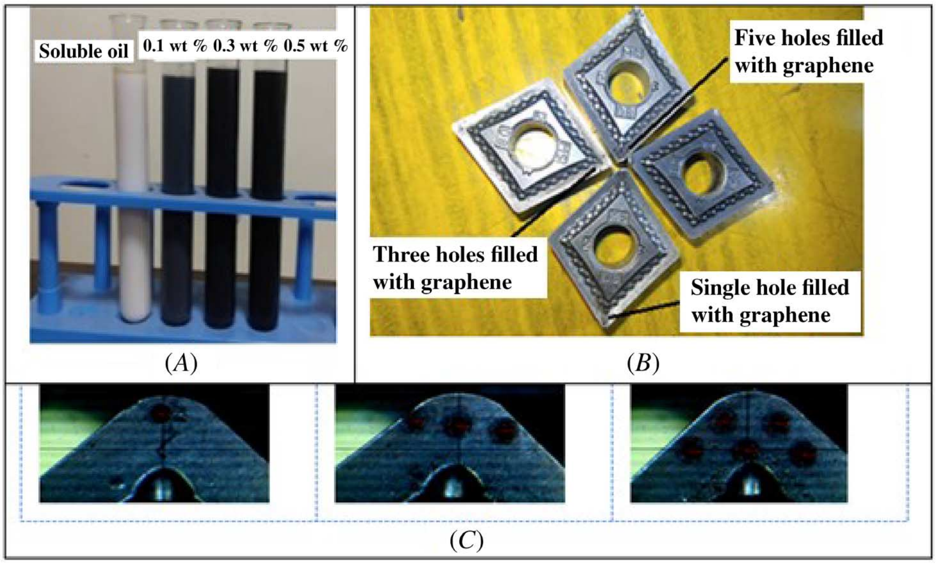
The present work explores the machining performance while MQL application of graphene-based cutting fluid and while using graphene added self-lubricating tools in machining Inconel718 and compares its performance with dry machining and MQL application of conventional cutting fluid. Economic analysis is also performed to estimate the most cost-efficient method of machining Inconel 718. A direct way to reduce carbon emissions to the environment is to reduce the consumption of energy. Machining of hard-to-machine material like Inconel 718 requires intensive energy. Thus, there is a need to develop methods or processes to reduce energy consumption and hence CO_2 emission, which in turn reduces the burden on the environment. Carbon footprint analysis in the present work is performed from the cradle to the grave, i.e., not only during machining operation but from the initial stage of manufacturing self-lubricating tools or nano-cutting fluid to the final finished part, to evaluate the environmental effect. Finally, the most sustainable method for machining Inconel 718 is identified based on machining performance, carbon footprint analysis, and economic analysis.

Materials and Methods

PREPARATION OF GRAPHENE-BASED CUTTING FLUIDS AND SELF-LUBRICATING TOOLS

Graphene of grade C500 is procured from XG Sciences. Graphene-based nanofluids of 0, 0.1, 0.3, and 0.5 weight percent (wt %) are prepared, taking soluble oil (1:20) as a base fluid and Triton X-100 as surfactant. The concentration of Triton X-100 is varied in the same ratio as the concentration of graphene to ensure proper stability and good thermal conductivity.[30] A two-step process is used to prepare nanofluids. Required quantities of graphene and Triton X-100 are added to water and sonicated using a probe sonicator for an hour. After ensuring proper dispersion, concentrated soluble oil is added to it in a ratio of 1:20. Graphene-inserted tools are prepared

FIG. 1 (*A*) Graphene-based nanofluids, (*B*) graphene-based cutting tools, and (*C*) location of holes.



by making microholes of 500-μm average diameter on the rake face of the tool using a femtosecond laser (126.77 W) and filling them with graphene. Three types of graphene-based tools are prepared, i.e., tools with one hole, three holes, and five holes on the rake face, i.e., G1, G3, and G5 tools, with the holes filled with graphene. Each hole is of 500-μm diameter and 1,000-μm depth. Figure 1*A*–*C* shows graphene-based nanofluids, graphene-filled self-lubricated tools, and a zoomed view of the hole location, respectively.

EVALUATION OF MACHINING PERFORMANCE

Inconel 718 rods of 30-mm diameter and 180-mm length are turned on a DMTG CDL6236 lathe machine (4/6 hp) at varying cutting velocities, i.e., 67, 87, 74, and 112 m/min, keeping the feed and depth of cut constant at 0.13 mm/rev and 0.5 mm, respectively. At each cutting velocity, two turns were machined to get appreciable tool wear and to replicate cutting force measurement. The final cylindrical workpiece is a rod of 22-mm diameter. Machining is performed under these conditions: dry machining using conventional coated tools (KC5010 TiAlN coated), MQL application of conventional soluble oil and graphene-based cutting fluids (0.1, 0.3, and 0.5 wt %) using conventional coated tools, dry machining using graphene-based self-lubricated tools (G1, G3, and G5 tools) using a new workpiece each time. The tool holder used is PCLNR 1616 K20 with a 95° approach angle for negative 80° rhombic inserts, CNMG120408 with a negative rake angle and zero clearance angle with a nose radius of 0.8 mm.

Cutting fluid is applied as MQL using the MQL system (Kenko: Make) by supplying compressed air through a compressor (3 hp). The performance of graphene-based nanofluids and self-lubricating tools is determined by measuring cutting forces and tool wear. Cutting forces generated during machining are measured using a Kistler dynamometer 9257A. Tool wear is measured using a Toolmakers microscope. Figure 2 shows the experimental setup.

CARBON FOOTPRINT ANALYSIS

Experimental results are used to perform carbon footprint analysis of Inconel 718 machining. The tangential cutting force (F_z) is used to determine the power utilized during machining. Tool wear, measured using a Toolmakers microscope, is used to determine the tool life, which in turn is used to determine the number

FIG. 2 Experimental setup.

of tool changes during the time of machining. The amount of carbon released during any machining process (CR_{mach}) is obtained by using equation (1).[22] The carbon emission factor (K_{mach}) for various operations gives the quantity of CO_2 in kg released per unit quantity of the operation. Carbon footprint analysis is performed for all experiments conducted in different environments.

$$CR_{mach} = CR_{power} + CR_{cf} + CR_{tool} + CR_{mat} + CR_{chip} + CR_{nano} \tag{1}$$

where:

$$CR_{power} = K_{elec}P_{mach} = K_{elec}(P_m t_m + P_{sb} t_i + P_c t_c + P_{mql} t_m + P_s t_s + nP_h t_h) \tag{2}$$

$$CR_{cf} = \frac{(t_i + t_m)}{T_{cf}}(CR_{cfp} + CR_{cfd}) \tag{3}$$

where:

$$CR_{cfp} = K_{cf}(CF_i + CF_{ex})$$

$$CR_{cfd} = K_{cfw}\left(\frac{CF_i + CF_{ex}}{\Delta}\right)$$

$$CR_{tool} = \frac{t_m}{T_{tool}}(K_t m_t) \tag{4}$$

$$CR_{mat} = K_m \times m_c \tag{5}$$

where:

$$m_c = \frac{\rho \times MRR \times t_m}{10^6} \text{ kg}$$

$$MRR = \frac{1{,}000 \times f \times d \times v}{60}$$

$$CR_{chip} = K_{chip} \times m_c \tag{6}$$

$$CR_{nano} = K_{nano} \times m_{nano} \tag{7}$$

where:

CR_{mach} = the total quantity of carbon released during the machining process (kg CO_2),

CR_{power} = carbon released during the production of power that is consumed in the machining process (kg CO_2),

CR_{cf} = carbon released during the production and disposal of cutting fluid (kg CO_2),

CR_{tool} = carbon released during the manufacturing of cutting tools used (kg CO_2),

