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ORIGINAL ARTICLE

Comparison of machinability and economic aspects in turning of Haynes-25 alloy under novel hybrid cryogenic-LN oils-on-water approach

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Abstract

Haynes-25 is a cobalt-based alloy resistant to oxidation and possesses high-temperature properties. Despite the excellent properties, the machinability of Haynes-25 is extremely difficult. Sustainable machining of this alloy is inevitable for producing earth-friendly products. Thus, researchers and scientists have been seeking alternative sustainable technologies to machine these alloys. In the present study, efforts are made to explore the machinability, energy consumption, and economic feasibility of a novel oils-on-water (OoW) lubrication approach mixed with cryogenic liquid nitrogen (LN). Twenty external turning experiments were performed under this novel cryogenic-LN oils-on-water (LNOoW) approach and compared with conventional machining approaches. Machining performance (temperature, cutting power and energy, tool wear and tool life, and surface quality) and economic aspects (production cost) were considered as response metrics. Column graphs are plotted for each metrics to compare the results. The results showed that the proposed LNOoW lubricooling approach reduced the cutting temperature and improved the surface quality of the workpiece significantly. Furthermore, less cutting power and electrical energy consumption were achieved in the proposed cooling/lubrication approach. The novel LNOoW approach also enabled an extension of about 97.56 to 111.11% of cutting tool life as compared to flood-assisted machining process. In addition, 11.76% of surface roughness and 38.725 ¥ cost reduction was obtained at the lowest level of feed rates. It was noted that better economic benefits could be obtained at the highest feed rate and the mid-range levels of cutting speeds. Furthermore, 50% economic benefits are achieved at medium cutting parameters in the LNOoW approach. Overall, the LNOoW approach out-performed in all the metrics. Therefore, the LNOoW approach has a high potential to replace the old cutting technologies. The present work can be used as fundamental guidelines for the machinist working in the metal processing industry to adopt the hybrid LNOoW approach successfully in the machining process.

Keywords Minimum quantity lubrication (MQL) · Oils-on-water (OoW) · Hybrid cooling/lubrication technique · Tool wear · Cobalt alloys · Sustainability · Surface quality · Temperature

1 Introduction and literature

Cobalt and its alloys are the ideal materials used in biomedical, chemical, automotive, and aerospace industries. This is because of their good physical and mechanical properties, such as good resistance against corrosion, high strength to weight ratio, and excellent temperature properties to withstand high temperatures. Figure 1 shows the Textron Lycoming gas turbine engine combustor and Dresser-Rand DR-990 industrial turbine made of Haynes-25 alloy. Cobalt alloys are some of the most difficult-to-cut materials that possess many machining problems like fast tool deterioration rate, very poor machined surface quality, and machining deformation. These problems are encountered during machining because the cobalt alloys have low thermal conductivity, high chemical reactivity rate, and very poor modulus of elasticity [1]. Poor heat conduction of the cobalt alloy results in increasing the temperatures in cutting zone, which causes the reduction in cutting-tool life. Ultimately, cutting edge failure of the tool, and noticeable chipping on the tool face occur [2].

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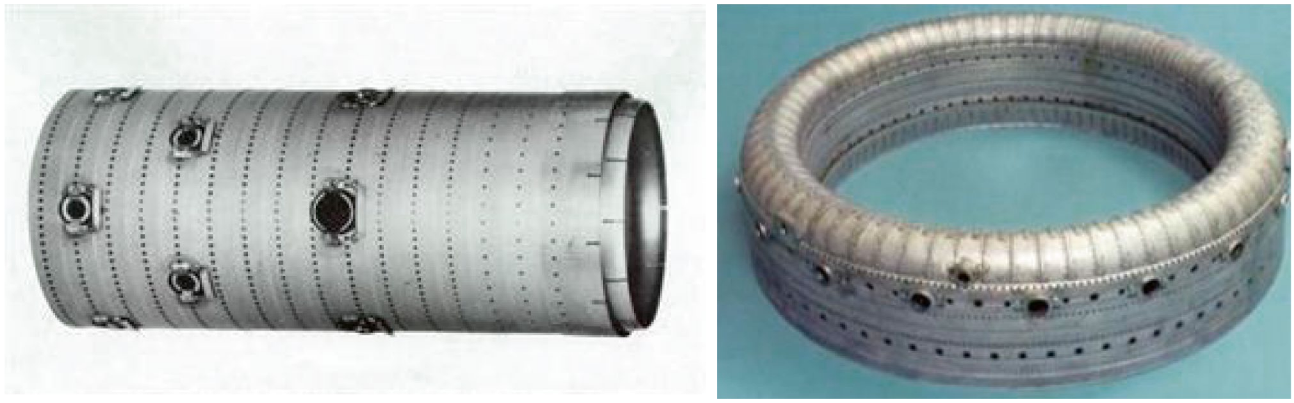

(a) (b)

Fig. 1 Application of Haynes-25 alloy (adopted from Haynes International). **a** Textron Lycoming gas turbine engine combustor. **b** Prototype combustor for Dresser-Rand DR-990 industrial turbine (adapted from Haynes International)

To overcome the problems mentioned above, various cooling and lubrication approaches are used. During the machining process of Haynes-25 alloy, flood cooling is mostly used. Flood cooling uses synthetic oils which are not only costly but are hazardous to the environment and operators as well [3]. Over the years, researchers have developed many near dry cutting methods to reduce the cost of Haynes alloy machining and minimize the use of cutting fluids as well. These methods include cryogenic machining using liquid nitrogen (LN) [4], water vapor cooling method [5], and minimum quantity lubrication (MQL) [6]. The application of MQL alone is not a sustainable solution for excellent surface quality and machinability. Similarly, liquid nitrogen alone also provides excellent cooling, but lack of lubrication creates serious issues to achieve the required surface quality. Thus, there is a dire need to develop a hybrid technology that can provide both cooling and lubrication.

To enhance the cutting performance, exploration of the most suitable cooling methods is becoming a very hot topic among researchers. Sivaiah and Chakradhar [7] investigated the performance of 17-4PH stainless steel using a turning process under minimum quantity lubrication (MQL), liquid nitrogen (LN), dry, and wet cutting environments. Results concluded that liquid nitrogen out-performed by promoting the machinability (in terms of cutting force, surface roughness, tool flank wear, and material removal rate) and surface integrity of the machined workpiece as clean cooling and manufacturing technique. Liu et al. [8] used a new environmental-friendly green cooling technique, in which water vapors were considered as a coolant medium. The vapors penetrated deep in the cutting zone due to the gaseous phase and hence improving the penetrability. Water vapors helped to reduce the coefficient of chip deformation and lower cutting temperatures. Tool life was extended by using the water vapors for both direct applications or with vapor and gas application during the cutting process compared to dry cutting. Khan et al. [9] investigated the lubrication effect on the 3D-printed titanium alloy under micromachining process conditions. They found that minimum quantity lubrication (MQL) and refined grain structure of the 3D-printed titanium alloy helps to improve the tool life, lower the burr formation, and improve the surface quality compared to dry milling. Liu et al. [8] studied the hot turning of 17-4PH steel under the MQL, wet, and dry environments. It was concluded that hot turning mixed under the MQL environment promoted the surface quality and chip formation significantly. Sartori et al. [10] proved that it is feasible to use MQL by mixing with LN and CO_2 for finish turning of cobalt alloy and reported the potential to reduce the tool crater wear. Khani et al. [11] proposed a technique in which a hybrid system was used to combine plasma-enhanced liquid nitrogen cooling to improve the machining process of 17-4PH steel. Their results showed that using the hybrid technique reduces the cutting force and flank wear significantly compared to dry or lone liquid nitrogen cutting. Sustainable class of cutting technologies are a better alternative to cutting fluids, in which with the help of compressed air coolant medium is atomized and supplied to the cutting zone which results in great permeability and penetration of the coolant [12]. Near dry cutting technologies are advantageous because they avoid environmental, economic, and many other inefficient problems caused by synthetic cutting fluids. MQL is the major technique that is widely used as a near dry technology. However, MQL has difficulties in reconfiguring dedicated transfer line systems in metal cutting industrial [13]. Itoigawa et al. proposed a new hybrid technique that simultaneously performs lubrication and cooling functions. This method employs oil mixed with the droplets of water commonly known as oil on water (OoW). The effectiveness of the hybrid cooling/lubrication technique is also proved by the other researchers during the turning of titanium alloy and cast iron comparing with the near dry cutting technique [14, 15]. MQL cooling capacity (when used alone) is quite satisfactory at room temperature but in industrial applications it is not sufficient for remarkable improvement of cutting quality and machining hard to cut materials at aggressive cutting parameters.

Cryogenic is one of the near dry cutting technologies used by the researchers, which effectively reduce the cutting temperatures and provide quite satisfying cutting quality of the hard-to-cut materials. Khanna et al. [16] holistically investigated the design and development of cryogenic machining technologies. The authors classified the cryogenic machining technologies and discussed cryogenic delivery techniques with near dry machining techniques such as minimum quantity lubrication (MQL). Gupta et al. [17] conducted turning experiments to evaluate the performance of hybrid cryo-lubrication-assisted machining of Ti–6Al–4 V alloy. From the results, it was noted that the use of hybrid N_2 with MQL can reduce tons of annual coolant consumption. Furthermore, the proposed technology also improved the surface quality and reduced the built-up-edges of chips, and tool wear. In another study, Gupta et al. [18] developed a novel cryogenic system to machine carbon fibre reinforced plastic (CFRP) composites. The authors concluded that their proposed cooling technology improved surface quality and decreased inverse delamination factor increased by 5–68% when compared with dry drilling.

Jamil et al. [19] investigated the feasibility of using cryogenic machining to replace the conventional cooling methods in hard turning of titanium alloy. They found that the use of LN as a cryogenic coolant improved the machining performance in terms of productivity and cost. Mia et al. [20] investigated the effect of cooling strategy in hard turning of difficult to cut material on the cutting performance and environmental aspects. Their results showed a great improvement in sustainability metrics and machinability compared with the dry cutting process. Sivaiah and Chakradhar [21] conducted experiments to optimize the cryogenic turning process parameters. Results revealed the influence of feed rate on the cutting performance was significant. Increasing the feed rate causes an increase in the tool wear rate and affects the surface quality. Use of cooling techniques as fourth controllable parameter to optimize the cutting conditions with the use of Taguchi technique during the machining process of 17-4PH steel. Results showed that 53.5% reduction of surface roughness was achieved by using optimum cutting process parameters and applying LN while machining. Some researchers [22] proposed another technique used as near dry cutting known as cryogenic air mixed minimum quantity lubrication (CAMQL) cooling method. CAMQL results showed remarkable cutting performance improvement for difficult to machine materials such as cobalt alloys. In CAMQL, MQL is used as a lubricator while the air and liquid nitrogen are used to dissipate the effect of high temperature during cutting. Thus, providing simultaneously two different functions which help to reduce tool wear and increase the surface integrity. CAMQL served as energy-saving technique, and its temperature is not as colder as solo LN, which will affect the material properties (increase hardness) while machining.

