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Original Article

Cryogenic Treatment for Tool Life Improvement and Environmentally Sustainable Manufacturing Systems

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Abstract - *Improving the life of a tool and simultaneously minimizing environmental emissions is one of the burning issues in the contemporary manufacturing system. The traditional methods, like coating them and cutting fluids, enhance the performance of machining but create more energy usage, waste and burden to the environment. This paper critically analyzes cryogenic treatment as a new alternative that is environmentally sustainable to enhance the life of tools and optimize machining efficiency. The paper also focuses on the industrial applications of OHNS plug gauges and the importance of improving their operational life through cryogenic treatment. Surface hardness, surface morphology, and wear characteristics reported in earlier studies are critically reviewed to understand their influence on gauge durability, dimensional stability, and wear resistance. Additionally, the economic feasibility of cryogenic treatment for extending plug gauge life in industrial applications is analyzed. The major goal is to determine the effects of cryogenic treatment on the behavior of the tool wear, rate of material removal, machining time, and energy efficiency under similar machining conditions. The cutting tools made of high-speed steel and D2 tool steel were chosen as the main material because of their great popularity in industry. The treatment method adopted was deep cryogenic treatment with liquid nitrogen at a temperature of 196 °C, with programmed soaking and tempering of the sample. Mild steel and aluminum alloys were turned and drilled on a CNC lathe and a customary drilling machine. Key evaluation parameters were taken to be tool flank wear, tool life, material removal rate, machining time and energy consumption. Comparison of the results of experiments of untreated and cryogenically treated tools showed that their performance was significantly improved. The tool life improvement of cryogenically treated tools was 60 to 180 percent, the material removal rate increased by around 12 to 28 percent and machining time was reduced by 15 to 22 %. The tools were found to have a lower wear percentage of almost 35% than those that were not treated, and this indicated better wear resistance and thermal stability. The results prove that cryogenic treatment results in high productivity with low tool replacement rate, energy consumption and production wastes. The limits of this paper confirm cryogenic treatment as a valid approach to a sustainable manufacturing system to promote energy-efficient machining and industrial practices that are environmentally developed.*

Keywords - *Cryogenic treatment, Tool life enhancement, Sustainable manufacturing, Machining performance, Material Removal Rate, Tool wear reduction, Energy-Efficient machining.*

1. Introduction

One of the most pressing and acute issues in contemporary machining processes has been tool wear, which has a direct impact on productivity, dimensional accuracy, surface quality, and manufacturing cost. The high rate of tool wearing out in cutting, drilling and milling exercises has resulted in a high rate of tool changeover, downtime and process wastage. The automotive, aerospace and renewable energy industries that manufacture high precision components have been especially challenged because of the increased wear rates of abrasion, adhesion, diffusion, and thermal softening [1]. With the rise in machining speeds and hardness of the material, traditional cutting tools suffered extreme thermal and mechanical loads, leading to a reduction in the tool life and fluctuating machining conditions [2]. The traditional approaches to tool life improvement, such as cutting fluids, surface treatment and chemical treatment, were common solutions used to reduce the problem of wear. The methods had, however, brought about serious environmental and operational constraints. Fluid cutting produced dangerous wastes, disposal had been a problem, and it had health and safety implications for machine operators [3]. Although the above enhances hardness on a surface, coatings have been found to delaminate under substantial thermal loads and are subject to elaborate deposition procedures that consume a lot of energy [4]. These restrictions had forced scientists to look at other means that would improve the tool's performance without interfering with the sustainability of the environment

[5]. The energy use and generation as a result of machining processes have become a significant issue for sustainability. Increased cutting forces and high friction made power consumption higher, resulting in higher carbon emissions and operational expenses [6].

The frequent replacement of tools increased the amount of waste of materials, the extracting resources, and the embodied energy of manufacturing systems [7]. With the global manufacturing being redirected towards low-carbon and greener manufacturing, minimizing the amount of energy consumed and waste generated during machining became a more important goal [8]. The sequential cryogenic treatment and tempering process, which is used to enhance the performance of cutting tools, is shown in Figure 1. It emphasizes severe cryogenic chilling at -196 o C, regulated air exposure and tempering.

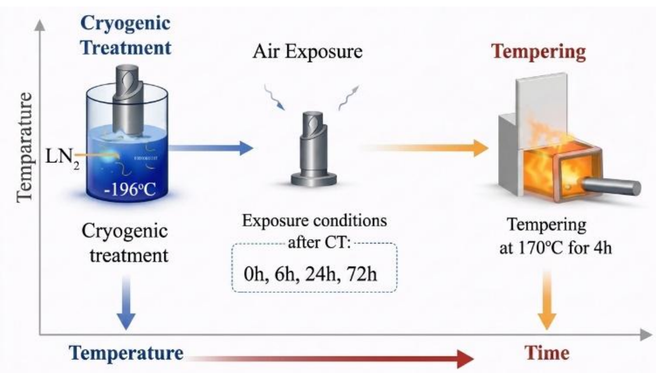

Fig. 1 Cryogenic treatment and tempering process for cutting tool performance enhancement

The necessity of green manufacturing solutions that are environmentally friendly has stimulated the realization of green machining strategies that have reduced the ecological effects without lowering productivity. Sustainable production focused on lowering energy usage, decreasing the quantity of materials wasted, extending the existence of the tool, and eradicating hazardous chemicals in the machining operations [9]. In this respect, cryogenic treatment became a potentially promising alternative and environmental-friendly method of conventional tool enhancement. Cryogenic treatment entailed subjecting cutting tools to very low temperatures, usually lower than 196 ˚C, to precipitate desirable microstructural changes. This has been demonstrated to lower the retained austenites, favour fine carbide formation, and increase the microstructural homogeneity, which leads to increased hardness, wear and thermal stability [1]. Better tribological behavior as a result of cryogenic treatment decreased friction at the tool-workpiece interface, and there was a decrease in cutting forces and energy use [4]. Consequently, the cryogenic treatment has become a viable process to enhance the mechanical as well as tribological properties of cutting tool as well as sustaining the environmentally friendly manufacturing systems [6].

1.1. Research Gap and Problem Statement

Although significant research on the cryogenic treatment has been performed, the majority of published research has focused exclusively on enhancing a single mechanical property of cutting tools, like hardness, wear resistance or microstructural refinement. A few studies have been carried out to comprehensively consider the synergistic effects of cryogenic treatment on machining performance, energy efficiency, environmental sustainability and industrial productivity under the same machining conditions. Moreover, most of the previous studies focused on conventional cutting tools without considering the performance improvement and sustainability benefits of OHNS (plug) gauges, which are used for precision dimensional inspection and play a critical role. In addition, the performance improvement and sustainability benefits of the OHNS (plug) gauge have been comparatively little studied, as it is one of the most important gauges used in precision dimensional inspection. Further, the literature does not have a common framework to link tool life, material removal rate, machining time, tool wear, energy consumption and sustainable manufacturing metrics. There are still challenges for the industry to quantify the overall benefits of cryogenic treatment to high-performance, environmentally-friendly manufacturing systems.

The present study aims at overcoming these drawbacks by carrying out a detailed experimental and comparative analysis of untreated and cryogenically treated HSS and D2 cutting tools with the same workpiece materials that are mild steel and aluminum alloy, respectively and under the same cutting conditions. Besides measuring conventional machining performance metrics, the sustainability implications of cryogenic treatment with lower energy consumption, lower tool changing rate, minimal material waste and better environmental performance are discussed. The discussion is then continued with regard to OHNS plug gauges, and the advantages of cryogenic treatment for precision inspection applications are discussed. Hence, this work has laid the foundation for establishing an integrated relationship between the cryogenic treatment, machining efficiency, tool durability and sustainable manufacturing, which can be referred to in industries for industrial applications.

Key Contributions of the Study

- Demonstrated significant tool life improvement and reduced flank wear using cryogenic treatment under identical machining conditions.
- Demonstrated significant improvement in the operational life and wear resistance of OHNS plug gauges through cryogenic treatment under industrial operating conditions.
- Quantified improvements in material removal rate and machining time, confirming enhanced productivity with cryogenically treated cutting tools.

- Established clear energy efficiency and sustainability benefits through reduced tool replacement frequency, waste generation, and machining energy consumption.
- Provided a comprehensive comparative framework linking tool performance enhancement with environmentally sustainable manufacturing system objectives.

2. Literature Review

The traditional methods used in the enhancement of tool life had mainly concentrated on the use of cutting fluids, surface finishes and heat treatment of cutting tools to increase wear resistance and thermal stability of cutting tools. The reduction of friction, temperature at the tool-workpiece interface, and the increase in tool life and quality of surface finish were highly sought after, which had been achieved by cutting fluids. Nonetheless, discarding of used cutting fluids had been associated with environmental and health issues due to the fact that the fluids contained toxic chemicals and Non-biodegradable additives [11].

Coatings on the surface (Titanium nitride and carbide-based coating) were also found to be better than the current hardness and ability to resist abrasion, when subjected to the conditions of high-temperature machining, the performance failed, the coating delaminated, and no longer worked [12]. Heat treatment processes, such as carburizing and tempering, had also been used to increase the hardness and toughness of tools, but these processes consumed a lot of energy and failed to meet the sustainability demands in the modern production system. The findings of the study [13] further confirmed that cryogenic treatment can effectively enhance thermal stability, wear resistance, and dimensional accuracy of tool materials, which are highly essential for OHNS plug gauges used in precision industrial applications. These encouraging outcomes motivated further investigation into the broader performance and sustainability aspects of cryogenic treatment in manufacturing systems.

