Available online at: http://publikasi.mercubuana.ac.id/index.php/ijiem
IJIEM (Indonesian Journal of Industrial Engineering & Management)
ISSN (Print) : 2614-7327 ISSN (Online) : 2745-9063

Parametric Optimization under Cryogenic Machining of Medium Carbon Low Alloy Steel EN-19 Using the Integrated Taguchi-Present Worth Method

Sunday Ayoola Oke[1*]
[1]Department of Mechanical Engineering, University of Lagos, Lagos, 100213, Nigeria

ARTICLE INFORMATION

Article history:

Received: 2 July 2021
Revised: 4 August 2021
Accepted: 16 August 2021

Category: Research paper

Keywords:
Optimization
Economic method
Taguchi method
Present worth method
Optimal setting

ABSTRACT

Medium carbon low alloy steel EN-19 is a commercially thriving workmaterial with 0.30 to 0.50% as carbon content and 0.60 to 1.65% as manganese content. The wide range of uses of medium carbon steel is for shafts, crankshafts, forgings, axles, couplings and gears. Given the broad industrial usage, the optimization of this work material is currently indispensable since it is a pointer to the economic management of drilling resources and a justifiable metric for performance assessment and evaluation. However, the present optimization models during machining have inaccurate predictions as they exclude the economic aspect of the material. In this article, a new combined Taguchi-present worth (T-PW) method is presented to account for the present worth of steel material within the optimization context using literature data. The amalgamation of the two-component methods of Taguchi and present worth is done at the signal-to-noise calculation. Then the response table, optimal parametric setting, the performance flow diagram and the present worth values are finally established. For the results, the optimal parametric setting was ascertained as $SP_3FR_1DOC_1$, obtained at 37.48 (level 3), 35.92 (level 1) and 36.31 (level 1) for speed, feed rate and depth of cut, respectively, interpreted as 900rpm (speed), 0.1mm/min (feed rate) and 0.5mm (depth of cut). The T-PW method yields PW_{SP} (62.85) as 1st, PW_{FR} (-64.64) as 2nd and PW_{DOC} (-65.13) as the 3rd position. It was found that the speed parameter is the best based on the optimization cum economic aspect assessment. The T-PW method predicts the optimization behavior while analyzing the economic aspect of the steel material. It would help in planning and analyzing the economic characteristics of the machining process.

***Corresponding Author**
Sunday Ayoola Oke
E-mail: sa_oke@yahoo.com

1. INTRODUCTION

Machine shop operators and engineers concur with the argument that hard material machining (i.e. drilling) creates challenges like no other (Feucht et al., 2014; Nagimova and Perveen, 2019; Das et al., 2020; Bharat and Bose, 2021). Accompanied with this, the drilling industry is regulated because it is a semi-automated system where the human component that drives the system is a significant part of the system. Officials from government's safety agencies are authorized to conduct unannounced routine safety-complaint checks. There are some crucial machine shop safety concerns they normally seek: general machine shop cleaning, machine safety and material safety. However, because the machine shop is human-centred, process engineers must enforce safety practices, maintain the workshop equipment to the highest standard of system and implement systems and technologies that comply with optimal safety practices. Thus, the process engineer in the machine shop must contend with numerous unique issues that come with the system, striving to solve human problems.

Unfortunately, the machine shop environment experiences significant heat dissipation while machining hard materials such as the EN-19 steel (Babu et al., 2005; Gurumurthy et al., 2016; Ramu et al., 2017). This is accompanied by the discharge of harmful cutting fluids, coolant and oils to the environment during set-up times or machining cleaning activities. The machine operator sometimes has a share of these harmful elements, which interacts with the skin to cause threatening diseases and cutaneous disorders regarding their use (Alomar, 1994). Notwithstanding, it is a very difficult task for the operator who pursues parts productivity to also comply fully with the appropriate safety rules enough to avoid contact with harmful lubricants in the traditional machining system (Azarov et al., 2017). Furthermore, despite the documented need to re-engineer the existing machine technology, the focus on alternative machining technologies in the context of replacing the traditional machining process and the generation of optimal process parameters with economic blends is limited and often ignored.

The EN-19 steel, which is hard, is commonly used in industries with wide applications in tools, shafts and gears (Ramu et al., 2017). Consequently, its demand for machining is enormous, requiring several hours of machining, contacts of the operator with the machining system, sub-optimal activities and huge cost of production both in material cost and the anticipated future cost of health interventions on operator's health after long exposure to the traditional machining system. However, cryogenic machining, which entails the replacement of the traditional fluid lubro-cooling liquid with a jet of liquid nitrogen that conserves the machined surface integrity and quality may be used instead of the conventional machining process (Dhar et al., 2006; Bicek et al., 2012; Balaji et al., 2015; Jovicevic-Klug et al., 2021). The use of sub-optimal parameters and the absence of economic consciousness while machining the EN-19 steel contributes more to the disparity (Okponyia and Oke, 2020). Consequently, research on green machining and resource optimization need to focus on the aforementioned gaps. Technological approach through the introduction of cryogenic equipment, optimization approaches through the Taguchi method and economic methods such as the present worth method will have substantial implications in tackling this gap (Okponyia and Oke, 2020).

Furthermore, most of the previous articles on cryogenic machining are not suitable to solve the concurrent optimization and economic justification problem because of the absence of economic parameters that leads to sub-optimal solutions when problems are solved (Mia, 2017; Ranjith et al., 2019; Rao et al., 2020; Rout et al., 2021; Oke and Fagbolagun, 2021). Therefore, it is essential to develop appropriate quantitative methods to solve this type of problem. But this literature gap was declared in almost a decade ago by Bicek et al. (2012) who observed the machining terrain and asserted that the trend in practice is to use environmental and health-friendly know-how coupled with economic justification. Unfortunately, the aspect of economic justification is missing in almost every article that afterwards reported on cryogenic machining experiments either in the drilling operation or for milling activities (see Singh and Grover, 2015; Dhananchezian et al., 2018; Nie and Zhang, 2018; Damir et al., 2018; Khann et al., 2019; Gross et al., 2019; Jovicevic-Klug and Podgornik, 2020; Ozbek, 2020).

Some authors have dealt with how cryogenic treatment affects the tools being used in the machining process (Singh and Grover, 2015; Choudhary et al., 2017; Rahul et al., 2019; Anthuvan et al., 2021; Prakash et al., 2021; Rout et al., 2021). For instance, Singh and Grover (2015) described the wear aspects of the electrode that was cryogenically treated electrical discharged machining (EDM) and claimed a substantial enhancement in the material removal rate of the EDM. This, they observed, was accompanied by a reduced tool wear rate after the electrode's cryogenic treatment. However, the authors omitted both the optimization aspect that may involve the Taguchi method in their work and the economic aspect that introduces the present worth analysis in their discussion of the article.

An additional article that confirmed the influence of cryogenic treatment on tools is by Ozbek (2020) where the author experimented on the coated tungsten tool while turning the AISI H11 steel. The author claimed that cryogenic treatment enhanced the abrasion resistance of the cutting tool. Nevertheless, the study seems to have ignored the optimization and economic aspects of cryogenic machining. Other investigators in the literature seem to settle on the effect of lubricating oils on the turning of metallic materials using cryogenic minimum quantity lubrication. The principal results showed that the cryogenic minimum quantity lubrication is a promising replacement to the conventional process of using wet lubricants. Besides, the author omitted the aspects of optimization and economics of cryogenic machining. Along with the same domain of study, Dhananchezian et al. (2018) analyzed the effect of using cryogenic cooling via the liquid nitrogen route and the parameters investigated were cutting temperature, chip morphology, cutting forces, tool wear and roughness value. They persuaded the cryogenic machining literature audience with the claim that in turning the duplex stainless steel 2205 using the PVD coated nano-multilayer TiAlN cutting tool insert with cryogenic cooling, there was a reduction in cutting temperature (ranging from 53 to 58%), lessening the cutting forces (ranging from 30 to 43%) and enhancement in the roughness value of the material (ranging from 18 to 23%) weighed against the dry machining. Despite this comprehensive analysis of the cryogenic machining situation, the authors failed to consider the optimization and economic aspects of the process.