From the above literature, it is evident that a novel cryogenic-LN oils-on-water (LNOoW) approach has not been used in the machining of Haynes-25 alloys. Furthermore, the application and performance evaluation of LNOoW in machining Hayness-25 alloys need to be investigated. In this context, this study investigates the tool wear rate, surface quality, cutting temperature, and machining sustainability under oil on water-based hybrid cooling technique (LNOoW) that enable developing a novel hybrid method for high quality machining of Cobalt alloy. To the author's knowledge, no study is available for applying simultaneous cooling/lubrication in the machining of Haynes-25 and investigating the machinability and sustainability altogether. A new cooling method by using the hybrid cooling and lubrication technique in which liquid nitrogen oil on water (LNOoW) is used in the turning process. A new external cost-effective cooling system is developed in which Cryo-LN is used with OoW to study the influence on the cutting performance in terms of cutting temperature, tool wear, surface quality and cutting force. The outcomes of the research provide fundamental guidelines for the implementation of sustainable technology in the industry for manufacturing critical components.

2 Experimental setup

The following section describes the details about the machine tool, the material used and measurement methods. In addition, details about the technological parameters and cooling approaches have been discussed.

2.1 Machine tools and materials

External turning experiments were performed on a CNC lathe machine (model: BOOHI SK50P, Baoji Zhongcheng, China). Uncoated carbide inserts with wiper geometry (model: YG8) were procured to machine difficult-to-cut Co-20Cr-15 W-10Ni (Haynes-25) material. The chemical composition, mechanical and physical properties of the workpiece material were measured at room temperature and shown in Table 1.

These properties are taken from the supplier and published literature [23]. The nose radius of the cutting tool was 0.8 mm. The cutting tool was mounted on the tool holder (MCLNL 1616-H12). The tool holder positioned the cutting tool at – 5° end and back rake angles as hard machining is

Table 1 Chemical composition (% weight) mechanical and physical properties of the workpiece material of the material (Haynes-25) (adapted from Haynes International)

Chemical composition								
C	Co	Cr	Fe	Ni	P	S	Si	W
0.1	Balance	20.28	1.58	10.20	< 0.005	< 0.0008	0.01	14.68
Mechanical properties of Haynes-25								
Ultimate tensile strength (MPa)				Hardness		% Elongation	2.0% Yield (MPa)	
941				210		49.50	446	
Physical properties								
Density (g/cm^3)		Specific heat (J/g K)		Thermal conductivity (W/mK)		Melting point (°C)		
9.17		0.395		9.51		1322–1415		

commonly set at a negative rake angle. The detailed specifications of the cutting tools are given in Fig. 2. Experimental setup for novel LNOoW and conventional flood-assisted turning process is shown in Fig. 3.

During the conventional flood-assisted machining, an emulsion was prepared by adding 8% Syntilio cutting oil in water. The emulsion was flooded in the cutting region with a flow rate of 5 L/min. Oil-on-water (OoW) are delivered from the MQL system in the cutting zone. For OoW, a biodegradable Blaser vegetable oil with a flow rate of 25 mL/h was mixed in water through the MQL system and impinged in the cutting zone. A liquid nitrogen tank was separately placed near the MQL system, and LN was impinged from a separate nozzle. However, MQL and LN carrying nozzles exit points were closely attached to get the proper mixture of LNOoW mist. It is pertinent to mention that the flow rate of LN was relatively less as compared to the solo LN application system.

2.2 Technological parameters and cooling approaches

In the present study, the effect of cutting parameters on the measured responses has been studied. The levels and values of the cutting parameters are shown in Table 2. Each experiment was performed two times at the same cutting conditions to obtain repeatability and consistent results. The cutting parameter values (Table 2) were chosen from the literature [24] and preliminary experiments.

The schematic diagram of LNOoW is shown in Fig. 2. Before discussing the LNOoW lubricooling approach, it is necessary to understand the working principle of OoW. The working principle of OoW is simple in which a minimal amount of biodegrading oil and clean water is transported by the universal MQL system to the cutting region. Oil-in-water can be sprayed through both internal (IOoW) and

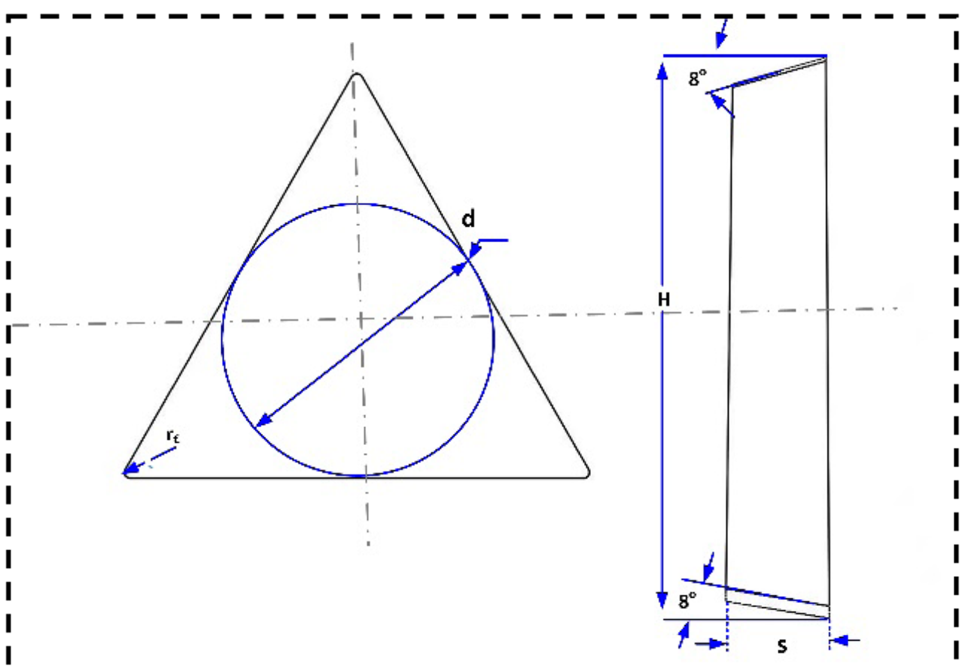

Fig. 2 Specification of cutting tool used in the experimentation

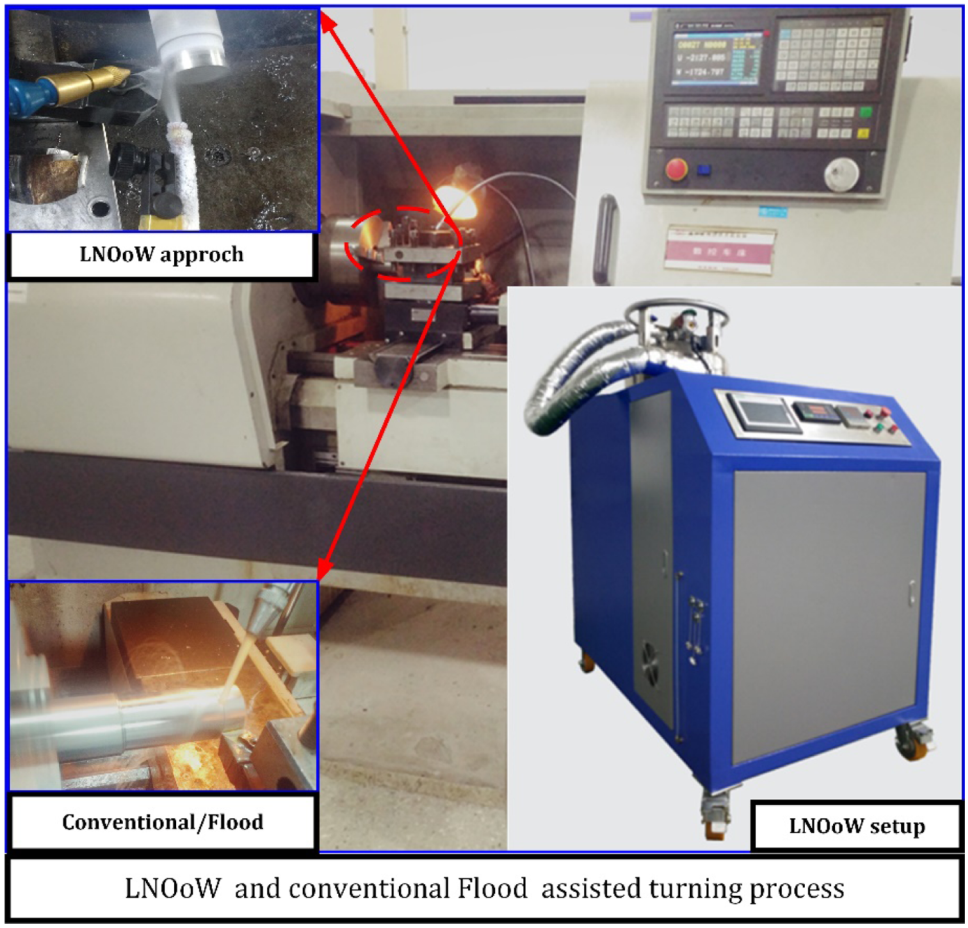

Fig. 3 Experimental setup for novel LNOoW and conventional flood-assisted turning process

external (EOoW) methods. In the present study, OoW was mixed with liquid nitrogen (LN) and sprayed by an external mechanism (Fig. 4). The new mechanism provides the cooling effects from the LN and lubrication effects from the direct penetration of OoW in the cutting region. The direction of LN was fixed towards the flank face, and the OoW was impinged on the rake face of the cutting tool. The flow rates of oil, water, and liquid nitrogen were kept constant in the present study because their effects on the process performance have already been studied [25]. The temperature of the liquid nitrogen was measured as -195 °C at the exit of the nozzle. The LNOoW based green lubricooling system was procured from DG Armorine Energy-Efficient and Eco-Friendly Tech Co., Ltd, China.