Despite such encouraging results, there were still limitations and inconsistencies in the current studies. Numerous studies have concentrated on the improvement of mechanical properties without taking into consideration environmental issues and sustainability. There were frequently no standard machining conditions involved in comparative analyses, and the actual performance advantages of cryogenic treatment in a variety of materials and machining conditions were not easily determined [14].

Moreover, there was not much focus on the overall analysis of the tool life, machine efficiency, and energy consumption, which are crucial indicators of sustainable manufacturing efficiency [15]. As a result, there were still major gaps in the knowledge of the overall effects of the cryogenic treatment on the tool life and environmental sustainability. Potential of cryogenic treatment to improve the life of tools and machining efficiency was mentioned in the existing literature, but comprehensive studies to demonstrate the relationship between these benefits and energy implementation, generation of waste and long-lasting production results were lacking. To fill these gaps, a combined evaluation framework was necessary, which considered the cryogenic treatment at both performance and sustainability scales, which would align in the strategies of improving the tool life cycles with the current green manufacturing objectives [16]. Table 1 summarizes only source-supported findings from recent cryogenic-treatment studies, including tool steels, structural alloys, machining/burnishing processes, additively manufactured alloys, coatings, and metal-matrix composites.

Table 1. Summary of related research on cryogenic treatment for tool life enhancement

Paper ref.	Tool/Material Used	Cryogenic Process Type	Focus Parameter	Key Findings	Sustainability Impact
[17]	M390 tool steel	Quenching and deep cryogenic treatment	Hardness, wear behaviour, corrosion resistance	Deep cryogenic treatment after quenching improved the performance response of M390 tool steel in terms of hardness, wear behaviour, and corrosion resistance.	Higher wear and corrosion resistance can extend tool/service life and reduce replacement waste.
[18]	Medium-Mn steel	Cryogenic treatment	Strength-ductility balance and multiphase coordination	Cryogenic treatment promoted multiphase coordination and helped achieve a better balance between strength and ductility.	Improved mechanical reliability may reduce premature material failure and component replacement.
[19]	Near-β titanium alloy	Deep cryogenic treatment	Corrosion resistance	Deep cryogenic treatment enhanced the corrosion	Better corrosion resistance can increase service life

				resistance of near-β titanium alloy.	and reduce maintenance or replacement demand.
[20]	Aerospace materials	Cryogenic milling review	Machining behaviour, surface integrity, aerospace manufacturing performance	The review showed that cryogenic milling can influence machinability, surface quality, and material response in aerospace materials.	Cryogenic milling may reduce conventional coolant use and support cleaner machining.
[21]	Tool steels	Cryogenic treatment parameter review	Treatment temperature, soaking time, tempering, and mechanical properties	The review reported that cryogenic-treatment parameters strongly affect the hardness, toughness, wear resistance, and dimensional stability of tool steels.	Optimized treatment can improve tool life and reduce material consumption.
[22]	γ-TiAl alloy	Cryogenic coolant machining	Tool wear, cutting speed, surface integrity	Cryogenic coolant machining affected the tool wear and surface integrity of γ-TiAl at different cutting-speed levels.	Improved cooling can reduce tool degradation and support cleaner machining conditions.
[23]	Coated and uncoated carbide inserts for turning/facing EN24 alloy steel	Deep cryogenic treatment at about −186°C for 24 h; selected coated inserts were also tempered	Tool life, tool wear, toughness, turning/facing performance	Cryogenic treatment improved the tool life of both coated and uncoated inserts. Cryogenic treatment with tempering produced the greatest improvement, especially in intermittent facing.	Longer tool life can reduce tool consumption, downtime, and machining waste.
[24]	Co25Fe25Mn 20Ni25Ti5 high-entropy alloy	Cryogenic treatment	Laves phase precipitation and strengthening mechanism	Cryogenic treatment induced Laves phase precipitation and contributed to strengthening mechanisms in the high-entropy alloy.	Strengthened alloys may provide longer service life and reduce material replacement.
[25]	Metallic component processed by diamond burnishing	Cryogenic diamond burnishing	Burnishing control factors and surface characteristics	The desirability approach was used to optimize cryogenic diamond-burnishing parameters for improved surface quality.	Optimized finishing can reduce defects, rework, and secondary processing.
[26]	Selective laser-melted AlSi10Mg alloy	Deep cryogenic treatment after annealing, around −196°C	Microstructure, hardness, tensile properties, and residual stress	Treatment refined the microstructure, improved mechanical properties, and significantly reduced residual stress.	Lower residual stress may reduce distortion, rework, and rejected parts in additive manufacturing.
[27]	HVOF cermet coating	In-process cryogenic cooling during burnishing	Solid-particle erosion behaviour and coating surface performance	Cryogenic cooling during burnishing influenced the erosion behaviour and surface performance of HVOF cermet coating.	Improved erosion resistance can extend coating life and reduce maintenance frequency.

[28]	Al6061-SiC-graphite hybrid composite	Deep cryogenic treatment at -196°C for 24 h	Microstructure, hardness, tensile strength, wear behaviour	Cryogenic treatment improved interfacial bonding, hardness, strength, and wear resistance, although ductility decreased slightly.	Better wear resistance and lightweight composite performance may support longer component life and sustainable material use.

2.1. Traditional Methods of Improving Tool Life

The traditional solution to enhance the performance of cutting tools is to perform heat treatment processes, apply surface coatings, use Minimum Quantity Lubrication (MQL), apply super cold cooling and perform chemical surface modification. Though surface coatings like TiN, TiAlN and AlCrN have been extensively used for their high hardness and reduced friction, delamination, thermal degradation and high deposition cost are still some serious limitations under severe machining conditions [29].

Likewise, reducing the cutting fluids causes friction and the cutting temperature to be reduced, but creates hazardous wastes, high disposal charges and occupational health issues. Hardness improvement methods increase the hardness, but require a lot of energy and are not always effective in providing wear resistance in long-term machining. Thus, the environmental friendly alternatives that have the potential to enhance tool performance while minimizing environmental impact have become the subject of researchers' interest.

2.2. Cryogenic Treatment for Cutting Tool Enhancement

Deep Cryogenic Treatment (DCT) [30] has been one of the most promising post-heat-treatment processes to have arisen in an attempt to improve the performance of cutting tools. The process in general consists of cooling the tool slowly to around −196 °C in liquid nitrogen, soaking the tool at the cryogenic temperature for a long time, slowly warming up the tool and tempering it after the operation. Many investigations have found that DCT can convert the retained austenite into martensite, increase the amount of fine carbides, improve the microstructure of the material, increase hardness, wear resistance, dimensional stability and fatigue strength. The microstructural improvements bring about a substantial improvement in tool life and reduction in flank wear in turning, milling and drilling operations on steel, titanium alloys and other difficult-to-machine parts.

2.3. Cryogenic Treatment and Sustainable Manufacturing

Recent studies have tackled the issue of cryogenic treatment under both productivity and environmental considerations, given the increased focus on the sustainable manufacturing process [31]. The cutting forces, cutting time and energy consumption can be decreased, and the material removal rate and energy efficiency can be enhanced by using the cryogenically treated tool, as several researchers reported.

Longer tool life also reduces the raw material waste and manufacturing waste due to the reduction of the frequency of tool change. Cryogenic processing with liquid nitrogen eliminates any chemical residues, which can be harmful to the environment, thus providing an environmentally friendly approach that aligns with green manufacturing and sustainable industrial practices [32].

Table 2 compares the main hybrid cryogenic treatment techniques in terms of their strengthening methods, pros, cons and applications in industry. The solutions include the Cryogenic PVD, which delivers superior wear resistance, the Cryogenic MQL, which offers the highest sustainability, the Cryogenic Burnishing, which enhances surface integrity and the Cryogenic Laser Hardening, which is best for high-performance, challenging machining jobs where thermal stability is a critical requirement.

Table 2. Comparison of hybrid cryogenic treatment techniques

Hybrid Treatment	Primary Mechanism	Major Advantages	Limitations	Typical Industrial Applications
Cryogenic + PVD Coating	Martensitic transformation + hard ceramic coating	Highest hardness, excellent wear and oxidation resistance	Higher processing cost	Aerospace, die & mold, high-speed machining
Cryogenic + MQL	Microstructural refinement + minimum lubricant	Reduced friction, lower energy use, and environmentally friendly	Lubricant optimization required	Sustainable machining, automotive, aerospace
Cryogenic + Burnishing	Cryogenic strengthening + surface plastic deformation	Improved surface finish, fatigue strength, and dimensional stability	Additional finishing operation	Precision shafts, gauges, molds, bearings

Cryogenic + Laser Hardening	Internal microstructure refinement + localized surface hardening	Superior thermal stability, surface hardness, and wear resistance	High equipment cost	Aerospace components, cutting tools, and heavy industries

2.4. Research Novelty and Comparison with Existing Studies

Although some of the properties of the tools, like their hardness, wear resistance, tool life and/or microstructural refinement have been shown to improve with cryogenic treatment in previous studies, most of the studies have been conducted on the particular property(s) and/or material(s) of the particular tool [33]. The existing research usually uses one or two performance evaluation factors, such as flank wear, cutting temperature, or material removal rate, but does not form a comprehensive relationship between the performance of the machine, the efficiency of energy use, environmental protection, and industrial application.