CR_{mat} = carbon released during the production of unused workpiece material that is removed as chips while converting raw material to finished product (kg CO_2),

CR_{chip}= carbon released during the recycling of chips (kg CO_2),

CR_{nano} = carbon released during the production of nanoparticles used (kg CO_2),

K_{elec} = the amount of CO_2 released per kilowatt hour of power generation, which equals 0.83 kg CO_2/kWh from Appendix C – Table A (2016–2017),[31] as in India,

P_{mach} = total power consumed during the machining process (kW),

P_m = power consumed during machining, which equals

$$\text{Tangential force} \times \text{Cutting velocity} = F_z v$$

$$t_m = \text{machining time calculated using the relation } t_m = \frac{\pi D L \delta}{1,000 \text{ vfd}} (s)$$

where:

D = diameter of workpiece in mm,

L = length of workpiece in mm,

δ = machining allowance,

f = feed in mm/rev,

d = depth of cut in mm,

v = cutting velocity in m/min,

P_{sb} = standby power that is used when the machine is idle (kW),

t_i = idle time (assumed to be 0.1 times the machining time, s),

P_c = power consumed by the compressor during MQL application (kW),

t_c = compressor running time (assumed to be 0.5 times the machining time, s),

P_{mql} = power consumed by MQL system (kW),

P_s = power consumed by sonicator while dispersing nanoparticles in cutting fluid (kW),

t_s = sonication time (s),

n = number of holes drilled on the cutting tools,

P_h = power consumed by a laser for making a hole (kW),

t_h = time taken to make a hole using laser (s),

T_{cf} = life of the cutting fluid (assumed to be 2 months),

CR_{cfp} = carbon released during the production of cutting fluid (kg CO_2),

CR_{cfd} = carbon released during disposal of cutting fluid (kg CO_2),

K_{cf} = amount of CO_2 released during the generation of 1 L of mineral oil (kg CO_2/L), which equals 2.85 kg CO_2/L,[22]

CF_i = initial quantity of cutting fluid used (mL),

CF_{ex}= excess quantity of cutting fluid used (mL),

K_{cfw} = the amount of CO_2 released during disposal of 1 L of waste cutting fluid (kg CO_2/L) (in the case of dry machining and MQL application, it is 0),

Δ = the quantity of concentrated cutting fluid,

T_{tool} = life of cutting tool (s),

K_t = amount of CO_2 released during the production of cutting tool, which equals 29.6 kg CO_2/kg,[22]

m_t = mass of cutting tool (kg),

K_m = the amount of CO_2 released during production of the workpiece material (Inconel 718), which equals 11.6 kg CO_2/kg,

m_c = mass of material removed in the form of a chip (kg),

ρ = density of workpiece material in g/cm^3,

MRR = metal removal rate in mm^3/s,

K_{chip} = the amount of CO_2 released during recycling of Inconel 718 chips, which equals 2.14 kg CO_2/kg,

K_{nano} = amount of CO_2 released during the production of graphene nanoparticles, which equals 0.137 kg CO_2/g,[32]

$$m_{nano} = Q_n \times fr \times t_m$$

where:

Q_n = quantity of graphene used per milliliter of cutting fluid (for 0.1 wt %: 0.00105 g; 0.3 wt %: 0.00315 g; 0.5 wt %: 0.00525 g), and

fr = flow rate of cutting fluid, which equals 10 mL/min.

ECONOMIC ANALYSIS

Because of the high price of nanoparticles, the use of nanofluids is of economic concern. Thus, economic analysis is performed for machining Inconel 718 at varying cutting velocities and using different cutting environments for one year. Assumptions considered while performing economic analysis are mentioned as follows.

- The dollar-to-rupee conversion is taken as 1 USD = ₹71.
- Machining is performed for 8 hours per day, with 6 working days per week and 52 weeks per year.
- The cost of water-soluble oil used as cutting fluid is ₹115/L (1.61 USD/L).
- The average price of water for industrial purposes in India is ₹255 per 5 kL (3.59 USD per 5 kL).[33]
- The price of graphene platelets from XG Sciences, USA, as per the quotation including the excise duty is ₹39/g (0.55 USD/g).
- The price of Triton X-100, Fisher Scientific, Qualigens, is ₹1,850/L (26.05 USD/L), as per the quotation.
- The price of electricity is taken as the industrial power rate in Andhra Pradesh, India, as ₹5.60/kWh (0.079 USD/kWh).[34]
- The price of AlTiN-coated CNMG120408 KC5010 MS tools, Kennametal, is ₹623/tool (8.77 USD/tool), as per the quotation.

Total expenditure (TE) in machining is determined by using equation (8)

$$\text{TE} = C_{cons} + C_{power} + C_{tools} \tag{8}$$

where:

$$C_{cons} = C_{cf} + C_w + C_g + C_{tx} \tag{9}$$

$$C_{power} = (\text{CP}_{sb} + \text{CP}_m + \text{CP}_c + \text{CP}_{mql} + \text{CP}_s + \text{CP}_h) \times 12 \tag{10}$$

C_{cons} = amount spent on consumables per year,

C_{cf} = amount spent on cutting fluid concentrate per year,

C_w = amount spent on water used in cutting fluid per year,

C_g = amount spent on graphene nanoplatelets per year,

C_{tx} = amount spent on Triton X-100 per year,

C_{power} = amount spent on power consumption per year,

CP_{sb} = amount spent on standby power consumption per month (i.e., when the machine is idle),
CP_m = amount spent on power consumption during machining per month,
CP_c = amount spent on power consumed by compressor per month,
CP_{mql} = amount spent on power consumed by MQL system per month,
CP_s = amount spent on power consumed by sonicator per month,
CP_h = amount spent on power consumed by laser equipment for hole making per month,
C_{tool} = amount spent on cutting tools used per year,

$$C_{\text{tool}} = \frac{t_m \text{ per year}}{T_{\text{tool}}} \times \frac{C_{\text{insert}}}{n} \tag{11}$$

C_{insert} = price of one insert, and
n = number of cutting edges per insert ($n = 4$ as CNMG tools are used).

Results and Discussions

Machining of Inconel 718 is performed at varying velocities, i.e., 67, 87, 74, and 112 m/min, using different conditions: dry machining using a conventional tool, dry machining using graphene self-lubricating cutting tools (G1, G3, and G5 tools), MQL machining using conventional cutting fluid Soluble Oil (SO) and MQL machining using graphene-based nanofluids (0.1, 0.3, and 0.5 wt %). Variation in machining performance, effect on the environment, and economic analysis is performed for all cases and compared to understand the sustainability in using graphene during machining Inconel 718.

MACHINING PERFORMANCE

Variation in Tangential Cutting Force

Power consumed by lathe during machining is mainly dependent on the tangential cutting force and cutting velocity. The tangential cutting force (F_z) obtained while machining Inconel 718 under varying speeds and machining environments is shown in figure 3.