Furthermore, some authors have taken a position to analyze the negative aspect of cryogenic machining. Consequently, Nie and Zhang (2018) dismiss the notion that cryogenic machining is perfect by pointing out that some white layers form while machining materials. The author verified their claims by experimenting on the machining of AISI 52100 steel by using cryogenic support. The authors claimed that cryogenic cooling can assist to limit the thickness of the formed white layer and also enhance the surface hardness at elevated cutting speed. Unfortunately, the study ignored the optimization aspect of parameters in the cryogenic process and some quantitative economic implications of the process.

But to the author's best knowledge, except for the publication by Oke and Fagbolagun (2021), not much has been done to solve the optimization approach in production with the economic viewpoint. Certainly, no single documentation exists to solve the optimization cum economic formulated problem in the cryogenic machining of difficult-to-machine materials. Further, there is no literature source to show that the problem has been solved for the cryogenic machining of EN-19 steel, which is one of the most widely used hard steel materials in several engineering applications.

Consequently, in this paper, motivated by the study of Oke and Fagbolagun (2021), the present author construct and analyze the Taguchi-present worth method. The proposed method applies the idea of present worth to the Taguchi method wherein a certain value is fixed as the level for each parameter and the interest rate is deployed to compute the present worth for each parameter. Then the parameters are ranked from the first to the last position. The basic idea behind the present worth is to introduce a financial concept to the machine shop such that consciousness in the utilization of scarce machining resources is made by the entire workers in the machine shop and the consciousness on waste avoidance is promoted as a culture among the staff.

Furthermore, in this article, it is argued that the process engineer that controls the machine shop should be orientated by the introduction of the unique and classical method of optimization, the Taguchi method into the machining planning for machine shops. Notwithstanding, by comparing the present article with the work that was done by others on cryogenic machining, a unique innovation in this research involves the integration of the present worth method to support the structure of the Taguchi method. But why should the present worth method be used to aid the Taguchi method's framework? Fascinatingly, the Taguchi method hinges on the three criteria of signal-to-noise ratio, which are known as the nominal-the-best, smaller-the-better and larger-the-better. It shows how the alternative parameters and the scenario created by their analysis meet up with the participation of the process engineer and help in attaining a more precise decision making on cryogenic machining operations. Then, the present worth helps the Taguchi method for accurate decisions on establishing the time value of money relevant to the turning or milling activities at the machine shop. By this, the amalgamation of the Taguchi method and the present worth method in the context of cryogenic machining helps the process engineer and the superior officers within the machine shop to make more informed decisions.

2. LITERATURE REVIEW

In this section, a review is presented on cryogenic machining. First, an introduction to the idea of cryogenic machining is made. Cryogenic machining is an innovative green practice in turning, milling or boring activities, whereby liquid nitrogen (LNZ) is deployed as a coolant, substituting the traditional oil-based emulsions, and directed to cool the cutting zone temperature thus concurrently affecting the cutting tool and the work material as the liquid nitrogen absorbs heat and evaporates it into the atmosphere (Balaji et al., 2015). It is now preferred to conventional machining for its tremendous advantages of reduced heat generation, enhanced dimensional accuracy, improved surface finish and extended tool life (Balaji et al., 2015). Cryogenic machining is a family name involving activities in milling (Pereira et al., 2016; Mia, 2017; Halim et al., 2018; Okafor and Jasra, 2019; Muthuraman and Karunakaran, 2021) and turning (Dhair et al., 2006; Sivaiah and Chakradhar, 2017; Jagadesh and Samuel; 2019; Uysal et al., 2020).

2.1 Cryogenic treatment

In industrial and infrastructural applications, corrosion resistance, high fracture toughness, high hardness, high wear resistance and high strength are crucial to withstanding the elevated mechanical stresses and temperature variations, wear loss and fatigue of the steel material widely used as inputs to processes. To understand the corrosive resistance of steel, for instance, several studies aspects have been reported; these include hardness and tensile strength, electrochemical study, atomic force microscopy, X-ray diffraction, and scanning electron microscopy (Ramesh et al., 2019). They examined the mechanical properties of cryogenically treated steel of which high strength mentioned in the above properties are included, the following tests are conducted: compressive strength, Young's modulus, bulk compressibility, poisons ratio, and brittleness (Khali and Emadi, 2020). Interestingly, analysis of an advanced hardness, magnetic hardness was demonstrated with the AISI D2 tool by Villa and Somers (2020) while transition occurred at cryogenic temperatures from austenite to martensite. The magnetic hardness was reported to decrease as the martensite was formed (Villa and Simers, 2020). They further asserted that progressive development of the martensite units at temperatures corresponding to cryogenic activities caused a decline in the number of austenite regions. Other properties have also been significantly explored to fully understand their association with mechanical stresses and temperature changes.

However, for several years, researchers and practitioners seem to be satisfied with the conventional heat treatment since the limits of characteristics of product properties desired were within the available technological process of conventional heat treatment. Notwithstanding, today's properties desired by industrial and structural applications substantially surpasses the capability of the conventional heat-treatment process. In this perspective, the conventional heat treatment method fails to satisfy the unusual demand for outstanding properties due to technological incapability. However, the literature survey excitingly declares that cryogenic treatment can offer enhancement in the properties of materials and steel belongs to this family of materials (Singh and Grover, 2015; Sivaiah and Chakradhard, 2017; Rao et al., 2020; Villa and Somers, 2020; Rout et al., 2021; Xue et al., 2021).

In many cryogenically treated steel specimens, it is difficult to physically judge whether a satisfactory cryogenic process has been performed on the steel specimens (Halim et al., 2018; Barylski et al., 2021; Jovicevic-Klug et al., 2021). However, it is generally agreed that microstructural and chemical analysis may be a useful route to a deep understanding of the characteristics of the treated steel (Jovicevic-Klug et al., 2021). Furthermore, Jovicevic-Klug et al. (2021), considered a wide spectrum of chemical and microstructural analysis for cryogenically treated samples, including X-ray photoelectron spectroscopy (XPS) scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), and energy-dispersive X-ray spectroscopy (EDS).

According to Dhokey et al. (2021), for the AISI H13 hot work tool, the specimens treated cryogenically exhibited tremendous enhancement in carbide density and hardness weighed against the conventionally treated samples. Furthermore, a threshold of wear resistance for the cryogenically treated samples compared with the conventionally treated sample was in the dimension of a double scale. The reason advanced by Dhokey et al (2021) is the precipitation of the fine tertiary carbide. Moreover, Barylski et al. (2021) declared that concerning the deep cryogenic treatment of Mg-Y-Nd-Zr alloy (WE54), a strengthening function of low-temperature treatment became evident. Also, there was an acceleration of the precipitation procedure.

Consequently, due to the tremendous benefits of cryogenic treatments of steel, it is now a wide practice to apply cryogenic treatments for steel samples globally, including steels AISI M2, M3.2 and M35 (Fantinieli et al., 2020; Jovicevic-Khug, 2021), AISI H13 steel (Dhokey et al., 2021), AISI D2 steel (Villa and Somers, 2020). A striking feature of these cryogenic treatments is the pronounced temperature that the experiments are conducted. For instance, while treating tool steels under nitrogen nebulization, for the AISI M2 steel, the treatment temperature was maintained at -190°C, a temperature that some authors qualify as deep cryogenic temperatures or about that temperature (Dhokey et al., 2021). While treating AISI H13 steel, Dhokey et al. (2021) maintained that experiments conducted at -196°C are deeply cryogenic. Furthermore, Villa and Somers (2020) also operated around -193°C and declared that it is a cryogenic temperature for the treatment of steel (AISI D2). Besides, while the term deep cryogenic treatment was mentioned by Ramesh et al. (2019) during the corrosion resistance enhancement study of structural steel undergoing cryogenic treatment, it is not clear what range of temperature is best suited for the structural steel samples. Nonetheless, information from the literature so far analyzed has revealed that -193°C and -196°C are important cryogenic temperatures.

