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Analysis of machinability and sustainability aspects while machining Hastelloy C4 under sustainable cutting conditions

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ABSTRACT

In recent years, developments in the defense, aerospace, and medical industries have significantly increased the expectations regarding material performances. In particular, the demand for materials that can withstand very high and/or very low temperatures and harsh mechanical/chemical conditions has increased. The superior qualities of superalloys can adequately meet this demand. However, the difficulties encountered in the machining of these alloys cause some burdens both ecologically and economically due to the use of cutting fluid. Therefore, the use of cost-friendly and sustainable cutting fluids in the production industry has a vital role, both in terms of machining performance and the environment. From this perspective, this paper focuses on the effects of various cutting environments, i.e., Dry, MQL, LN_2, N_2, CO_2, Vortex, LN_2 + MQL, N_2 + MQL, CO_2 + MQL, and Vortex +MQL on the machining performance of Ni-based C4 alloy. Additionally, it was aimed to reveal the effect of cooling/lubrication methods on sustainability by performing a sustainability analysis. Firstly, surface roughness, power consumption, tool wear and mechanisms, and cutting temperature were considered as performance characteristics. When examined in terms of machinability, Vortex + MQL gave the best result in terms of surface roughness and power consumption, while LN_2 gave the best result in terms of cutting temperature. Then, a comprehensive sustainability analysis was carried out. As a result, the CE_{SMO} follows the order of Dry > MQL > LN_2 > LN_2 + MQL > CO_2 > CO_2 + MQL > N_2 > N_2 + MQL > Vortex > Vortex + MQL. While employing Vortex + MQL cutting condition, the CE_{SMO} decreased by about 11.37% as compared to Dry cutting condition. While using a combination of different sustainable lubrications or coolants, the overall carbon emissions decreased in the range of about 15–25% approximately as compared to the employment of the individual cutting conditions (i.e., coolant/lubricants).

1. Introduction

The machining industry is one of the largest manufacturing industries in the world, and this demand is increasing every year. However, as the production capacity in this industry increases, the number of resources consumed and emissions to the environment also increase. In other words, the energy required for production causes both carbon dioxide emissions and climate change. When the situation is analyzed with more concrete data, the global environmental cost resulting from production activities is approximately 4.7 trillion US dollars every year [1]. Thus, sustainable manufacturing processes are also a necessity for the metal cutting industry due to the efficient use of resources and the responsibility of transferring resources to future generations [2]. The philosophy of sustainability lies at the basis of sustainable manufacturing. Sustainability is often defined as "meeting the needs of today without compromising the ability of future generations to meet their own needs" [3]. In more familiar terms, sustainability is based on basic elements such as environment, economy, health, and safety. Therefore, in order to contribute to sustainable production, these issues need to be evaluated in depth. Moreover, the inclusion of sustainable development processes in the production industry is quite urgent and essential. In particular, the metal cutting industry should be based on sustainable production principles. One of the biggest reasons for this is that factors such as high energy consumption, waste material, use of

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petroleum-based cutting fluid, etc., are seen in the metal cutting industry. These resources are consumed more, especially during the machining of difficult-to-machine materials such as superalloys, and therefore it is important to perform sustainability analysis in the machining of such materials.

In recent years, developments in the defense, aviation, and space industries have significantly changed the need for material specifications. The demand for materials that can withstand harsh conditions, especially at very high and very low temperatures, has increased. Superalloys have largely met the needs thanks to their high strength, strong oxidation resistance, creep resistance, thermal stability, and thermal fatigue resistance [4]. Of the three different types of alloys, nickel-based superalloys are used more than iron and cobalt-based alloys [5]. The reason for this can be related to both the better knowledge of its theory and its characteristic features. However, there are several challenges when machining superalloys. Superalloys, which stand out among existing materials due to their usage properties, pose a challenge to both researchers and manufacturers due to their processing difficulties. For this reason, these materials are also known as difficult-to-machine materials [6]. The main reasons for defining it this way are features such as high shear strength and energy consumption, high hot hardness, and low thermal conductivity [7]. Additionally, the presence of abrasive carbide in the alloy causes the life of the cutting tools to be significantly shortened. Although cutting fluid is used to eliminate all these restrictions, this causes concerns about the ecological system and sustainability.

Cutting fluids perform basic tasks such as cooling, lubrication, and removing chips from the cutting area. Additionally, it enters the tool-chip-workpiece interface, reducing friction and helping to prevent heat generation. For this reason, the use of cutting fluid is a very common practice in metal cutting operations [8]. With the use of cutting fluid, tool life is effectively increased, and better dimensional control and good surface quality are achieved. However, approximately 85% of cutting fluids used worldwide are mineral-based cutting fluids [9]. Excessive cutting fluid use significantly affects the environment, employee health, and production costs. Mineral-based cutting fluids are subjected to a special physical and/or chemical treatment by an environmental protection agency (EPA) to remove toxic components before disposal [10]. In terms of employee health, it is known that operators suffer from various diseases, such as skin diseases, respiratory diseases, lung problems, etc., in environments where they are exposed to cutting fluid for a long time [11]. Therefore, the use of conventional cutting fluid poses a major disadvantage to sustainable manufacturing goals. As a result, it is very important to reduce the amount of cutting fluid used without reducing machining efficiency [12]. Thus, green and worker-health-friendly manufacturing can be carried out while maintaining or, in some cases, increasing manufacturing efficiency. Moreover, in such a case, it is possible to use resources correctly and transfer a cleaner environment and more resources to future generations. Here, the minimum quantity lubrication (MQL) system and the use of cryogenic gases as coolants come to the fore.

MQL system is a system in which a very small amount of cutting oil (10–100 mL) is sprayed into the cutting area by means of pressurized air. Due to the low amount of oil used in the MQL system, cutting oil enters the tool-chip-workpiece interface more easily. Thus, it reduces friction and heat generation by creating a film layer [13]. However, it is known that the MQL system is much more suitable for soft and medium machining conditions, but it has some disadvantages, such as not providing sufficient cooling efficiency in heavy cutting conditions [14,15]. One of the alternatives used in such cases is the cooling method using cryogenic gases [16]. Although there are inconsistencies in the literature about the exact temperature at which cryogenic cooling begins, temperatures of −150 °C or below are accepted according to most research and standards organizations [17]. It generally refers to the cooling method applied by spraying cryogens such as helium, hydrogen, neon, nitrogen, carbon dioxide, oxygen, and normal air into the cutting area [18]. There are various studies in which systems, such as MQL, N_2, LN_2, CO_2, Vortex, etc., are used separately and/or in a hybrid way as coolant/lubricants in machining operations. For example, Amigo et al. [19] investigated the effect of cooling/lubrication methods on machining efficiency by turning AISI 1055 and superalloys such as Inconel 718 and Haynes 263. Finally, they reported that oil emulsion was the best option for Inconel 718 and that cryogenic cooling with CO_2 was more efficient for Haynes 263. Jamil et al. [20] investigated the effect of cryogenic coolants on machining performance in turning Ti-6Al-4 V alloy. Using liquid nitrogen (LN_2) and carbon dioxide (CO_2-snow) as coolants, the researchers selected tool wear, cutting force, surface roughness, and chip curl diameter as output parameters. In conclusion, the CO_2-snow was claimed to show promising results. Musfirah et al. [21] studied the effect of LN_2 on machining performance during high speed machining of Inconel 718. The results revealed that cryogenic cooling was more effective than dry cutting in reducing tool wear, cutting force, surface roughness, subsurface deformation, and machined part contamination. Cica and Kramar [22] observed the effect of high pressure coolant (HPC) Inconel 718 on machining performance. The analysis results revealed that HPC-assisted machining is better than the conventional cooling method as it enables the reduction of overall carbon emissions at high cutting speeds. Çakıroğlu [23] investigated the effect of dry, minimum amount of lubrication and cooling methods using a Vortex tube on the machining performance in the finish turning of Inconel 718 and reported that the MQL method gave better results. Şirin [24] investigated the effect of various cooling methods (dry, MQL, CO_2, LN_2, N_2, CO_2 + MQL, LN_2 + MQL, and N_2 + MQL) on machining performance during the turning of Hastelloy C22. The researcher reported that the N_2 + MQL hybrid cooling/lubrication technique gave the greatest effect on machining performance. Shah et al. [25] worked on the effect of dry, conventional cooling, LCO_2, and LN_2 techniques on sustainable machining during drilling. According to the test results, it was claimed that LN_2 and LCO_2 were more sustainable methods compared to their competitors.

When the literature review is examined, it is seen that most of the existing studies compare two or three cooling methods. Therefore, it is thought that a comprehensive study will fill an important gap in the literature. For this purpose, in the current study, the effects of Dry, MQL, LN_2, N_2, CO_2, Vortex, LN_2 + MQL, N_2 + MQL, CO_2 + MQL and Vortex +MQL methods on the processing performance were studied. Additionally, it was aimed to reveal the effect of cooling/lubrication methods on sustainability by performing a sustainability analysis. All details, findings, discussion, and conclusion of the study are presented in the sections below.

2. Material and methods

2.1. Methodology of experiments

Ø80 × 250 mm Hastelloy C4 superalloy bar workpiece was used in turning experiments. The chemical composition of Hastelloy C4 superalloy material used in turning experiments is presented in Table 1. Fresh tools were used during the experiments. Teague Tec DCMT 11T304 TT5080 with MT positive chip breaker was used as a cutting tool. The cutting tool was mounted on a max speed 4500 rpm Accuway JT 150 CNC lathe with Akko SDJR 2020 K11 tool holder. The specifications of the CNC lathe and all experimental procedures are given in Table 2. Different cryogenic (also known as subzero) conditions were tested during the experiments. Cutting parameters such as cutting speed, feed rate, and depth of cut were kept constant throughout the entire study. When the literature is examined, gases such as air, N_2, CO_2, Ar, and He

Table 1
Hastelloy C4 chemical composition.

Cr	Mo	Fe	Co	Mn	Ti	Si	C	Ni
16	15	3	2	1	0.7	0.08	0.01	balance

Table 2
Specifications of experimental procedure.

Component	Specifications
CNC lathe	Accuway JT 150 Capacity 11 kW Max spindle speed 4500 rpm
Workpiece	Hastelloy C4 superalloy Ø80 × 250 mm
Experimental parameters	Cutting speed 75 m/min Feed rate 0.1 mm/rev Cutting depth 0.5 mm
Tool	Taegu Tec DCMT 11 T304 TT5080 with MT chipbreaker PVD coated cemented carbide
Holder	Akko SDJR 2020 K11
MQL	SKF LubriLean Vario Flow rate 80 mL/h Pressure 8 bar Nozzle diameter 2 mm
LN_2 and N_2 storage tank	Taylor Wharton XL 45 HP Flow rate 20 mL/h Pressure 15 bar Nozzle diameter 3 mm
CO_2 storage cylinder	Ozoto Flow rate 20 mL/h Pressure 15 bar Nozzle diameter 3 mm
Vortex tube	VimaxX R-30 Flow rate 20 mL/h Pressure 8 bar Nozzle diameter 3 mm
Conditions	Dry, MQL, LN_2, N_2, CO_2, Vortex, LN_2 + MQL, N_2 + MQL, CO_2 + MQL, Vortex+MQL

can be preferred as cryogens [26]. However, since the most used cryogens are N_2 and CO_2, this was taken into account when determining the cryogen conditions in this study. In the present study, air (with Vortex tube), liquid phase N_2 (LN_2), gaseous phase N_2, and liquid phase CO_2 were preferred as cryogen conditions. Air at high pressure and high velocity enters the Vortex tube (cold air apparatus) tangentially through a nozzle. The expanding air in the tube then becomes a rapidly rotating Vortex. The air passing through the orifice cools and is sent to the desired location through a nozzle [27]. The working principle of the Vortex tube is given in Fig. 1a. Vortex tube outlet temperature values vary according to different air inlet pressures. In accordance with the information provided by the manufacturer, the inlet pressure of the vortex tube was set to 8 bar. With an 8 bar air inlet pressure value, the air outlet temperature value reaches −40 °C (Fig. 1b). The specifications of the Vortex tube used in the study and all experimental details are given in Table 2.