Dry machining showed maximum tangential force at almost all cutting velocities. Tangential forces are found to increase and then decrease with variation in cutting velocities, showing maximum force at 74 m/min. MQL application of conventional soluble oil reduced tangential cutting force compared with dry machining at all cutting velocities. Conventional soluble oil, when applied in the form of aerosols using the MQL system, forms minute droplets, which could effectively enter the tool-workpiece and tool-chip interaction areas. This helps with better cooling and lubrication in these areas, leading to reduced tangential forces. The application of graphene-based nanofluids showed a further decrease in tangential force, and this decrease was found to be more

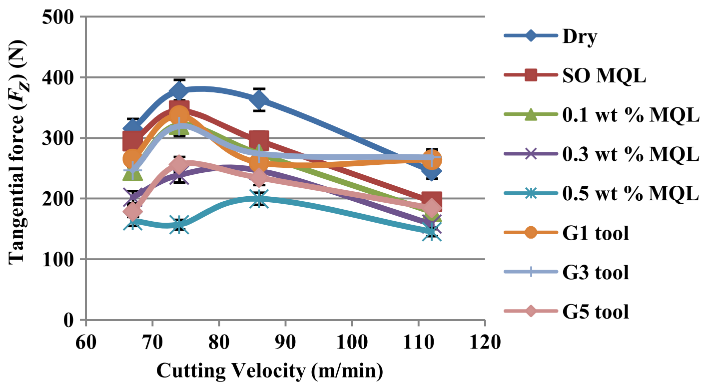


FIG. 3 Variation of tangential force with cutting velocity.

with an increase in the concentration of graphene. Nanofluid (0.5 wt %) showed maximum reduction in tangential force. Graphene[35] is found to act as a good lubricant in powder form as well as in the form of dispersion when applied at the nano- as well as the microscale. The addition of graphene to soluble oil may have increased its lubrication property, thereby providing much better lubrication at lower velocities. At higher velocities, when the temperature at the machining zone is high, evaporation of cutting fluid may have left graphene in the interaction zones, which may also have provided better lubrication at the zones, leading to reduced cutting forces. Use of graphene-based tools in dry machining also showed reduced tangential force compared with dry machining with conventional tools except at 112 m/min with G1 and G3. At 112 m/min, G1 and G3 tools broke because of crack initiation near the drilled holes. The formation of crack has reduced the strength, leading to instant failure. Thus, the location of holes has to be carefully planned for a better tool life of self-lubricating tools. G5 tool showed the lowest tangential force among all self-lubricating tools. The quantity of graphene-filled in the G5 tool is nearly five times that in G1 tool and in G3 tool is nearly three times that in G1 tool. More graphene on the rake face of G5 tool may have formed a layer between the chip and the tool, thereby reducing friction and hence cutting forces. Thus, graphene, when applied with cutting fluid as MQL or when applied in dry form as a solid lubricant, provides better results compared with dry machining and hence increases the machinability of Inconel 718.

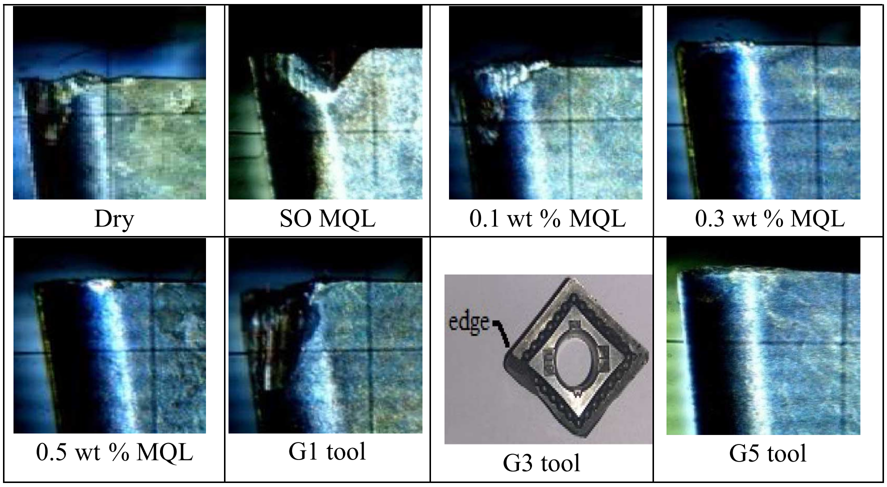
Variation in Tool Flank Wear

Table 1 shows the variation of tool flank wear in micrometers at all velocities in different environments. At 86 m/min, G3 tool broke, and at 112 m/min, G1 and G3 holes broke. Thus, flank wear was taken as a very large value, i.e., 1,500 μm. Dry machining showed the highest flank wear at all cutting velocities. The use of conventional cutting fluid as MQL reduced flank wear by nearly 50 % compared with dry machining. With the use of graphene-based cutting fluid as MQL, flank wear was found to further decrease. Graphene cutting fluid (0.3 wt %) showed the lowest flank wear. Graphene cutting fluid (0.5 wt %) showed higher flank wear than 0.3 wt %. This may be due to an increase in viscosity of 0.5 wt % graphene-dispersed cutting fluid. Increased viscosity led to the formation of a protective layer between the tool, workpiece, and chip, providing better lubrication and hence lower cutting force. But higher viscosity prevented easy dissipation of heat, leading to the accumulation of heat. Also, thermal conductivity of 0.5 wt % graphene cutting fluid is found to be less than 0.3 wt % graphene cutting fluid,[30] showing less heat conduction capacity. At high temperatures, the diffusion rate is high, which may have led to an increase in flank wear compared with 0.3 wt %. Graphene-based self-lubricating G1 and G3 tools showed lower flank wear at low velocity, i.e., at 67 m/min, compared with dry machining, but the wear was found to be nearly the same or higher at higher velocities. Increased wear was due to instability of the tool tip caused by fluctuating stresses acting on it. Crack initiation in these tools subjected to fatigue stresses led to rapid propagation, leading to quick tool failure. Thus, proper care must be taken to decide upon the location of holes to prevent the instability of tools. G5 tool showed lower flank wear compared with dry machining. Owing to the higher thermal conductivity of graphene, the formation of graphene film over the rake face as well as between the chip and the tool may have helped in better heat dissipation, preventing rapid flank wear. Also, the presence of graphene layers at the

TABLE 1
Variation of tool flank wear at all velocities

	67	74	87	112
Dry	742.27	821.66	918.42	981.57
SO MQL	432.09	473.68	552.63	626.31
0.1 wt % MQL	236.97	355.30	426.51	465.79
0.3 wt % MQL	126.42	150.09	152.72	279.05
0.5 wt % MQL	163.24	189.49	194.73	305.26
G1 tool	410.53	818.42	1,392.19	1,500
G3 tool	397.15	896.24	1,500	1,500
G5 tool	176.49	221.06	268.42	405.50

FIG. 4 Tool flank wear for all cases at a velocity of 87 m/min.



machining zone reduced friction and provided lubrication, thereby reducing forces acting on the tool. Thus, the application of graphene as a dispersant in cutting fluid as well as a solid lubricant could reduce flank wear, thereby increasing tool life and reducing the number of tool changes, thereby reducing the cost of manufacturing products made of Inconel 718. **Figure 4** shows the images of tool flank wear at a velocity of 87 m/min.

VARIATION OF CARBON FOOTPRINT

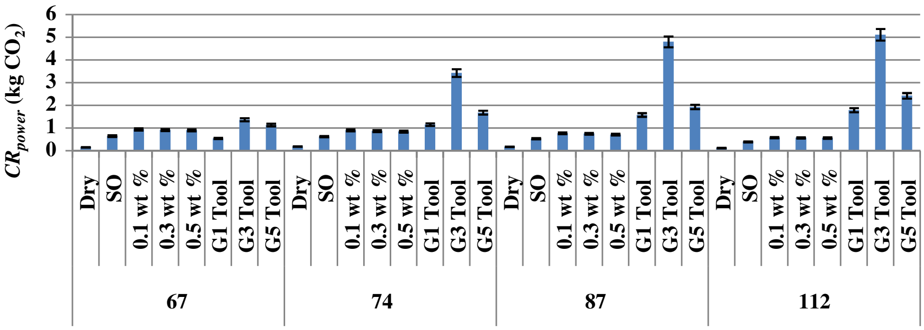
The total amount of carbon released during the entire machining process is evaluated using equation (1) by summing up the carbon released due to power consumption by the machine tool, compressor, sonicator, and other accessories used during machining (equation (2)), the production and use of cutting fluids (equation (3)), production of cutting tools consumed (equation (4)), production of the workpiece material consumed (equation (5)), recycling of chips (equation (6)), and production of nanoparticles (equation (7)).