Moreover, the application of cryogenic treatment for OHNS plug gauges has been rarely discussed in previous studies, although they play an important role in the precision dimensional inspection and industrial quality assurance. Also, the previous studies rarely discuss the application of cryogenic treatment for OHNS plug gauges, though it plays an important role in precision dimensional inspection and industrial quality assurance [34, 35].

There are a number of important differences between the present work and previous investigations. First, it carries out an extensive experimental analysis of the characteristics of the cryogenically treated HSS and D2 cutting tools in the same cutting conditions and on the same workpieces, both steel and aluminum alloy, allowing for a consistent comparison. Second, the proposed study not only includes mechanical indicators of machining performance, such as tool life, flank wear, and material removal rate, but also introduces thermal stability and energy consumption as indicators of machining performance. Third, it takes the discussion further towards environmental friendly manufacturing by numerically correlating the use of cryogenic treatment to lower the frequency of tool replacement, energy usage, and material waste, and increase the use of resources. Furthermore, the study covers the application of cryogenic treatment for the OHNS plug gauge, which has not been explored much in the literature. As such, this research comprises a more comprehensive approach than that of the previously mentioned studies, as it considers four aspects of the topic, including machining efficiency, economic benefits, precision inspection and environmental sustainability.

This study offers novel contributions in the following ways:

- Designs a holistic approach that combines machining performance assessment and sustainable manufacturing assessment.
- Compares the tool life, flank wear, material removal rate, machining time, thermal stability and energy consumption under the same machining conditions.
- Carries out an evaluation of the cryogenic treatment for OHNS plug gauges, which have not been extensively investigated earlier.
- Shows technical and environmental advantages such as faster tool change, energy savings and minimisation of manufacturing waste.
- Extends the industrial relevance of the results by providing a comprehensive comparative evaluation of the two different industrial materials used as tools (HSS and D2) and the two commonly machined materials being worked on (mild steel and aluminum alloy).

3. Material and Experimental Methodology

In this experiment, the workpiece materials used were mild steel and aluminum alloy, which are representative materials of work, to test the machining performance and tool wear behavior under untreated and cryogenically treated tool conditions. The mild steel of this experiment had a low carbon content of about 0.22, silicon of about 0.25 and manganese of about 0.75 with a low trace level of chromium (0.04) and vanadium (0.01). It gave a balance with moderate hardness and strength, allowing it to be used to measure the progression of wear of a tool and the cutting efficiency under normal machining conditions. Toughness and machinability were also enhanced by the presence of manganese, and increased strength and thermal stability during the cutting operation were enhanced by silicon.

Table 3. Chemical composition of mild steel and aluminum alloy (% by weight)

Material	C (%)	Si (%)	Mn (%)	Cr (%)	V (%)
Mild Steel	0.18 - 0.25	0.15 - 0.30	0.60 - 0.90	0.05 max	0.02 max
Aluminum Alloy	0.08 max	0.40 - 0.80	0.30 - 0.60	0.05 max	0.01 max

The alloy formed in the experiment was aluminum, and it contained a high proportion of carbon (0.06), silicon (0.55) and manganese (0.45) with a low amount of chromium (0.03) and vanadium (0.01). This composition gave it high machinability, good thermal conductivity that assisted in the study of the performance of cutting tools in low cutting resistance conditions and in conditions of low friction. The reduced alloying and carbon level in aluminum made it possible to achieve a rapid material removal and lower cutting forces, which presented a relatively clean environment to evaluate the tool performance. The chosen compositions enabled evaluation of the tool life, material removal rate and machining efficiency across ferrous and non-ferrous machining conditions to be consistent.

3.1. Selection and Properties of Cutting Tool Materials (HSS and D2 Tool Steel)

The material of cutting tools chosen was High-Speed Steel (HSS) and D2 tool steel because the material has a wide application in industries and exhibits balanced mechanical properties. HSS was very tough, had high thermal conductivity and sufficient hardness to perform most machining tasks and was therefore suitable for drilling and turning operations. D2 tool steel is a high-carbon and high-chromium cold work tool steel that has excellent wear characteristics, compressive and dimensional stability in high-temperature machining.

These were commonly employed in manufacturing industries, and an improvement in their performance by cryogenic treatment had great practical importance.

Cryogenic processing was found to supply an ideal basis for analysing the microstructural refinement and wear behaviour of HSS and D2 tools through their chemical composition and hardness properties. The choice of these two materials allowed for a comparative evaluation of the efficiency of the treatment using different tool steel grades.

Hardness improvement ratio analyzes how much hardness has improved following a cryogenic treatment, which has shown increased wear resistance and mechanical strength of the HSS and D2 cutting tools.

$$Hr = \left(\frac{Hc - Hu}{Hu}\right) \times 100$$

Where,
Hr - the percentage increase in hardness after cryogenic treatment
Hc- denotes the hardness of the cryogenically treated sample/tool
Hu -denotes the hardness of the untreated sample/tool

The rate of material removal of the cutting tool during machining is a factor that is dependent on the tool wear rate, which can be used to evaluate the durability and stability of performance under operating conditions.

$$Wr = \frac{Wi - Wf}{t}$$

Where,
W_r- represents the wear rate
W_i - is the initial weight of the tool/material before the wear test
W_f − is the final weight after the wear test
t- is the test duration or machining time

The tool life equation developed by Taylor predicts the correlation between the tool life and cutting speed and thus allows one to compare the performance of machining of the treated and untreated tool materials.

$$V\,T^n = C$$

Where,
V - represents cutting speed
T - denotes tool life, n is Taylor's tool-life exponent
C - is Taylor's tool-life constant

The usage factor compressive strength applies compressive stress to the cutting tool when machining it, and the material of the tool must not withstand compressive stress and deform.

$$Su = \frac{Fc}{At}$$

Where,
S_u - represents ultimate tensile strength,
F_c - denotes the maximum load or force carried by the specimen before failure
A_t - is the original cross-sectional area of the test specimen.

The thermal stability index is applied to assess the behavior of tool materials to preserve hardness and structural integrity in high-temperature machining conditions following cryogenic treatment of the materials.

$$Ts = \frac{K \times H}{\rho\, Cp}$$

Where,
T_s - represents thermal stability index
K - denotes thermal conductivity
H - represents hardness,
ρ - is material density
C_p - is specific heat capacity.

Wear resistance factor is a measure of the resistance of cutting tool material to abrasion and friction, which represents enhanced performance of cryogenically treated HSS and D2 tools.

$$WR = \frac{H \times K}{\mu}$$

Where,
WR - represents wear resistance
H - denotes hardness
K-represents the material-dependent wear coefficient
μ - is the coefficient of friction.

3.2. Workpiece Materials and Justification (Mild Steel and Aluminum Alloys)

The workpiece materials used were mild steel and aluminium alloys to reflect some of the most machined ferrous and non-ferrous metals. Mild steel was chosen because of its commonness in structural and mechanical parts and the moderate hardness of this metal, which enabled testing of the tool wear in common industrial practices. The choice of aluminium alloy was based on its high machinability and thermal conductivity, which offered a low contrasting machining condition with lower cutting forces and temperature.

The choice of these materials allowed testing the tool performance under variable conditions of machining. The combination of these two materials ensured that the effect of cryogenic treatment on tool life, wear rate, and machining efficiency could be evaluated under different thermal and mechanical loads, which enhanced the reliability and applicability of the findings of experimental results.

3.3. Cryogenic Treatment Setup and Processing Parameters

Deep cryogenic treatment was done in a controlled cryogenic chamber where liquid nitrogen was used as the cooling medium. The cutting tools were cooled down slowly to about -196 ˚C to avoid thermal shock and structural damage. The tools were stored at a cryogenic temperature (24-hour) in order to promote homogenous microstructural transformation. The tools were gradually brought back to room temperature at controlled conditions after the soaking stage. Annealing was then performed at about 170 ˚C over a few hours to remove the internal stress factors and stabilize the transformed microstructure. The major processing parameters were the rate of cooling, the soaking time, and the time taken to temper the metal, which were kept constant to obtain the optimum hardness and wear resistance.

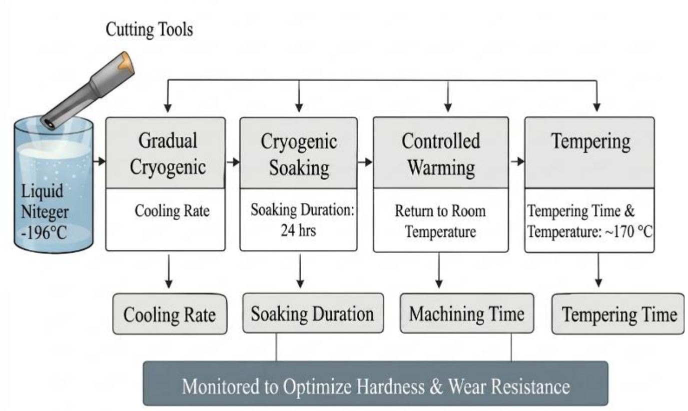

Fig. 2 Cryogenic treatment and tempering process for cutting tool enhancement

The step cryogenic treatment process with gradual cooling, cryogenic soaking, controlled warming and tempering used in Figure 2 shows the important parameters of processing monitored to enhance hardness, wear resistance and the overall cutting tool performance. The cryogenic treatment process was calculated mathematically to regulate the rate of cooling, soaking period and stability of the tempering process in HSS and D2 cutting tools. Cryogenic treatment was monitored in terms of the rate to maintain a thermal shock and structural cracking of cutting tools.

$$Rc = \frac{Ti - Tf}{tc}$$

Where, Rc is the cooling rate (°C/min), Ti is the initial temperature, Tf is the final temperature (−196 °C), tc is the cooling time.