Since CO_2 (Fig. 2a) and N_2 (Fig. 2b) are in the liquid phase at room temperature, cryogens were applied through a vacuum jacketed hose from the storage cylinder to the application area in the cutting zone. The cryogenic cooling setups are demonstrated in Fig. 3c. CO_2 was stored in the storage cylinder at a pressure of 60 bar. The pressure was set to 15 bar by means of a pressure reducer at the outlet of the CO_2 storage cylinder, and all experiments were carried out under this pressure. The Taylor Wharton XL 45 HP storage tank was used to store excess nitrogen with liquid phase. The storage tank is capable of liquid and gas output, and both N_2 and LN_2 experiments were carried out under 15 bar outlet pressure. While applying cryogenic cooling conditions, a specially manufactured stainless-steel nozzle with a diameter of 3 mm was used to minimize thermal impact. The cryogenic nozzle is fixed at a distance of 20 mm from the cutting tool rake face and at an angle of 30° to avoid any adverse conditions (chip impact, etc.).

The MQL experiments were carried out by means of an SKF LubriLean Vario lubrication supply unit. The manually adjustable MQL lubrication unit can transport the aerosol mist up to a distance of 20 m without any difficulties. Biodegradable, vegetable-based corn oil was added to the MQL system reservoir. In previous studies [28], corn oil was preferred due to its superior lubrication performance. The aerosolized air/oil mixture was transported to the nozzle through a 12 mm diameter polyurethane hose. The 2 mm diameter stainless steel nozzle was positioned in the cutting zone at 20 mm from the rake face end of the cutting tool and at a 30° angle. In all MQL experiments, 80 mL/h flow rate, 8 bar pressure, nozzle type, diameter, and position were kept constant.

2.2. *Other conducted experimental measurements*

During the turning experiments, power consumption measurements were taken with a Fluke 1732 three-phase energy logger connected to the CNC lathe main input transformer (Fig. 3d). The measurements were recorded with a software during the experiments. The power consumption data was obtained by means of magnetic holder connectors mounted on the A, B, and C three-phase channels. The power consumption meter was calibrated before each turning experiment and made ready for the new experiment.

Surface roughness refers to the sum of defects such as cutting tool machining marks, deviations, and waviness that occur on the workpiece sample surface during machining. These defects reduce the actual contact surfaces between machine elements, increase friction, accelerate wear, and reduce the fatigue and notch impact strength of the workpiece. Therefore, the evaluation of surface roughness is an extremely important output parameter in machining operations. In the ISO 4287:1997 standard, namely Geometrical Product Specifications (GPS) - Surface texture: Profile method - Terms, definitions, and surface texture parameters, Ra, Rt, Rz, Rq, Rv, etc., there are numerous roughness parameters. However, in the manufacturing industry, Ra - arithmetic mean height is often preferred due to easy application, measurement, and availability. In this study, a portable Mahr Marsurf PS10 surface roughness measuring device was used for surface roughness measurements (Fig. 3e). With reference to ISO 4288:1996 standard: for Ra measurements, sample length, cut-off, and evaluation length were kept constant at 0.8 mm, 0.8 mm, and 4.8 mm, respectively.

Cutting temperature is an important parameter, especially during machining operations under severe conditions. The high temperatures can damage the cutting tool, machine tool, or measuring devices (camera, etc.). Therefore, it must be detected and controlled in machining operations such as turning, where there is continuous chip formation from the workpiece. Optris PI 450 infrared camera (IR) was used to detect the maximum value of the temperature at the cutting tool-workpiece-chip interfaces in the cutting zone (Fig. 3a). The IR was fixed at a safe distance of 300 mm and covered the whole cutting zone. Depending on the material, the emissivity value plays a critical role in accurately measuring the temperature in this measurement. The emissivity value of Hastelloy C4 in this investigation was selected at 0.5.

Cutting tool flank wear and life tests were determined with a Dino-Lite AM73915MZT4 digital scale microscope according to ISO 3685:1993 standard (Fig. 3g). The microscope scale was fixed for all measurements, and the tool was considered to have completed its life when the cutting tool flank wear reached $VB_{(max)}$: 0.3 mm in each condition. To determine the cutting tool wear mechanisms after turning experiments, Zeiss LEO 44 SEM device was used. In the SEM images obtained for the interpretation of cutting tool side wear, the magnification scale was selected as 80× for side views and 90× for top views. The experimental details and measurements are given in Fig. 3.

3. Results and discussion

3.1. *Experimental results*

3.1.1. *Surface roughness*

Fig. 4 shows the relationships between cooling/lubrication methods and average surface roughness. The Ra value under dry machining is also included in the comparison to see the clear effect of cooling/lubrication methods. Accordingly, when Fig. 4 is examined, it is seen

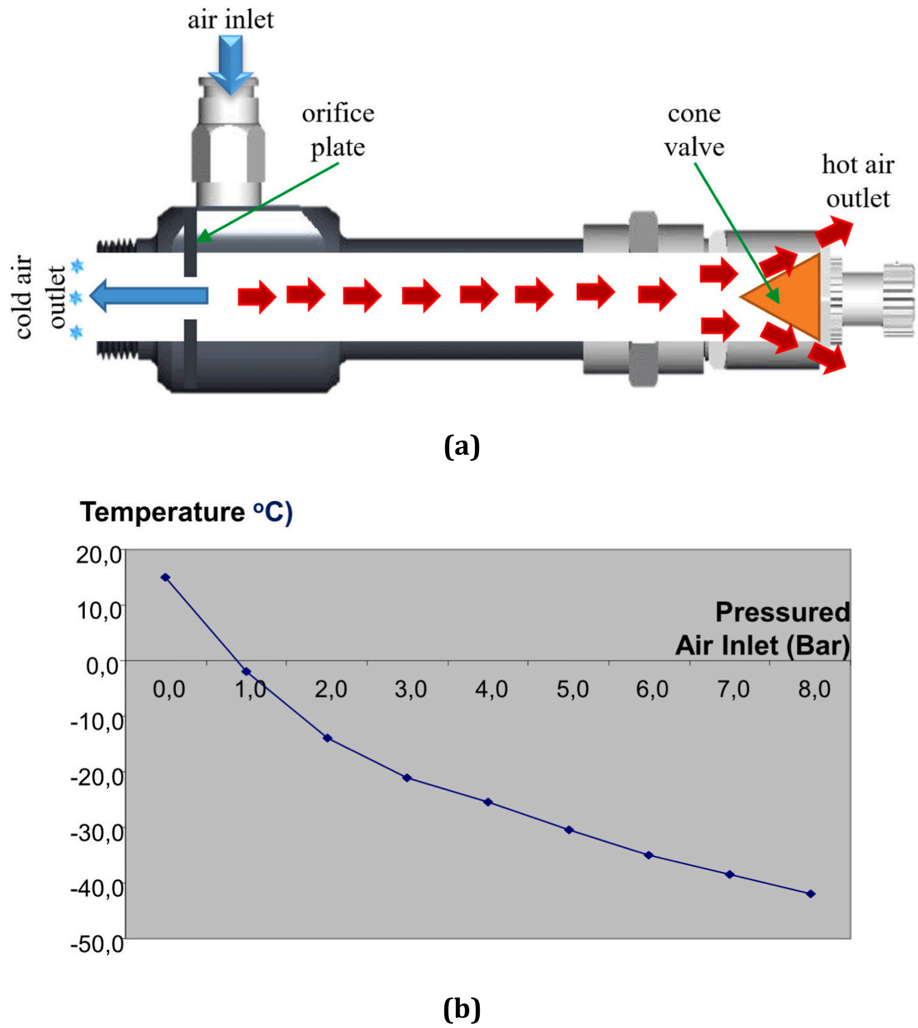

Fig. 1. Vortex tube (a) setup and working principles, (b) air inlet pressure-temperature graph (*from manufacturer).

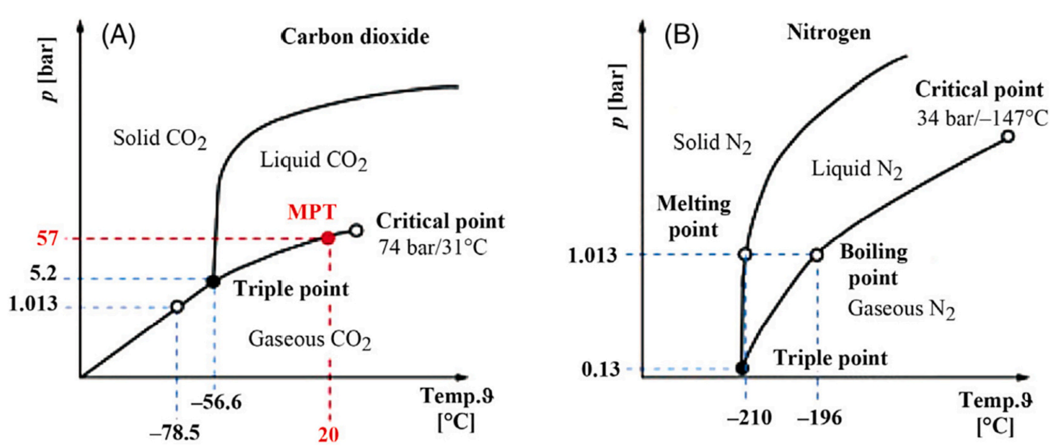

Fig. 2. a) CO_2 phase diagram, b) N_2 phase diagram [29–31].

that the highest Ra value is obtained by dry machining. With the introduction of cryogenic cooling and Vortex tube methods, the Ra value has decreased at varying rates. Compared to dry cutting, the decrease in Ra value was 5.81%, 11.66%, 10.82%, and 14.90% for LN_2, N_2, CO_2, and Vortex, respectively. This situation is associated with the fact that coolants reduce the heat and friction in the cutting zone. By using cryogenic fluids and Vortex, less heat is induced in the cutting tool and machined surfaces. This results in lower tool wear and fewer defects on the machined surface. In addition, the chips generated during cutting can adhere to the machined surfaces due to the effect of temperature and reduce the surface quality. In this study, it is thought that the use of cryogenic cooling and Vortex and the removal of chips without elongation and removal from the cutting zone are among the reasons for the positive effect on surface quality. Danish et al. [32] investigated the

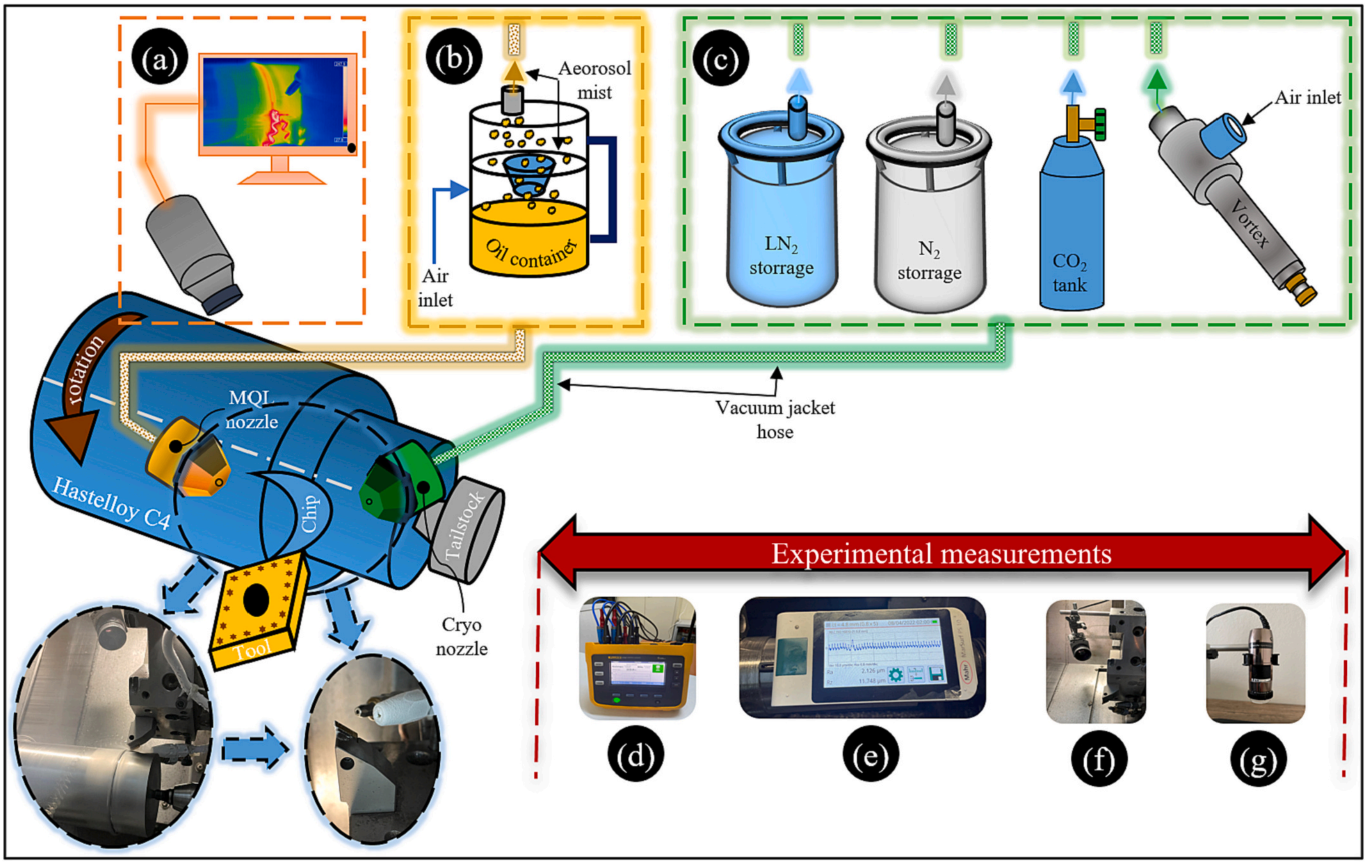

Fig. 3. Experimental details, (a) Cutting temperature measurement, (b) MQL system, (c) Cryogenic cooling setup, (d) Power analyzer, (e) Surface roughness device, (f) Thermal imager, and (g) Digital microscope.