Table 2 The values and levels of cutting parameters used in the experimental study

Cutting parameter(s)	Levels
Cutting speed (m/min)	30,60,90, 120
Feed rate (mm/rev)	0.4,0.8
Depth of cut (mm)	0.8
Cooling approaches	LNOoW and conventional flood approach

The metal cutting industry is using the conventional flood cooling method for the last century. Conventional cooling provides good surface quality; however, it negatively affects the environment and workers' health and safety. The flow rate of flood coolant was kept at 5 L/min during the experiments. Castrol (Syntilo 9930) water-soluble cutting fluid was used in flood assisted machining process. The cutting fluid was mixed with water at an eight percent fraction by weight. The machine tool has a built-in coolant storage tank with a total capacity of 50 Liters, and the total coolant life is 15 days (one shift per day).

3 Response measurements

This section describes the measurements of all responses. The new model of production cost is also developed and discussed in the following subsections.

3.1 Cutting temperature

Measurement of cutting temperature is an inevitable task because it affects the life of the cutting tool. Extreme temperature in the cutting zone significantly reduced the life

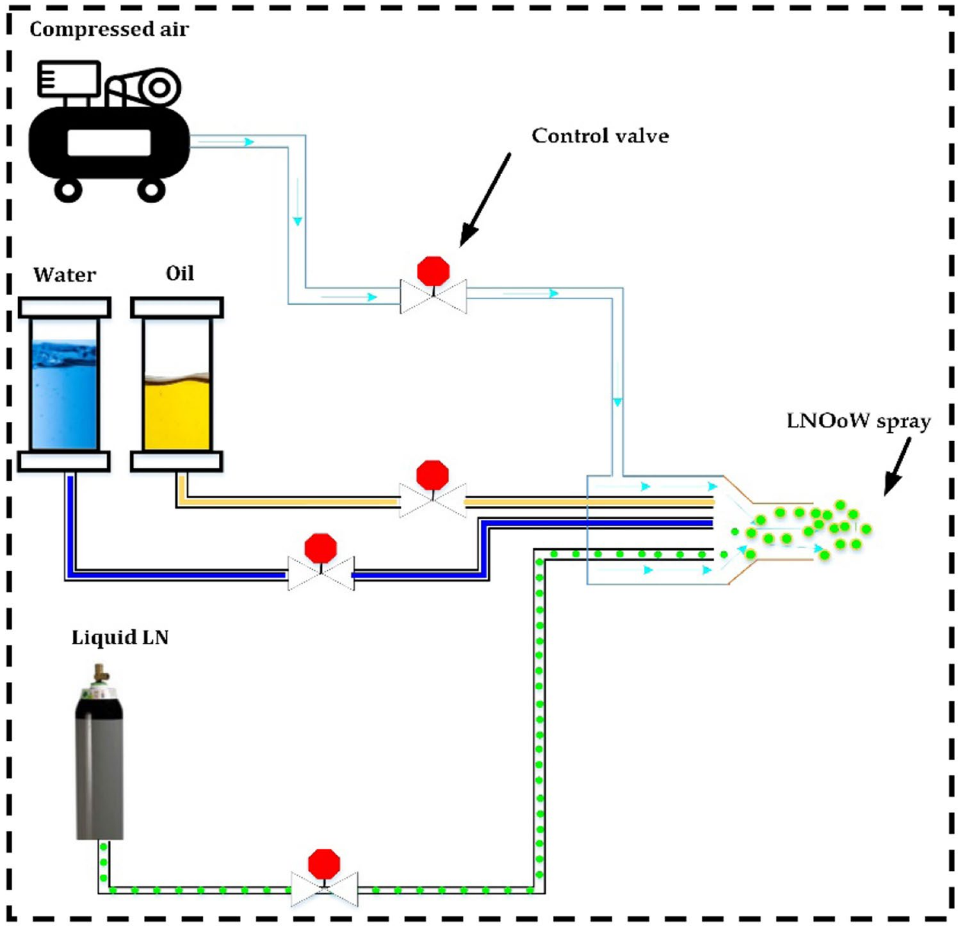

Fig. 4 Schematic view of LNOoW lubricooling approach

of the cutting tool. In the present study K-type thermocouple (aluminum–chromium) is used to measure the cutting temperature. The one end of the thermocouple wire was inserted into the insulated workpiece, and the second end was fixed on the rake face of the cutting tool. A small hole (~ϕ 0.8 mm) was drilled on the rake face with the help of the EDM process to insert the thermocouple wire (Fig. 5). The wire was inserted approximately 3.5 mm away from the newly generated workpiece surface. Voltage values were obtained from the thermocouple device, and a data acquisition system was used to get temperature values from the voltage values.

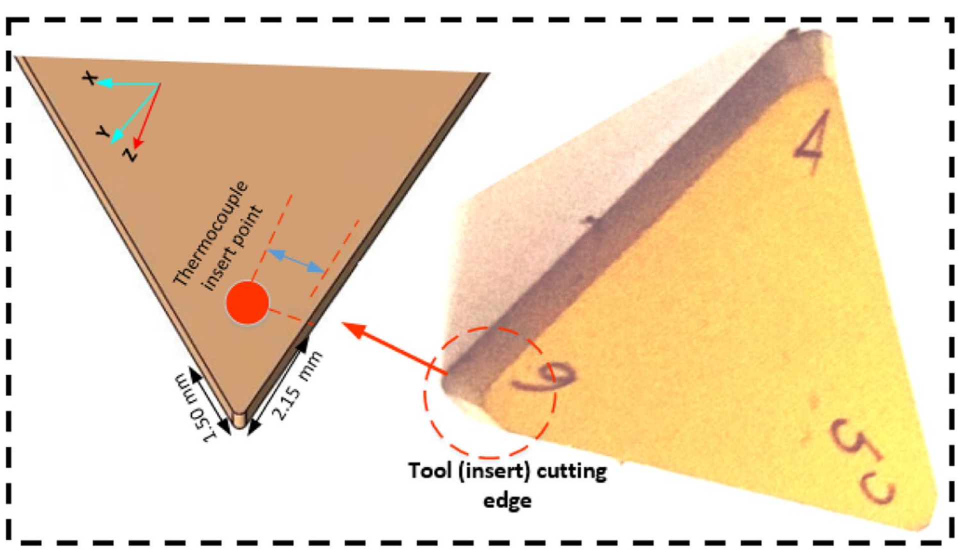

Fig. 5 Temperature measurement procedure on the rake face of the cutting tool

3.2 Surface quality of the workpiece

The surface quality of the workpiece was assessed by measuring the average surface roughness, SR (Ra) of the workpiece. After each turning experiment, SR values were measured using a portable surface tester (Mahr: Perthometer-M1). It is pertinent to mention that surface roughness values were measured three times at three different locations on the machined surface of the workpiece. It was done to avoid errors and to ensure precision. The surface roughness measurement procedure is shown in Fig. 6.

3.3 Tool wear and tool life

According to the International Standard Organization (ISO) "the change of shape of the tool from its original shape, during cutting, resulting from the gradual loss of tool material or deformation is called wear." In the present study, average flank wear of 0.30 mm was chosen as a tool life criterion according to ISO standard 3685 [24]. After a specific cutting length, the cutting insert was de-attached from the holder and tool wear was measured using ARTCAM optical microscope (model: 130-MT-WOM ARTRAY Co, Ltd, Tokyo, Japan). To get the tool life, tool wear was measured multiple times after a specific cutting time. For the accurate estimation of tool life, the interpolation method was used. The measurement setup of cutting tool life is depicted in Fig. 7.

According to ISO 3685, when the average value of Vb reached the restrictive value (0.3 mm), the cutting time was calculated to measure the tool life. A mathematical model is developed to estimate the cutting time, and then the model was validated doing machining experiments. The cutting length l_c is defined in Eq. (1).

$$l_c = f \times t_c \tag{1}$$

The general regression model to predict the tool wear is given in Eq. (2).

$$V_b = b \times e^{cl_c} \tag{2}$$

where average flank wear of cutting insert was represented by V_B, e is Euler's number, l_c is a total cutting length and c and b are constant values. f_z is feed per tooth, and D_c is tool diameter.

The relationship between feed rate, cutting time, and cutting length is shown in Eqs. (3) and (4).