In the literature survey conducted in this article, cryogenic treatment has been described as a promising method to revolutionize material processing in the industrial and structural application areas. To this end, several articles seem to validate the cryogenic treatment with various untreated conditions of steel. For instance, an excellent comparison of untreated conditions of Al7050-T7451 specimens was compared with the cryogenically treated specimens by Bansal et al. (2020) to validate the cryogenic treatment process. It was concluded that microhardness in the cryogenically treated samples reveals higher values than in the untreated samples. A second validation of the cryogenic process was shown by Ramesh et al. (2019) as structural steel that was cryogenically treated for corrosion resistance was compared with untreated samples. It was ascertained that samples that were treated with the cryogenic process had improved corrosion resistance weighted against those not treated cryogenically.

In another validation exercise conducted by Dhokey et al. (2021), the authors focused on the chromium-based medium carbon content steel, the AISI H13 and used the existing cryogenic treatment method to prove that it is superior to the conventional heat treatment method. The authors concluded that substantial enhancement in the carbide density and hardness was noticed in the cryogenically treated AISI H13 samples weighed against the conventionally treated samples. In a similar study, Xue et al. (2021) employed the in-situ elevated energy x-ray diffraction and simulation by the dynamics of molecules to analyse the development of structures for a B2 stage fortified CuZr oriented bulk metallic glass composite in various conditions of structures while engaging cryogenic treatment. A close association between the characteristics of phase transformation in the CuZr stage and the hydrostatic pressure, ambient temperature and uniaxial stress on the B2 CuZr stage for the prestrained specimen of the composite was reported.

2.2 Comparison of Taguchi-present worth method with other optimization and selection techniques

2.2.1 Response surface methodology

The response surface methodology (RSM), which originated from the combined efforts of George E.P. Box and K.B. Wilson in 1951, establishes the association between numerous explanatory variables and at least one variable. The concept of RSM, which has attracted cryogenic machining researchers, is to deploy a series of designed experiments to attain optimal response. While Rao et al. (2020) demonstrated the use of RSM to predict the material removal rate of Inconel 825 alloy by deploying cryogenically treated tungsten carbide tool, the Taguchi-present worth (T-PW) method newly proposed in this work is different from it. The difference is that while the response surface methodology needs a substantial number of experiments, the Taguchi-present worth method uses the minimum number of experiments to establish the optimum process situations and concurrently accounts for the dollar worth in terms of the time value of money (Okponyia and Oke, 2020).

2.2.2 Artificial neural network

Furthermore, Rao et al. (2020) used the artificial neural network (ANN) as an additional method to predict the MRR for the problem discussed in the preceding reference. However, the ANN model was found to exceed the performance of the RSM earlier discussed. Nevertheless, in comparing the ANN model with the T-PW method of the present work, it was found that the ANN model has the weakness of unknown duration of the network, making predictions unclear about when it will be accomplished. Compared with the T-PW method, the proposed T-PW method has the advantage of saving time and concurrently introducing the time value of money into evaluations.

2.2.3 Taguchi-based grey relational analysis

Besides, the Taguchi-based grey relational analysis is another technique used in cryogenic machining analysis. The authors integrated the Taguchi method and grey relational analysis and processed AISI. 17-4PH stainless steel using parameters involving cutting speed, feed rate, depth of cut and physical vapour deposit on AlTiN treated tungsten carbon (Sivaiah and Chakradhar, 2017). Another group of authors (Ranjith et al., 2019) advanced the use of the combined Taguchi method and the grey relational analysis by deploying the technique to optimize parameters during the cryogenic turning operation of AA6063 aluminium alloy. The present author concurred with Sivaiah and Chakradhar (2017) in the choice of some parameters to test the AA6063 workpieces. The common parameters include speed, feed rate and depth of cut while the physical vapor deposition on the tool as a parameter was excluded in the investigation.

Although both the Taguchi-based grey relational analysis and the T-PW method have the advantage of using fewer data to produce substantial quantitative and qualitative information, the T-PW method has an added advantage of accounting for the time value of money, a model's attribute omitted in the Taguchi-based grey relational analysis.

2.2.4 Taguchi method

A technique that progressively dominates the cryogenic machining literature is the Taguchi method (Khare and Agarwal, 2017). The Taguchi method, proposed by Genichi Taguchi, is a multi-phase process planning executing and appraising the outcome of matrix experiments to enhance the quality of products with the least economy of experiments and time. Despite the advantages demonstrated in the extensive use of the Taguchi method in the literature, it is often realized that combining some other techniques with the Taguchi method often overcome some of the shortcomings of the Taguchi method. While identifying the inability to account for the time value of money as a significant weakness in the Taguchi method, the proposed method T-PW method introduced in the present article overcomes this weakness.

2.3 Cryogenic cooling approaches

In an introductory discussion on cooling approaches, three important approaches may be identified in Patil and Jadhav (2019) including cryogenic pre-cooling of the workpiece, cryogenic spraying and jet cooling, and indirect cryogenic cooling.

3. METHODS

3.1 Chemical composition of the EN-19 steel

Among the EN 19 steel material options, a popular variant is the EN 19/708M40 steel grade that has the chemical composition with the max elements P and S of 0.035 and 0.040, respectively, and ranges of C, Si, Mn, Cr and Mo in the bands of 0.36-0.44, 0.10-0.40, 0.70-1.00, 0.90-1.20 and 0.15-0.25, respectively. This grade of steel finds substantial applications in bolts, gears and shafts.

3.2 Advantages of the Taguchi-present worth method

Nowadays, establishing influential improvements in the performance of machining systems have been pursued by deploying the Taguchi method aimed at enhancing quality, minimizing cost and offering robust solutions through its experimental design platform. In cryogenic machining, this is also widely practiced. Alternatively, research in manufacturing systems has deployed the present worth method that allows the process engineer to determine if or not the price that the machining system pays to sustain the cryogenic machining system is adequate.

However, an emerging idea is the combined utilization of methods, which is more effective than the institution of individual methods to manage the production process. Consequently, in this paper, the Taguchi method has been merged with the present worth method. This new method has the benefit over other methods specified as follows. The method can concurrently optimize the machining parameters with the generation of substantial quantitative information from limited experimental trials and permitting an evaluation of whether the price paid by the owners is adequate. This stimulates performance among the operators as they are conscious that the outcome of evaluation determines the sustainability of the machine shop, which alternately establishes their jobs.

3.3 Steps to conduct the Taguchi-present worth method

The following steps are applicable to achieve the method (Oke and Fagbolagun, 2021).

Step 1: Establish the factors and levels from the machining process

Step 2: Determine the associated orthogonal matrix for the machining problem

Step 3: Bring out the factor table such that the elements of the orthogonal arrays are mapped to the values of each factor with level to provide a platform to migrate to the signal to noise ratio computation

Step 4: Determine the signal to noise aspect of computation by considering the goal of the experiment along with three criteria of lower the better, nominal the best and the higher the better

Step 5: Set up the response table by

working with the signal to noise ratios and the pattern generated by the orthogonal array for the levels. The values of the signal to noise ratios for all entries at a level are averaged.

Step 6: Establish the optimal parametric values by choosing the maximum signal to noise ratio under each level.