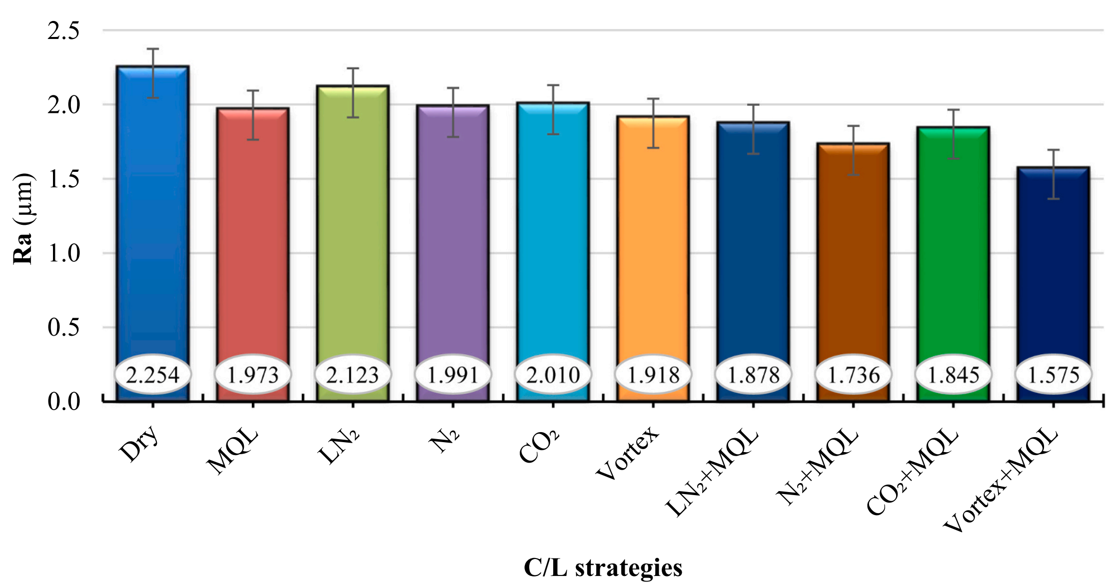

Fig. 4. Surface roughness results against cooling/lubrication strategies.

effectiveness of Dry, MQL, LN_2, and CO_2 during the cutting of Inconel 718. Researchers have claimed that cryogenic cooling is the most effective cooling method in reducing the Ra value. They stated that the reason for this situation is to reduce the cutting temperature and remove chips from the cutting area, as stated in the comments in this study.

When cryogenic gas and cooled air-based cooling methods are compared, it is seen that the lowest Ra value is obtained with the Vortex. The main reason here is associated with the positive effect of the Vortex on tool wear. The relationship between Vortex, tool wear, and surface roughness has also been emphasized in various studies in the literature [33].

It was observed that the effect of the hybrid cooling/lubrication conditions obtained by incorporating the MQL system into the machining process was greater (Fig. 4). For example, compared to LN_2,

LN_2 + MQL provided an 11.54% improvement. Moreover, compared to N_2, CO_2, and Vortex, the N_2 + MQL, CO_2 + MQL, and Vortex + MQL offered 12.80%, 8.20%, and 17.88% improvement, respectively. The use of cryogenic cooling and Vortex cooling can provide significant improvements to the cutting area. However, with the introduction of lubrication, the oil penetrating the tool-chip-workpiece interface reduces friction and has a more positive effect on the average surface roughness [34]. In summary, among all cooling/lubrication conditions, the best Ra value was obtained with Vortex + MQL. Compared to the reference environment (dry machining condition), the maximum improvement in Ra value was 30.12%.

3.1.2. Cutting temperature

Fig. 5 shows the effect of machining environments on cutting temperature. Accordingly, it is understood from Fig. 5 that the highest cutting temperature value occurs under dry machining, with 325 °C. With the use of the MQL system, there was a decrease of 11.38% in cutting temperature compared to dry machining. The MQL method, which sprays a very small amount of cutting oil into the cutting area with compressed air in a pulverized manner, creates a thin film layer on the tool-chip-workpiece surfaces, reducing friction and thus encouraging the cutting temperature to decrease [35]. Compressed cold air delivered to the cutting zone through the use of Vortex reduced the cutting temperature by 15.38% compared to the dry cutting environment. In addition to cooling the environment with the Vortex, removing chips from the area contributed to this reduction. Moreover, it has been observed that there are more significant decreases in the cutting temperature with the inclusion of cryogenic gases and liquids with high cooling properties, such as LN_2, N_2, and CO_2, in the process. Compared with dry machining, LN_2, N_2, and CO_2 reduced the cutting temperature by 39.99%, 26.46%, and 30.46%, respectively. Especially liquid N_2 can make cooling much more effective by penetrating the cutting zone in fluid form.

Therefore, among all cooling/lubrication conditions, the lowest cutting temperature was obtained with LN_2. This has been attributed to the fact that liquid nitrogen absorbs the heat generated during the cutting process and evaporates rapidly as it is released into the atmospheric environment [36]. However, in terms of cutting temperature, hybrid environments (MQL system used with cryogenic gas and liquids) did not make a significant contribution. This situation is attributed to the insufficient cooling performance of the MQL system under heavy machining conditions [37]. Nguyen et al. [38] claimed that although the MQL system is useful in low and medium cutting conditions, the rapid evaporation of a small amount of oil in the MQL system due to very high temperatures reduces its effectiveness under heavy cutting conditions (i.e., during high cutting speeds and/or machining of difficult-to-machine materials).

3.1.3. Power consumption

In this sub-section of the study, it is aimed to investigate the effect of some environmentally friendly cooling methods on power consumption during machining by keeping the cutting parameters constant [39]. Power consumption values are presented in Fig. 6. As expected; the highest power consumption was obtained under dry cutting with 225.1 W. This situation is associated with high cutting force and high friction value at the tool-chip-workpiece interface. In addition, the failure to remove the chips generated during cutting from the cutting area may be one of the reasons for the higher power consumption of the machine tool [28].

With the introduction of cooling/lubrication agencies, improvements in power consumption have emerged. When these are listed starting from the best, the ranking is (1) Vortex + MQL-24.07%, (2) N_2 + MQL-23.45%, (3) CO_2 + MQL-20.07%, (4) Vortex-19.23%, (5) N_2–16.65%, (6) LN_2 + MQL-15.81%, (7) CO_2–15.01%, (8) MQL-14.74%, and (9) LN_2–13.17%, compared to dry machining. In the MQL method, cutting oil, which forms a thin film at the tool-chip-workpiece interface, helps reduce the cutting force by reducing friction, thus reducing power consumption [40]. The results of the MQL method and the LN_2, N_2, and CO_2 methods were close to each other, and the differences were negligible. Therefore, one of these methods may be preferred, considering production costs. The lower energy consumption in cryogenic liquid/gas compared to dry machining is associated with the lowering of the cutting temperature. With the use of cryogenic liquid/gas, the cutting zone can be cooled significantly, and thus, cutting temperature and tool wear can be limited. Therefore, lower power consumption occurs as the cutting edge maintains its sharpness. Moreover, it is seen that the decreasing trend in energy consumption continues when the MQL system is used together with refrigerant liquids/gases. This situation is associated with the effective performance of both cooling and lubrication duties thanks to the hybrid method in heavy cutting conditions such as the machining of superalloys [41]. Finally, the lowest consumption among all experimental conditions was obtained with the use of MQL + Vortex. Since the effect of the MQL system on lubrication is known, the situation is associated with the properties of

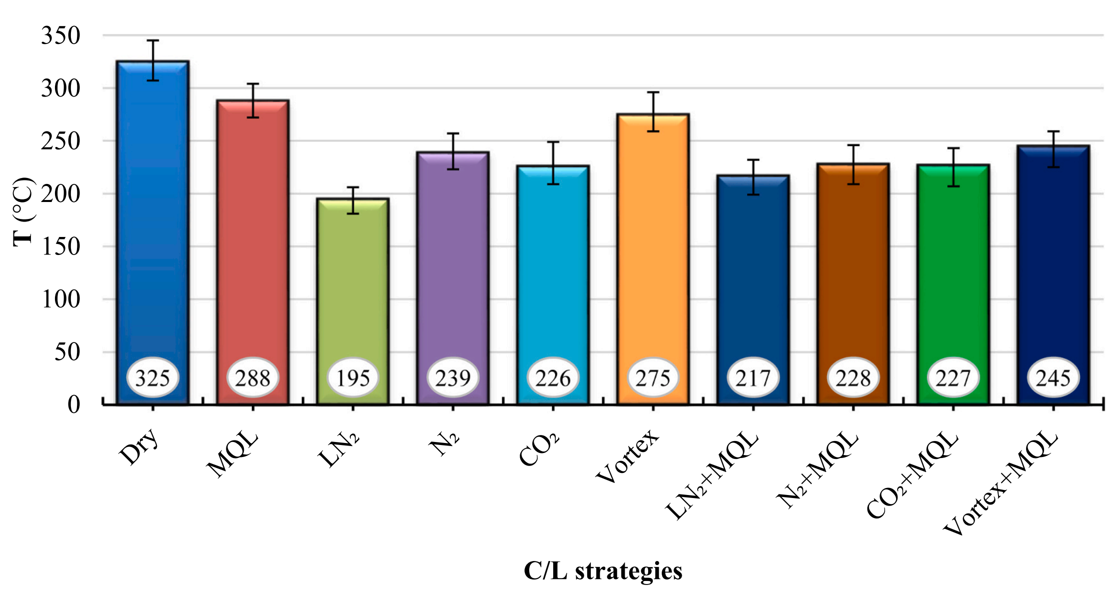

Fig. 5. Temperature results against cooling/lubrication strategies.

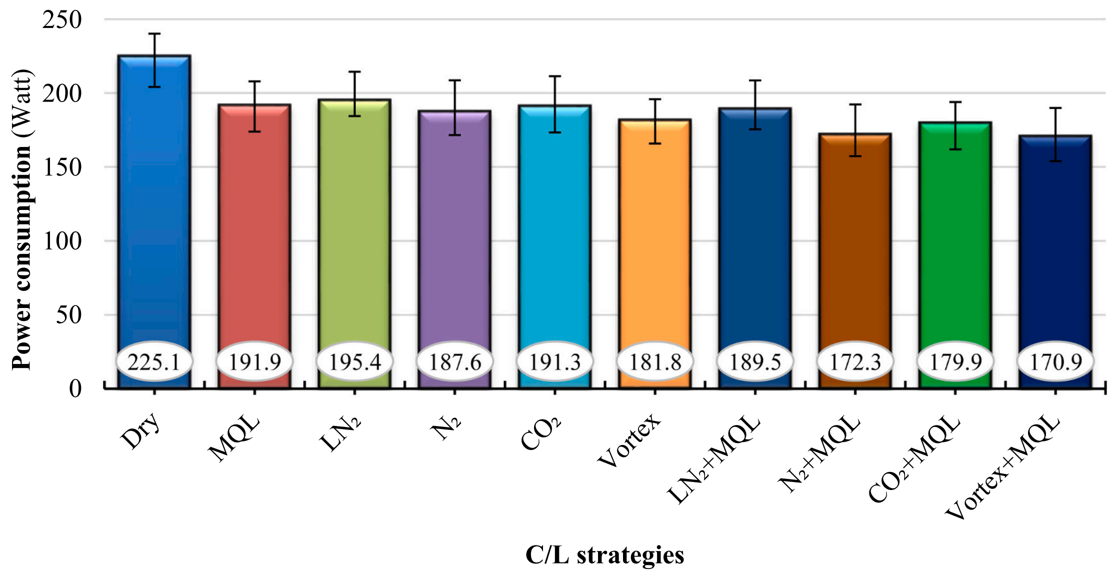

Fig. 6. Power consumption results against cooling/lubrication strategies.