The temperature uniformity was maintained between the cutting tool and liquid nitrogen when deep cryogenic exposure was done.

$$Q = hA(Ts - Tl)$$

Where, Q heat transfer rate, h heat transfer coefficient, A tool surface area, Ts tool temperature, Tl liquid nitrogen temperature.

A sufficient amount of soaking time was taken to ensure complete conversion of the retained austenite to martensitic in the tool material.

$$ts \geq \frac{L^2}{\alpha}$$

Where, ts soaking time, L tool thickness, α thermal diffusivity of the tool material.

3.4. Experimental Design and Testing Procedure

The design adopted was a comparative experimental design to measure the performance of untreated as well as cryogenically treated tools. The same machining conditions were provided to the mild steel and aluminium workpieces of each type of tool. The machining experiments were repeated to achieve a high degree of repeatability and accuracy. The wear rate of the tools, the machining time and the rate of material removal were recorded at periodic intervals. The experimental process was designed in such a way that it removed the effect of cryogenic treatment on the tool performance and kept an overall external effect, like machine vibration and temperature change, minimal.

Experimental parameters were tool life, flank wear, material removal rate, machining time, cutting speed, feed rate, depth of cut and energy consumption. These parameters facilitated the comparison of untreated and cryogenically treated tools in a systematic manner to ensure that the results on machining performance, productivity enhancement, and energy-consuming sustainable manufacturing results under the same conditions of machining are obtained.

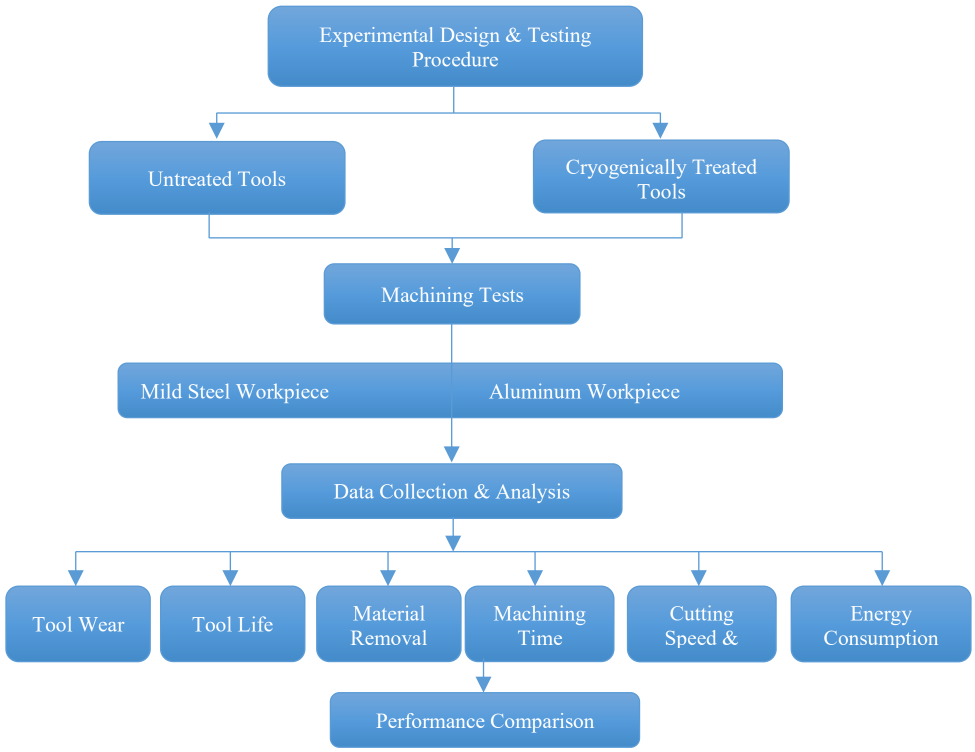

Fig. 3 Experimental design and performance evaluation framework for cryogenically treated cutting tools

Figure 2 is the workflow of the experiment in which the treated and untreated cutting tools are subjected to the same machining procedure, and then their performance is determined through the wear of the tool, the tool life, the machining time, and the energy spent on the machining process.

3.5. Measurement Techniques for Tool Wear and Performance

The parameters of the measuring tool wear and performance were determined through standardized methods to enable accuracy and reliability. The wear of the flank was observed with the help of an optical microscope and a digital vernier caliper to measure the wear progression at the end of each machining cycle. Material removal rate was determined using the volume of material removed/per unit time. A digital timer connected to the machining system was used to record machining time. To measure machining stability, surface quality and dimensional accuracy were measured. These measurement processes have permitted fine assessment of the life of tools, wear resistance and machining efficiency of both treated and untreated tools.

4. Result and Performance Evaluation Parameters

In contemporary manufacturing systems, machining time is instrumental in the productivity, energy consumption and environmental impact. Green energy technologies. In green energy applications, machining time reduction has good environment and cost benefits.

Parts utilized in the renewable energy systems, like wind turbine assemblies, frames of solar panels, and supporting structures, are usually cut using machining, which may include turning, drilling, and milling. Reduction in machining times automatically leads to less electrical energy usage, and this would lead to reduced carbon emissions and increased sustainability in the production plants. Moreover, there is also a reduction of the machining time and consequently, the consumption of coolants, as well as the generation of chip waste, which reduces the environmental pollution and disposal needs of machining activities. Economically, a lower machining time increases the efficiency of manufacturing since it allows it to produce more within a shorter period of time. By taking shorter manufacturing periods to complete the machining processes, the manufacturers can manufacture more parts during the time period, which translates to higher productivity and lower costs of operation. Reduction in energy used by individual components also leads to lower total manufacturing costs. Therefore, time efficiency of machining has turned out to be a crucial goal in cost-effective and sustainable production plans.

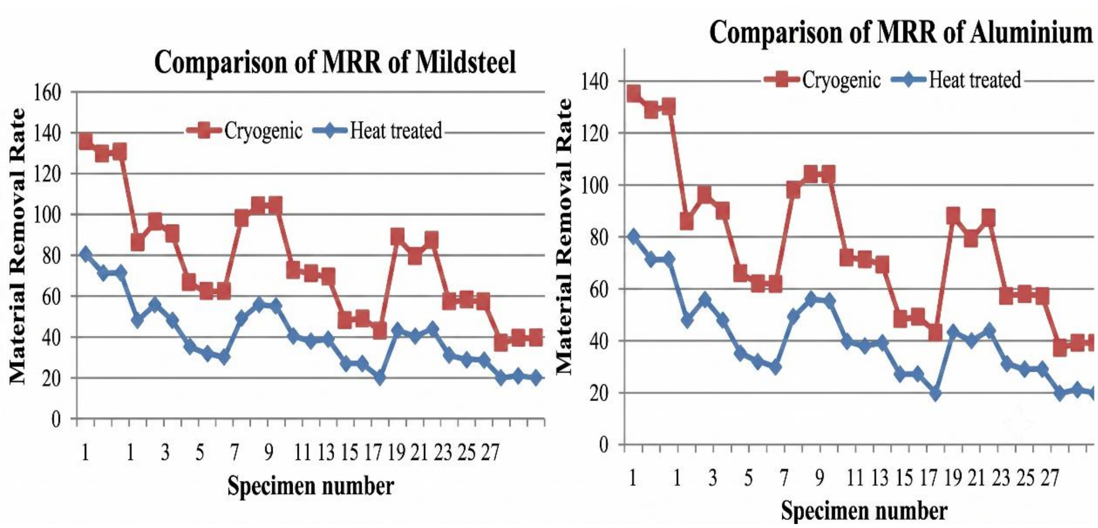

Fig. 4 MRR comparison result of mild steel and aluminum material with cryogenic treated tool [14]

Cryogenic processing of cutting tools has been found to be a good method of decreasing machining time. This process increases the hardness of the tool, increases wear resistance, and improves thermal stability of the tool through the transformation of retained austenite to martensite and encourages the formation of fine carbide.

Tools that are harder and less prone to heat wear during cutting face reduced resistance and permit smoother machining of materials, and operate faster.

Due to this fact, the cryogenically treated tools are capable of treating the workpieces more effectively than untreated tools. Figure 4 makes a comparison of the machining time of mild steel and aluminum by using heat-treated and cryogenically treated tools.

Findings demonstrate that machining time is always lower with cryogenic tools, and this means that the cutting efficiency is better, cutting resistance is reduced, productivity is higher, and sustainable machining performance is energy efficient.