Step 7: Fix *n* as the level for each parameter and *i* as the interest rate to comprise the present worth for each parameter. Consider the beneficial and non-beneficial factors in the analysis as they occupy the different sides of the performance diagram. The beneficial side is the upper side and the non-beneficial side is the lower side.

Step 8: Determine the present worth of each parameter.

Step 9: Rank the parameters according to the highest to the lowest values.

Step 10: Conclude that the parameter with the highest value is the desired outcome. This parameter is optimized and concurrently reveals to the process engineer the price paid by the owner is adequate or not. The parameter with the lowest value is not desired as the optimized results produce less than expected. It shows the inadequacy of the price paid by the owner of the machine shop.

4. RESULTS AND DISCUSSIONS

4.1 The Taguchi method

The Taguchi method was originally designed for telephone-switching system quality improvement where Genichi Taguchi was actively involved in process improvement in Electrical Communication Laboratory, a Japanese establishment around the 1950s. However, it has been effectively extended to machining operations where the present author argue that its effectiveness has been downplayed in the machining industry. Consequently, an approach is proposed by combining the Taguchi method with the present worth method by including the interest rate in the signal-to-noise ratio calculation. As most researchers would agree, combining the Taguchi method with the present worth method introduces an interaction of a technical optimization method (i.e. Taguchi method) with an economic method (present worth method) to produce a richer and more insightful method to understanding the machining operation for the EN-19 steel material.

Besides, amalgamating the Taguchi method and the present worth method is particularly helpful in understanding the contradictions between the two methods. With the combined effort of the two methods, the limitations of the Taguchi method in being incapable of declaring the state of the economy of the machining workstation and that of the present worth method in its inability to optimize the machining operations' parameters are balanced by the strengths of each method. This will ascertain that researcher's understanding is enhanced through the amalgamation of various perspectives of the machining operation. In this article, the combined method was applied to the machining operation for an EN-19 steel material to optimize the material removal rate, surface roughness and tool wear rate.

While Patil and Jadhav (2019) carried out experimental research on the EN19 steel, through cryogenic machining, and established the design of the experiment for the process, it is argued that the parametric setting, at optimal levels for the parameters, including speed, feed and depth of cut is not understood. Besides, the economic aspects of the work, which may be achieved through the amalgamation of the Taguchi method and the present worth method that deepen researchers understanding of the economics of cryogenic machining was omitted in the work. However, through an innovative perspective, the proposal for the optimal parametric setting and the amalgamation of the Taguchi method and the present worth method is presented in this section of the article. Besides, it is essential to explain the concepts of speed and tool wear, which are important in this work.

Speed - Though higher thresholds of spindle speed lead to increased material removal rate with tremendous improvement in productivity, but the surface integrity of the EN19 steel material during the machining process regarding the roughness average measurements may be compromised. Concurrently, the tool life gets deteriorated and extra costs, unplanned for in the budgetary allocations, may be expended on tool regrinding or replacement costs. Thus, there should be an intermediate position where minimum tool wear is experienced, the least possible surface integrity is compromised and an adequate speed is maintained in processing the EN19 steel material. This point of agreement is the optimal threshold and it is, therefore, desirable to operate during the drilling process for cost-effective operations.

Tool wear - In any machining processes where cryogenic cooling are heavily pronounced such as turning, milling and drilling processes, tool wear and damage largely depends on machining parameters such as the spindle speed, depth of cut, feed rate, point angle and drill size and the responses such as the degree of the torque and thrust force. Tool wear and damage depend on loss and the method of application of the cryogenic coolant since the principle of cryogenic cooling naturally imposes sustainability attributes into the tool. Given that the well-known phenomenon of tool wear and damage is mechanical wear, and the much-pronounced temperature-dependent phenomena are the adhesive wear and the thermal wear, the liquid nitrogen, on the application as a cryogenic coolant lowers their temperatures since their activities increase with temperature increases. Thus there is less rate of abrasive wear and thermal wear on the application of cryogenic coolant and the tool life is preserved from wear and damage and extended thereby avoiding tool regrinding and tool replacement costs that wipe away machining operation's profit.

By commencing with Table 1, which reveals the design of the experiment in Patil and Jadhav (2019), Table 1 is produced to cover the signal to noise ratio.

Table 1. Taguchi's Orthogonal arrays, factors and signal to noise ratios for the cryogenic machining problem

							S/N ratio type			
	Orthogonal array			Factors			LTB	NB	NB	
Expt. No.	SP	FR	DOC	SP	FR	DOC	SP	FR	DOC	S/N ratios (sum)
1	1	1	1	300	0.10	0.50	49.54	-7.62	-7.62	34.30
2	1	1	2	300	0.10	0.75	49.54	-7.62	-11.14	30.78
3	1	1	3	300	0.10	1.00	49.54	-7.62	-13.64	28.28
4	1	2	1	300	0.15	0.50	49.54	-11.14	-7.62	30.78
5	1	2	2	300	0.15	0.75	49.54	-11.14	-11.14	27.26
6	1	2	3	300	0.15	1.00	49.54	-11.14	-13.64	24.76
7	1	3	1	300	0.20	0.50	49.54	-13.64	-7.62	28.28
8	1	3	2	300	0.20	0.75	49.54	-13.64	-11.14	24.76
9	1	3	3	300	0.20	1.00	49.54	-13.64	-13.64	22.26
10	2	1	1	600	0.10	0.50	55.56	-7.62	-7.62	40.32
11	2	1	2	600	0.10	0.75	55.56	-7.62	-11.14	36.80
12	2	1	3	600	0.10	1.00	55.56	-7.62	-13.64	34.30
13	2	2	1	600	0.15	0.50	55.56	-11.14	-7.62	36.80
14	2	2	2	600	0.15	0.75	55.56	-11.14	-11.14	33.28
15	2	2	3	600	0.15	1.00	55.56	-11.14	-13.64	30.78
16	2	3	1	600	0.20	0.50	55.56	-13.64	-7.62	34.30
17	2	3	2	600	0.20	0.75	55.56	-13.64	-11.14	30.78

Table 1. Taguchi's Orthogonal arrays, factors and signal to noise ratios for the cryogenic machining problem (continued)

	Orthogonal array			Factors			S/N ratio type LTB	NB	NB	
Expt. No.	SP	FR	DOC	SP	FR	DOC	SP	FR	DOC	S/N ratios (sum)
18	2	3	3	600	0.20	1.00	55.56	-13.64	-13.64	28.28
19	3	1	1	900	0.10	0.50	59.08	-7.62	-7.62	43.84
20	3	1	2	900	0.10	0.75	59.08	-7.62	-11.14	40.32
21	3	1	3	900	0.10	1.00	59.08	-7.62	-13.64	37.82
22	3	2	1	900	0.15	0.50	59.08	-11.14	-7.62	40.32
23	3	2	2	900	0.15	0.75	59.08	-11.14	-11.14	36.80
24	3	2	3	900	0.15	1.00	59.08	-11.14	-13.64	34.30
25	3	3	1	900	0.20	0.50	59.08	-13.64	-7.62	37.82
26	3	3	2	900	0.20	0.75	59.08	-13.64	-11.14	34.30
27	3	3	3	900	0.20	1.00	59.08	-13.64	-13.64	31.80

Key: Speed – SP (rpm); feed rate (mm/min)– FR; depth of cut (mm) – DOC; Larger-the-better – LTB; Nominal-the-best – NB

It was decided to use the lower-the-better criterion of the signal to noise ratio for the speed parameter since Krishnamoorthy (2011) argued for a higher value of cutting speed to reduce the thrust force and obtain superior surface finish in machining, which are two important responses in the cryogenic machining of materials.