$$v_f = {}^{f_z \times \times v_c \times 1000}/_{D_c \times \pi} \tag{3}$$

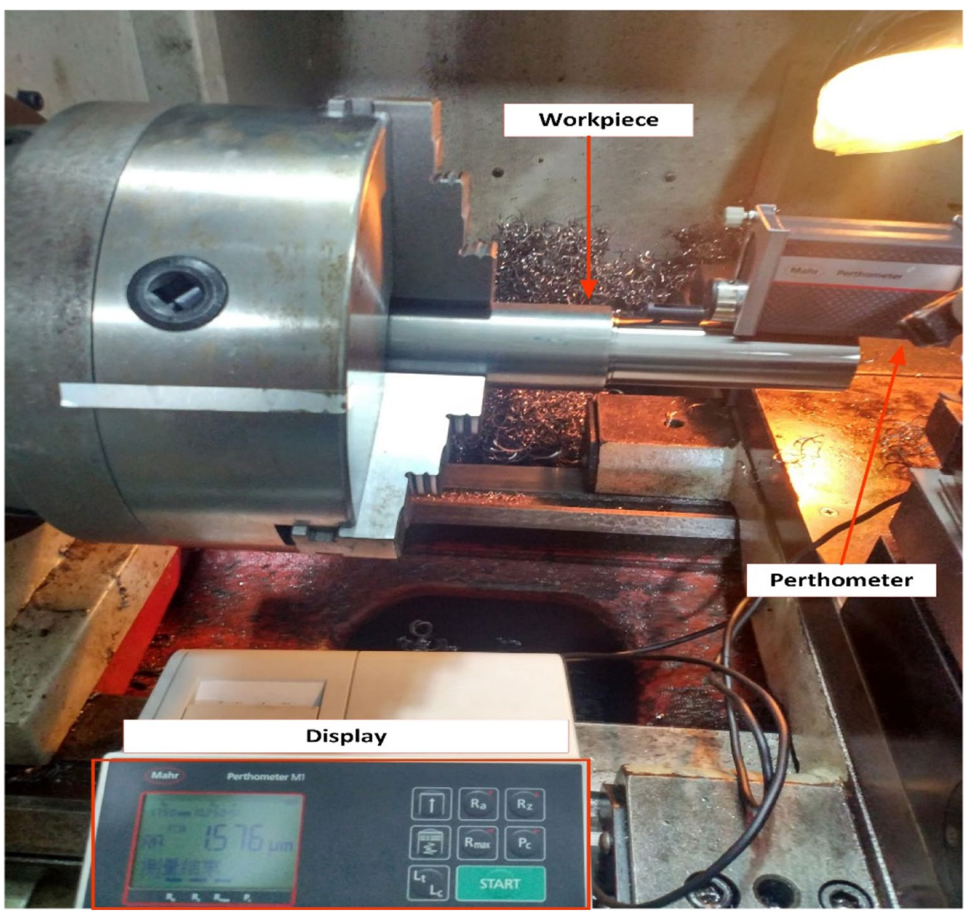

Fig. 6 Surface roughness measurement device and procedure

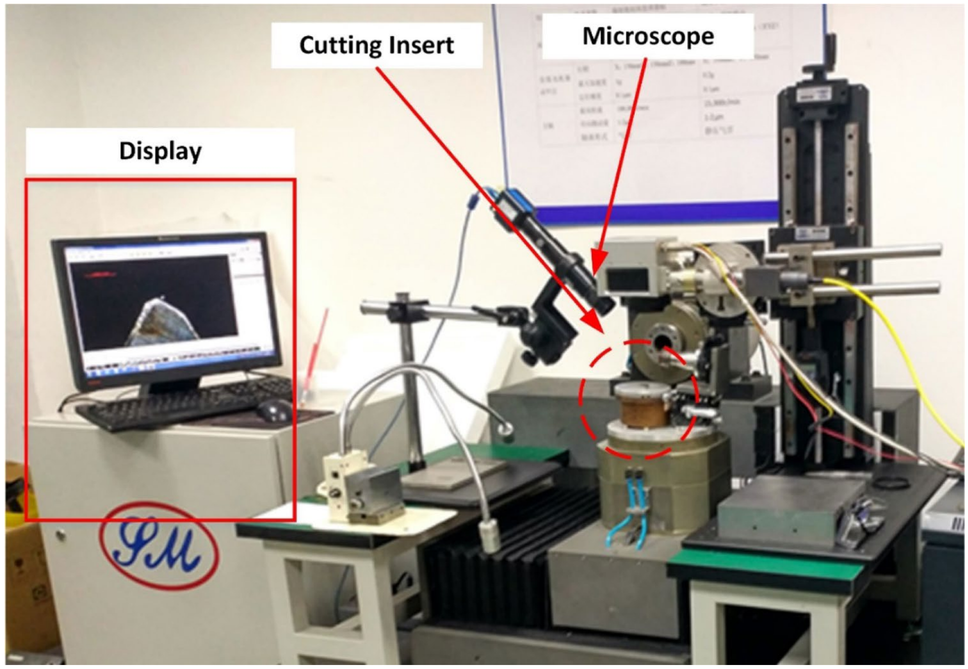

Fig. 7 Cutting tool wear measurement and setup

$$l_c = v_f \times T_L \quad (4)$$

Equation (5) is obtained by putting the values of v_f and l_c in Eq. (2).

$$V_b = b \times e^{1000 \times c \times v_c \times f_z \times z \times T_L} / _{D_c \times \pi} \quad (5)$$

Values of flank wear were predicted from Eq. (5). The mathematical model helps to predict the flank wear values accurately.

3.4 Production time

In machining processes, usually only cutting time is considered in the empirical modeling of time. However, in the present study, idle time (t_i), setup time (t_{su}), air cutting time (t_a), cutting time (t_c), tool change time (t_{tc}), lubrication time (t_{lub}), and cooling time (t_{col}) are considered. In ideal conditions, lubrication time should be equal to cooling time. However, in practical lubrication mist and LN spray (in case of LNOoW) is started during the air cutting time for generating the proper mist. However, on the other side, the flood coolant is only used while cutting starts. Thus, coolant time in the flood cooling approach is almost equal to cutting time. The total production time can be defined as in Eq. (6)

$$T_P = t_i + t_{su} + t_a + t_c + t_{tc} + t_{lub/col} \quad (6)$$

3.5 Electrical power and energy consumption

Power consumption at the process level, spindle level, and machine tool level was measured using a customized-built smart meter as shown in Fig. 8.

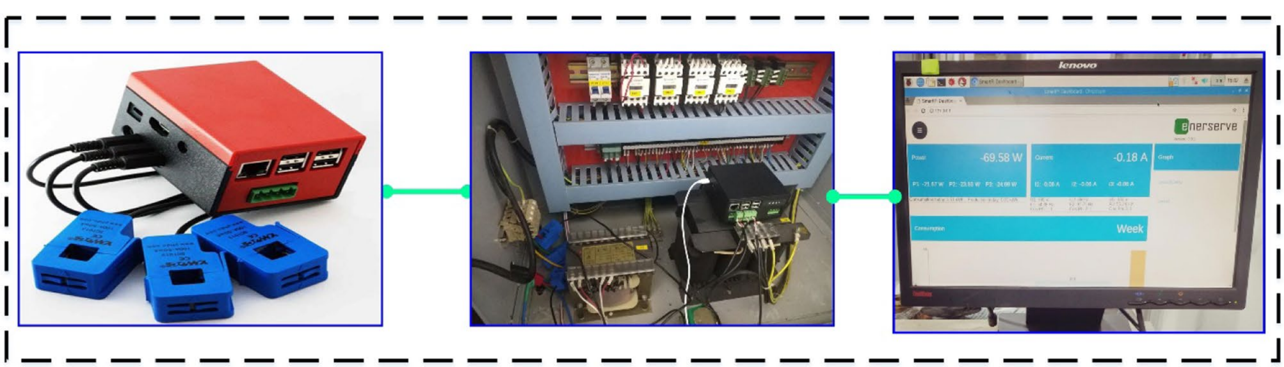

Fig. 8 Electrical power measurement and data storage system

The mathematical model for electrical power consumption is illustrated in Eq. (1). The power consumed by the subunits of the machine tool is highlighted in Eq. (8).

$$P = I \times V \times \sqrt{3} \times cos\varphi \tag{7}$$

$$P(t) = P_i(t) + P_{su}(t) + P_{air}(t) + P_{cs}(t) + P_{tc}(t) + P_l(t) \tag{8}$$

$P(t)$ is a sum of different electric power consumed during the various functionality states of the machine tool. In Eq. (7), P denotes the power consumption. Similarly, idle power (P_i), setup power (P_{su}), air cutting power (P_{ira}), standby power (P_{sb}), cutting power (P_c), the power consumed during the cutting tool change (P_{tc}), and lubrication (air compressor) power (P_l) are the various component of total power.

The electrical energy is obtained by multiplying the cutting time with the electrical power consumed. The formula used to measure the electrical energy is given in Eq. (9). The energy consumed during the various stages of the machining process is shown in Eq. (10)

$$E = P(t) \times t \tag{9}$$

$$E_{total} = \int_0^{t_i} P_i(t)dt + \int_0^{t_{su}} P_{su}(t)dt + \int_0^{t_h} P_h(t)dt + \int_0^{t_{ab}} P_{air}(t)dt + \int_0^{t_{aa}} P_{air}(t)dt + \int_0^{t_c} P_c(t)dt + \int_0^{t_{tc}} P_{sb}(t)dt + \int_0^{t_c} P_{col/lub}(t)dt \tag{10}$$

3.6 New holistic modeling approach for production cost

It is necessary to investigate the economic sustainability of new machining technologies through total cost or specific cost before introducing them to the metal cutting industry. If the production cost of the new technology is higher than traditional approaches, then it is not sustainable economically. The scholars proposed many models to estimate the production cost. However, most of the proposed cost models only dealt with either dry cutting or conventional machining [26]. The previous models included machining cost, cutting tool change cost, energy cost, and cutting-tool cost. However, the cost of new coolants and lubricants was missing.

In the present study, a new cost model has been proposed for LNOoW-assisted machining process. New cost components such as LN, coolant, and environmental aspects have been added to the proposed models.

3.6.1 Energy cost

The cost incurred due to electrical energy consumption is called energy cost. In the present study unit cost of the Guangdong electric grid has been used. The cost of electrical energy consumption can be defined as

$$C_e = x_e\left(\int_0^{t_i} P_i(t)dt + \int_0^{t_{su}} P_{su}(t)dt + \int_0^{t_a} P_a(t)dt + + \int_0^{t_c} P_c(t)dt + \int_0^{t_{tc}} P_{sb}(t)dt + \int_0^{t_c} P_{col/lub}(t)dt\right) \tag{11}$$

In Eq. (11), x_e is a unit cost of electrical energy consumption and C_e is energy cost.

3.6.2 Cost of liquid nitrogen LN

The application of liquid nitrogen in the LNOoW lubri-cooling approach is novel, and the cost of LN has never been added to the total production cost under LNOoW-assisted hard turning. The cost of consumed LN can be obtained from the following expression.

$$C_{LN_2} = x_{LN_2} \times (t_{air} + t_c) \times Q_{LN} \tag{12}$$

In Eq. (12), C_{LN_2} is a total of liquid nitrogen consumed, Q_{LN} is LN flow rate, and x_{LN} is a cost of one litter of LN.

3.6.3 Cost of conventional emulsion

The water-based emulsion was used as a coolant in the flood-assisted machining process. Emulsion stored in the tank is used multiple times. However, it has a certain lifetime. After the lifetime of the emulsion is reached, proper cleaning and disposal is required. The cost of the emulsion can be found as

$$C_{emulsion} = x_{emulsion} \times S \tag{13}$$

The cost of 1 litter emulsion is expressed by x_{emulsion} and S is the total amount of emulsion consumed in a specific experiment, and $C_{emulsion}$ is the total emulsion cost.

3.6.4 Cleaning related cost

After completing the machining of the Hynes-25 alloy, cleaning the workpiece a machine is required, which incurred additional cost. The cleaning cost can be calculated as

$$C_{cl} = x_{cl} \times MRV \tag{14}$$

C_{cl} (total cleaning cost) highly depends upon the unit cleaning cost (x_{cl}) and MRV. This cost is only incurred in the conventional flood-assisted machining process.