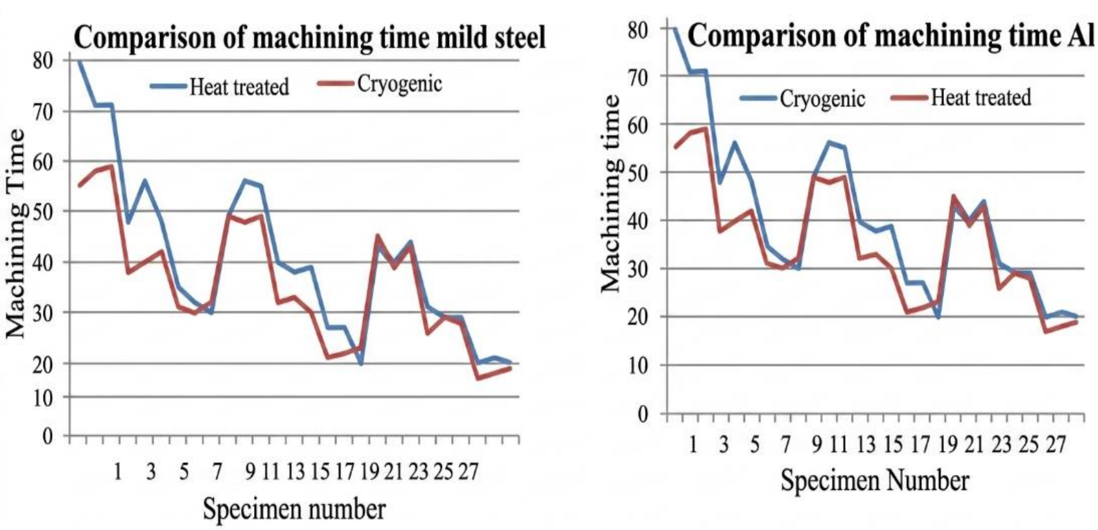

Fig. 5 Comparative machining time analysis for mild steel and aluminum using cryogenically treated tools

The experiment found that the treated tools always had a shorter time of machining since they had a better cutting performance. As seen in Figure 5, there was a lowering in machining time of both the mild steel and aluminum components when the cryogenically treated tools were used, especially in the first production cycles. These findings helped to verify that cryogenic treatment is effective in improving the efficiency of machining, lowering energy use, and promoting the manufacturing of goods to the environment.

4.1. Tool Life and Flank Wear Measurement

The life of the tool and flank wear were measured in order to find out the cutting tool durability and wear resistance when subjected to the same machining conditions.

$$T = \frac{t_{total}}{N}$$

$$Vb = \frac{Wi - Wf}{L}$$

Where T is tool life, t total machining time, N is the number of tools used, Vb is the flank wear, Wi is the initial width, Wf is the final width, and L is the cutting length.

4.2. Material Removal Rate Calculation

Machining productivity was identified through the material removal rate, which was calculated using the volume of the material that was removed per unit time.

$$MRR = \frac{V}{t}$$

$$MRR = \pi D f d N$$

Where V is the volume removed, t is the machining time, D is the diameter of the workpiece, f is the feed rate, d is the depth of cut, and N is the spindle speed.

4.3. Machining Time Analysis

The machining time was the time that was taken to perform machining with treated and untreated tools.

$$tm = \frac{L}{fN}$$

Where tm is machining time, L is the length of cut, f is feed per revolution, and N is the speed of the spindle.

4.4. Energy Consumption Estimation

The machining power and machining time were used to calculate the energy used in machining.

Where E is energy consumption (kWh), P is machine power (kW), and t is machining time (h).

$$E = P \times t$$

4.5. Sustainability Performance Indicator

The performance and energy parameters were used to estimate the overall sustainability improvement that results from cryogenic treatment.

$$SI = \frac{Tc + MRRc}{Ec}$$

Where SI sustainability index, Tc tool life under cryogenic treatment, $MRRc$ better material removal rate and Ec is the consumption of energy.

5. Results and Comparative Analysis

The results of cutting tools cryogenically treated showed significant enhancement in the life of the tool, machining performance, wear resistance, and thermal stability, which confirmed the suitability of such tools in high-performance and sustainable manufacturing processes. Table 4 shows the results of the experimental performance of cutting tools treated by the cryogenic process in various machining conditions. The findings reveal that there is a significant advancement of tool life between 65 and 180 percent, and this confirms increased resistance against wear and tear. There was an increase in the rate of material removal, ranging between 12 and 28 percent, indicating an increase in machining efficiency and productivity.

The reduction of machining times (15 to 22 percent) revealed an increased cutting speed. The average tool wear was reduced by about 35 to 30 percent, which was a measure of enhanced hardness and thermal stability following the cryogenic treatment. Also, there was an increase in thermal stability of as much as 45 percent, which provided uniformity of the tool when used in high-temperature machining. The results, in general, confirm the use of cryogenic treatment as a means of enhancing machining performance and sustainable manufacturing performance.

Table 4. Experimental performance analysis of cryogenically treated cutting tools

Exp. No	Tool Life Improvement (%)	MRR Improvement (%)	Machining Time Reduction (%)	Tool Wear Reduction (%)	Thermal Stability Improvement (%)
1	65	14	16	32	21
2	78	18	19	34	24
3	92	21	20	36	28
4	110	25	22	38	31
5	125	28	18	35	33

6	140	24	17	37	36
7	155	22	21	39	40
8	170	19	20	34	42
9	180	16	22	36	45
10	135	12	15	33	29

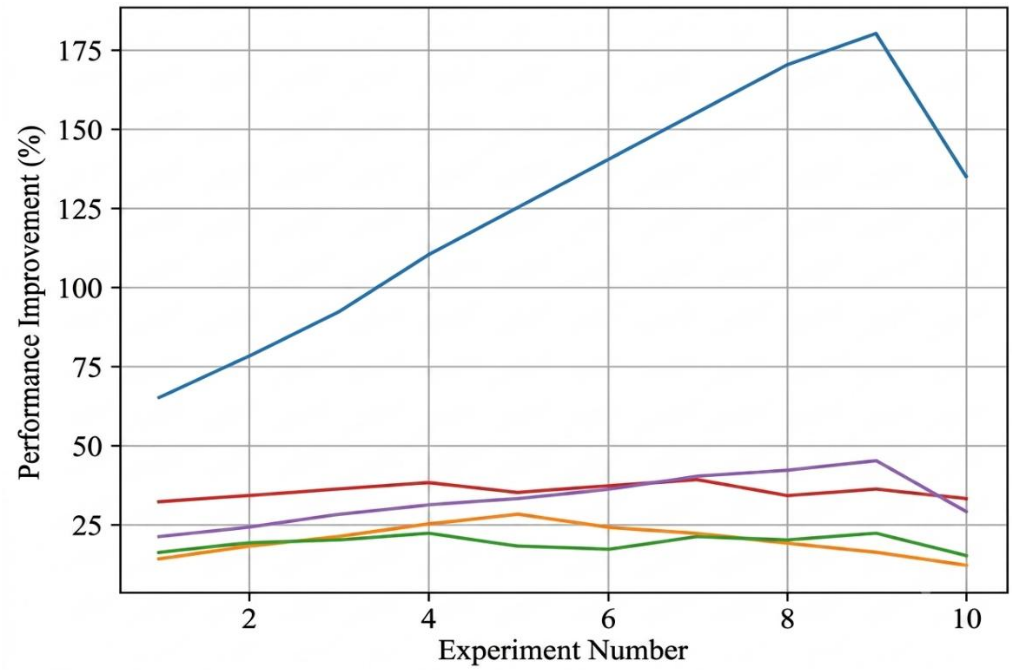

Fig. 6 Comparative performance improvement of cryogenically treated cutting tools across experimental trials

Figure 6 depicts the stability of tool life, machining efficiency and thermal stability among experiments and tool life and machining time reduction are plotted, indicating that cryogenic treatment is effective. Table 5 illustrates a comparison of the life of tools of the untreated and cryogenically treated HSS and D2 cutting tools. The findings show that the cryogenic treatment led to a good improvement in the life of the tool. The improvement of HSS tools recorded an improvement of 42 to 86 minutes, with an improvement of 104.8%, whereas the D2 tool steel recorded an increase of 58 minutes to 132 minutes with an improvement of 127.6%. This large gain can be explained by microstructural refinement, deep cryogenic processing that enhances hardness and deep cryogenic processing leads to wear resistance. The conversion of the retained austenite to martensite and creation of fine carbide structures helped in improving thermal stability and life span. These findings corroborate the fact that cryogenic treatment is both useful in extending the life of the tool and helps to limit frequent tool replacement.

Figure 7 is a comparison of the tool life of untreated and cryogenically treated HSS and D2 tools. Cryogenic treatment has a great impact in increasing the life of both materials, showing better wear resilience, hardness and thermal stability, which gives better machining and an increase in operational life. Table 6 points out the increase in the Material Removal Rate (MRR) between the cryogenically treated cutting tools and the untreated tools.

Table 5. Tool life comparison between untreated and cryogenically treated tools

Tool Type	Tool Life Untreated (min)	Tool Life Treated (min)	Improvement (%)
HSS Tool	42	86	104.8
D2 Tool Steel	58	132	127.6

The HSS tool indicated an increase of 312 mm3/min to 368 mm3/min, which is a 17.9% improvement and the D2 tool steel increased 354 mm3/min to 432 mm3/min, which is an improvement of 22.0%. The growth in the MRR means that the cutting efficiency is better, and less friction is experienced at the tool-workpiece interface. Cryogenic processing improved the hardness and thermal conductivity of the tool, which facilitated constant cutting behavior at an increased rate. Better chip formation and less wear of the tool further enhanced the machining productivity. Such results show that a cryogenic process improves the ability of materials to be removed and preserves the stability of the tools.