Equation (1), suggested in Oji and Oke (2020) expresses the mathematical representation of the larger-the-better criterion used for the speed:

$$\text{S/N} = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

where y_i is the performance attributed containing the i^{th} observed value
n is the trial experimental number

For feed rate, the nominal-the-best criterion of the signal to noise ratio is chosen, Equations (2) and (3) (Oji and Oke, 2020).

$$\text{S/N} = -10 \log_{10} y_i^2 / s^2 \quad (2)$$

where y_i is the performance attributed containing the i^{th} observed value, n is the trial experimental number and s^2 is the variance of observations, given as

$$s^2 = \frac{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}{n-1} \quad (3)$$

The motivation for this choice is the argument given by Krishnamoorthy (2011) that elevated feed rates stimulate increased thrust force and this is associated with a rough surface finish. By a converse argument, minimum feed rates stimulate increased heat generation while working on the material, and this is often compared with lowered material removal rates. Hence Krishnamoorthy (2011), maintained that an appropriate feed rate is needed. Consequently, the author suggested the nominal- the best criterion of the signal to noise ratio for the feed rate while machining. This is represented as Equations (2) and (3).

Furthermore, the choice of the signal to noise ratio criterion for the depth of cut may also be the nominal-the-best as the argument proposed is similar to the feed rate. Here, elevated depth of cut stimulates increased thrust force and it is related to a rough surface finish. Through a converse argument, minimum depth of cut motivates increased heat generation in a cryogenic machining environment. This is however often accompanied by lowered material removal rate. Consequently, the present author suggested the nominal the best criterion of the signal to noise ratio for the depth of cut and this is given by Equations (2) and (3).

The next stage of computation is the development of a table to contain the orthogonal arrays, factor and signal to noise ratios for the cryogenic machining problem. But there are 27 experimental trials used in Patil and Jadhav (2019) and an L27 orthogonal array was used. The same is repeated in the present article. Thus, the orthogonal array is displayed at the second to the fourth column of Table 1. Columns 5 to 8 are a reproduction of the critical data produced by Patil and Jadhav (2019). Column 8 is the result for the speed parameter, which was computed based on the larger-the better signal to noise criterion, given in Equation (1). To compute the first element in the cell under the speed parameter the value of 200 (Experimental trials 1) is started with. The application of the formula in a Microsoft Excel spreadsheet yielded 49.54 for the experimental trial 1 result. The result is the same up to experimental trial 9 and changes to 55.56 in experimental trial 10 to 18 and finally changed to 59.08 in experimental trial 19 to 27. For the feed rate parameter, in experimental trial 1, -7.62 was obtained. This value was maintained in experimental trials 2 and 3 and subsequently changed till all the 27 experimental trials were obtained. Furthermore, the value of the SN ratios for all the three parameters, speed, feed rate and depth of cut were added as a next column to the S/N ratios for DOC to obtain 34.3 for experimental trial 1 until a final value of 31.8 was obtained for experimental trial 27.

Now, the issues are to summarize the averages of the obtained values to response Table 2. In the table, the second column is for the speed parameter.

Table 2. Taguchi SN ratio response table

Level	SP	FR	DOC
1	27.94	35.92*	36.31*
2	33.96	32.51	32.79
3	37.48*	30.29	30.29
Delta	9.54	5.63	6.02
Rank	1	3	2

*Optimum value

However, it has three levels i.e. levels 1, 2 and 3. But level 1 is obtained as follows. By going back to Table 1, the entries in the orthogonal array carrying a mark "1" under SP are noted. This spreads from experimental trials 1 to 9. The corresponding values of experimental trial 1 in the S/N ratios (sum) column are 34.30. For experimental trial 2, it is 30.78 and it goes on until experimental trial 9 is reached with a value of S/N ratio as 22.26. All these nine values of 34.30, 30.78, 28.28, 30.78, 27.26, 24.76, 28.28, 24.76 and 22.26 are summed up and the average obtained as 27.94, which is recorded under SP at level 1. Still for SP, but level 2, Table 1 is referred to again and the column of SP is of interest to the investigator. These values of "2", which means level 2 run from experimental trials 10 to 18. Here, the corresponding values under the S/N ratios (sum) are noted as 40.32, 36.80, 34.30, 36.80, 33.28, 30.78, 34.30, 30.78 and 28.28. The average of these numbers is 33.96 and it is put in the second row of numbers under "SP", indicating the values for level 2. By following the same procedure, 37.48 is obtained for level 3 under the SP (speed) parameter. But note that among the three values of 27.94, 33.94 and 37.48 for levels 1, 2 and 3, respectively under SP, 37.48 is the maximum and hence asterisked.

By following the same procedure observed for SP to compute for FR and DOC, the values are shown in Table 2 with the highest values being 35.92 for FR and 36.31 for DOC. Then the delta value for each parameter is computed as the difference between the smallest and largest value along a column. For SP, the delta value is 9.54. For FR and DOC, the delta values are 5.63 and 6.02, respectively. Now, all the delta values are considered and the highest is ranked first, next to the highest is ranked second and the third one is ranked third. Thus, speed is ranked first, depth of cut is ranked second and the feed rate is ranked third. The implication is that speed is the best and the most influential parameter on cryogenic machining while the depth of cut is a less influential parameter but next to speed in ranking, and feed rate is the least influential parameter on the cryogenic machining process. However, the optimal parametric setting is $SP_3FR_1DOC_1$, obtained at 37.48 (level 3), 35.92 (level 1) and 36.31 (level

1) for speed, feed rate and depth of cut, respectively. This is interpreted from Table 4.1 of Patil and Jadhav (2019) as the optimal parametric setting of 900 rpm for speed, 0.1mm/min for feed rate and 0.5mm for depth of cut.

4.2 The combined Taguchi method and the present worth method

It is argued that most of the works in the domain of machining are limited to analyzing the optimization problem with the Taguchi method. However, to extend the horizon of the literature, an attempt is made to amalgamate the present worth method to the Taguchi method and hereby show the application to the cryogenic machining problem defined by Patil and Jadhav (2019). In the original problem, experiments were conducted using a CNC machine that possesses a cooling assembly with cryogenic cooling aided by the liquid oxygen stored in a cryocan with security values and regulators. The arrangement, according to Patil and Jadhav (2019), comprises two flows of liquid nitrogen targeted at the rake and flank surfaces through exterior copper nozzles having 0.9 mm as the interior diameter. The machine trials were conducted on a wrought Ti6Al4V workpiece and adopting the TiAlN wrought tungsten carbide insert DNMG 150608. The steps to follow are elaborated in section 3.

To apply the T-PW method, Equation (4) is adopted:

$$PW_{S/FR/DOC} = L\,(1 + i)^{-n} \quad (4)$$

where $PW_{S/FR/DOC}$ is the T-PW value of the cryogenic machining system discussed in Patil and Jadhav (2019), L shows the value of the parameter at the nth level and n is the level. By treating the speed parameter at level 1, the $PW_{S/1}$, which is the T-PW value of the speed parameter at level 1, gives the followings as L = 27.94, n = 1 and i = 12% = 0.12

$$PW_{SP1} = 27.94\,(1+0.12)^{-1} = 24.95$$

Now, by following this procedure, the values for PW_{SR2} and PW_{SP3} are calculated as 27/07 and 26.68, respectively. Furthermore, all other values involving PW_{FR1}, PW_{FR2}, and PW_{FR3} together with PW_{DOC1}, PW_{DOC2} and PWDOC3 are calculated and displayed in Table 3.