Variation in Carbon Released Due to Power Consumption (CR_{power})

Figure 5 shows the variation of carbon released due to power consumption (CR_{power}) for all experimental conditions.

Carbon released due to power consumption is directly proportional to power consumed. The total power consumed is the summation of power consumed during machining operation, standby power for idle time of the

FIG. 5 Variation in carbon released due to power consumption (CR_{power}).



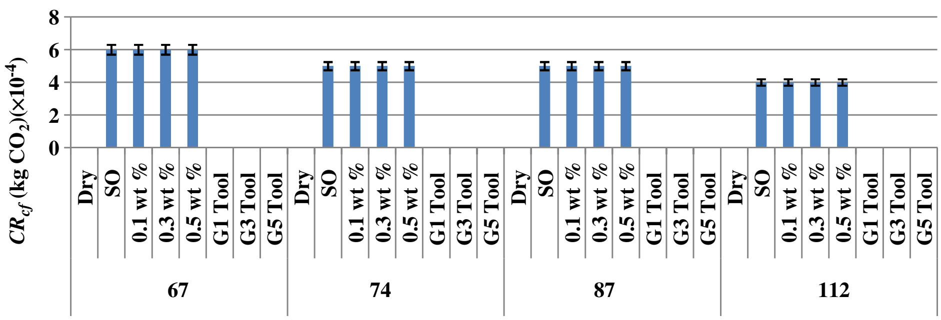
machine, power consumed by the compressor, sonicator, and by the laser for drilling holes. Power consumed during machining operation is the product of the tangential cutting force and cutting velocity. Variation of the tangential cutting force is shown in figure 2. The tangential cutting force is highest for dry machining, followed by MQL application of conventional cutting fluid and dry machining using G1, G3 and G5 tools, followed by MQL application of 0.1, 0.3, and 0.5 wt % graphene nanofluids, showing the least tangential cutting force. Thus, power consumed during the machining operation also varies in the same order at a particular cutting velocity. Although this is highest for dry machining using a conventional cutting tool, considering overall power consumption, dry machining showed the lowest power consumption compared with all other machining environments such as MQL application of conventional as well as nanofluids and dry machining using graphene-based self-lubricating tools. In the case of dry machining, power is consumed only during the machining operation, whereas with MQL application, apart from power consumption during machining, power is also consumed by the compressor and MQL system used to apply cutting fluid at the cutting zone. With the use of nanofluids, additional power is consumed by sonicator, which is used to disperse nanoparticles into the cutting fluid. With graphene-based self-lubricating cutting tools, apart from power consumed in machining, power is also consumed for drilling microholes using the laser. The more the tool wear, the higher the number of tool replacements, and hence more new self-lubricating tools have to be produced by drilling holes and filling them with graphene for use. As G1 and G3 tools showed the highest tool wear, the power consumption for drilling microholes using laser is higher and hence the amount of carbon released with the use of these tools is higher. Although tool wear with G5 tool is less, more holes have to be drilled in each new tool compared to G1 and G3 tools, leading to increased power consumption even for fewer tool replacements.

Thus, dry machining with the conventional cutting tool showed the least carbon emission due to power consumption compared with all other cutting environments.

Variation in Carbon Released Due to Use of Cutting Fluids (CR_{cf})

Figure 6 shows the variation in carbon released due to use of cutting fluids (CR_{cf}), which include carbon released due to the production of cutting fluid used (CR_{cfp}) as well as disposal of cutting fluids (CR_{cfd}). In the present experimentation, a small quantity of cutting fluid is applied as MQL, and it gets evaporated at the machining zone, eliminating the need for its disposal, so $CR_{cfd} = 0$. Carbon released due to the production of cutting fluid used (CR_{cfp}) is proportional to the quantity of cutting fluid used. As cutting velocity increases, machining time decreases, and hence with constant flow rate using MQL supply, the amount of cutting fluid consumed decreases, and hence there are decreases in CR_{cfp} as well as CR_{cf}, as seen in figure 6. The addition of graphene does not affect CR_{cf}, as the quantity of cutting fluid consumed is same at a particular velocity. Dry machining does not use any cutting fluid, so CR_{cf} is zero for all experiments performed using dry machining.

FIG. 6 Variation in carbon released due to use of cutting fluids, CR_{cf}.



Variation in Carbon Released Due to the Manufacturing of Cutting Tools Used (CR_{tool})

Figure 7 shows the variation of carbon released by tools consumed for all experimental conditions. The tool flank wear shown in Table 1 is used to determine tool life (T_{tool}) under each machining condition, which in turn was used to determine the number of tools consumed during the machining time (t_m). Carbon released due to the use of cutting tools is proportional to the number of tools consumed. Dry machining using G1 and G3 tools showed a large amount of release in carbon at 74, 86, and 112 m/min. This is due to the early failure of tool caused by fracture, while with G5 tool, tool wear was found to be less; hence, carbon released with its usage in machining is less. Dry machining released a large amount of carbon at 67 m/min. The use of cutting fluids decreased the tool wear at all velocities and hence reduced the consumption of cutting tools and the amount of carbon released. The use of graphene cutting fluids as MQL has decreased the tool wear by 0.3 wt % showing the least tool wear at all cutting velocities. Hence, number of tools consumed is fewer, and the amount of carbon released with the use of cutting tools is lower.

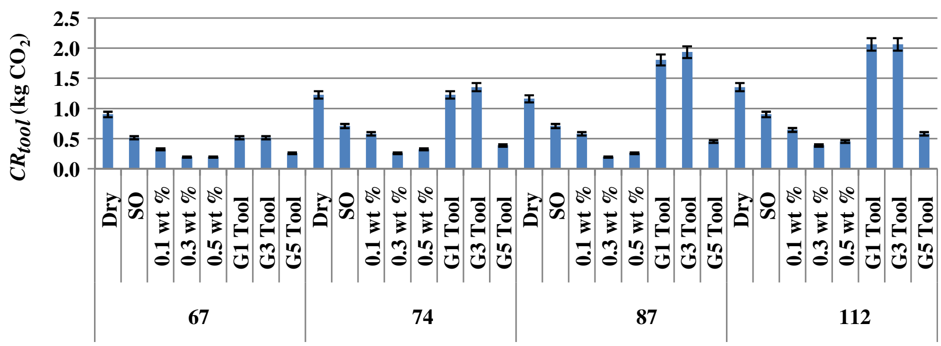
Variation in Carbon Released during the Production of Material Removed as Chip (CR_{mat}) and Recycling of Chip (CR_{chip})

CR_{mat} is carbon released during the production of unused workpiece material, which is removed in the form of a chip while converting raw material to finished product. The amount of energy consumed to form workpieces in the form of rods used in machining depends on the type of material and manufacturing process used for its production. This is used to determine the amount of carbon released during the production of material per unit mass (K_m), which in turn is used to determine the amount of carbon released during material removed as a chip during the present machining process (CR_{mat}). CR_{chip} is carbon released during the recycling of the chip. As a part of the recovery process, chips are to be recycled. The amount of energy consumed during the recovery of chips is based on the type of chip material and the process used for chip recovery, which in turn can help in evaluating the amount of carbon released during chip recovery per unit mass (K_{chip}); this in turn can be used determine carbon released due to recovery of chips produced in the machining process (CR_{chip}). As the same quantity of material is removed in all experiments in the form of chips, carbon released during the production of material removed as a chip (CR_{mat}), and carbon released during recycling of the chip (CR_{chip}), i.e., 13.4274 kg CO_2 and 2.4771 kg CO_2, respectively, irrespective of the type of machining environment used, i.e., dry machining using conventional cutting tools or using graphene-based self-lubricating tools or MQL application of conventional or graphene-based cutting fluids.