3.6.5 Disposal-related cost

In the metal processing industry, metalworking fluids (MWFs) have been used since the last century. The annual consumption of fluids in the world has reached up to 2×10^9L and the disposal volume is even more than the consumed volume. The negative consequence of MWFs is rancid odors and contamination. Thus, ISO states that it is inevitable to dispose of the used coolant to reduce earth pollution. The disposal cost can be calculated as in Eq. (15). In Eq. (15), x_d and C_d are the unit and total cost for disposing of the used coolant.

$$C_d = x_d \times S \tag{15}$$

3.6.6 Cutting-tool cost

Cutting inserts were used in the turning experiments, and the cost of cutting inserts was also included in the empirical model of the cost. Tool cost usually shares less percent of the total cost. However, it can share a significant fraction of the total cost when cutting difficult-to-cut materials such as Haynes-25 alloy. Cutting tool cost mainly depends upon the total life of the tool, and it can be defined as

$$C_{CT} = {}^{x_{CT}}/_{T_L} \times \left({}^{\pi \times D \times l}/_{v \times f}\right) \tag{16}$$

The cost of cutting tools mainly depends upon the tool life. The unit cost of the cutting tool is illustrated by x_{CT}; tool life if represented by T_L.

3.6.7 Workpiece cost

Workpiece cost is the cost of the material procured for product fabrication. The workpiece is given in Eq. (17).

$$C_{Wp} = x_{Wp} \times MRV \tag{17}$$

MRV is the total amount of material removed for a specific cutting experiment and x_{Wp} represents the unit cost of the workpiece.

3.6.8 Carbon tax, C_{ctx}

CO_2 is emitted when the electrical energy and resources are consumed during the machining process. A carbon tax is a fee imposed on the burning of carbon-based fuels (coal, oil, gas). The total carbon emission (CE_T) can be found as

$$CE_T = E_{total} \times CES \tag{18}$$

All the experiments were performed in Guangdong city of China. Thus, the carbon emission signatures of Guangdong province were calculated for the first time and used to find the environmental cost [27].

$$CES = \eta \times (112 \times \%C + 49 \times \%NG + 66 \times \%P) \tag{19}$$

In Eq. (19), %P, %NG, and %C are the percentage of petroleum, natural gas, and coal used in the local power grid of the industrial city.

$$C_{ctx} = CE_T \times K_{CO_2} \tag{20}$$

C_{ctx} is a total carbon tax for a specific experiment, and a constant amount of carbon tax (imposed by environment protection agencies) is denoted by K_{CO_2} [28].

3.6.9 MoH cost

Machining overhead (MoH) cost is the sum of all the indirect costs incurred while manufacturing a product. A lower MoH indicates the higher efficiency and more profit of the process. The MoH cost highly depends upon the machining cost rate (h_r). Components of machining cost rate (h_r) are shown in Table 3. The overhead cost can be calculated as

$$C_{MoH} = h_r \times \left(t_i + {}^1/_f\left(l_a + l_c + {}^{t_{ct} \times l_c}/_{T_L}\right)\right) \tag{21}$$

where h_r can be calculated from the methods adopted in Khan et al. [23]. The values are shown in Table 1.

3.6.10 Oil-on-water system cost

Cutting oil is used in the OoW system with a minimal flow rate of 30 mL/h. The cost of this oil was also calculated as follows.

$$C_{OoW} = x_{OoW} \times (t_{air} + t_c) \times Q_{OoW} \tag{22}$$

In Eq. (22), Q_{OoW} is a flow rate of oil-on-water. x_{OoW} and C_{OoW} are the unit volume cost and total cost of consumed oil-on-water.

Table 3 Components of machining cost rate (h_r) [29]

No.	Type of cost	Unit	Values
1	Lighting and HVAC loads are 0.3 and 8.0 kW;C_{HVAC}	¥/h	6.009
2	Machine depreciation cost; C_{dep} Machine-tool life (12 years)	¥/h	39.16
3	Labor cost;C_{labor}	¥/h	15.5

3.6.11 Total production cost

As illustrated in Eqs. (23) and (24), the total production cost is a sum of all direct and indirect costs. The variables used in these equations have been explained in the previous subsections and nomenclature.

$$C_P(LNOoW) = (X_e \times E_T + h_r) \times T_P + {}^{x_{CT}}/_{T_L} \times \left({}^{\pi \times D \times l}/_{v \times f}\right) + x_{Wp} \times MRV + x_{LN_2} \times \left(t_{air} + t_c\right) \times Q_{LN_2} + x_{OoW} \times \left(t_{air} + t_c\right) \times Q_{OoW} + CE_T \times K_{CO_2} \tag{23}$$

$$C_P(Flood) = (X_e \times E_T + h_r) \times T_P \times + {}^{x_{CT}}/_{T_L} \times \left({}^{\pi \times D \times l}/_{v \times f}\right) + x_{Wp} \times MRV + \left(x_{emulsion} + x_d\right) \times S + x_{cl} \times MRV + CE_T \times K_{CO_2} \tag{24}$$

4 Results and discussion

The following section has been divided into two parts, i.e., machinability aspects and economic aspects. In the first section, temperature, electrical power and energy, tool life, tool wear, and surface quality of the workpiece are investigated. In the second section, the economic aspects of both cooling/lubrication approaches have been compared and validated from the industrial study. The results of the measured responses are shown in Table 4.

4.1 Machinability aspects

In the subsections, machinability aspects of the proposed study are discussed.

4.1.1 Temperature

The cutting temperature of the cutting zone was measured with the help of a thermocouple, as discussed in the previous section. Figure 9a, b illustrates the variation in cutting temperature with the varying cutting speed and feed rate. At the lower level of feed rate (0.4 mm/rev) and cutting speed of 30, 60, 90, 120, and 150 m/min, the calculated reduction in the cutting temperature was 6.5%, 12.09%, 9.59%, 9.9%, and 7.8%, respectively, in proposed LNOoW novel cooling/lubrication process as compared to flood approach. Similarly, at a higher value (0.8 mm/rev) of feed rate and cutting speed of 120 m/min, it was possible to achieve a reduction of about 13.88% of cutting temperature.

Overall, the least cutting temperature was noted at the lowest values of cutting speeds and feed rate. In fact, at a low level of cutting speed, temperature elevation was less due to less plastic deformation and shearing. The less cutting

Table 4 Design of experiment and response measurements

	Input parameters			Response measures				
Exp. No.	Vc (m/min)	Feed (mm/rev)	Cooling	SR (µm)	Temp (ºC)	Energy (kJ)	TL (min)	Cost (¥)
1	30	0.4	Flood	1.45	215	279.47	7.58	8.93
2	60	0.4	Flood	1.32	248	147.72	4.45	5.90
3	90	0.4	Flood	1.21	271	104.64	2.22	6.07
4	120	0.4	Flood	0.98	302	80.852	0.91	8.93
5	150	0.4	Flood	0.85	330	65.497	0.45	13.11
6	30	0.8	Flood	1.67	245	140.274	7.08	4.80
7	60	0.8	Flood	1.41	276	74.754	4.36	3.23
8	90	0.8	Flood	1.32	298	52.912	2.17	3.32
9	120	0.8	Flood	1.11	336	40.743	0.89	4.78
10	150	0.8	Flood	1.02	360	33.05497	0.41	7.36
11	30	0.4	LNOoW	1.4	201	278.36	8.68	5.47
12	60	0.4	LNOoW	1.23	218	147.176	5.75	3.53
13	90	0.4	LNOoW	1.2	245	104.279	3.32	3.50
14	120	0.4	LNOoW	0.9	272	80.478	1.21	6.09
15	150	0.4	LNOoW	0.75	304	65.246	0.95	7.53
16	30	0.8	LNOoW	1.61	215	139.88	8.18	2.81
17	60	0.8	LNOoW	1.35	241	75.049	5.46	1.81
18	90	0.8	LNOoW	1.27	268	51.615	3.47	1.67
19	120	0.8	LNOoW	0.96	292	40.625	1.33	2.77
20	150	0.8	LNOoW	0.86	310	32.882	0.81	3.48

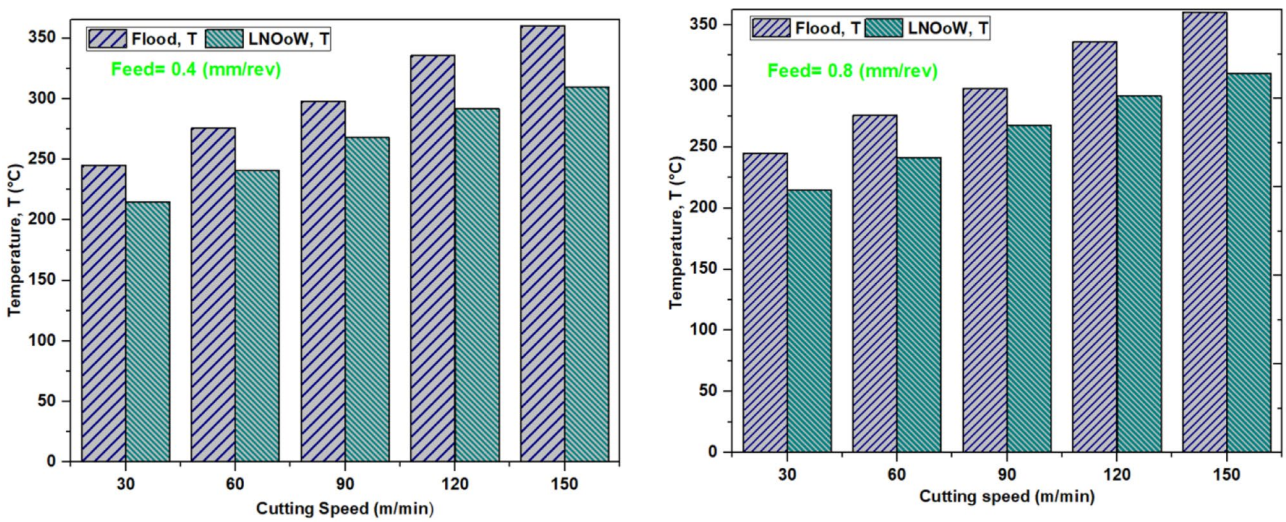

Fig. 9 The comparison of temperature proposed LNOoW and conventional environments. **a** Feed rate = 0.4 mm/rev. **b** Feed rate = 0.8 mm/rev

temperature in the LNOoW cooling/lubrication approach was noted due to the Joule–Thomson effect of LN [25]. The LN spray was successful in penetrating the primary cutting zone and decreased temperature rapidly. It is a fact that the ability of heat evacuation depends upon the thermal conductivity of the coolant/lubricant used. In the current situation, the enhanced thermal conductivity of liquid nitrogen helped to reduce the cutting temperature. Another reason for reduced temperature in the LNOoW approach was the combined cooling/lubrication mechanism. The nanodroplets emitted from the OoW system were combined by the LN and produced an effectively efficient lubricooling effect. Supercritical LN (-195 °C) comes out of the nozzle with a rapid expansion, and it helps reduce the cutting temperature. On the other side, Castrol (Syntilo 9930) water-soluble cutting fluid could not provide sufficient cooling while cutting Haynes-25 alloy.