Table 3. Static combined Taguchi-present worth method performance evaluation

	Speed		Feed rate		Depth of cut	
Level	*SP*	PW_{SP}	*FR*	PW_{FR}	*DOC*	PW_{DOC}
1	27.94	24.95	35.92	32.07	36.31	32.42
2	33.96	27.07	32.51	25.92	32.79	26.14
3	37.48	26.68	30.29	21.56	30.29	21.56

Key: *SP* – speed, PW_{SP} – T-PW value for the speed parameter, *FR* – feed rate, PW_{FR} – T-PW value for the feed rate parameter, *DOC* – depth of cut, PW_{DOC} – T-PW value for the depth of cut parameter

From Table 3, the performance flow diagram is drawn and the overall T-PW value calculated to decide on the state of the system. By commencing with the speed parameter, the performance flow diagrams in Fig. 1a, 1b and 1c are obtained. In considering the speed parameter, reference is made to the criterion of the signal-to-noise ratio chosen earlier, which is the larger-the-better criterion defined as beneficial since an increase in speed is often desired without any detrimental effects on the thrust force and the surface roughness. As such, all the three arrows to draw for the speed parameter should take the upward direction (beneficial), as follows:

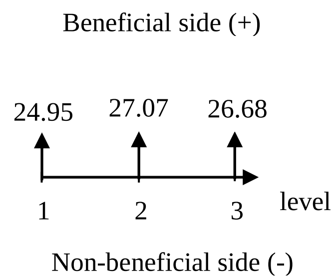

Fig. 1a. T-PW method's performance flow for parameter SP (spindle speed)

$$PW_{SP}\,(\text{T-PW}) = 24.95\,(1+0.12)^{-1} + 27.07\,(1+0.12)^{-2} + 26.68\,(1+0.12)^{-3} = 62.85.$$

By considering the feed rate parameter, the nominal the best is chosen. The assumption here is that once it is not beneficial, the other aspect, non-beneficial treatment is made for the parameter. Hence the analysis is on the non-beneficial side of the performance flow diagram, Fig. 1b.

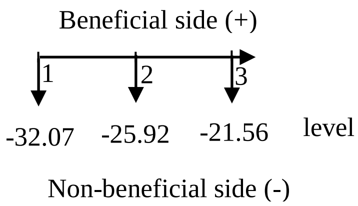

Fig. 1b. T-PW method's performance flow for parameter FR (feed rate)

PW_{FR} (T-PW) = $-32.07 (1+0.12)^{-1} -25.92 (1+0.12)^{-2} -21.56 (1+0.12)^{-3} = -64.64$

Furthermore, by similarly considering the depth of cut to the feed rate parameter, the performance flow diagram will have the entries on the non-beneficial side as in Fig. 1c.

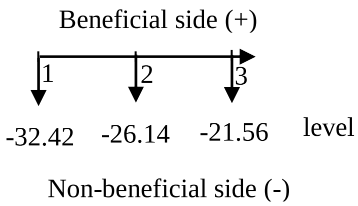

Fig. 1c. T-PW method's performance flow for parameter DOC (depth of cut)

Then, PW_{DOC} (T-PW)= $-32.42 (1+0.12)^{-1} - 26.14 (1+0.12)^{-2} -21.56 (1+0.12)^{-3} = -65.13$
The summary of the results is presented in Table 4.

Table 4. The T-PW at optimal values of cryogenic machining parameters

Description	PW_{SP}	PW_{FR}	PW_{DOC}
Value	62.85	-64.64	-65.13

From Table 4, the highest value (i.e. 64.85) is allocated to PW, which means that the speed parameter is the best. This choice implies that in machining, the speed parameter should be given the highest priority.

Furthermore, the proposed method consists of the Taguchi method integrated with the present worth method. However, on the application of the Taguchi method, the optimal parametric setting was obtained (Table 2) as $SP_3FR_1DOC_1$, obtained at 37.48 (level 3), 35.92 (level 1) and 36.31 (level 1) for speed, feed rate and depth of cut, respectively, interpreted as 900rpm (speed), 0.1mm/min (feed rate) and 0.5mm (depth of cut). Based on this result, the machine shop could set the maximum values obtainable due to the system's capacity constraint. But the evaluation of the system is limited to its optimization and there is no link of these values provided on the economic analysis of the workshop. Besides, incorporation of the economic content into the model gives a further sense of system commitment to account for the time value of money. So as the Taguchi-present worth method is applied, it yields PW_{SP} (62.85) as 1st, PW_{FR} (-64.64) as 2nd and PW_{DOC} (-65.13) as the 3rd position, which is an enhancement of the Taguchi method's value. Consequently, the new method enhances the performance of the Taguchi method to evaluate the machining process.

4.3 Novelty and advantages of the new method

The main objective of this study is to propose a new method, the Taguchi-present worth method that combines the Taguchi method with the present worth method by including the interest rate in the signal-to-noise calculation. This article challenges the existing literature in the machining industry for the exclusion of economic factors in process optimization. At present, many machining shops now suffers the effects of depending on operators and process engineers with only the technical machining knowledge and skill without competence in economic issues. Training programs for operators and process engineers currently assumes that the economic knowledge is only for the accountant or the engineering manager. So, there is no linkage between the working mechanism of the Taguchi method and economic aspects. This article challenges that assumption and practices and argues that performance metrics for optimization using the Taguchi method should be tied to the present worth method on an understanding. The present work is based on the time value of the money concept. Furthermore, it is known that the machine shop pays less in interest on borrowed loans from banks if the operators and process engineer's performance are tied to interest rates. Thus, the machine shop has more money to spend and it is encouraged to make huge equipment purchases because of low interest payable on borrowed money. The claimed novelty is the development of derivatives of the present worth method, which shows the dynamic state of the cryogenic machining operation. This idea breaks away from the established Taguchi method of parametric optimization that calculates the average signal-to-noise ratio to determine the optimal parametric setting and the delta values. It is argued that the Taguchi method is an established pattern of optimization thought and the new method of T-PW method starts a new part of research that combines the technical process parameters with the economic parameters that are founded on the time value of money, which argues that a dollar today is different from a dollar in the future. The T-PW method opens up some exciting possibilities such as integrating the control chart models to the T-PW method such that proactive control of the machining parameters with "within control" or "out-of-control" concepts of the X bar chart and reliant methodologies could be attained. The incorporation of sustainability indices into the T-PW framework such that the environmental conscious machining could also be practiced is a possibility to enhance future scholarship.

While the Taguchi method can be useful in the optimization of cryogenic machining parameters through the development of optimal parametric setting and the selection of parameters from the analysis of the delta values, the T-PW method is useful in tackling the weakness of the Taguchi method in its insensitive behavior to the time value of money and economic concerns. Consequently, the first benefit is that the T-PW method highlights the importance of the time value of money, arguing that a dollar at hand today is worth more when promised in the future. It implies that the dollar at hand presently could be invested for capital gains. Besides, concurrent optimization is aided by the T-PW method together with a mechanism to establish if the cryogenic machining system delivers value. Furthermore, emphasis is made on the company's cost of capital so that all employees are conscious that the survival of the organization and their continuity in doing their jobs depend on how they manage their operations as it influences the cost of capital positively or negatively. An additional benefit of the T-PW method over the Taguchi method that is currently being used is the ability of the new method to incorporate the inherent uncertainty of forecasts by most heavily discounting far-future projections.

5. CONCLUSION

In cryogenic machining practice, many of the formulated optimization problems are sufficiently expressive, making it very difficult to achieve optimal solutions in a reasonable solution time because the route to the solution is very complex. However, it is known that cryogenic machining systems are expensive and requires precise suggested output for cost-effective operations. To conquer these challenges, a new parametric optimization method, namely the Taguchi-present worth method is introduced. The newly involved term is the present worth factor that incorporates the interest rate and the level operating in the Taguchi method at the signal-to-noise ratio development. The proposed method is shown to be feasible when applied to a practical machining situation involving the cryogenic machining of EN-19 steel, a hard material using an environment where retrofitted lathe equipment with the liquid nitrogen cryogenic cooling system is installed. The proposed method also enhances the results of the Taguchi method that are existing in the literature. If the present worth term is embedded at the signal-to-noise stage of the Taguchi method, it could be a cost-effective solution for machining process control.