Variation in Carbon Released during the Production of Nanoparticles Used (CR_{nano})

Cossutta, McKechnie, and Pickering[32] performed life cycle assessment of graphene produced by different methods. When graphene is produced on a commercial scale, global warming potential for producing 1 g of graphene is found to be 0.284 kg CO_2 when produced using electrochemical exfoliation method, 0.081 kg CO_2 when produced

FIG. 7 Variation in carbon released due to cutting tools used (CR_{tool}).



using chemical oxidation method, and 0.046 kg CO_2 when produced by chemical reduction method. The average of all these, 0.137 kg CO_2/g = K_{nano}, is used in the present analysis. Carbon released due to the use of graphene nanoparticles in the machining depends on the quantity of graphene consumed. Figure 8 shows the variation in carbon released during the production of graphene nanoparticles that are used in the machining process (CR_{nano}). Carbon released is found to increase with the increase in the concentration of graphene in cutting fluid. With the increase in cutting velocity, machining takes less time, and hence the cutting fluid consumption is less and the consumption of graphene dispersed in cutting fluid is less. Thus, carbon release is found to decrease with an increase in cutting velocity. For graphene-based self-lubricating tools, the quantity of graphene used is proportional to the volume of holes filled, which in turn is proportional to number of holes. Since the dimensions of the holes are in micrometers, the quantity of graphene used is also very small. The quantity of graphene used is also proportional to the number of tool changes. Thus, the more the tool wear, the more tool changes, and hence the quantity of graphene consumed will be larger. Thus, carbon released is of the order G3 tool > G5 tool > G1 tool. However, this is very small compared to the amount of carbon released using graphene-based cutting fluids. Carbon released using graphene-based self-lubricating holes is in the range of 0.0005–0.0057 kg CO_2, which is very small compared with that released with the use of graphene cutting fluids and hence is not visible in figure 8.

Variation in Carbon Released during Total Machining Process (CR_{mach})

Figure 9 shows the variation in carbon released during the total machining process (CR_{mach}). At lower velocity, i.e., at 67 m/min, dry machining showed the lowest release of carbon, while at all remaining velocities, the MQL application of 0.3 wt % graphene-based cutting fluid showed the lowest release of carbon. At a high velocity, i.e., at

FIG. 8 Variation in carbon released during the production of graphene used in machining (CR_{nano}).

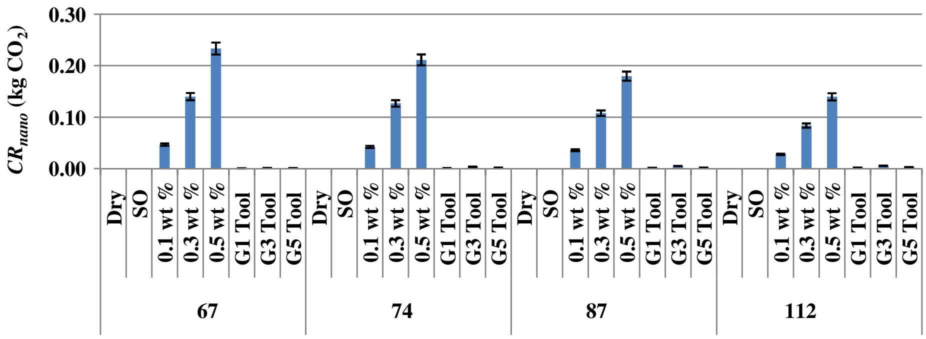


FIG. 9 Variation in carbon released during the total machining process (CR_{mach}).

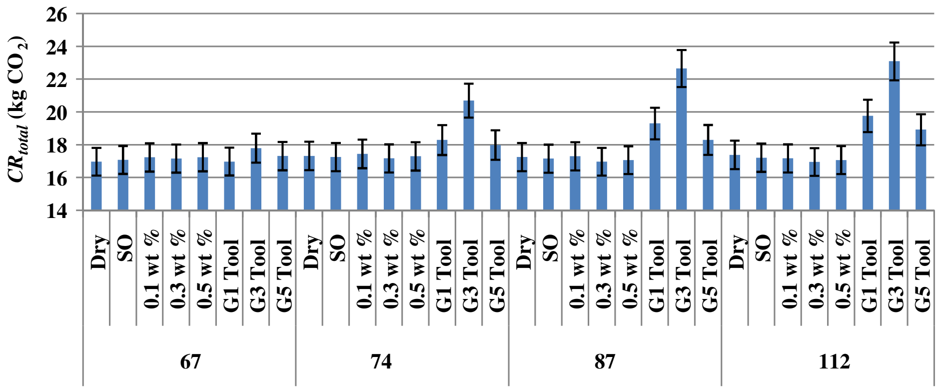


TABLE 2
Decrease in carbon emission with MQL application of 0.3 wt % graphene-based cutting fluid

	Cutting Velocity, m/min		
	74	87	112
Decrease in carbon emission with regard to dry machining per year, kg CO_2	797	1,700	3,334

112 m/min, the MQL application of graphene-based cutting fluid reduced carbon emission compared with dry machining as well as with the MQL application of conventional cutting fluid. Because of a higher power consumption in the drilling of microholes using a laser, graphene-based self-lubricating tools showed higher carbon emission. Also, in the case of G1 and G3 tools, the failure of tools led to higher consumption of cutting tools and more hole drilling processes to make the tool self-lubricating, which in turn increased the amount of carbon released into the atmosphere. In the case that the location of holes is properly chosen to maintain the strength of the tool and an alternative method for hole drilling is adopted that consumes less power, then the use of a graphene-based self-lubricating tool can lead to improved machining performance as well as reduced carbon emission. Table 2 shows that carbon emission reduced by ≈790–3,350 kg CO_2 with an MQL application of 0.3 wt % graphene-based cutting fluid compared with dry machining in a year by a single machine tool. This decrease is enormous when all machine tools in the whole world are considered.

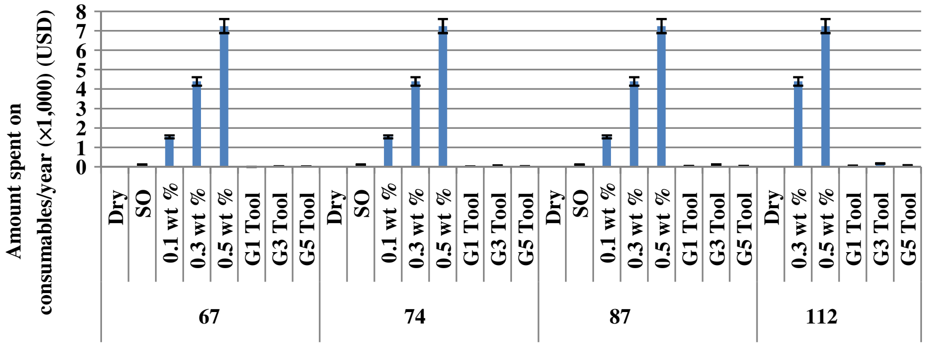
VARIATION IN ECONOMIC PERFORMANCE

TE in machining is determined by summation of the amount spent on consumables (C_{cons}), power consumed (C_{power}), and cutting tools (C_{tools}). Economic analysis is performed for one year.

Variation in the Amount Spent on Consumables

Consumables used in machining are cutting fluid concentrate, water, graphene, and Triton X-100. Figure 10 shows the amount spent on consumables. Dry machining does not use any of the consumables mentioned. Thus, the cost of consumables in dry machining is ₹0 (0 USD). The cutting fluid used is water-soluble oil in which concentrated cutting oil is added to water in a ratio of 1:20. Graphene-based cutting fluids contain graphene dispersed in cutting fluid with Triton X-100 as surfactant. Graphene-based self-lubricating tools have holes drilled and filled with graphene. The amount spent on consumables is found to be the highest with an MQL application of 0.5 wt % graphene-dispersed cutting fluid. This is due to the consumption of the highest quantity of graphene and surfactant Triton X-100.