4.1.2 Electrical power and energy consumption

Electrical power consumption was measured during the various stages (air cutting, idle, cutting, and tool change stages) of the machine tool with the help of a smart meter. During the external turning process, electrical power consumption is highly influenced by the wear of the cutting insert, the presence and type of coolant/lubricant, and the values of friction at the chip-tool interface. In the present study, cutting power was measured under two various types of cooling and hybrid cooling/lubrication approaches. Irrespective of cooling/lubrication environments, cutting power has also been examined under cutting conditions such as depth of cut, feed rate, and cutting speed. Figure 10a, b demonstrate the effect of five levels of cutting speed and two levels of cooling/lubrication approaches on the cutting power.

It can be seen from Fig. 10a, cutting power increases with the increase in cutting speed. This phenomenon is due to the fact that the spindle motor consumes more power at higher cutting speeds [30]. In addition, at aggressive cutting conditions, more power is required to remove the material. A similar trend for power consumption was also noted when the feed rate increased. At a lower feed rate (Fig. 10a), power consumption was 700 W. However, at a higher feed rate, 765 W power was consumed. Furthermore, for all cutting experiments hybrid cooling/lubrication LNOoW approach consumed less power consumption as compared to flood-assisted turning of Haynes-25 alloy. A maximum of 2.33% and 3.91% reduction in power consumption was observed at lower and higher feed rates, respectively. The less power consumption (Fig. 8) at all cutting conditions in the LNOoW approach is due to the increased chip flow at all levels of cutting speeds [31]. This helps to reduce the coefficient of friction at the tool-workpiece interface. Another reason for power reduction is associated with the reduction of chip thickness while applying the hybrid LNOoW cooling approach.

Due to the industrial revolution, electrical energy consumption in the industry and manufacturing sector is overall increased in the last few decades. It is important to mention that, in China, in 2015, 83.79% of total energy consumed by the industrial sector was shared by manufacturing sector only (Fig. 11) [32]. In Fig. 11, TEC is defined as total energy consumed.

With the growing concerns regarding the amount of energy consumption, the manufacturing sector is considered to play a significant role in reducing energy consumption. As a result, a reliable and precise estimation model of energy consumption that can reflect the electrical energy consumption during various machining states is required.

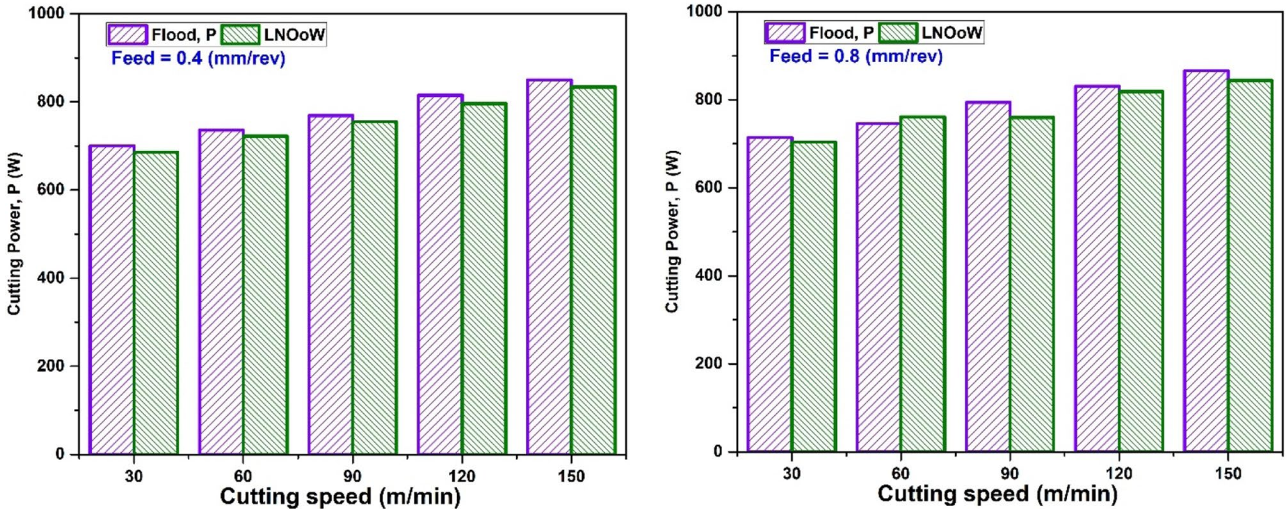

Fig. 10 The variation of cutting power under proposed LNOoW and flood cooling approach. **a** Feed rate = 0.4 mm/rev. **b** Feed rate = 0.8 mm/rev

Total energy consumption is a sum of electrical energy consumption and embodied energy consumption. In the present study, the effect of cutting parameters and cooling/lubrication approaches on electrical energy consumption is investigated. Figure 12 highlights the variation in electrical energy consumption as the cutting speed changes. Due to the lower power consumption in the LNOoW approach, less electrical energy is consumed in the LNOoW approach

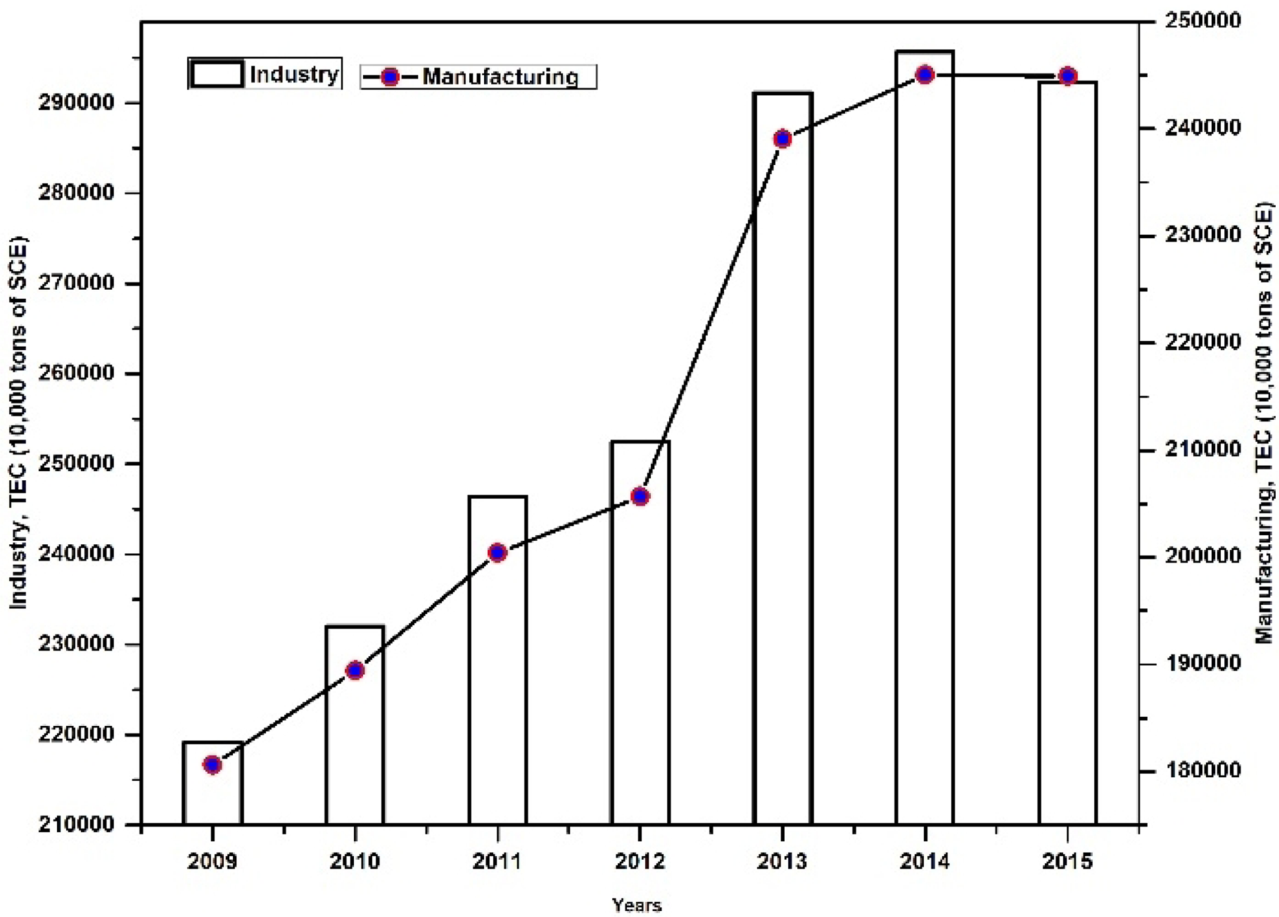

Fig. 11 Total energy consumption (TEC) in the industry and manufacturing sector of China [32]

at all cutting conditions. From Fig. 12, it is also noted that the amount of energy consumption decreases as the cutting speed increases. This phenomenon is due to the reduction in the cutting time as the cutting speed increases.

4.1.3 Tool life and tool wear

Cutting tool wear defines the ease of machinability of the workpiece in the machining process [19]. Thus, it is inevitable to measure the tool wear because it defines the surface roughness and power consumption. Rake and flank wear on the cutting edge of inserts were measured using a microscope, and tool life was predicted according to the proposed mathematical model. Using uncoated carbide inserts, severe friction was generated between chip and rake face, flank face and the new machine surface of the workpiece. The tool wear of the cutting insert highly depends upon the chemical composition of the workpiece and tool material, use of specific coolant and lubricant, and tool geometry.

Rake and flank sides of fresh/new cutting tools are shown in Fig. 13a, d. Figure 13b, c show the rake wear of cutting inserts used in flood and hybrid LNOoW cooling approaches, respectively. A relatively high temperature was observed at the tool-chip interface in the flood-assisted cooling approach, as shown in Fig. 9. This phenomenon leads towards the chip sticking with the rake surface and causes high rake wear. Chip adhesion was also noted in the conventional flood-assisted turning of Haynes-25 alloy. However, in the case of LNOoW, relatively less rake wear was observed due to the hybrid lubricooling effect of the LNOoW mechanism. In Fig. 13b, it was noted that the damage of the rake face is very accentuated on the entire tool. However, in Fig. 13c, crater wear pattern (near edge) is significant, but its width is less.