In this article, the Taguchi method was merged with the present worth method to obtain a new method, the Taguchi-present worth method. However, in previous studies on Taguchi method optimization, some authors have shown how the variants of the Taguchi method could be developed and applied in different contexts. For example, Oji and Oke (2020) proposed two additional variants to the Taguchi method with the argument that concurrent optimization and prioritization of parameters is feasible and applied to the maintenance system in a total quality management context. Okanminiwei and Oke (2020) further validated the approaches in a study where the downtime of handling equipment was optimized to validate the two models, namely the Taguchi-Pareto and Taguchi-ABC methods. Consequently, future study is recommended to integrate Taguchi-Pareto and Taguchi-ABC methods with the present worth method as two separate methods of the Taguchi-present worth method. These two methods will bring diversity into the solution portfolio for the machining problem as they will incorporate prioritization into what is already known. In addition, in the future, the incorporation of sustainability factors and elements representing the industrial revolution 4.0 may add value to the cryogenic machining literature. Furthermore, the following could be studied: (1) the dynamic combined T-PW method using a polynomial form where the derivative of the present worth with respect to the interest rate is developed. The derivative of the present worth with respect to the level term could be established (2) the exponential form of the dynamic combined T-PW method with derivatives of the present worth developed with respect to the interest rate. The second instance is where the derivative of the present worth is expressed regarding the level term. These derivatives could be used in studying the dynamic behavior of the cryogenic machining process while the work material is the EN-19 steel.

REFERENCES

Alomar A. 1994. Occupational skin disease from cutting fluids, Dermatologic Clinics, 12(3): 537-546. https://doi.org/10.1016/S0733-8635(18)30158-X

Anthuvan R.N., Kumar S.P., Prakash R.A., Arunkarthik B., Akhilesh A. 2021, Machinability study in milling of Ti-6Al-4V using cryogenic treated and coated tool, Materials Today: Proceedings, In Press. https://doi.org/10.1016/j.matpr.2021.03.451

Azarov A.V., Zhukova N.S., Antonov F.G., 2017. Water-spray systems reducing negative effects of fine-dispersion dust at operator’s workplaces of machine-building industries, Procedia Engineering, 206: 1407-1414.https://doi.org/10.1016/j.proeng.2017.10.653

Babu P.S., Rajendran, P., Rao K.N., 2005. Cryogenic treatment of M1, EN19 and H13 tool steels to improve wear resistance, Institute of Engineers (India) Journal-MM, 86(10): 64-66.

Balaji V., Ravi S., Chandran P.N., Damodaran K.M., 2015. Review of the cryogenic machining in turning and milling process, International Journal of Research in Engineering and Technology, 4(10): 38-42. https://doi.org/10.15623/ijret.2015.0410008

Bansal A., Singla A.L, Diviedi V., Goyal D.K., Singla J., Gupta M.K., Krolczyk G.M., 2020. Influence of cryogenic treatment on the mechanical performance of friction stir Al-Zn-Cu alloy weldments, Journal of Manufacturing Processes, 56: 43-53. https://doi.org/10.1016/j.jmapro.2020.04.067

Barylski A., Aniolek K., Derez G., Kupka M, Kaptaez S., 2021. The effect of deep cryogenic treatment and precipitation hardening on the structure, micromechanical properties and wear of the Mg-Y-Nd- Zr alloy, Wear, 468-469, Article 283587.https://doi.org/10.1016/j.wear.2020.203587

Bharat N., Bose P.S.C. 2021, An overview on machinability of hard to cut materials using laser assisted machining, Materials Today: Proceedings, 43(1):665-672. https://doi.org/10.1016/j.matpr.2020.12.587

Bicek M., Dimont F., Courbon C., Pusavea F., Rech J., Kpac J., 2012. Cryogenic machining as an alternative turning process of normalized and hardened AISI 52100 bearing steel, Journal of Material Processing Technology, 212(12): 2609-2618. https://doi.org/10.1016/j.jmatprotec.2012.07.022

Choudhary R., Garg H., Prasad M., Kumar D., 2017, Effect of cryogenic treatment of tool electrode on the machining performance and surface finish during electrical discharge machining of Hastelloy C-4, Materials Today: Proceedings, 4(2): 1158-1166. https://doi.org/10.1016/j.matpr.2017.01.132

Damir A., Sadek A., Attia H., 2018. Characterization of machinability and environmental impact of cryogenic turning of Ti-6Al-4V, Procedia CIRP, 69: 893-898. https://doi.org/10.1016/j.procir.2017.11.070

Das R.K., Sahoo A.K., Kumar R., Panda A. 2020, Performances of time-controlled pulse minimum quantity lubrication in machining of hard to cut material: A brief review, Materials Today: Proceedings, 23(3): 545-548. https://doi.org/10.1016/j.matpr.2019.05.404

Dhar N.R., Kamruzzaman M., Khan M.M.A, Chattopadhyay A.B., 2006, Effects of cryogenic cooling by liquid nitrogen jets on tool wear, surface finish and dimensional deviation in turning different steels, International Journal of Machining and Machinability of Materials, 1(1): 115-131. https://doi.org/10.1504/IJMMM.2006.010662

Dhananchezian M., Rishabapriyan M, Rajashekar G., Narayanan S.S., 2018, Study the effect of cryogenic cooling on machinability characteristics during turning duplex stainless steel 2205, Materials Today: Proceedings, 5(5): 1206-12070. https://doi.org/10.1016/j.matpr.2018.02.181

Dhokey N.B., Maske S.S., Ghosh P., 2021. Effects of tempering and cryogenic treatment on wear and mechanical properties of hot work tool steel (HB), Materials Today. Proceedings, 43(5): 3006-3013. https://doi.org/10.1007/s11665-018-3552-y

Fantoneli D.G., Parcianellon C.T., Rosendo T.S., Reguly A., Tier M.D., 2020. Effect of heat and cryogenic treatment on wear and toughness of HSS AISI M2, Journal of Materials Research and Technology, 9(6): 12354-12363. https://doi.org/10.1016/j.jmrt.2020.08.090

Feucht F., Ketelaer J., Wolff A., Mori M., Fujishima M. 2014, Latest machining technologies of hard-to-cut materials by ultrasonic machine tool, Procedia CIRP, 14: 148-152. https://doi.org/10.1016/j.procir.2014.03.040

Gross D., Bigelmaier M, Meier T., Amons S, Ostrowicki N., Hanenkamp N., 2019. Investigation of the influence of lubricating oils on the turning of metallic materials with cryogenic minimum quantity lubrication, Procedia CIRP, 80: 95-100.

Gurumurthy, Sharma S. S., Gowrishankar, Sowmith, Abhishek and Devar A., 2016, Study of mechanical properties of dual-phase EN 19 steel (AISI4140), Indian Journal of Science and Technology, 9(37): 1-6. https://doi.org/10.17485/ijst/2016/v9i37/97422.