FIG. 10 Variation in amount spent on consumables (C_{cons}).



Variation in Amount Spent on Power Consumption per Year

During the machining process, power is consumed by the machine tool when it is in the idle condition, i.e., standby power (P_{sb}), and when it is performing machining operation (P_m). While applying cutting fluid as MQL, power is consumed by the compressor (P_c) and MQL system (P_{mql}). While using graphene-based cutting fluids, power is consumed by a sonicator, which is used to disperse graphene in cutting fluid (P_s). For graphene-based self-lubricating tools, microholes are to be drilled using a laser, which consumes power (P_h). The total amount spent on power consumption per year is determined and is presented in figure 11.

The amount spent on standby power (C_{sb}) is constant for all cases. The amount spent during the machining process (CP_m) is directly proportional to the tangential force and cutting velocity. At all cutting velocities, dry machining showed the highest tangential force, followed by MQL application of conventional cutting fluid, dry machining using G1, G3, and G5 tools, and MQL application of 0.1, 0.3, and 0.5 wt % graphene-based cutting fluid. A similar trend is seen with variation in power consumed during machining. Although MQL machining consumed less power during machining, the use of accessories like the compressor and MQL system increased power consumption and the use of a sonicator further elevated power consumption while using graphene-based cutting fluids. Considering the overall amount spent on power consumption, at low velocity, i.e., at 67 m/min, dry machining showed the lowest expenditure, while at all remaining velocities, the amount spent on dry machining is similar to that spent using the MQL application of conventional cutting fluid and graphene-based cutting fluid. More is spent on power consumption while performing dry machining using graphene-based self-lubricating tools. This is due to the fracture of G1 and G3 tools, which led to more tool changes and more microhole drilling operations. Although tool wear with G5 tool is less, more holes have to be drilled in each new tool compared with G1 and G3 tools, leading to increased power consumption even for fewer tool replacements.

Variation in Amount Spent on Cutting Tools per Year

The amount spent on cutting tools per year is in proportion to tool wear shown in Table 1. Figure 12 shows the variation in the amount spent on cutting tools (C_{tools}). Due to more wear with dry machining, the amount spent on tools is higher. The MQL application of conventional cutting fluid showed less tool wear than dry machining and hence a lower amount spent on tools. With MQL application of graphene-based cutting fluid, tool wear decreased with 0.3 wt %, showing the least tool wear, and hence it showed the lowest amount spent on tools. With graphene-based self-lubricating tools, G1 and G3 tools showed more tool wear and G5 showed the lowest tool wear, and hence the trend of the amount spent on cutting tools is similar.

Variation in TE per Year

Figure 13 shows the variation of TE per year obtained using equation (8), which is obtained by considering the amount spent on consumables (equation (9)), power consumption (equation (10)), and cutting tools

FIG. 11 Variation in amount spent on power consumption (C_{power}).

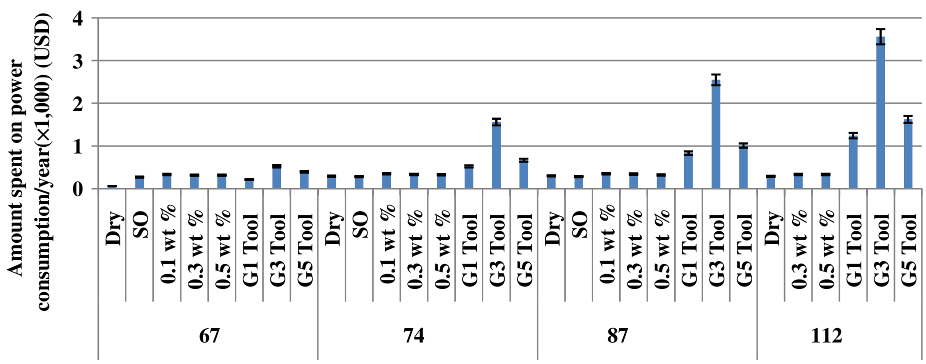


FIG. 12 Variation in amount spent on cutting tools (C_{tools}).

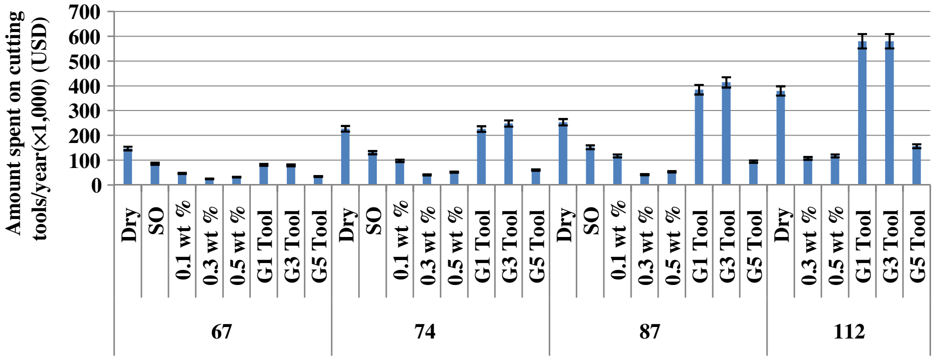
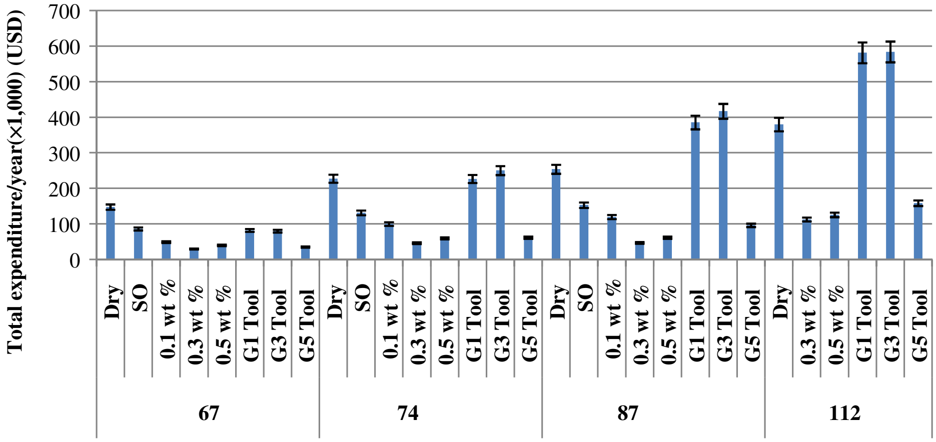


FIG. 13 Variation in TE per year.



(equation (11)). As the amount spent on cutting tools is a dominant factor while machining Inconel 718, the trend of TE is similar to that of the amount spent on cutting tools. G1 and G3 tools showed maximum expenditure at 74, 86, and 112 m/min due to higher tool wear and fracture. The fracture of tools was due to improper location of microholes. Thus, proper care must be taken to decide upon the location of

TABLE 3
Percentage decrease in expenditure w.r.t dry machining

	67	74	87	112
Dry	…	…	…	…
SO	41.55	42.25	39.74	36.14
0.1 wt %	66.82	55.98	52.87	52.09
0.3 wt %	79.78	79.67	81.52	70.35
0.5 wt %	72.89	73.64	75.84	66.93
G1 tool	44.56	0.28	−51.75	−53.04
G3 tool	45.76	−10.11	−64.18	−53.68
G5 tool	75.95	72.82	62.09	58.27

microholes. Exempting machining with G1 and G3 tools, dry machining showed the highest expenditure that increased with cutting velocity. TE was reduced with the MQL application of conventional cutting fluid. TE was further reduced with the MQL application of graphene-based cutting fluids, with 0.3 wt % showing the least expenditure. G5 tool showed lower cutting forces and tool wear due to the proper location of graphene-filled holes, which in turn reduced the TE while machining with G5 tool. MQL application of 0.3 wt % graphene-based cutting fluid showed the least expenditure. Table 3 shows the percentage decrease in TE with regard to dry machining at each velocity. Model calculations of carbon footprint analysis and economic analysis for MQL application of 0.3 wt % graphene based nanofluid at 112 m/min while machining Inconel 718 is given in Appendix.