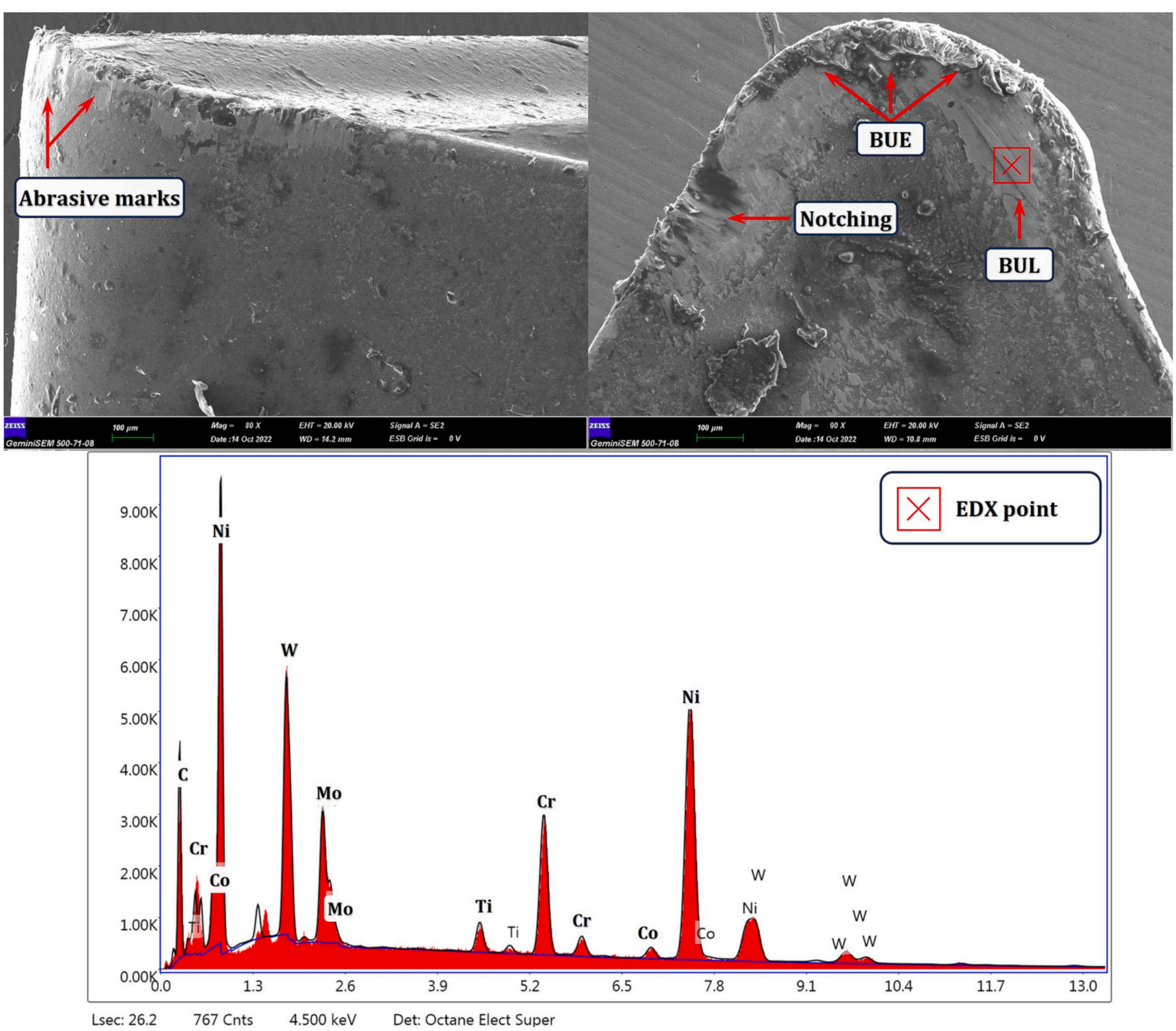

Fig. 7. SEM and EDX analysis of worn tool under dry cutting environment.

the Vortex tube. Compared to the Vortex tube cooling system, observation of higher power consumption in other cryogenic liquids/gases has been associated with increased workpiece hardness.

3.1.4. Tool wear

In this subsection, worn inserts were subjected to SEM and EDX analyses, and the damage mechanisms on them were observed, and images are indicated in Figs. 7 and 8. When Figs. 7 and 8 are examined, it can be seen that the damage mechanisms on each cutting edge are almost the same. In other words, abrasive marks, notching, BUE, BUL, and adhesion played an active role in the damage to the flank and rake faces of the cutting tool. In particular, it can be clearly said from SEM and EDX analyses that the dominant damage mechanism is adhesion wear. In previous studies, researchers have highlighted the effectiveness of various wear mechanisms during the machining of Ni-based superalloys [42,43]. It is evident that the severe cutting conditions during the machining of Ni-based superalloys are a combination of heavy loads, high temperatures, and intense adhesive interaction with the workpiece material, resulting in built-up chip (BUE) on the cutting edge and built-up layer on the rake face [44,45]. It was reported by Fox-Rabinovich et al. [42] that A considerable amount of surface damage and unstable attrition wear conditions are directly related to BUE formation. The unstable BUE formation on the cutting edge may separate from the tool material at the end of a certain cycle, causing serious damage to the cutting tool [46]. As a matter of fact, from the SEM images given in Figs. 7 and 8, it is thought that this mechanism is the main reason for the

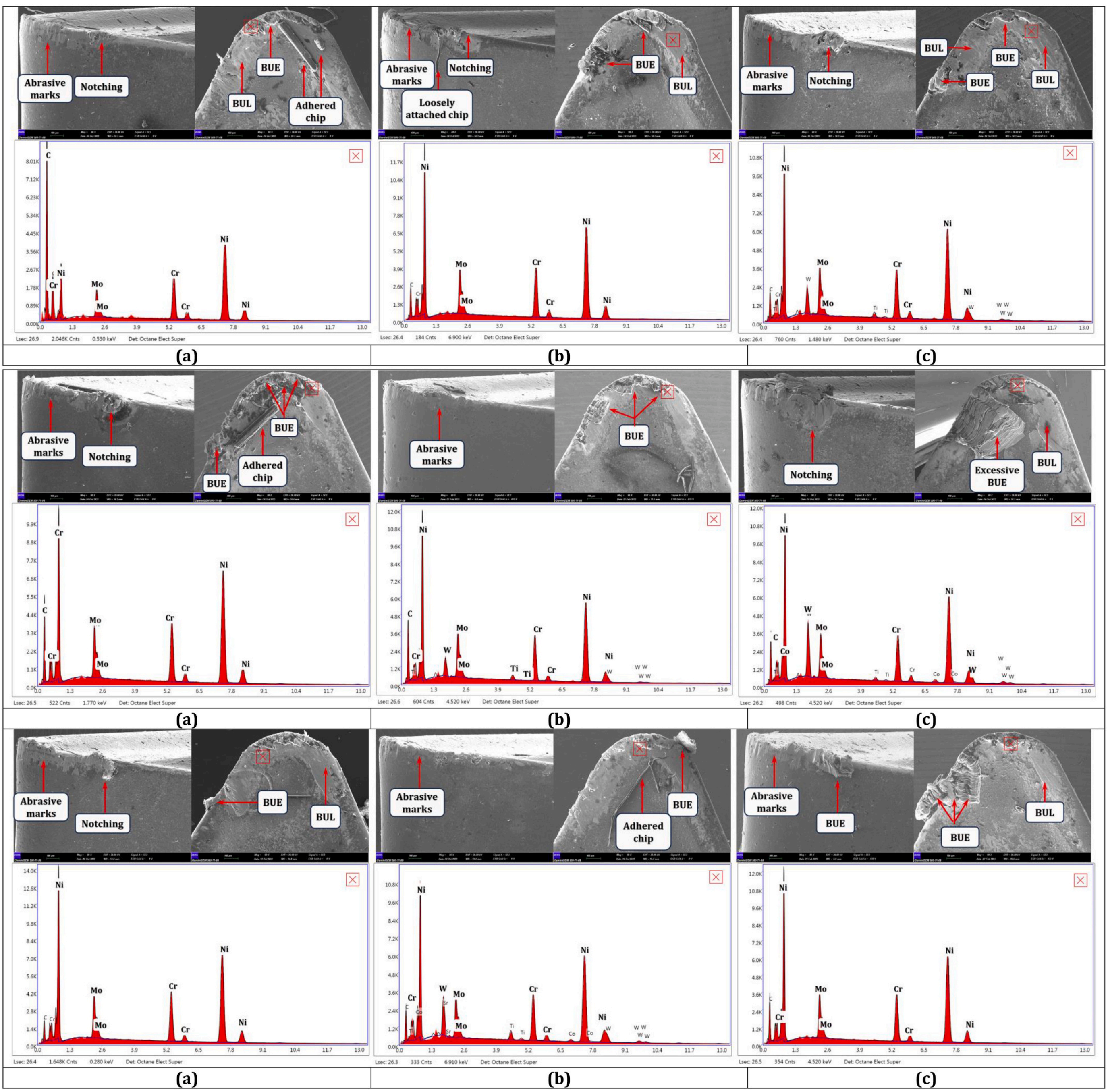

Fig. 8. SEM and EDX analysis of worn tool under a) MQL, b) LN_2, c) N_2, d) CO_2, e) Vortex, f) LN_2 + MQL, g)N_2 + MQL, h) CO_2 + MQL, i) CO_2 + MQL, and j) Vortex+MQL cutting environment.

notching that occurs at the depth of cut line. Ezugwu et al. [47] reported that notching at the depth of the cutting zones of the tool was the most common failure mode. They also reported that there are various theories about the mechanisms that cause notching at the depth of the cut line, and therefore, it is difficult to have a consensus on this issue. However, researchers have claimed that the most basic theory is that the stress on the tool, the deformation-hardened layer, and the work material adhere to the notched area and then separate from its place.

Although the cooling/lubrication methods used in this study to limit tool damage and mechanisms reduced the physical amount of damage, they were not effective enough in reducing the dominance of the adhesion wear mechanism.

3.2. Sustainability analysis

3.2.1. Economic assessment

Assessing economic feasibility plays a vital role in maintaining a balance across all elements of sustainability, as it stands as a pivotal and foundational principle of sustainability. When evaluating the financial aspects of any manufacturing process, it is necessary to take into account a wide range of elements that cover the entire life cycle of the product. This includes examining various factors, from the initial investment in the pre-processing stage to the ultimate stage of post-processing [48]. The total machining costs while turning Haynes C4 under different sustainable cutting environments (i.e., Dry, MQL, LN_2, N_2, CO_2, Vortex, LN_2 + MQL, N_2 + MQL, CO_2 + MQL, and Vortex + MQL) have been comprehensively estimated based on various factors that directly or indirectly affect the entire process. For the comparative and comprehensive evaluation of costs incurred during the turning operations under different cutting environments, the costs incurred after machining for 6.78 min or after the removal of 28.000 mm^3 of material have been estimated.

The evaluation of the economic feasibility of a subtractive machining operation (SMO) is determined by different factors that impact each stage of the turning process, including pre-processing, processing, and post-processing. In the pre-processing stage, factors such as the machine-tool investment, expenses incurred due to advanced and sustainable coolant/lubricant delivery systems, and operator charges manipulate the overall machining cost of the operations [49]. During the processing stage of the turning process, factors like the lifespan of the cutting tool, power consumption, and amount of lubricant/coolant utilized during the process come into play. Lastly, in the post-processing phase, factors such as swarf recycling, expenses incurred due to cleaning of emulsion, and consumption of power influence the overall cost. Fig. 9 describes all the crucial factors of any SMO that influence the economics of the process. The total of these factors, or rather the cost elements, provide detailed insight into the economic feasibility of any SMO, which can be acquired using the following formula:

$$C_{SMO} = C_1 + C_2 + C_3$$

where:

C_{SMO} = Total cost incurred during the SMO.

C_1 = Expenses incurred during the primary stage of SMO (i.e., pre-processing).