Halim N.H.A, Chettaron C.H, Ghani J.A., Azhar M.F., 2018. Machining-induced microstructure of Inconel 718 in cryogenic environment, Progress in Industrial Ecology: An International Journal, 12(3): 234-246. https://doi.org/10.1504/PIE.2018.097061

Jagadesh T., Samuel G.L., 2019. The influence of deep cryogenic treatment and in-situ cryogenic micro turning of Ti-6Al-4V on cutting forces, surface integrity and chip morphology, International Journal of Precision Technology, 8(2/3/4): 312-334. https://doi.org/10.1504/IJPTECH.2019.100956

Jovicevic-Klug P., Jenko M., Jovicevic-Klug M., Setin B., 2021.Effect of deep cryogenic treatment on surface chemistry and microstructure of selected high-speed steels, Applied Surface Science, 548, Article 149257.https://doi.org/10.1016/j.apsusc.2021.149257

Joviecevic–Klug P. and Podgornik B., 2020. Comparative study of conventional and deep cryogenic treatment of AISI M3: 2

(EN 1. 2295) high-speed steel, Journal of Materials Research and Technology, 9(6): 13118-13127. https://doi.org/10.1016/j.jmrt.2020.09.071

Khare S.K., Phull G.S., Verma R.K., Agarwal S., 2021, A comparison between optimization techniques of cutting parameters under cryogenic machining process, Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2020.02.567

Khalil R. and Emadi H., 2020, An experimental investigation of cryogenic treatments reflects on porosity, permeability and mechanical properties of Marcellus downhole core samples, Journal of Natural Gas Science and Engineering, 81, Article 103422. https://doi.org/10.1016/j.jngse.2020.103422

Khann N., Agrawal C., Shadgaar J., Larsen, Phadmis V.A., 2019, Eco-friendly machining using retrofitted cryogenic machining system, Materials Today: Proceedings, 18(7): 2806-2813. https://doi.org/10.1016/j.matpr.2019.07.147

Krishnamoothy A., 2011, Some studies on modelling and optimization in drilling carbon fibre reinforced plastic composites, Ph.D. Thesis, Faculty of Mechanical Engineering, Anna University, Chennai, India

Mia M., 2017, Multi-response optimization of end milling parameters under through tool cryogenic cooling condition, Measurement, 111: 134-145.https://doi.org/10.1016/j.measurement.2017.07.033

Muthuraman P., Karunakaran K., 2021, Optimisation of face milling process parameters by GRA with deep cryogenic treated milling cutter, Materials Today: Proceedings, 37(2): 1631-1617. https://doi.org/10.1016/j.matpr.2020.07.168

Nagimova A., Perveen A. 2019, A review on Laser Machining of hard to cut materials, Materials Today: Proceedings, 18(7):2440-2447. https://doi.org/10.1016/j.matpr.2019.07.092

Nie G-C., Zhang X-M., 2018, An experimental study of the white layer formation during cryogenic assisted hard machining of AISI52100 steel, Procedia CIRP, 77: 223-226. https://doi.org/10.1016/j.procir.2018.09.001

Ozbek N.A., 2020, Effects of cryogenic treatment types on the performance of coasted tungsten tools in the turning of AISI H11 steel, Journal of Materials Research and Technology, 9(4): 9442-9456. https://doi.org/10.1016/j.jmrt.2020.03.038

Oji B.C. and Oke S.A. 2020, Optimisation of bottling process using "hard" total quality management elements, The TQM Journal, 33(2): 473-502. https://doi.org/10.1108/TQM-03-2020-0057

Okanminiwei L. and Oke S.A., 2020, Optimisation of maintenance downtime for handling equipment in a container terminal using Taguchi scheme, Taguchi-Pareto method and Taguchi-ABC method, *Indonesian Journal of Industrial Engineering & Management*, 1(2): 69-90. https://doi.org/10.22441/ijiem.v1i2.9912

Oke S.A. and Fagbolagun I.O., 2021, Optimisation of packaging process parameters using combined Taguchi method-present worth method/inflationary factor validated, International Journal of Industrial Engineering and Engineering Management, Accepted for publication.

Patil V.A., Jadhav B.R., 2019, Experimental investigation of cryogenic machining of EN-19 steel, Journal of Emerging Technologies and Innovation Research, 6(4): 634-638

Pereira O., Rodriguez A., Ayesta I., Garcia J.B., Fernandez-Abia A.I., Lepez De Lacalle L.N., 2016, A cryolubri-coolant approach for finish milling of aeronautical hard-to-cut materials, International Journal of Mechatronics and Manufacturing Systems, 9(4): 370-384. https://doi.org/10.1504/IJMMS.2016.082872

Prakash D., Tariq M., Davis R., Singh A., Debnath K., 2021, Influence of cryogenic treatment on the performance of micro-EDM tool electrode in machining of magnesium alloy AZ31B, Materials Today: Proceedings, 39(4): 1198-1201. https://doi.org/10.1016/j.matpr.2020.03.589

Rahul, Datta S., Biswal B.B. 2019, Experimental studies on electro-discharge machining of Inconel 825 super alloy using cryogenically treated tool/workpiece, Measurement, 145: 611-630. https://doi.org/10.1016/j.measurement.2019.06.006

Ramesh S., Bhuvaneshwari B., Palani G.S., Lad D.M., Mondal K., Gupta R.K., 2019, Enhancing the corrosion resistance performance of structural steel via a novel deep cryogenic treatment process, Vacuum, 159: 468-475. https://doi.org/10.1016/j.vacuum.2018.10.080

Ramu V., Nishoksriam S.R., Deep H., 2017, Carbon steel EN8 and EN 19 tool wear reduction by cryogenic treatment, International Journal of Engineering Technology Science and Research, 4(5): 697-703

Ranjith R., Somu C., Tharanitharan G., Venkatajalapathi T., Naveenkumar M., 2019, Integrated Taguchi cum grey relational experimental analysis (GREAT) for optimization and machining characterization of cryogenic cooled AA6063 aluminium alloys, Material Today: Proceedings, 18(7): 3597-3605. https://doi.org/10.1016/j.matpr.2019.07.291

Rao P.S., Kumar S., Khan M.Y., 2020, Comparison of predicted capabilities of MRR parameter using RSM and ANN for dry turning of Inconel 825 alloy using cryogenically treated tungsten carbide tool, Materials Today: Proceedings, In press. https://doi.org/10.1016/j.matpr.2020.10.163

Rout I.S., Pandian P.P., Raj A. 2021, Experimental study of response parameters during machining of Inconel 718 with cryogenically treated ceramic round tool using cutting fluid, Materials Today: Proceedings, In Press, https://doi.org/10.1016/j.matpr.2021.04.573

Okafor A.C., Jasra P.M., 2019, Effects of milling methods and cooling strategies on tool wear, chip morphology and surface roughness in high speed end milling of Inconel-718, International Journal of Machining and Machinability of Materials, 21(112): 3-42. https://doi.org/10.1504/IJMMM.2019.10017480

Okponyia K.O. and Oke S.A., 2020, Exploring aluminium alloy metal matrix composites in EDM using coupled factor-level-present worth analysis and fuzzy analytic hierarchy process, International Journal of Industrial Engineering and Engineering Management,2(1): 25-44. https://doi.org/10.24002/ijieem.v2i1.3781

Singh A. and Grover N.K., 2015, Wear properties of cryogenic treated electrodes on machining of EN-31, Materials Today: Proceedings, 2(4-5): 1406-1413. https://doi.org/10.1016/j.matpr.2015.07.060

Sivaiah P., Chakradhard D., 2017, Multi-objective optimization of cryogenic turning process using Taguchi-based grey relational analysis, International Journal of Machining and Machinability of Materials, 19(4): 297-312. https://doi.org/10.1504/IJMMM.2017.086161

Uysal A., Caudrill J.R, Javahir I.S., 2020, Minimizing carbon emissions and machining costs with improved human health in sustainable machining of austenitic stainless steel through multi-objective optimization, International Journal of Sustainable Manufacturing, 4: 281-299. https://doi.org/10.1504/IJSM.2020.107154

Villa M., Somers M.A.J., 2020. Cryogenic treatment of an AISI D2 steel: The role of isothermal martensite formation and martensite conditioning, Cryogenics, 110, Article 103131. https://doi.org/10.1016/j.cryogenics.2020.103131

Xue P., Huang, Y., Pauly S., Guo F., Ren Y., Jiang S., Guo F., Fan H., Ning H., 2021, Structural evolution of a CuZr-based bulk metallic glass composite during cryogenic treatment observed by in-situ high-energy X-ray diffraction, Journal of Alloys and Compounds, 871, Article 159570. https://doi.org/10.1016/j.jallcom.2021.159570