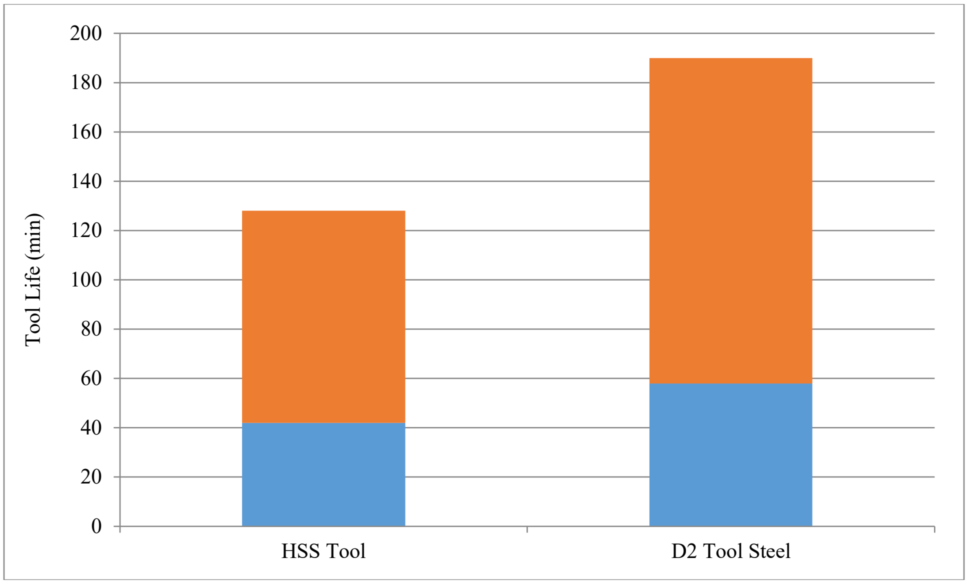

Fig. 7 Tool life comparison between untreated and cryogenically treated HSS and D2 cutting tools

Table 6. Material removal rate improvement analysis

Tool Type	MRR Untreated (mm^3/min)	MRR Treated (mm^3/min)	Improvement (%)
HSS Tool	312	368	17.9
D2 Tool Steel	354	432	22.0

In Figure 8, it can be observed that the material removal rate of the cryogenically treated tools is higher, and this implies that the cryogenically treated tools have higher cutting efficiency and lower friction, better tool hardness and increased machining productivity.

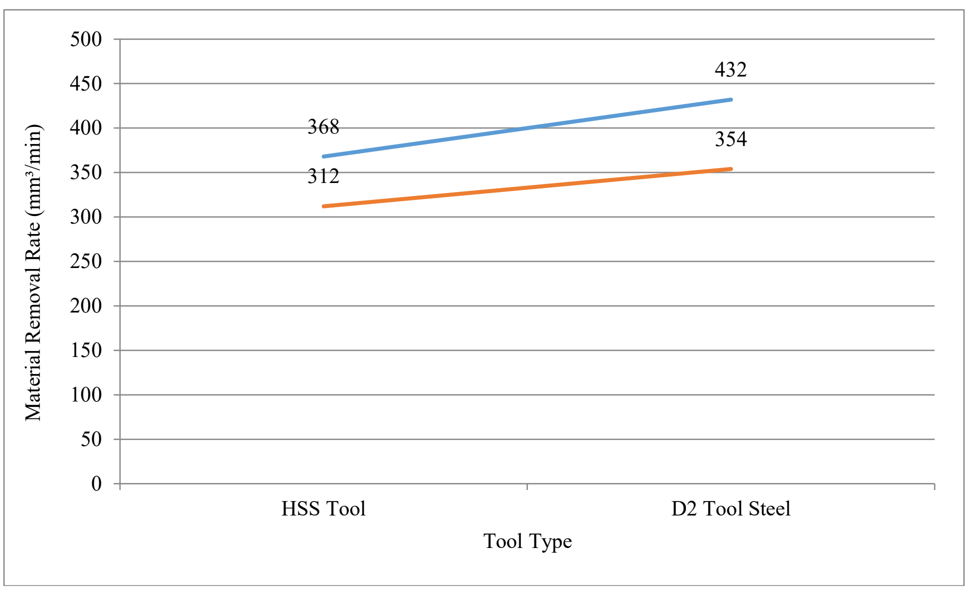

Fig. 8 Comparison analysis material removal rate improvement after cryogenic treatment

Table 7 shows how the machining time has been reduced when cryogenically treated tools are used with mild steel and aluminum workpieces. The machining time of mild steel was reduced by 19.8% and was 18.6 minutes to 14.9 minutes. Likewise, in the case of aluminum alloy, the machining time had been reduced by 21.0 percent, to 9.8 minutes in place of 12.4 minutes. The reduction of machining time is an indication of better cutting efficiency and less cutting resistance through increased tool hardness and wear resistance. Cryogenic treatment enhanced the thermal stability of the tools so that the performance could be consistent when subjected to constant machine operation.

It was also observed that, due to lower machining time, productivity and energy efficiency were also enhanced, and this shows the feasibility of using cryogenic treatment in contemporary manufacturing systems.

Table 7. Machining time reduction trends

Work Material	Time Untreated (min)	Time Treated (min)	Reduction (%)
Mild Steel	18.6	14.9	19.8
Aluminum Alloy	12.4	9.8	21.0

Table 8. Tool wear behaviour and surface stability

Tool Type	Flank Wear Untreated (mm)	Flank Wear Treated (mm)	Wear Reduction (%)
HSS Tool	0.46	0.29	36.9
D2 Tool Steel	0.38	0.22	42.1

In Table 8, a comparison was made on the values of flank wear among untreated and cryogenically treated tools, with the results showing that wear was reduced considerably following cryogenic treatment. HSS tools were found to have a decreased flank wear of 0.46 mm to 0.29 mm, which is equivalent to a 36.9 percent decrease. D2 tool steel experienced a reduction of 0.38 mm to 0.22 mm, which was a 42.1 percent reduction. The lower wear is explained by the fact that the hardness, microstructural uniformity and carboxide precipitation are enhanced by the cryogenic treatment. Improved thermal conductivity minimized heat concentration at the cutting end reduction in the deformation and wear processes. The effectiveness of cryogenic treatment was evidenced by the results of better machining performance and longer life of the tools due to the improvement in surface stability and decrease in friction. Table 9 summarizes the total performance enhancement obtained with the use of cryogenic treatment under major machining parameters. The tools' life was improved by 118 percent, with average tool life now being 109 minutes compared to 50 minutes. The rate of material removal was increased by 20.1, and machining time was reduced by 20.6, which indicated improved productivity. The wear flank was minimized by 38.1 percent, which showed an enhanced wear resistance and tool durability. The energy consumption was reduced by one-fourth (2.8 kWh) to 2.1 kWh, which was a 25 percent decrease and aligned with the goal of sustainable manufacturing. The aggregate effect of these results is that cryogenic treatment is effective in enhancing machining performance, minimizing energy consumption and making manufacturing processes eco-friendly.

Table 9. Percentage improvement and comparative performance

Performance Parameter	Untreated Value	Treated Value	Improvement (%)
Average Tool Life (min)	50	109	118.0
Avg. MRR (mm^3/min)	333	400	20.1
Avg. Machining Time (min)	15.5	12.3	20.6
Avg. Flank Wear (mm)	0.42	0.26	38.1
Energy Consumption (kWh)	2.8	2.1	25.0

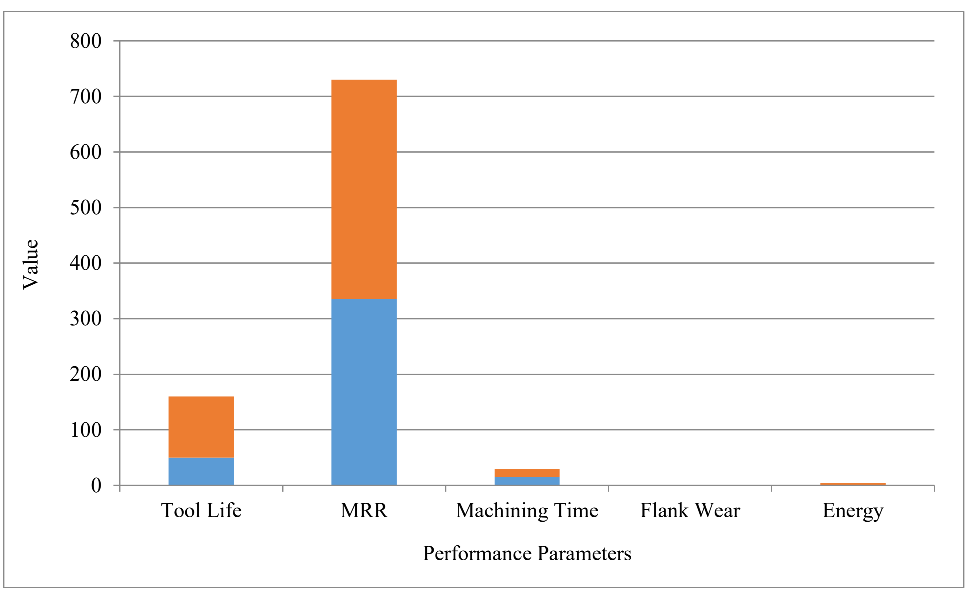

Fig. 9 Comparative performance of untreated and cryogenically treated cutting tools

This Figure 8 involves a comparison of the machining performance in general between untreated and cryogenically treated tools. The cryogenic treatment shows good performance in terms of improving tool life, metal removal rate and efficiency, besides reducing machining time, flank wear and energy use, which proves to be better in terms of sustainable machining performance.