C_2 = Expenses incurred during the secondary stage of SMO (i.e., processing).

C_3 = Expenses incurred during the tertiary stage of SMO (i.e., post-processing).

3.2.1.1. Estimation of costs incurred in the primary stage of SMO. As previously stated, this phase involves factors such as the machine-tool investment, expenses incurred due to advanced and sustainable coolant/lubricant delivery systems, and operator charges. The expenses associated with the setup of the turning equipment and the operator expenses involved in managing this advanced setup are the primary factors that affect the economic aspects of the preliminary processing phase. The absence of any extra coolant/lubrication setup cost is a distinguishing feature of the dry cutting environment that helps in reducing the costs in the preliminary stage. On the other hand, the MQL, LN_2, N_2, CO_2, Vortex, LN_2 + MQL, N_2 + MQL, CO_2 + MQL, and Vortex + MQL cutting conditions involve additional expenses for setting up delivery systems. These supplementary setups contribute to the overall cost-

Table 3
Machining costs of each cutting environment at different stages of SMO and their cumulative cost.

Sr. No.	Cutting environment	C_1 ($)	C_2 ($)	C_3 ($)	C_{SMO} ($)
1	Dry	5.14164	21.54223	0.0040	26.6879
2	MQL	6.71627	16.58573	0.0245	23.3265
3	LN_2	6.36912	18.56694	0.0040	24.9401
4	N_2	8.81308	14.10175	0.0040	22.9188
5	CO_2	8.22758	14.52461	0.0040	22.7562
6	Vortex	8.82484	12.58659	0.0040	21.4154
7	LN_2 + MQL	6.99479	16.05761	0.0285	23.0809
8	N_2 + MQL	9.59923	11.71087	0.0285	21.3386
9	CO_2 + MQL	9.15290	12.18144	0.0285	21.3628
10	Vortex + MQL	9.97562	11.25316	0.0285	21.2573

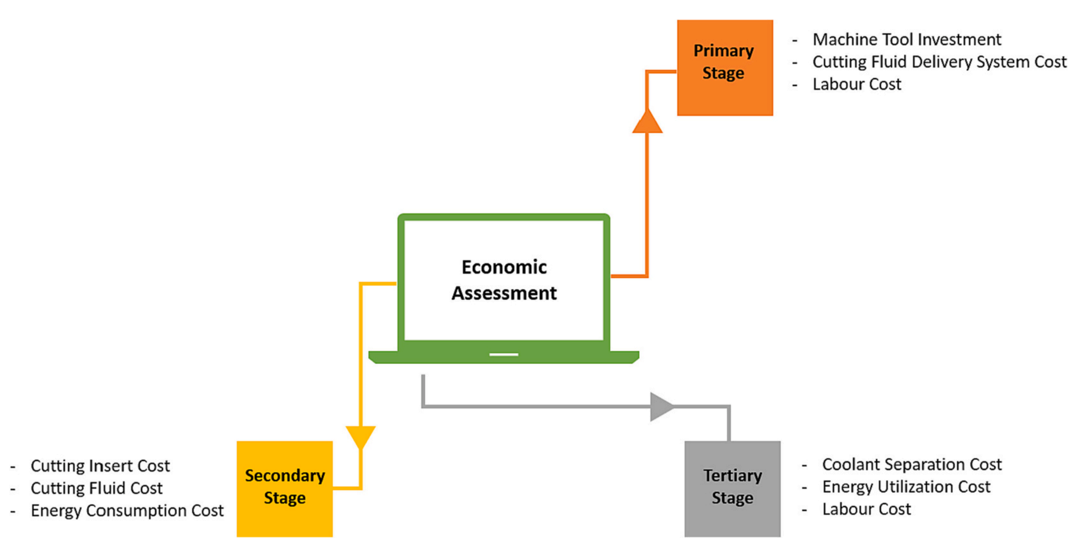

Fig. 9. Crucial factors during any SMO that manipulate the overall machining cost.

effectiveness of the turning process as they result in increased setup and operator charges. Table 3 compares the overall costs incurred during the primary stage of the turning process under different cutting environments.

3.2.1.2. Estimation of costs incurred in the secondary stage of SMO. This phase involves factors like the cutting tool (i.e., Taegu Tec DCMT 11 T304 MT TT5080, which is a PVD AlTiN coated cutting tool), cutting fluids (i.e., MQL, LN_2, N_2, and CO_2), and the power consumed during the turning process under different cutting conditions. Cutting fluids plays a vital role in SMO by effectively regulating the temperature at the interface between the tool and workpiece. This directly enhances the quality of the surface and prolongs the lifespan of the cutting insert. The MQL cutting condition can be considered a suitable and sustainable alternative to traditional methods because it only requires a small quantity of oil (approximately 10–100 mL/h). In contrast, the water-based cutting fluid utilizes a larger amount of fluid (around 30 L/h) depending on the process parameters [50–52]. The utilization of gases like N_2 and CO_2 helps in preventing the oxidation of the workpiece and swarf. The presence of air is crucial in minimizing the oxidation of tools while conducting SMO at high cutting speeds. N_2 prevents the formation of a film on the surface, which allows the smooth flow of the swarf on the rake face of the cutting insert [53,54]. While machining hard-to-cut Ti-based and Ni-based materials, CO_2 is highly efficient in minimizing crater wear on carbide tools [55].

Another factor within the processing stage involves the expenses incurred due to the cutting insert utilization. Numerous studies found in the literature have highlighted that the expenses associated with the cutting insert play a significant role in estimating the C_{SMO} [48,56,57]. Therefore, the proper employment of optimum cutting conditions and process parameters is important from the sustainability point of view. The tool utilized for this study is a PVD AlTiN-coated Taegu Tec DCMT 11 T304 MT. While turning under a different cutting condition, an unused fresh edge of the cutting tool was used. The cost of the cutting tool used in this experimental study is $ 21.54. The cost resulting from the power used in the SMO is an essential factor in the processing stage. The power usage during the turning operations of the Haynes C4 has been estimated for various cutting conditions, and the associated energy cost has been included in the C_{SMO}. The calculations were based on a tariff of 0.085 $/kWh for the electricity used. Table 3 compares the overall costs incurred during the secondary stage of the turning process under different cutting conditions.

3.2.1.3. Estimation of costs incurred in the tertiary stage of SMO. The final stage of an SMO is important as it directly supports the aspects and idea of sustainability. In this stage, there are various factors to consider, including the expenses associated with separating coolant, cleaning the emulsion, and the energy used in waste processing and management. Additionally, the cost of labor is a significant factor in determining the overall expense of waste processing. However, this final stage has minimal influence in deciding the C_{SMO}. Table 3 compares the overall cost incurred during the final stage of the SMO under different cutting conditions. The overall SMO costs for various cutting conditions can be observed in Fig. 10.

It can be explicitly seen from Fig. 10 that the C_{SMO} incurred is highest for the dry cutting condition and lowest for the Vortex + MQL cutting condition. The C_{SMO} follows the order of Dry > LN_2 > MQL > LN_2 + MQL > N_2 > CO_2 > Vortex > CO_2 + MQL > N_2 + MQL > Vortex + MQL. Table 3 shows that while employing Vortex + MQL cutting condition, the C_{SMO} decreased by about 20.35% as compared to dry cutting condition. While employing a combination of sustainable lubricating/cooling conditions (i.e., LN_2 + MQL, N_2 + MQL, CO_2 + MQL, and Vortex + MQL), the overall machining costs decreased in the range of about 6–20% approximately as compared to the employment of the individual cutting conditions (i.e., Dry, MQL, LN_2, N_2, CO_2, and Vortex).

In the primary stage of the SMO, the C_1 technically depended on the machine tool's utilization time. Hence, with the increase in tool life, the C_1 increases directly. In the primary phase, dry cutting condition accounted for the lowest C_1, whereas on the other hand, the Vortex + MQL cutting condition accounted for the highest C_1. The C_1 increased by about 94% while utilizing Vortex + MQL as compared to dry cutting condition. However, this cutting condition provided increased tool life.

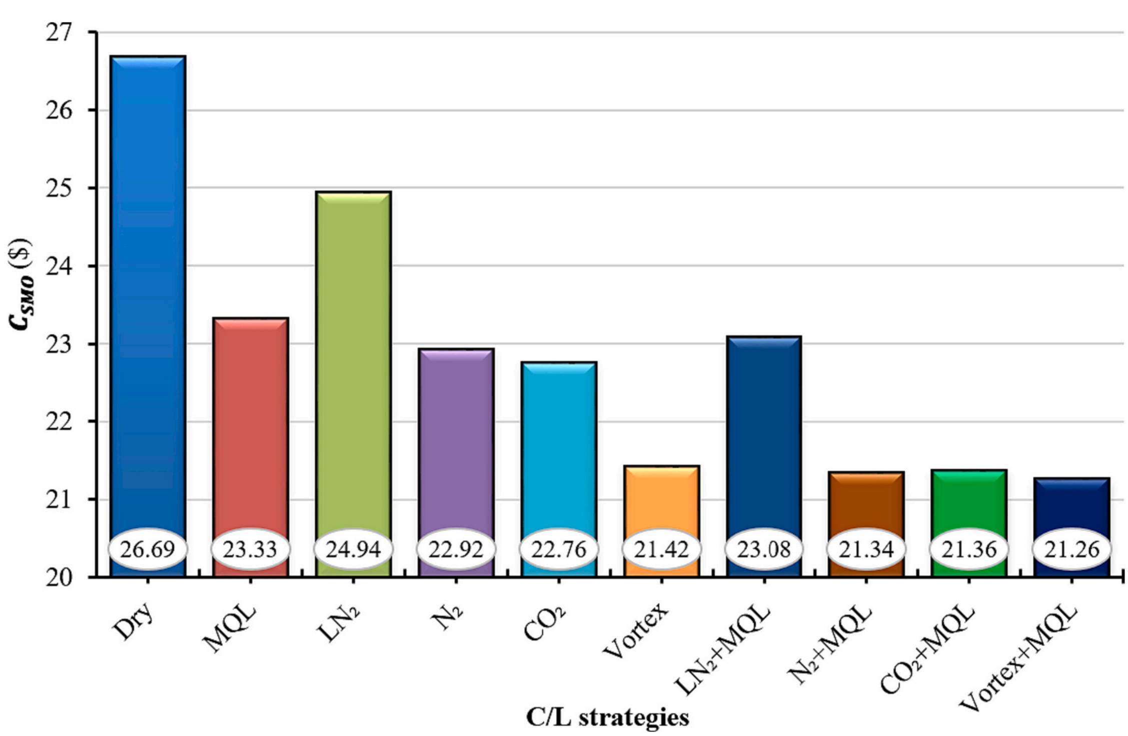

Fig. 10. Total cost incurred during the SMO under different sustainable C/L strategies (i.e., Dry, MQL, LN_2, N_2, CO_2, Vortex, LN_2 + MQL, N_2 + MQL, CO_2 + MQL, and Vortex + MQL).

The costs incurred due to the consumption of power were also dependent on the time and thus followed a similar trend as the C_1. The flow rate of the utilized sustainable lubricants/coolants also had a considerable effect on the overall machining costs.

The cutting insert is the factor that greatly manipulates the $C_{SMO}$and contributes significantly to the overall cost. This observation has also been reported by various authors [48,56,57]. While employing Vortex + MQL, the costs due to the utilization of cutting insert decreased by about 48% as compared to that of Dry. While employing a combination of different sustainable lubricating/cooling conditions, the cutting insert utilization costs decreased in the range of about 25–48% approximately as compared to the employment of the individual cutting conditions. The expenses associated with separating coolant, cleaning the emulsion, and the energy used in waste processing and management were higher for the cutting conditions that involved MQL due to the involvement of the part cleaning costs.

3.2.2. *Assessment of carbon emissions*

The evaluation of the environmental sustainability of any SMO is an essential aspect of driving the industry towards a sustainable future. To assess any process or product's environmental viability, it is important to estimate the carbon emissions (CE) associated with it. The carbon footprint (CFP), which encompasses both direct and indirect CO_2 emissions produced during a process or across the different stages of a product's lifespan, provides a measure of the amount of CO_2 released. Essentially, it provides a metric for evaluating the CE [58,59]. The CFP of a manufactured product measures the overall amount of greenhouse gases released during its complete lifespan, including processes like obtaining raw materials, production, usage, and eventual reutilization, recycling, or disposal [60]. The CE from any unit functional process (UFP) (i.e., CE_{UFP}) can be calculated from the UFP's activity data (AD) (i.e., AD_{UFP}) and the carbon emission factor (CEF_{UFP}) [61]. The CE_{UFP} can be estimated by utilizing the equation given below:

$$CE_{UFP} = AD_{UFP} \times CEF_{UFP}$$

The CEF acts as a catalyst that transforms any UFP's AD into the overall CE of the UFP. Here, the AD represents the data provided as input or output for a production unit within a particular timeframe. For evaluating the sustainability of the turning operations from an environmental perspective under different cutting conditions, the CE during the various phases of SMO was calculated. Fig. 11 shows the aspects considered for the assessment of the CE during the SMO. For the comparative and comprehensive evaluation of the CE from the turning operations under different cutting environments, the CE obtained after machining for 6.78 min or after the removal of 28,000 mm^3 of material has been estimated.