Abrasive wear occurs as a result of the interaction between the workpiece and the cutting edge. This interaction results in the abrading away of relief on the flank of the tool. This loss of relief is referred to as a wear land. It depends on the hardness of Haynes-25, elastic properties, and geometry of the used cutting tool of the two mating surfaces [33]. The larger the amount of elastic deformation a surface can sustain, the greater will be its resistance to abrasion. A hard material like Haynes-25 causes more abrasion wear than ductile steel [33].

Figure 13e, f demonstrate the flank wear mechanism of cutting inserts at a cutting speed of 90 m/min in both cutting environments. As expected, high abrasive wear of edge of cutting insert was observed in flood-assisted cooling approach. This high flank wear was also associated with poor thermal conductivity of cutting fluid compared to the liquid nitrogen in LNOoW. Even at a high cutting speed ($vc = 90$ m/min), LNOoW lubricooling approach reduced the cutting temperature and provided the necessary lubrication, which helps to reduce the friction in the cutting region.

The life of cutting edge of uncoated carbide insert can be defined as the total time accumulated before tool failure occurs, measured in minutes or volume of material removed. Figure 14 indicates the life of a single edge of the cutting tool at various cutting parameters. It can be seen that at all cutting conditions, the new hybrid LNOoW lubricooling

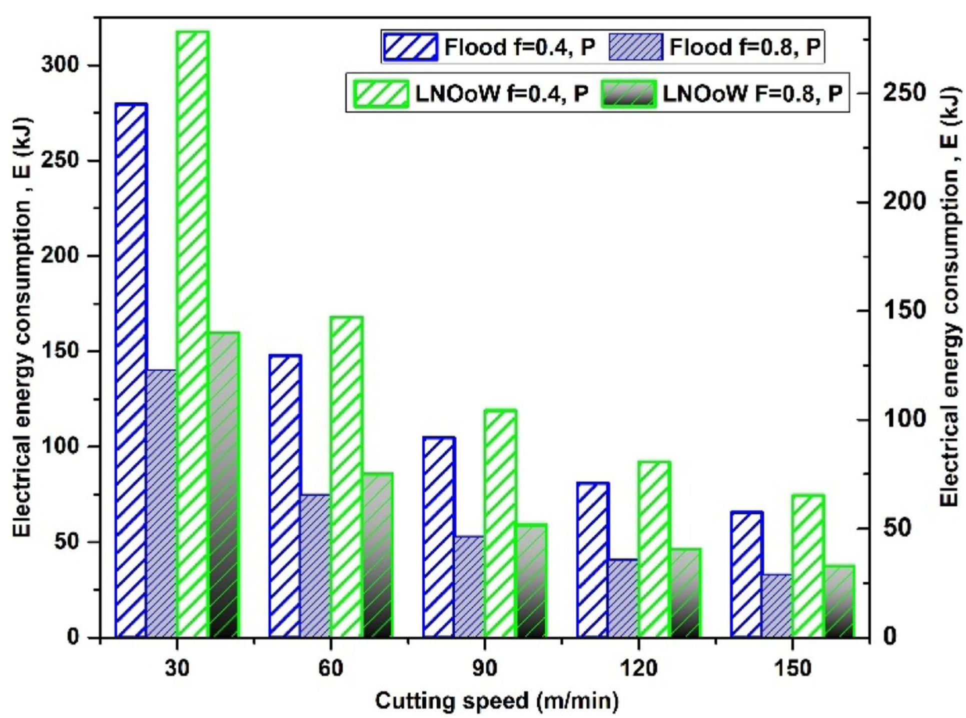

Fig. 12 The comparison of electrical power consumption under proposed LNOoW and flood cooling approaches

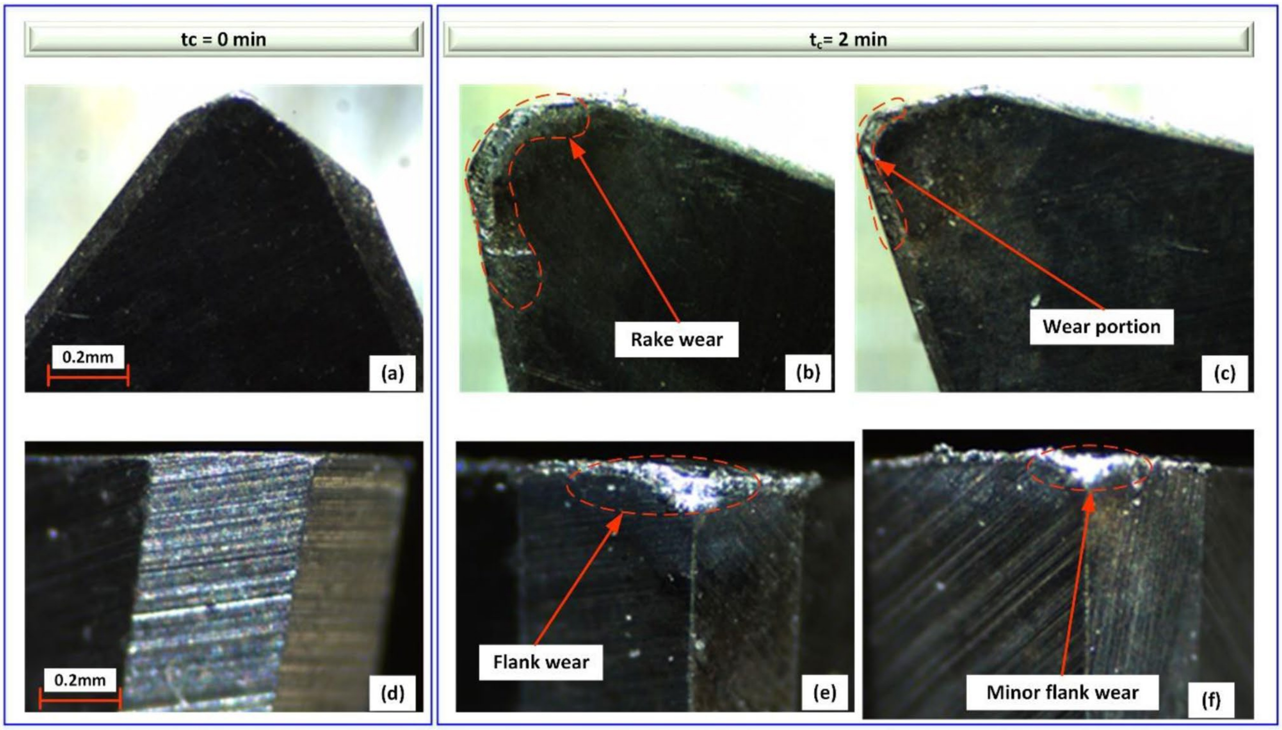

Fig. 13 Crater and flank wear of cutting tools at same cutting condition. **a**, **d** New tool. **b**, **c** Crater wear ($vc=90$ m/min, $f=0.4$ mm/rev, $a_p=0.8$ mm). **e**, **f** Flank wear ($v_c=90$ m/min, $f=0.4$ mm/rev, $a_p=0.8$ mm)

approach out-performed, which results in the cutting tool taking a long time before reaching failure. Abrasive wear, mechanical failure, heat failure, and edge notch were the most common failure which caused the cutting tool to reach its life.

At lower cutting speeds, both cooling and lubrication approach worked better. However, at higher cutting speeds new LNOoW lubricooling approach yielded 11.11% more tool life.

4.1.4 Surface quality

Average surface roughness was measured after each experiment to assess the surface quality of the workpiece. Figure 15 displays the variation and comparison results of surface roughness under the two cooling/lubrication approaches. From the figure, it is observed that the surface finish improves as the cutting speed is increased. However, an opposite trend is found when the feed rate was increased. Higher chip thickness is obtained at the increased (0.8 mm/rev) feed rate level, and it requires more force to deform the workpiece. On the other side, lower cutting speeds result in a high coefficient of friction during the cutting process [34]. Furthermore, high temperatures produced at higher cutting speeds reduce the chances of buildup edge (BUE) at the rake face of the cutting insert, it results in longer tool life.

Overall, a better surface finish is achieved in the LNOoW lubricooling approach at all cutting conditions. The application of liquid nitrogen in the cutting region significantly reduces the coefficient of friction (CoF) [35]. In addition, it generates a lubricating hydrodynamic film between the uncoated carbide tool and Haynes-25 alloy. Hong witnessed the reduction of 72% CoF in the primary cutting zone when LN was applied, and it resulted in lower surface roughness compared to the conventional machining process [36]. Another reason for the better surface finish in hybrid LNOoW is also associated with a better wetting region per unit volume of liquid [37]. The effective and simultaneous penetration of OoW droplets mixed with LN removes the chips from the cutting zones smoothly, which results in the just-machined surface not being subjected to friction. The higher anti-abrasion capability was acquired under LNOoW, wherein the addition of water improved the strength and longevity of the lubrication layer [37]. It was found that the anti-adhesion capacity of the cutting tool increased with the decrease in environmental temperature.

At a lower level of feed rate (0.4 mm/rev) and highest cutting speed, 11.76% of surface roughness was reduced in the LNOoW hybrid lubricooling approach. However, at a higher value of feed rate and highest cutting speed, the LNOoW approach reduces surface roughness by 15.68%. Overall, it is recommended to use the new LNOoW lubricooling approach

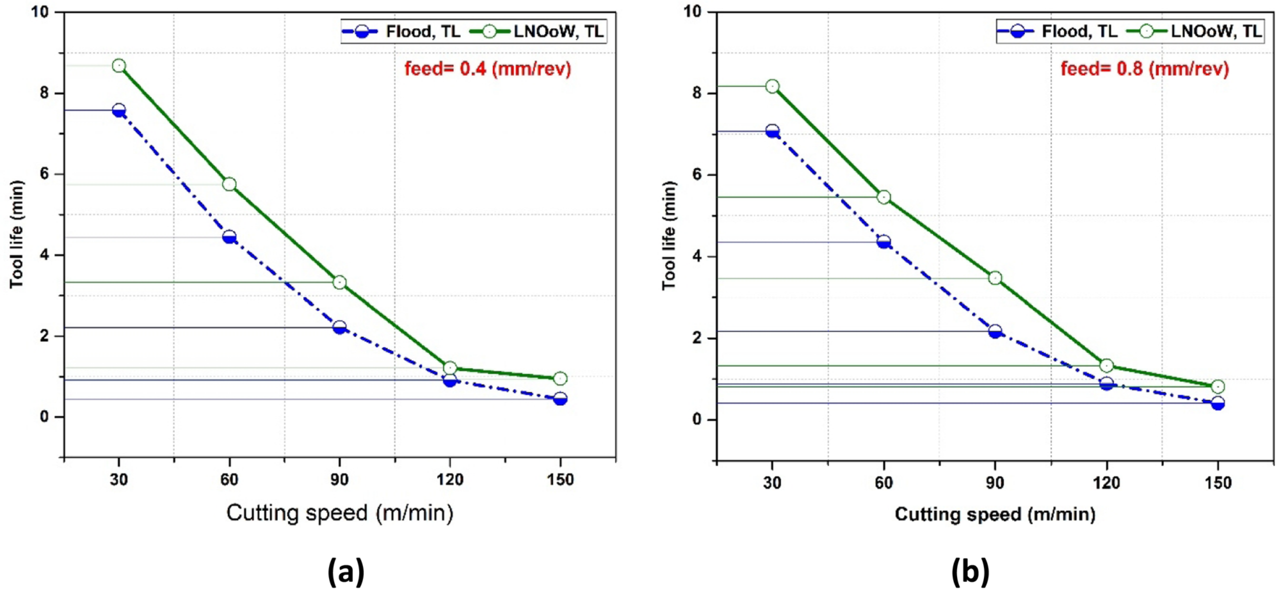

Fig. 14 Tool life comparison under both cooling/lubrication approaches. **a** Feed rate = 0.4 mm/rev. **b** Feed rate = 0.8 mm/rev

to improve the surface quality. From Fig. 15, it is noted that the proposed LNOoW approach has produced a better surface finish at all cutting conditions.