Conclusion

The effect of graphene-based nanofluids and self-lubricating tools in machining Inconel 718 is analyzed by comparing machining performance, environmental impact, and economic analysis with dry machining and MQL application of conventional cutting fluids.

- Graphene-based cutting fluid provided better lubrication and helped in reducing tangential cutting forces. MQL application of 0.5 wt % graphene-based cutting fluid showed the lowest tangential force.
- MQL application of 0.3 wt % graphene-based cutting fluid showed the lowest tool wear. Tool wear decreased by ≈70–84 % with 0.3 wt % graphene-based nanofluid compared with dry machining over a velocity range of 65–115 m/min.
- Graphene-based self-lubricating G5 tool showed better performance than dry machining. The location of microholes should be properly chosen to take advantage of graphene-based self-lubricating tools. Hence, graphene-based cutting fluid as well as self-lubricating tools showed improved performance over dry machining and MQL application of conventional cutting fluid while machining Inconel 718.
- MQL application of 0.3 wt % graphene-based cutting fluid showed maximum reduction in carbon emission with regard to dry machining, leading to the most environmentally friendly process among the considered cases.
- Carbon emission reduced by nearly 790–3,335 kg CO_2 per year per machine tool while machining Inconel 718 in the cutting velocity range of 70–115 m/min.
- MQL application of 0.3 wt % graphene-based cutting fluid showed the lowest TE, leading to the most economical process among the considered cases.
- Expenditure reduced by 70–80 % while machining using the MQL application of 0.3 wt % graphene-based cutting fluid.

Thus, the MQL application of 0.3 wt % graphene-based cutting fluid while machining Inconel 718 showed improved machining performance and is also economical and environmentally friendly, leading to sustainable manufacturing.

FUTURE SCOPE

The influence of contributions of auxiliary systems such as chip conveyor systems, lubrication systems, and heating, ventilation and air conditioning systems on the total power of the system can be studied in detail under each machining environment.

ACKNOWLEDGMENTS

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Appendix: Model Calculations for 0.3 wt % Graphene-Based Nanofluid at 112 m/min

MODEL CALCULATIONS FOR CARBON FOOTPRINT ANALYSIS

Details of Machine Tool

- Voltage: 230 V
- Current: 50 A
- Power factor: 0.75

Machining Conditions

- Feed, $f = 0.13$ mm/rev
- Depth of cut, $d = 0.5$ mm
- Cutting velocity, $v = 112$ m/min

Carbon Footprint Analysis Model Calculations

$$CR_{mach} = CR_{power} + CR_{cf} + CR_{tool} + CR_{mat} + CR_{chip} + CR_{nano} \tag{A.1}$$

Carbon Released during Production of Power Consumed in Machining Process (kg CO_2): CR_{power}

K_{elec} = amount of CO_2 released per kilowatt hour of power generation, = 0.83 kg CO_2/kWh, from Appendix C – Table A (2016–2017),[31] as in India.

P_m = power consumed during machining = tangential force × cutting velocity

$$P_m = F_z \times v = \frac{158.2 \times 112}{60{,}000} = 0.2953\,\text{kW} \quad \text{Machining time, } t_m = \frac{\pi DL\delta}{1{,}000\,\text{vfd}} = \frac{3.14{*}30{*}150{*}10}{1{,}000{*}\frac{112}{60}{*}0.13{*}0.5} = 1{,}164.56\,(\text{s}) \tag{A.2}$$

P_{sb} = standby power that is used when the machine is idle = 0.0024 kW

Ideal time $t_i = 0.1{*}t_m = 116.45$ s (the ideal time is 10 % of the machining time)

P_c = power consumed by the compressor during MQL application = 2.238 kW

Compressor running time, $t_i = 0.5{*}t_m = 582.28$ s (compressor running time = 50 % of machining time)

P_{mql} = power consumed by MQL system = 0.006 kW

P_s = power consumed by sonicator while dispersing nanoparticles in cutting fluid = 0.6 kW sonication time, t_s = 1,400s

n = number of holes drilled on the cutting tool = 0 for 0.3 wt % graphene-dispersed cutting fluid as a conventional tool is used.

G5 Graphene Self-Lubricated Tools

n = 5 times the number of cutting tool edges used

If T_{tool} is tool life (s), the number of cutting tool edges used $= \frac{t_m}{T_{tool}} = \frac{1{,}164.5}{135.88} = 9$ (for G5 tool at 112 m/min)

$n = 5 \times 9 = 45$

P_h = power consumed by a laser for making a hole = 0.125 kW

t_h = time taken to make a hole using laser (0.5 h) = 30 × 60 = 1,800 s

$nP_h t_h = 45 \times 0.125 \times 1{,}800 = 10{,}125\ \text{kWs}$

$$CR_{power} = K_{elec}P_{mach} = K_{elec}(P_m t_m + P_{sb}t_i + P_c t_c + P_{mql}t_m + P_s t_s + nP_h t_h)$$
$$= \frac{0.83(0.2953*1,164.56 + 0.0024*116.45 + 2.238*582.28 + 0.6*1,400 + 0)}{3,600} = 0.5747\ \text{kg}\ CO_2 \quad (A.3)$$

Carbon Released during Production and Disposal of Cutting Fluid (kg CO_2): CR_{cf}

K_{cf} = amount of CO_2 released during the generation of one liter of mineral oil (kg CO_2/L) = 2.85 kg CO_2/L[22]
CF_i = initial quantity of cutting fluid used (L) = 0.5
CF_{ex}= excess quantity of cutting fluid used (L) = 0
K_{cfw} = amount of CO_2 released during disposal of 1 L of waste cutting fluid (kg CO_2/L) (in the case of dry machining and MQL application, it is 0) = 0
Δ = quantity of concentrated cutting fluid = 1:20 = 0.05
T_{cf} = life of the cutting fluid (assumed to be 2 months)

$$CR_{cfp} = K_{cf}(CF_i + CF_{ex}) = 2.85(0.5 + 0) = 1.425$$
$$CR_{cfd} = K_{cfw}\left(\frac{CF_i + CF_{ex}}{\Delta}\right) = 0$$
$$CR_{cf} = \frac{(t_i + t_m)}{T_{cf}}(CR_{cfp} + CR_{cfd}) = \frac{(116.45 + 1,164.56)}{2 \times 30 \times 24 \times 3,600}(1.425 + 0) = 0.0003521\ \text{kg}\ CO_2 \quad (A.4)$$

Carbon Released during Manufacturing of Cutting Tools Used (kg CO_2): CR_{tool}

The number of cutting tool edges used = $\frac{t_m}{T_{tool}} = \frac{1,164.5}{197.45} = 6$ (tool life, T_{tool} =197.45 s for 0.3 wt % graphene cutting fluid)
K_t = amount of CO_2 released during production of cutting tool = 29.6 kgCO_2/kg[22]
m_t = mass of cutting tool edge = 0.00218 kg

$$CR_{tool} = \frac{t_m}{T_{tool}}(K_t m_t) = \frac{1,164.56}{197.45}(29.6 \times 0.00218) = 0.38716\ \text{kg}\ CO_2 \quad (A.5)$$

Carbon Released during Production of Unused Workpiece Material Removed as Chips While Converting Raw Material to Finished Product (kg CO_2): CR_{mat}