3.2.2.1. *Cumulative CE resulting from SMO (CE_{SMO}).*

The SMO (i.e., turning for this study) for Haynes C4 has been conducted under 10 different cutting environments (i.e., Dry, MQL, LN_2, N_2, CO_2, Vortex, LN_2 + MQL, N_2 + MQL, CO_2 + MQL, and Vortex + MQL). The overall amount of CE resulting from the power utilized by the SMO, the usage of cutting inserts and of cutting fluids, and the chip recycling phase have been computed, which gives the cumulative CE resulting from the turning operations for this study.

3.2.2.1.1. *CE resulting due to power utilization (CE_{PU}).* The amount of power utilization during the SMO is greatly surpassed by the energy needs of supporting equipment used in secondary processes. These additional processes include technical air ventilation, the operation of coolant pumps, and managing lubricant and coolant supplies [62]. Hence, it is crucial to find out the total CE resulting due to the power utilization since it contributes a great deal to the cumulative CE from the entire SMO. As previously stated, the AD and CEF of a UFP can be utilized to estimate the cumulative CE originating from the UFP. In this

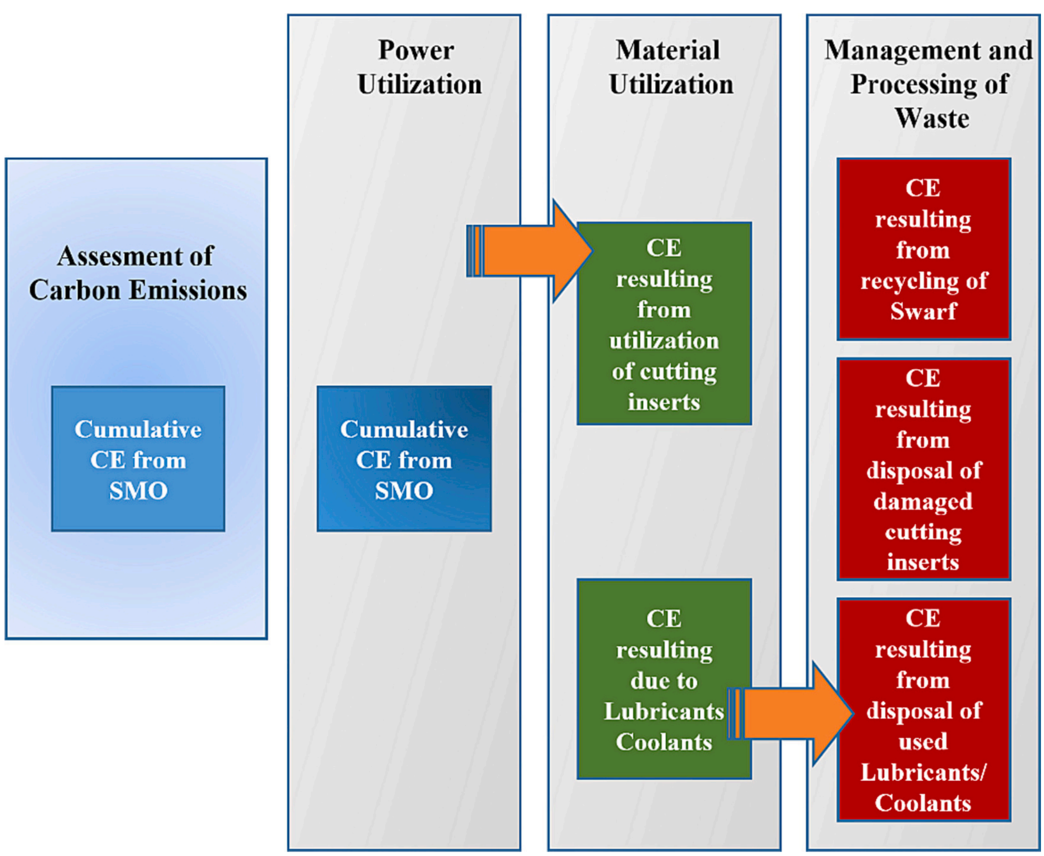

Fig. 11. Aspects considered for the estimation of cumulative CE from SMO.

context, the AD represents the power utilized during the SMO, while the assumed CEF represents the factor of power utilized throughout the study [63]. 0.721 kg CO_2/kWh was taken as the value of CEF_{PU}. The equation shown below can be used to calculate the CE_{PU} [64]:

$$CE_{PU} = PU_{SMO} \times CEF_{PU}$$

where:

PU_{SMO} = cumulative power utilized during the SMO.
CEF_{PU} = Power utilization's CEF.

Table 4 displays the obtained CE values resulting from the power utilized for the turning process conducted under various cutting conditions.

3.2.2.1.2. CE from the usage of cutting inserts and of cutting fluids (CE_{MU}). The carbon emissions resulting from the use of cutting inserts and lubricants/coolants are significant factors in determining the overall environmental impact. To estimate the cumulative carbon emissions produced during the SMO, it is necessary to consider the usage of cutting tools (i.e., CE_{CT}) and lubricants/coolants (i.e., CE_{LC}) in various cutting conditions. These emissions can be calculated using the equations shown below:

$$CE_{MU} = CE_{LC} + CE_{CT}$$

where:

$$CE_{LC} = Q_{LC} \times CEF_{LC}$$

$$CE_{CT} = t/t_{life} \times CEF_{CT} \times W_{CT}$$

The equations given above help in calculating the overall CE_{MU}. In these equations, Q_{LC} represents the quantity of lubricant/coolant used, t stands for the time taken for completing the turning tests, t_{life} is the lifespan of the cutting tool, CEF_{LC} and CEF_{CT} denote the CEF of the lubricant/coolant and the cutting tool, respectively, and W_{CT} is the weight of the cutting tool. The CEF_{CT} and CEF_{LC} for this research work are taken as 30.04 kg CO_2/kg and 1.09 kg CO_2/L for MQL [65–67]. The CEF_{LC} for LN_2 and N_2 cutting condition is taken as 0.32 kg CO_2/L [57]. It is assumed that the CO_2 gas utilized is acquired as a byproduct of a particular primary process and thus the overall emissions due to the utilization of the CO_2 gas are taken as negligible or zero [68–70]. Table 4 displays the overall CE from the usage of lubricant/coolants and cutting tools during the turning operations under different cutting environments.

3.2.2.1.3. CE from the management and processing of waste (CE_{MPW}). To enhance the sustainability of the SMO, it is crucial to address waste processing and management. Proper handling of the by-products generated during the SMO, including used lubricants/coolants, damaged cutting tools, and swarf, is essential. The consideration of CE becomes vital during the disposal of these by-products. This phase involves evaluating the CE associated with the management and processing of waste, such as CE during the recycling of swarf (CE_{RoS}), CE obtained during the disposal process of damaged cutting tools (CE_{DCT}), and CE obtained during the disposal process of used lubricants/coolants (CE_{DLC}) [57]. The CE_{RoS}, CE_{DCT}, and CE_{DLC} can be estimated by using the below-mentioned equations:

$$CE_{RoS} = EC_{RoS} \times CEF_{EC} \times W_S$$

$$CE_{DCT} = W_{CT} \times CEF_{DCT}$$

$$CE_{DLC} = A_{DLC} \times CEF_{DLC}$$

Here, EC_{Ros} is the energy utilized by the recycling equipment during the swarf recycling stage, CEF_{EC} is the factor of energy utilized, M_S is the total weight of the swarf obtained, W_{CT} is the cutting tool's weight, CEF_{DCT} and CEF_{DLC} are the factors considered for the disposal process of the damaged cutting tools and lubricants/coolants, and A_{DLC} is the quantity of lubricants/coolants disposed of, The CE_{MPW} can be calculated by the cumulative sum of CE_{RoS}, CE_{DCT}, and CE_{DLC}. The CE_{RoS} has been estimated on the basis of the reference criteria set (i.e., 28,000 mm^3 or 6.78 min). Due to the unavailability of CEF data for Haynes C4, which is a Ni-based superalloy, the CEF of another Ni-based superalloy (i.e., Inconel 718) has been considered for the recycling of swarf. Its value has been set at 3.7 kg CO_2/kg [22]. Embodied energy can also be utilized to calculate CE_{RoS}. The term "embodied energy" refers to the amount of energy required in order to manufacture 1 kg metal ingot by means of recycling [71]. The CE due to the management and processing of waste is displayed in Table 4. The cumulative CE from the turning process under different cutting conditions can be seen in Fig. 12.

As can be seen in Fig. 12, the CE_{SMO} obtained is highest for the dry cutting condition and lowest for the Vortex + MQL cutting condition. The CE_{SMO} follows the order of Dry > MQL > LN_2 > LN_2 + MQL > CO_2 > CO_2 + MQL > N_2 > N_2 + MQL > Vortex > Vortex + MQL. Table 4 shows that while employing Vortex + MQL cutting condition, the CE_{SMO} decreased by about 11.37% as compared to Dry cutting condition. The above order of CE shows that utilization of MQL or rather a combination of MQL and another cutting condition (i.e., Dry, MQL, LN_2, N_2, CO_2, and Vortex) decreased the CE as compared to the utilization of the individual cutting conditions. The CE_{MPW} was the major contributor to the overall CE of the turning process, wherein the CE obtained during the recycling of the swarf was the highest. The obtained cumulative CE values are very less, which is due to the set reference criteria (i.e., machining for 6.78 min or removal of 28,000 mm^3 chip volume). The CE resulting due to the power consumption while employing Vortex + MQL cutting condition, decreased approximately by about 25% as compared to that of dry cutting condition. While employing a combination of sustainable lubricating/cooling conditions (i.e., LN_2 + MQL, N_2 + MQL, CO_2 + MQL, and Vortex + MQL), the overall CE decreased in the range of about 15–25% approximately as compared to the employment of the individual cutting conditions (i.e., Dry, MQL, LN_2, N_2, CO_2, and Vortex). The respective values of CE_{RoS} (i.e., 0.8127 kg CO_2/kg) and CE_{DCT} (i.e., 0.00013 kg CO_2/kg) were identical for all cutting conditions due to the fact that the same reference criteria (i.e., 28,000 mm^3 chip volume or 6.78 min) were set for every cutting condition to have an equal ground for comparison.

Table 4
Carbon emissions from different stages of SMO obtained under different cutting conditions.

Sr. No.	Cutting environment	CE_{PU} (\$)	CE_{MU} (\$)	CE_{MPW} (\$)	CE_{SMO} (\$)
1	Dry	0.018340	0.29096	0.81292	1.12221
2	MQL	0.015635	0.23704	0.81534	1.06802
3	LN_2	0.015920	0.23683	0.81292	1.06566
4	N_2	0.015284	0.17115	0.81292	1.00150
5	CO_2	0.015586	0.18185	0.81292	1.01035
6	Vortex	0.014812	0.16973	0.81292	0.99745
7	LN_2 + MQL	0.015439	0.22990	0.81542	1.06076
8	N_2 + MQL	0.014038	0.17111	0.81636	0.99935
9	CO_2 + MQL	0.014657	0.17748	0.81622	1.00836
10	Vortex + MQL	0.013924	0.16409	0.81652	0.99453

4. Conclusion

In this study, Hastelloy C4 was processed under cooling conditions such as Dry, MQL, LN_2, N_2, CO_2, Vortex, LN_2 + MQL, N_2 + MQL, CO_2 + MQL, and Vortex + MQL, and the effects of cooling conditions on surface roughness, power consumption, tool wear were examined, and its effect on cutting temperature was investigated. Additionally, sustainability analysis was applied to determine the impact of cooling conditions on sustainability. The results obtained at the end of the study are presented below.