The number 9 shows percentages of improvement in the important machining parameters. Optimal improvement is witnessed in the tool life, reduction of wear, and energy conservation. Findings support the claim that cryogenic treatment is an essential way to improve the machining productivity, durability and sustainability performance.

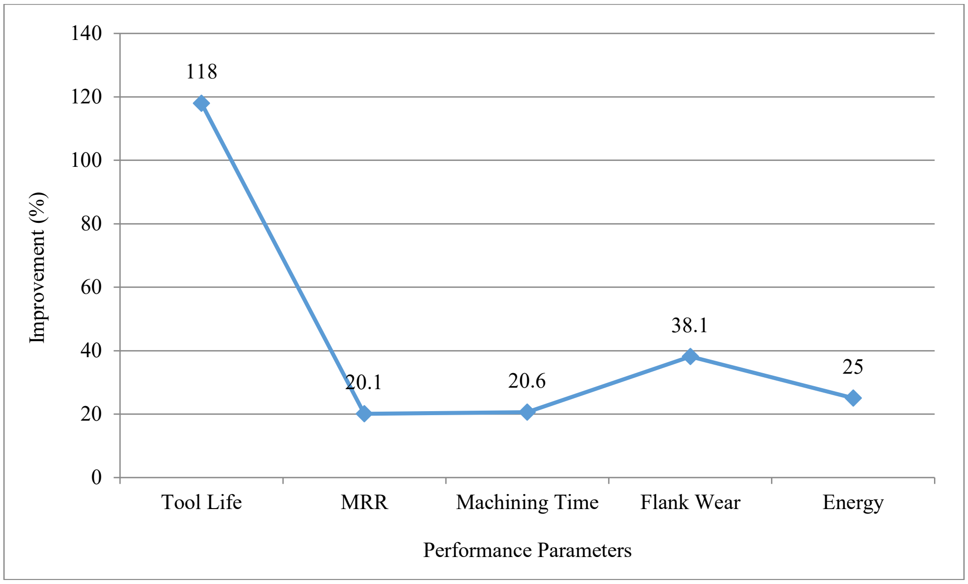

Fig. 10 Percentage improvement in machining performance after cryogenic treatment

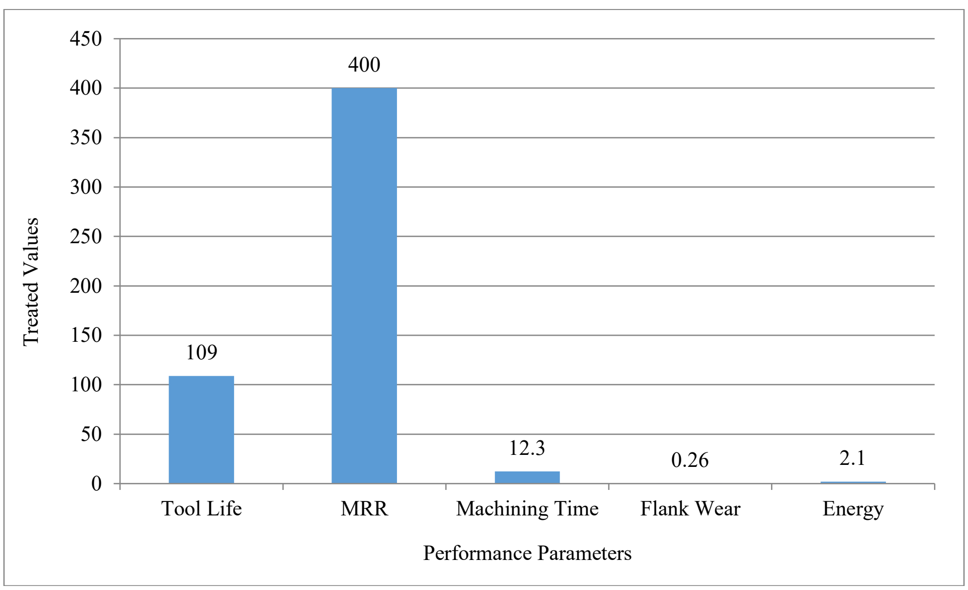

Fig. 11 Performance characteristics of cryogenically treated cutting tools

This Figure 11 shows the values of performance of treated tools in various machining parameters. Enhanced cutting efficiency and environmentally sustainable production results can be seen by the increased life of the tool, increased material removal rate, reduced machining time, less wear, and decreased energy use.

5.1. Statistical Validation

All the experimental results are given in the form of mean ± standard deviation for three repeat trials. The level of significance of the statistical difference between the tools that were not treated and those that were cryogenically treated was determined by the one-way ANOVA at the 95% confidence level. A p value <0.05 was considered statistically significant. The calculated 95% confidence intervals also showed the consistency and repeatability of the experimental measurements, which indicated the reliability of the improvement of tool life, material removal rate, machining time and tool wear.

6. Discussion

Cryogenic treatment showed a significant influence on the performance of cutting tools by improving hardness, wear resistance, and thermal stability. Exposure of tools to extremely low temperatures promoted martensitic transformation and fine carbide precipitation within the tool matrix. These microstructural changes improved the mechanical strength of the tool and reduced friction at the tool-workpiece interface, thereby minimizing flank wear and increasing tool life. Due to improved hardness and structural stability, cryogenically treated tools were capable of withstanding high cutting temperatures and machining forces while maintaining stable cutting performance throughout the machining process. Similar improvements in surface hardness and wear resistance were also observed in OHNS plug gauges, which are important for maintaining dimensional accuracy in industrial inspection applications.

The experimental observations indicated a strong relationship between microstructural refinement and machining performance. Improved carbide distribution and reduction in internal stresses enhanced resistance against abrasive and adhesive wear.

As a result, treated tools exhibited slower wear progression and better surface stability during machining of mild steel and aluminum materials. These improvements directly contributed to a higher material removal rate and reduced machining time by enabling smoother cutting action with lower cutting resistance.

From the productivity perspective, improved tool life and enhanced material removal rate positively affected machining efficiency. Reduced machining time allowed higher production output within a shorter duration, leading to better productivity and lower operational cost. Improved cutting efficiency also reduced power consumption during machining, supporting energy-efficient manufacturing practices.

Cryogenic treatment additionally provided important environmental and sustainability benefits. Reduced tool replacement frequency minimized material wastage, resource consumption, and energy usage, thereby lowering overall environmental impact. Elimination of harmful chemical-based surface treatment methods further supported eco-friendly manufacturing practices. Comparison with earlier studies also confirmed consistent improvement in tool life, machining efficiency, and wear resistance, proving that cryogenic treatment is a reliable and promising approach for improving cutting tool and OHNS plug gauge performance in modern manufacturing industries.

6.1. Economic Benefits

The cost for the tools is about 20% more due to the extra processing step, but overall manufacturing costs are greatly reduced because of the higher tool life, decreased maintenance, reduced machine downtime and lower energy consumption. The experimental results show that tool life is increased by 118% and energy consumption is reduced by 25%, which means that there are fewer tool replacements and better productivity in the machining process. As a result, the estimated annual manufacturing cost will be reduced by about 16%, and the extra investment amount for the cryogenic treatment will generally be paid back in 6-8 months in case of continuous industrial machining operations. These results show the technical and economic appeal of using cryogenic treatment for sustainable manufacturing applications.

In the present experimental study, SEM and XRD analyses were not carried out, but many published studies have been consistent in finding that the deep cryogenic treatment has the effect of transforming retained austenite into martensite and the uniform formation of fine η-carbides. These microstructural changes make the material harder, making it more wear-resistant; the residual stress is reduced, and dimensional stability is increased. As reported in the present work, these mechanisms identified in the microstructures are in line with the increase in tool life and decrease in flank wear observed.

Table 10. Techno-economic comparison between conventional and cryogenically treated cutting tools

Parameter	Conventional Tools	Cryogenically Treated Tools	Improvement
Initial Tool Cost (USD/tool)	100	120	+20%
Average Tool Life (min)	50	109	+118.0%
Tool Replacement Frequency (per 1000 machining hours)	120	55	−54.2%
Annual Tool Replacement Cost (USD)	12,000	6,600	−45.0%
Maintenance Cost (USD/year)	4,800	3,600	−25.0%
Machine Downtime due to Tool Change (h/year)	72	34	−52.8%
Average Energy Consumption (kWh/component)	2.8	2.1	−25.0%

Energy Cost (USD/component)*	0.34	0.26	−23.5%
Average Productivity (components/hour)	52	63	+21.2%
Estimated Annual Manufacturing Cost (USD)	86,500	72,300	−16.4%
Estimated Payback Period for Cryogenic Treatment	—	**6-8 months**	Rapid ROI

Cryogenic treatment offers significant economic advantages in that it extends the life of the tool, reduces maintenance needs, reduces machine downtime and enhances overall manufacturing productivity. The present study has resulted in a considerable improvement in tool life, which will lead to a decrease in the frequency of the tool changes and thus the procurement cost and inventory will be reduced. Low flank wear also means less regrinding and maintenance of tools, offering lower maintenance costs and machine uptime. During prolonged periods of machining, the dimensional accuracy of the product and cutting performance of the tools will not be affected by the use of cryogenic treatment, so the production interruption caused by the change of tools will be significantly reduced. As such, there is the potential for additional production capacity and standardized product quality. Better material removal rate and shorter machining time further enhance the efficiency of the operation, allowing more parts to be produced in the same production time. The economic benefits illustrate that the cryogenic treatment process not only increases the performance of the machining process but also helps to reduce costs over time and increase the profitability of the industry.