K_m = amount of CO_2 released during the production of workpiece material (Inconel 718) = 11.6 kg CO_2/kg[32]
ρ = density of workpiece material, 8.129 g/cm^3

$$\text{Metal removal rate, MRR} = \frac{1,000 \times f \times d \times v}{10^6} = \frac{1,000 \times 0.13 \times 0.5 \times 112}{60}\ \text{mm}^3/\text{s} = 121.33\ \text{mm}^3/\text{s}$$
$$\text{Mass of material removed in form of chip (kg)}, m_c = \frac{\rho \times MRR \times t_m}{10^6} = \frac{8.129 \times (121.33) \times 1,164.56}{10^6}\ \text{kg} = 1.15752\ \text{kg}$$

$$CR_{mat} = K_m \times m_c = 11.6 \times 1.1485 = 13.4274\ \text{kg}\ CO_2 \quad (A.6)$$

Carbon Released during Recycling of Chips (kg CO_2): CR_{chip}

K_{chip} = amount of CO_2 released during recycling of Inconel 718 chips = 2.14 kg CO_2/kg,[32]

$$CR_{chip} = K_{chip} \times m_c = 2.14 \times 1.15752 = 2.4771\ \text{kg}\ CO_2 \quad (A.7)$$

Carbon Released during Production of Nanoparticles Used (kg CO_2): CR_{nano}

K_{nano} = amount of CO_2 released during the production of graphene nanoparticles = 0.137 kg CO_2/g
Q_n = quantity of graphene used per milliliter of cutting fluid (for 0.1 wt %: 0.00105 g; 0.3 wt %: 0.00315 g; 0.5 wt %: 0.00525 g)
fr = flow rate of cutting fluid = 10 mL/min

$$m_{nano} = Q_n \times fr \times t_m = 0.00315 \times \frac{10}{60} \times 1,164.56 = 0.61139\,\text{g}$$
$$CR_{nano} = K_{nano} \times m_{nano} = 0.137 \times 0.61139 = 0.08376\,\text{kg}\,CO_2 \quad (A.8)$$

Substituting all values in equation (A.1),

$$CR_{mach} = CR_{power} + CR_{cf} + CR_{tool} + CR_{mat} + CR_{chip} + CR_{nano}$$

$$= 0.5747 + 0.0003521 + 0.38716 + 13.4274 + 2.4771 + 0.08376 = 16.9505\,\text{kg}\,CO_2$$

For dry machining at 112 m/min, carbon released during machining process, $CR_{mach} = 17.3826\,\text{kg}\,CO_2$
When machining is done for 1,164.56 s (machining time, t_m), the decrease in carbon released with the use of 0.3 wt % graphene cutting fluid compared with dry machining = 17.3826 − 16.9505 = 0.4321 kg CO_2
If machining is done continuously for a year, the decrease in carbon released $= \frac{0.4321}{1,164.56}(52 \times 6 \times 8 \times 3,600) = 3,334\,\text{kg}\,CO_2$
1 year = 52 weeks, 1 week = 6 working days, 1 day =8 working hours, 1 hour = 3,600 s

MODEL CALCULATIONS FOR ECONOMIC ANALYSIS

TE in machining is determined by using equation (A.9):

$$TE = C_{cons} + C_{power} + C_{tools} \quad (A.9)$$

Amount Spent on Power Consumption per Year: C_{power}

$$C_{power} = (CP_{sb} + CP_m + CP_c + CP_{mql} + CP_s + CP_h) \times 12 \quad (A.10)$$

Machining time per day = 7.27 h
Idle time per day (0.1 times machining time) = 0.73 h
Total working hours per day = 8 h
The price of electricity is taken as the industrial power rate in Andhra Pradesh, India, as ₹5.60/kWh (0.079 USD/kWh).[34]

TABLE A.1
Amount spent on consumables per year: C_{cons} (equation (9))

	Quantity Consumed per Day	Quantity Consumed per Year	Cost per Unit	Total Amount Spent, USD
Cutting fluid concentrate (1:20): C_f	$=\frac{1}{21} \times \frac{10\,\text{mL/min}}{1,000} \times 60\ \text{min} \times 8\,\text{h} = 0.228\text{L}$	71.314 L	1.619 USD/L	115.51
Water (20:1): C_w	$=\frac{20}{21} \times \frac{10\,\text{mL/min}}{1,000} \times 60\ \text{min} \times 8\,\text{h} = 4.571\text{L}$	1,426.15 L	3.59 USD/5,000 L	1.02
Graphene: C_g	$=\frac{0.312}{105} \times (4.571 + 0.228) \times 1,000 = 14.26\,\text{g}$	4,450.01 g	0.5439 USD/g	2,420.36
Triton X-100: C_{tx}	0.2285 L	71.31 L	26.05 USD/L	1,857.62
Total amount spent on consumables (C_{cons}) (equation (9))				4,394.51

TABLE A.2
Amount spent on power consumption/year: C_{power} (equation (10))

	Power Consumption per Month, kWh	Amount Spent on Power Consumption per Month, USD	Total Amount Spent on Power Consumed per Year, USD
Standby power: CP_{sb}	$= 0.73h \times 0.0024\,\text{kW} \times 25 = 0.0438\,\text{kWh}$	0.0034602	0.041522
Machining: CP_m	$= F_z \times v \times \text{machining time } \frac{158.20}{1{,}000} \times \frac{112}{60} \times 7.27 \times 25 = 53.6719\,\text{kWh}$	4.24	50.88
Compressor: CP_c	$=$ kWh of compressor $\times$ compressor running time $\times 25 = 2.238 \times \frac{8}{2} \times 25 = 223.8\,\text{kWh}$	17.6802	212.16
MQL system: CP_{mql}	$=$ kW of MQL system $\times$ MQL running time $\times 25 = 0.006 \times 8 \times 25 = 1.2\,\text{kWh}$	0.0948	1.1376
Sonicator: CP_s	$=$ kW of sonicator $\times$ sonicator running time $\times 25 = 0.6 \times 5 \times 25 = 76\,\text{kWh}$	5.925	71.1
[a] Laser for making holes: CP_h	…	…	…
Amount spent on power consumption per year: C_{power}			335.319

Note: [a] For 0.3 wt % graphene-based nanofluid, the conventional cutting tool is used, so power spent by the laser used for drilling holes equals zero.

In the case of G5 graphene self-lubricated tools, where five holes are drilled using a laser on each cutting edge,

$$\begin{aligned}
&\text{number of cutting edges used per month} = \frac{\text{machining time/month}}{\text{Tool life}} = \frac{8*60*60*25}{135.88} = 5{,}300\\
&\frac{\text{power consumption}}{\text{month(kWh)}} = \text{number of cutting edges used per month} \times \text{number of holes per edge}\\
&\quad \times \text{time taken to drill a hole} \times \text{kW for drilling one hole} = 5{,}300 \times 5 \times 0.5 \times 0.125 = 1{,}656.25\,\text{kWh}\\
&\text{The total amount spent on power consumed per year(USD)} = 1{,}656.25 \times 0.079 \times 12 = 1{,}570.12
\end{aligned} \tag{A.11}$$

Amount Spent on Cutting Tools Used per Year: C_{tool}

$$C_{\text{tool}} = \frac{t_m \text{per year}}{T_{\text{tool}}} \times \frac{C_{\text{insert}}}{n} = \frac{52 \times 6 \times 8 \times 60 \times 60}{197.45} \times \frac{9.47}{4} = 107{,}740 \tag{A.12}$$

(Tool life, $T_{tool} = 197.45$ s for 0.3 wt % graphene cutting fluid)
TE in machining $= C_{\text{cons}} + C_{\text{power}} + C_{\text{tools}} = 112{,}680$ dollars per year
For dry machining at 112 m/min, TE in machining = 380,000 dollars per year
The percentage decrease in expenditure with regard to dry machining at 112 m/min $= \frac{(380-112.68)}{380} \times 100 = 70.35\,\%$ (as shown in **Table 3**).

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