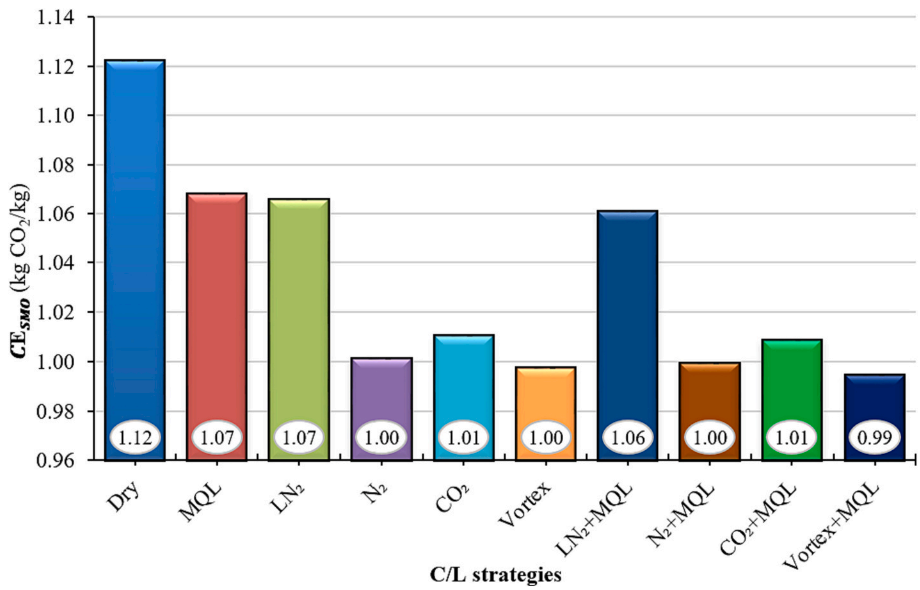

Fig. 12. Cumulative CE obtained while turning Haynes C4 under various C/L strategies.

- Among all cooling/lubrication conditions, the best Ra value was obtained with Vortex + MQL. Compared to the reference environment (dry machining condition), the maximum improvement in Ra value was 30.12%.
- The highest cutting temperature value occurs under dry machining, with 325 °C. With the use of the MQL system, there was a decrease of 11.38% in cutting temperature compared to dry machining. Moreover, LN_2, N_2, and CO_2 reduced the cutting temperature by 39.99%, 26.46% and 30.46%, respectively. Especially liquid N_2 can make cooling much more effective by penetrating the cutting zone in fluid form. Therefore, among all cooling/lubrication conditions, the lowest cutting temperature was obtained with LN_2.
- With the introduction of cooling/lubrication agencies, improvements in power consumption have emerged. When these are listed starting from the best, the ranking is (1) Vortex + MQL-24.07%, (2) N_2 + MQL-23.45%, (3) CO_2 + MQL-20.07%, (4) Vortex −19.23%, (5) N_2–16.65%, (6) LN_2 + MQL-15.81%, (7) CO_2–15.01%, (8) MQL-14.74%, and (9) LN_2–13.17%, compared to dry machining.
- Abrasive marks, notching, BUE, BUL, and adhesion played an active role in the damage to the flank and rake faces of the cutting tool. In particular, it can be clearly said from SEM and EDX analyses that the dominant damage mechanism is adhesion wear. Although the cooling/lubrication methods reduced the physical amount of tool damage, they were not effective enough in reducing the dominance of the adhesion wear mechanism.
- The C_{SMO} follows the order of Dry > LN_2 > MQL > LN_2 + MQL > N_2 > CO_2 > Vortex > CO_2 + MQL > N_2 + MQL > Vortex + MQL. While utilizing Vortex + MQL cutting condition, the C_{SMO} decreased by about 20.35% as compared to dry cutting condition. Whereas, while using a combination of different sustainable lubrications or coolants, the overall machining costs decreased in the range of about 6–20% approximately as compared to the employment of the individual cutting conditions.
- The CE_{SMO} follows the order of Dry > MQL > LN_2 > LN_2 + MQL > CO_2 > CO_2 + MQL > N_2 > N_2 + MQL > Vortex > Vortex + MQL. While employing Vortex + MQL cutting condition, the CE_{SMO} decreased by about 11.37% as compared to dry cutting condition. While using a combination of different sustainable lubrications or coolants, the overall CE decreased in the range of about 15–25% approximately as compared to the employment of the individual cutting conditions (i.e., coolant/lubricants).

Generally evaluated, according to the results obtained in this study, all cooling conditions showed an improvement compared to dry processing. This has also been confirmed through sustainability analysis.

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Methodology, Sustainability analysis, Validation, Software.
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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] A. Moldavska, T. Welo, A holistic approach to corporate sustainability assessment: incorporating sustainable development goals into sustainable manufacturing performance evaluation, J. Manuf. Syst. 50 (2019) 53–68, https://doi.org/10.1016/j.jmsy.2018.11.004.

[2] J.R. Gamage, A.K.M. DeSilva, Assessment of research needs for sustainability of unconventional machining processes, Proc. CIRP. 26 (2015) 385–390, https://doi.org/10.1016/j.procir.2014.07.096.
[3] S. Imperatives, Report of the World Commission on Environment and Development: Our Common Future, Accessed Feb. 10, 1987.
[4] E. Kaya, B. Akyüz, Effects of cutting parameters on machinability characteristics of Ni-based superalloys: a review 7 (2017) 330–342, https://doi.org/10.1515/eng-2017-0037.
[5] R. Binali, A.D. Patange, M. Kuntoğlu, T. Mikolajczyk, E. Salur, Energy saving by parametric optimization and advanced Lubri-cooling techniques in the machining of composites and superalloys: a systematic review, Energies. 15 (2022), https://doi.org/10.3390/en15218313.
[6] R.S. Revuru, N.R. Posinasetti, V.R. VSN, A. M, Application of cutting fluids in machining of titanium alloys—a review, Int. J. Adv. Manuf. Technol. 91 (2017) 2477–2498, https://doi.org/10.1007/s00170-016-9883-7.
[7] M.K. Sinha, A. Pal, K. Kishore, A. Singh, Archana, H. Sansanwal, P. Sharma, Applications of sustainable techniques in machinability improvement of superalloys: a comprehensive review, Int. J. Interact. Des. Manuf. 17 (2023) 473–498, https://doi.org/10.1007/s12008-022-01053-2.
[8] M.A. Makhesana, K.M. Patel, G.M. Krolczyk, M. Danish, A.K. Singla, N. Khanna, Influence of MoS2 and graphite-reinforced nanofluid-MQL on surface roughness, tool wear, cutting temperature and microhardness in machining of Inconel 625, CIRP J. Manuf. Sci. Technol. 41 (2023) 225–238, https://doi.org/10.1016/J.CIRPJ.2022.12.015.
[9] S. Debnath, M.M. Reddy, Q.S. Yi, Environmental friendly cutting fluids and cooling techniques in machining: a review, J. Clean. Prod. (2014), https://doi.org/10.1016/j.jclepro.2014.07.071.
[10] S. Zhang, J.F. Li, Y.W. Wang, Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions, J. Clean. Prod. 32 (2012) 81–87, https://doi.org/10.1016/j.jclepro.2012.03.014.
[11] Ç.V. Yıldırım, M. Sarıkaya, T. Kıvak, Ş. Şirin, The effect of addition of hBN nanoparticles to nanofluid-MQL on tool wear patterns, tool life, roughness and temperature in turning of Ni-based Inconel 625, Tribol. Int. 134 (2019) 443–456, https://doi.org/10.1016/j.triboint.2019.02.027.
[12] M. Danish, M.K. Gupta, A. Garcia-Collado, Use of sustainable cooling/lubrication strategies in improving the tribological and machining characteristics of gun metal (2023), https://doi.org/10.1177/09544062231201830.
[13] M.F. Zakaria, M.A. Suhaimi, S. Sharif, G.-D. Yang, M.S. Shaharum, M.K.M. Kamal, K. Zakaria, The application of cold air and nano-MQL as cooling strategy in high speed milling of titanium alloy Ti-6Al-4V: a review, AIP Conf. Proc. 2129 (2019) 20175, https://doi.org/10.1063/1.5118183.
[14] R. Arafat, N. Madanchi, S. Thiede, C. Herrmann, S.J. Skerlos, Supercritical carbon dioxide and minimum quantity lubrication in pendular surface grinding – a feasibility study, J. Clean. Prod. 296 (2021), 126560, https://doi.org/10.1016/j.jclepro.2021.126560.
[15] O. Pereira, P. Català, A. Rodríguez, T. Ostra, J. Vivancos, A. Rivero, L.N. López-de-Lacalle, The use of hybrid CO2+MQL in machining operations, Proc. Eng. 132 (2015) 492–499, https://doi.org/10.1016/j.proeng.2015.12.524.
[16] F. Ahmed, F. Ahmad, S.T. Kumaran, M. Danish, R. Kurniawan, S. Ali, Development of cryogenic assisted machining strategy to reduce the burr formation during micro-milling of ductile material, J. Manuf. Process. 85 (2023) 43–51, https://doi.org/10.1016/J.JMAPRO.2022.11.036.
[17] D. Zindani, K. Kumar, A brief review on cryogenics in machining process, SN Appl. Sci. 2 (2020) 1107, https://doi.org/10.1007/s42452-020-2899-5.
[18] Y. Yildiz, M. Nalbant, A review of cryogenic cooling in machining processes, Int. J. Mach. Tool Manuf. 48 (2008) 947–964, https://doi.org/10.1016/j.ijmachtools.2008.01.008.
[19] F.J. Amigo, G. Urbikain, O. Pereira, P. Fernández-Lucio, A. Fernández-Valdivielso, L.N.L. de Lacalle, Combination of high feed turning with cryogenic cooling on Haynes 263 and Inconel 718 superalloys, J. Manuf. Process. 58 (2020) 208–222, https://doi.org/10.1016/j.jmapro.2020.08.029.
[20] M. Jamil, N. He, W. Zhao, L. Li, M.K. Gupta, M. Sarikaya, A.M. Khan, R. Singh, Heat transfer efficiency of cryogenic-LN2 and CO2-snow and their application in the turning of Ti-6AL-4V, Int. J. Heat Mass Transf. 166 (2021), 120716, https://doi.org/10.1016/j.ijheatmasstransfer.2020.120716.
[21] A.H. Musfirah, J.A. Ghani, C.H.C. Haron, Tool wear and surface integrity of Inconel 718 in dry and cryogenic coolant at high cutting speed, Wear. 376–377 (2017) 125–133, https://doi.org/10.1016/J.WEAR.2017.01.031.
[22] D. Cica, D. Kramar, Machinability investigation and sustainability analysis of high-pressure coolant assisted turning of the nickel-based superalloy Inconel 718, Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 237 (2022) 43–54, https://doi.org/10.1177/09544054221092939.
[23] R. Çakıroğlu, Machinability analysis of inconel 718 superalloy with AlTiN-coated carbide tool under different cutting environments, Arab. J. Sci. Eng. 46 (2021) 8055–8073, https://doi.org/10.1007/s13369-021-05626-3.
[24] E. Şirin, Evaluation of tribological performance of MQL technique combined with LN_2, CO_2, N_2 ecological cooling/lubrication techniques when turning of Hastelloy C22 superalloy, Tribol. Int. 188 (2023), 108786, https://doi.org/10.1016/j.triboint.2023.108786.
[25] P. Shah, N. Khanna, Chetan, Comprehensive machining analysis to establish cryogenic LN2 and LCO2 as sustainable cooling and lubrication techniques, Tribol. Int. (2020), 106314, https://doi.org/10.1016/j.triboint.2020.106314.
[26] Ş. Şirin, Investigation of the performance of cermet tools in the turning of Haynes 25 superalloy under gaseous N2 and hybrid nanofluid cutting environments, J. Manuf. Process. 76 (2022) 428–443, https://doi.org/10.1016/J.JMAPRO.2022.02.029.
[27] S. Eiamsa-ard, P. Promvonge, Review of Ranque–Hilsch effects in vortex tubes, Renew. Sustain. Energy Rev. 12 (2008) 1822–1842, https://doi.org/10.1016/J.RSER.2007.03.006.
[28] Ç.V. Yıldırım, Ş. Şirin, T. Kıvak, H. Ercan, M. Sarıkaya, An attempt towards green machining of Ni-based Hastelloy C4 alloy: effect of vegetable oils and their combination with TiO2 and SiO2 nanoparticles on outputs, Sustain. Mater. Technol. 37 (2023), e00668, https://doi.org/10.1016/J.SUSMAT.2023.E00668.
[29] N. Tapoglou, M.I.A. Lopez, I. Cook, C.M. Taylor, Investigation of the influence of CO2 cryogenic coolant application on tool wear, Proc. CIRP. 63 (2017) 745–749, https://doi.org/10.1016/J.PROCIR.2017.03.351.
[30] F. Pušavec, A. Stoić, J. Kopač, The role of cryogenics in machining processes, Teh. Vjesn. 16 (2009) 3–10.
[31] Ş. Şirin, in: N. Khanna, K.K. Gajrani, K. Giasin, J.P. Davim (Eds.), Sustainable Materials and Manufacturing Technologies, 1st ed, CRC Press, 2023, pp. 125–151, https://doi.org/10.1201/9781003291961.
[32] M. Danish, M.K. Gupta, S. Rubaiee, A. Ahmed, M. Sarıkaya, G.M. Krolczyk, Environmental, technological and economical aspects of cryogenic assisted hard machining operation of inconel 718: a step towards green manufacturing, J. Clean. Prod. 337 (2022), 130483, https://doi.org/10.1016/j.jclepro.2022.130483.
[33] Y. Su, N. He, L. Li, A. Iqbal, M.H. Xiao, S. Xu, B.G. Qiu, Refrigerated cooling air cutting of difficult-to-cut materials, Int. J. Mach. Tool Manuf. 47 (2007) 927–933, https://doi.org/10.1016/j.ijmachtools.2006.07.005.
[34] Ç.V. Yıldırım, T. Kıvak, M. Sarıkaya, Ş. Şirin, Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL, J. Mater. Res. Technol. 9 (2020) 2079–2092, https://doi.org/10.1016/j.jmrt.2019.12.069.
[35] M. Sarikaya, Optimization of the surface roughness by applying the Taguchi technique for the turning of stainless steel under cooling conditions, Mater. Tehnol. 49 (2015) 941–948, https://doi.org/10.17222/mit.2014.282.
[36] M. Dhananchezian, M. Pradeep Kumar, Cryogenic turning of the Ti-6Al-4V alloy with modified cutting tool inserts, Cryogenics (Guildf). 51 (2011) 34–40, https://doi.org/10.1016/j.cryogenics.2010.10.011.
[37] M. Jamil, N. He, W. Zhao, H. Xiang, M.K. Gupta, A. Iqbal, A.M. Khan, Assessment of energy consumption, carbon emissions and cost metrics under hybrid MQL-dry ice blasting system: a novel cleaner production technology for manufacturing sectors, J. Clean. Prod. 360 (2022), 132111, https://doi.org/10.1016/J.JCLEPRO.2022.132111.
[38] T.K. Nguyen, I. Do, P. Know, A tribological study of vegetable oil enhanced by nano-platelets and implication in MQL machining, Int. J. Precis. Eng. Manuf. 13 (2012) 1077–1083.
[39] M. Jamil, W. Zhao, N. He, M.K. Gupta, M. Sarikaya, A.M. Khan, S.M. R, S. Siengchin, D.Y. Pimenov, Sustainable milling of Ti–6Al–4V: a trade-off between energy efficiency, carbon emissions and machining characteristics under MQL and cryogenic environment, J. Clean. Prod. 281 (2021), 125374, https://doi.org/10.1016/J.JCLEPRO.2020.125374.
[40] V.S. Sharma, G. Singh, K. Sørby, A review on minimum quantity lubrication for machining processes, Mater. Manuf. Process. (2015) 37–41, https://doi.org/10.1080/10426914.2014.994759.
[41] Ç.V. Yıldırım, Experimental comparison of the performance of nanofluids, cryogenic and hybrid cooling in turning of Inconel 625, Tribol. Int. 137 (2019) 366–378, https://doi.org/10.1016/j.triboint.2019.05.014.
[42] G. Fox-Rabinovich, B.D. Beake, K. Yamamoto, M.H. Aguirre, S.C. Veldhuis, G. Dosbaeva, A. Elfizy, A. Biksa, L.S. Shuster, Structure, properties and wear performance of nano-multilayered TiAlCrSiYN/TiAlCrN coatings during machining of Ni-based aerospace superalloys, Surf. Coatings Technol. 204 (2010) 3698–3706, https://doi.org/10.1016/j.surfcoat.2010.04.050.
[43] M. Sarıkaya, M.K. Gupta, I. Tomaz, D.Y. Pimenov, M. Kuntoğlu, N. Khanna, Ç. V. Yıldırım, G.M. Krolczyk, A state-of-the-art review on tool wear and surface integrity characteristics in machining of superalloys, CIRP J. Manuf. Sci. Technol. 35 (2021) 624–658, https://doi.org/10.1016/J.CIRPJ.2021.08.005.
[44] M. Sarıkaya, V. Yılmaz, A. Güllü, Analysis of cutting parameters and cooling/lubrication methods for sustainable machining in turning of Haynes 25 superalloy, J. Clean. Prod. 133 (2016) 172–181, https://doi.org/10.1016/j.jclepro.2016.05.122.
[45] Ç.V. Yıldırım, Ş. Şirin, T. Kıvak, M. Sarıkaya, The effect of nanofluids reinforced with different surfactants on the machining and friction-wear properties of Waspaloy, Tribol. Int. 181 (2023), 108316, https://doi.org/10.1016/j.triboint.2023.108316.
[46] M. Jamil, N. He, W. Zhao, A.M. Khan, H. Xiang, M.K. Gupta, A. Iqbal, A novel low-pressure hybrid dry ice blasting system for improving the tribological and machining characteristics of AISI-52100 tool steel, J. Manuf. Process. 80 (2022) 152–160, https://doi.org/10.1016/J.JMAPRO.2022.05.056.
[47] E.O. Ezugwu, Z.M. Wang, A.R. Machado, The machinability of nickel-based alloys: a review, J. Mater. Process. Technol. 86 (1998) 1–16, https://doi.org/10.1016/S0924-0136(98)00314-8.
[48] G. Kshitij, N. Khanna, Ç.V. Yıldırım, S. Dağlı, M. Sarıkaya, Resource conservation and sustainable development in the metal cutting industry within the framework of the green economy concept: an overview and case study, Sustain. Mater. Technol. 34 (2022), e00507, https://doi.org/10.1016/J.SUSMAT.2022.E00507.
[49] M. Jamil, N. He, Z. Wei, M.K. Gupta, A.M. Khan, A novel quantifiable approach of estimating energy consumption, carbon emissions and cost factors in manufacturing of bearing steel based on triple bottom-line approach, Sustain. Mater. Technol. 36 (2023), e00593, https://doi.org/10.1016/J.SUSMAT.2023.E00593.
[50] X. Wang, C. Li, Y. Zhang, W. Ding, M. Yang, T. Gao, H. Cao, X. Xu, D. Wang, Z. Said, S. Debnath, M. Jamil, H.M. Ali, Vegetable oil-based nanofluid minimum quantity