4.2 Economic aspects

Production cost is an important metric to evaluate the process performance. In the present study, a new mathematical model has been proposed in Sect. 3.6 to predict the production cost of the part produced by the machining of Haynes-25 alloy. The newly proposed cost model includes both direct and indirect costs. Furthermore, the environmental cost and LN cost have been added for the first time to estimate the production cost.

Figure 16 depicts the variation of production cost (PC) with the changing cutting parameters. Production cost significantly decreased as the feed rate was doubled (compare Fig. 16a, b). This decrease in the production cost was due to the reduction in cutting time; as the cutting time was reduced, fewer resources were consumed to produce a unit part. On the other hand, at high cutting speeds, tool life tends to decrease drastically especially while cutting difficult-to-cut material such as Haynes-25 alloy. In both cutting environments, it is clear from the analysis that

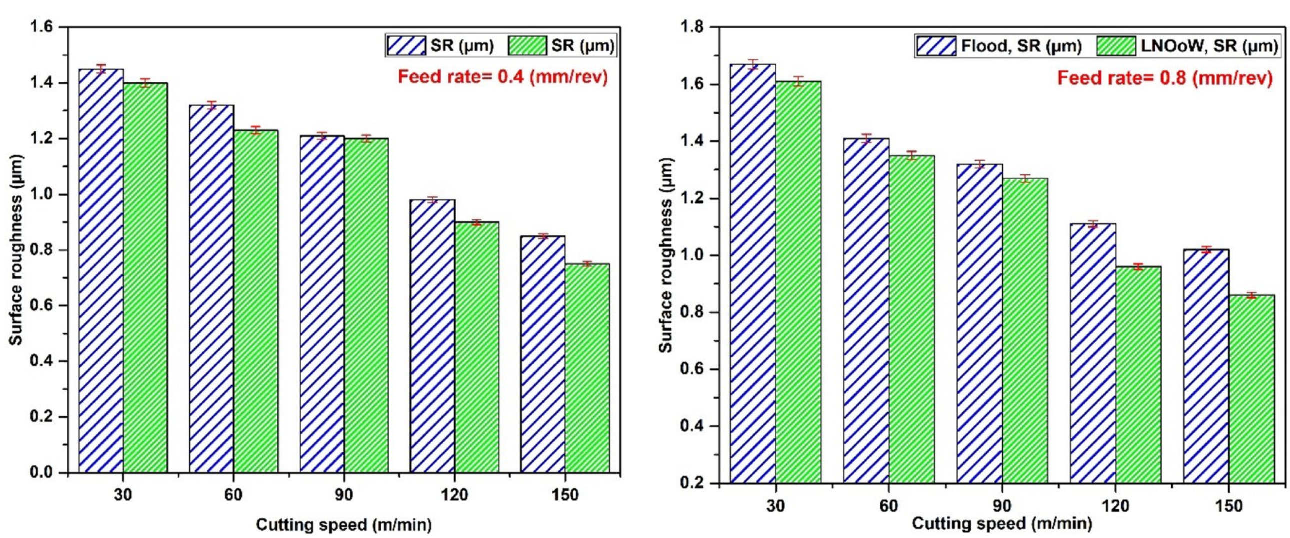

Fig. 15 Comparison of surface quality of workpiece. **a** Feed rate = 0.4 mm/rev. **b** Feed rate = 0.8 mm/rev

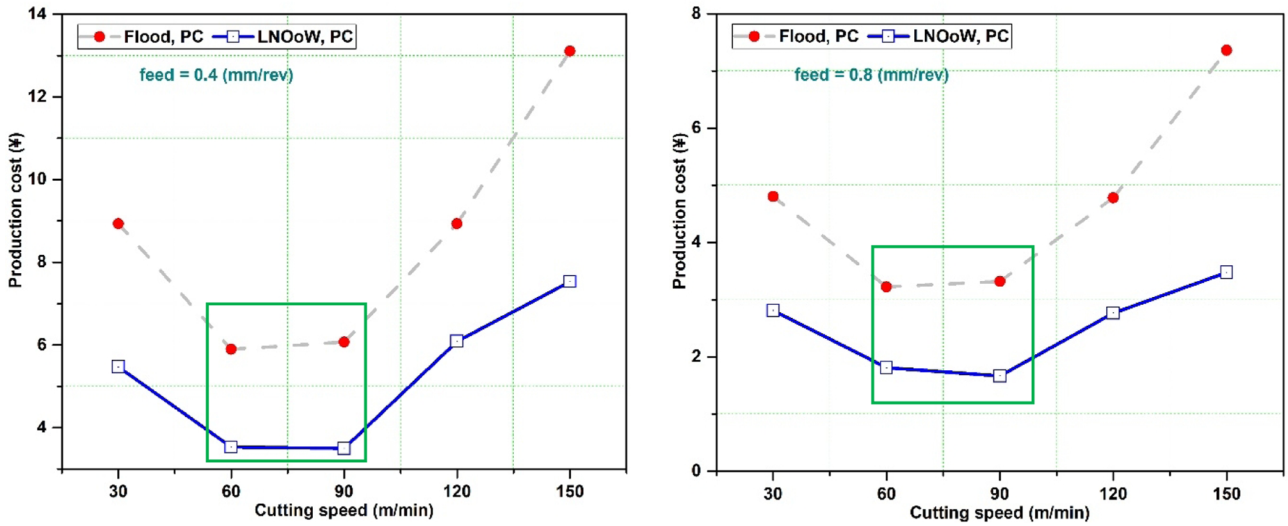

Fig. 16 Variation in production cost (PC) and its comparison at **a** feed rate = 0.4 mm/rev and **b** feed rate = 0.8 mm/rev

initially, the production cost decreases with the increase of cutting speed. However, after the cutting speed of 90 m/min, the production cost increases proportionally with the cutting speed. Thus, for the lowest production cost, it is recommended that cutting parameters should be at the highest value of feed rate between the range of 60 m/min and 90 m/min of cutting speed.

As mentioned earlier, production cost depends upon the many direct and indirect factors. In the present study, an extended cost model has been proposed, which includes not only direct electricity energy cost but also considers various resources consumed in the external turning of Haynes-25. In the holistic cost estimation model cost of various kinds of resources has been considered. The lowest cost of the LNOoW approach is mainly associated with the longer tool life (less tool cost). The additional cost of cleaning and disposal in the conventional flood emulsion cooling approach is responsible for the higher cost. Nonetheless, cryogenic LN at a lower flow rate (0.2 L/min) is an economical alternative. Liquid nitrogen absorbs the heat from the cutting zone and immediately evaporates without leaving any residues on the workpiece surface. However, the flow rate of LN more than 1 litter per minute is not economical and useful in the machining process. Efforts are also needed to conduct expensive research on the economical production and storage of LN, which may further reduce the production cost.

The LNOoW approach reduced the production cost from 38.72 to 42.52% at experiments conducted at a lower feed rate value. Even more, the LNOoW reduces the production cost up to 52.78% at the highest feed rate (0.8 mm/rev) and highest cutting speed (150 m/min).

5 Conclusion

In the present study, machinability and economic aspects of the proposed hybrid LNOoW lubricooling approach were investigated and compared with conventional flood-assisted machining. Cutting temperature, electrical power and energy consumption, tool life and tool wear, surface quality, and production cost were taken as the response metrics to evaluate the process efficiency. A novel empirical model for production cost was also proposed. The key outcomes of the study are as follows:

- The application of LN combined with the OoW mechanism has significantly improved the process performance (surface quality, temperature, and production cost).
- The proposed LNOoW approach enhanced the anti-adhesion capacity of the cutting tool, which decreased the cutting temperature at all cutting conditions.
- Application of OoW combined with liquid nitrogen in the cutting region significantly reduced the CoF [35], which helps to reduce the cutting power as compared to flood-assisted machining.
- Abrasion wear was the most dominant observed wear mechanism in both cooling approaches. Overall, the LNOoW approach produced more tool life, especially at the aggressive cutting conditions proposed method produced nearly 11% more tool life as compared to conventional machining.
- Excellent cooling due to cryogenic LN and OoW mechanism improved the strength and longevity of the lubrication layer between tool and Haynes-25 alloy. Thus, 11.76% to 15.66% improvement in surface quality was

observed in LNOoW lubricooling approach, when compared with conventional machining.
- The holistic economic analysis showed that medium cutting parameters are recommended for the lower-priced products. At the lowest cutting parameters (lowest f and v_c), 38.72%, and at the highest cutting parameters (f and v_c), 52.72% lower-price products were produced by using the new proposed lubricooling approach as compared to flood-assisted machining.

5.1 Limitation and future work of the study

The effect of LNOoW on workers' health and safety was not studied. Environmental impacts (such as CO_2 emissions) of the new cooling/lubrication approach are also out of the scope of the study. In addition, in the present study, our focus was to investigate electrical power consumption. However, future studies will also include the embodied energies of the consumed resources. The transportation and leakage-related losses will also be considered in future research work.

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Author contribution All authors have contributed equally.

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Availability of data and material The necessary data used in the manuscript is already present.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication All authors are agreed upon the current version of submission for publication.

Conflict of interest The authors declare no competing interests.

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