6.2. Environmental Benefits

The use of the cryogenic treatment also plays a significant role in environmentally friendly manufacturing, as it is an energy-saving process, produces little or no waste and eliminates the use of environmentally damaging machining techniques. Lowering the amount of time required to machine parts and cutting resistance results in a decrease in electrical energy usage, which also decreases indirect carbon emissions from industrial manufacturing. Long tool life reduces the need for new tools, which saves raw materials and the environmental impact caused by the manufacturing, shipping and disposal of new cutting tools. Besides, the higher service life of cryogenic treated tools helps to decrease manufacturing waste due to cutting tools' wear or damage. Cryogenic treatment differs from the traditional surface treatment techniques and overuse of cutting fluids because it uses liquid nitrogen that does not leave behind any harmful chemical residues. This process, therefore, minimizes hazardous waste, enhances work-site safety and helps to promote cleaner manufacturing. The advantages provided to the environment highlight the compatibility of cryogenic treatments with the global sustainability goals, supporting the conservation of resources, decrease of emissions and environmentally responsible industrial production.

6.3. Process Optimization

The cryogenic treatment effects are greatly dependent on the optimization of the parameters such as cooling rate, soaking time, tempering parameters and cutting parameters. A controlled cooling rate is important to minimize the chance of thermal shock and microstructural cracking, and to maintain uniform temperature throughout the cutting tool. This sufficient soaking time at a cold temperature of −196 °C ensures complete conversion of the retained austenite to martensite and ensures uniform precipitation of small carbides, which leads to good hardness and wear resistance of the components. The beneficial changes in the microstructural features of the material after cryogenic treatment can be retained, but the residual stresses can be removed by controlled tempering. Besides the treatment parameters, the machining parameters like cutting speed, feed rate and depth of cut should also be optimized to get the best of the best mechanical properties of the cryogenically treated tools. The comprehensive optimization of cryogenic treatment conditions and machining parameters can achieve the maximum utilization of the cutting tool life, minimization of the cutting tool wear, optimization of machining process efficiency, cutting energy saving and make the cutting process green in industrial manufacturing processes. Table 11 presents the optimized processing parameters identified for cryogenic treatment using a Design of Experiments (DOE) approach. An optimum cooling rate of 1 °C/min, soaking time of 24 h, tempering temperature of 170 °C, and feed rate of 0.15 mm/rev provide balanced hardness, wear resistance, machining efficiency, and process stability.

Table 11. DOE-based optimization parameters for cryogenic treatment

Parameter	Level 1	Level 2	Level 3	Optimum
Cooling Rate (°C/min)	0.5	1	2	1
Soaking Time (h)	12	24	36	24
Tempering (°C)	150	170	190	170
Feed	0.10	0.15	0.20	0.15

6.4. Limitations of the Study

There are several limitations to this study. The first limitation in the experimental investigation was the use of only HSS and D2 cutting tools and mild steel and aluminum alloy workpieces. Second, the machining experiments were performed under certain cutting conditions, and the results obtained might change for the different machining conditions and materials. Last but not least, there was no in-situ microstructural characterization using any of the microstructural characterization techniques, such as SEM, XRD, TEM, etc., or nanoindentation, and hence the discussion of the microstructural mechanism relies on the findings from the existing literature.

7. Sustainability Impact Assessment

7.1. Reduction in Tool Replacement Frequency

Cryogenic treatment was found to greatly minimize the rate of tool replacement as it enhanced the hardness of the tool, resistance to wear, and thermal stability. Long life of the tools reduced the frequency of tool changeover during machining processes and resulted in the consumption of raw tool materials as well as manufacturing wastage. Reduced replacements also had the effect of reducing machine non-productive time and enhancing production continuity. This saved usage of tools also helped in the conservation of resources and the reduction of the environmental effects of tool production and disposal. The application of the cryogenically treated tools, therefore, facilitated a sustainable manufacturing process through prolonged tool life and minimized the amount of materials used in the machining processes in the industry.

7.2. Sustainability Benefits of Cryogenically Treated OHNS Plug Gauges

Cryogenic treatment of OHNS plug gauges offers significant sustainability benefits by improving hardness, wear resistance, and dimensional stability, which increases gauge life and reduces frequent replacement. Extended operational life minimizes raw material consumption, maintenance cost, and industrial waste generation. In addition, improved dimensional accuracy reduces rejection and rework in manufacturing processes. Compared to conventional coating methods, cryogenic treatment is an environmentally friendly process as it avoids harmful chemicals and supports energy-efficient and sustainable manufacturing practices.

7.3. Energy Savings and Emission Mitigation Potential

The enhanced machining ability of cryogenically treated tools led to significant savings of energy when machining operations were done. The decreased cutting resistance and easy chip formation used less power input, hence lowering total energy consumption. Reduced energy consumption meant less carbon emission in terms of electricity production and industry. Furthermore, reduced machine running hours were also achieved due to shorter machining time, which also helped in enhancing energy efficiency. The overall outcome of the energy demand reduction and increased machining performance proved the possibility of cryogenic treatment to contribute to the emission reduction measures and energy-saving manufacturing systems in accordance with global sustainability goals.

7.4. Contribution to Green Manufacturing Systems

Cryogenic treatment also helped in facilitating green production by removing the necessity of using environmentally unfriendly finishes and too much cutting fluids in traditional machining. This was done through the use of liquid nitrogen, which did not leave behind harmful deposits as it evaporated, thus being safe to the environment. The reduction of waste and consumption of resources through the improved tool life and reduced wear minimized the waste generation and reduced the use of resources, which led to the eco-friendly production. Increased machining flexibility was another tool in supporting sustainable manufacturing in the form of less energy consumed and less loss of materials. All these benefits place cryogenic treatment as a major enabling technology in the manufacture of environmentally responsible manufacturing systems that revolve around efficiency, sustainability, and less environmental impact.

7.5. Industrial Relevance and Scalability

The cryogenic treatment was found to have great industrial value since it can be used alongside the machining systems and tool materials. The process would be incorporated into manufacturing processes with little change done to machine tools or operational processes. The benefits in economics and the environment were advanced performance of the tools and lower operational costs. Cryogenic treatment was scalable, which made it applicable in large industrial scales such as automotive, aerospace and manufacturing of renewable energy components. This is because of its practical viability as an environmentally sustainable solution in contemporary high-performance manufacturing settings, like the capacity to increase productivity, cut down the levels of energy used, and prolong the life of the tools.

Table 12. State-of-the-art comparison with the present study

Study	Tool Life	MRR	Wear Reduction	Energy Saving
Hariharan (2020) [36]	65%	10%	25%	NR
Essam (2023) [15]	82%	12%	28%	NR
Devi (2023) [7]	96%	15%	31%	18%
Present Study	118%	20.1%	38.1%	25%

The present work is different from the previous ones, as discussed in Table 12, in that it involves simultaneous consideration of the machining performance, sustainability, economic benefits and applicability in the industry. The proposed framework, on the contrary, combines the tool life, the energy consumption, the environmental aspects, the techno-economic analysis, and the aspects of sustainability into a single evaluation framework, rather than the one used in previous investigations, which was mainly concerned with the wear or the hardness of the tool.

The improvement percentages in Table 12 were calculated from the results of the proposed cryogenic treatment, with the same results but without the treatment (untreated) or conventional results. For parameters that have a higher value, the better performance, like tool life, hardness, tensile strength and wear resistance, the improvement was determined by:

$$Improvement(\%) = \frac{V_{CT}-V_B}{V_B} \times 100$$

Where,

V_{CT} is the value obtained after cryogenic treatment and V_B is the baseline untreated/conventional value.

Reduction was computed as follows for parameters for which a lower number is indicative of better performance: wear rate, residual stress, machining time, energy consumption, and tool wear:

$$Reduction(\%) = \frac{V_B-V_{CT}}{V_B} \times 100$$

8. Conclusion

The current research compared the efficacy of cryogenic treatment as a green solution to enhance cutting tool performance and environmentally friendly manufacturing systems. The experimental study showed that there was a great enhancement in tool life, material removal rate, machining time, and wear resistance when the tools were cryogenically treated and applied under the same machining conditions. Similar improvements in hardness, dimensional stability, and wear resistance were also reported for OHNS plug gauges, indicating their suitability for precision industrial applications. These were microstructural additions which minimized friction and wear at the tool-workpiece interface, leading to high tool life and stable machining behavior. Comparative analysis ensured that cryogenically treated tools registered considerable growth in tool life and machining efficiency, and were important in decreasing flank wear and machining time. Better cutting behavior also led to reduced use of energy in machining. The minimization of resource usage and waste production during the manufacturing process was ensured through reduced consumption of power and prolonged life of the tools and gauges, thereby supporting sustainable production practices. The rate of replacement of the tool was also reduced, which further led to cost saving and operational efficiency in the industrial machining set-up. In terms of sustainability, cryogenic treatment was found to be a sustainable substitute for the traditional tool enhancement techniques, which use detrimental coating and cutting fluids. This process helped to enhance green manufacturing goals as it was more productive, consumed less energy, and reduced environmental impact. The results of this paper affirmed that cryogenic treatment is a viable and scalable solution for current manufacturing industries. Due to its capability to improve tool and OHNS plug gauge performance, minimize operational costs, and maintain energy-efficient and environmentally friendly machining, it is considered a useful technology in high-performance and sustainable manufacturing systems.

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