lubrication turning: academic review and perspectives, J. Manuf. Process. 59 (2020) 76–97, https://doi.org/10.1016/J.JMAPRO.2020.09.044.
[51] P. Shah, A. Gadkari, A. Sharma, A. Shokrani, N. Khanna, Comparison of machining performance under MQL and ultra-high voltage EMQL conditions based on tribological properties, Tribol. Int. 153 (2021), 106595, https://doi.org/10.1016/J.TRIBOINT.2020.106595.
[52] S. Huang, T. Lv, M. Wang, X. Xu, Effects of machining and oil mist parameters on electrostatic minimum quantity lubrication–EMQL turning process, Int. J. Precis. Eng. Manuf. Technol. 5 (2018) 317–326, https://doi.org/10.1007/s40684-018-0034-5.
[53] M.C. Shaw, J.O. Cookson, Metal Cutting Principles, Oxford University Press, New York, 2005.
[54] V.A.M. Cristino, P.A.R. Rosa, P.A.F. Martins, Cutting under active and inert gas shields: a contribution to the mechanics of chip flow, Int. J. Mach. Tool Manuf. 50 (2010) 892–900, https://doi.org/10.1016/j.ijmachtools.2010.06.003.
[55] A.E.I. Elshwain, N. Redzuan, Effect of cooling/lubrication using cooled air, MQL+ cooled air, N2 and CO2 gases on tool life and surface finish in machining–a review, Adv. Mater. Res. 845 (2014) 889–893.
[56] H. Salvi, H. Vesuwala, P. Raval, V. Badheka, N. Khanna, Sustainability analysis of additive + subtractive manufacturing processes for Inconel 625, Sustain. Mater. Technol. 35 (2023), e00580, https://doi.org/10.1016/j.susmat.2023.e00580.
[57] C. Agrawal, J. Wadhwa, A. Pitroda, C.I. Pruncu, M. Sarikaya, N. Khanna, Comprehensive analysis of tool wear, tool life, surface roughness, costing and carbon emissions in turning Ti–6Al–4V titanium alloy: cryogenic versus wet machining, Tribol. Int. (2020), 106597, https://doi.org/10.1016/j.triboint.2020.106597.
[58] T. Wiedmann, J. Minx, A definition of 'carbon footprint', Ecol. Econ. Res. Trends. 1 (2008) 1–11.
[59] B.P. Weidema, M. Thrane, P. Christensen, J. Schmidt, S. Løkke, Carbon footprint, J. Ind. Ecol. 12 (2008) 3–6, https://doi.org/10.1111/j.1530-9290.2008.00005.x.
[60] T. Gao, Q. Liu, J. Wang, A comparative study of carbon footprint and assessment standards, Int. J. Low-Carbon Technol. 9 (2014) 237–243, https://doi.org/10.1093/ijlct/ctt041.
[61] J. Guo, Feature Based Cost and Carbon Emission Modelling for Wire and Arc Additive Manufacturing, 2012.
[62] T. Gutowski, C. Murphy, D. Allen, D. Bauer, B. Bras, T. Piwonka, P. Sheng, J. Sutherland, D. Thurston, E. Wolff, Environmentally benign manufacturing: observations from Japan, Europe and the United States, J. Clean. Prod. 13 (2005) 1–17, https://doi.org/10.1016/j.jclepro.2003.10.004.
[63] T.O. Sadiq, S.A. Olawore, J. Idris, Energy consideration in machining titanium alloys with a low carbon manufacturing requirements: a critical review, Int. J. Eng. Res. Africa. 35 (2018) 89–107, https://doi.org/10.4028/www.scientific.net/JERA.35.89.
[64] Z. Jiang, D. Gao, Y. Lu, L. Kong, Z. Shang, Quantitative analysis of carbon emissions in precision turning processes and industrial case study, Int. J. Precis. Eng. Manuf. - Green Technol. (2019), https://doi.org/10.1007/s40684-019-00155-9.
[65] C. Li, Y. Tang, L. Cui, P. Li, A quantitative approach to analyze carbon emissions of CNC-based machining systems, J. Intell. Manuf. 26 (2015) 911–922, https://doi.org/10.1007/s10845-013-0812-4.
[66] J.B. Dahmus, T.G. Gutowski, An Environmental Analysis of Machining, 2004, pp. 643–652, https://doi.org/10.1115/IMECE2004-62600.
[67] E. Usluer, U. Emiroğlu, Y.F. Yapan, G. Kshitij, N. Khanna, M. Sarıkaya, A. Uysal, Investigation on the effect of hybrid nanofluid in MQL condition in orthogonal turning and a sustainability assessment, Sustain. Mater. Technol. 36 (2023), e00618, https://doi.org/10.1016/j.susmat.2023.e00618.
[68] N. Khanna, P. Shah, J. Wadhwa, A. Pitroda, J. Schoop, F. Pusavec, Energy consumption and lifecycle assessment comparison of cutting fluids for drilling titanium alloy, Proc. CIRP. 98 (2021) 175–180, https://doi.org/10.1016/j.procir.2021.01.026.
[69] N. Khanna, P. Shah, L.N.L. de Lacalle, A. Rodríguez, O. Pereira, In pursuit of sustainable cutting fluid strategy for machining Ti-6Al-4V using life cycle analysis, Sustain. Mater. Technol. 29 (2021), e00301, https://doi.org/10.1016/j.susmat.2021.e00301.
[70] N. Kashyap, R.A. Rahman Rashid, N. Khanna, Carbon emissions, techno-economic and machinability assessments to achieve sustainability in drilling Ti6Al4V ELI for medical industry applications, Sustain. Mater. Technol. 33 (2022), e00458, https://doi.org/10.1016/j.susmat.2022.e00458.
[71] G.P. Hammond, C.I. Jones, Embodied energy and carbon in construction materials, Proc. Inst. Civ. Eng. - Energy. 161 (2008) 87–98, https://doi.org/10.1680/ener.2008.161.2.87.