OPTIMISATION OF MACHINING PARAMETERS FOR SURFACE ROUGHNESS, POWER CONSUMPTION AND OTHER RESPONSES DURING THE CNC LATHE DRY MACHINING OF EN24 ALLOY STEEL

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ABSTRACT

Design and analysis of optimisation protocols used for performance enhancement of machining based components manufacturing is currently an active area of machining science. This experimental investigation research deals with determining and optimising the effects of three input parameter metrics on the performance realisation of good surface quality output and energy consumption during the dry machining process of EN 24 steel material by turning on the CNC lathe. The input parameter metrics considered were cutting speed, depth of cut and feed rate. The study, employed Taguchi full factorial design approach in planning the experimental process and estimate the effects of the input metrics on the response; three phase digital energy meter to capture electrical power consumption data online; offline recorded surface roughness data and used Minitab 18 statistical software analysis of variance to assess the influence of cutting parameters on the response parameters, and the Signal to noise ratio main effects plot as the optimisation tool for the various response parameters. The paper aimed to determine the appropriate cutting parameter settings required on the lathe machine in order to produce EN 24 components of better surface quality at minimum energy expenditure. The experimental data analysis results established the optimum operating conditions at varied cutting parameter settings with respect to the different response parameters and the results were presented for the surface roughness, material removal rate and specific cutting energy use.

Keywords: Keywords: Machining optimisation, energy efficiency, Analysis of variance, Surface roughness, specific cutting energy

NOMENCLATURE

CNC	Computer Numerical Control

ANOVA	Analysis of Variance
MRR	Material Removal Rate
S/N	Signal to noise
ZPC	Zimbabwe Power Company
PVD	Powder vapour deposition
DF	Degrees of freedom
SS	Sum of squares
MS	Mean squares
Ra	Average surface roughness

1.0 INTRODUCTION

Product surface quality improvement, realised resource-efficiently (at minimum energy and cost), has always been an important objective in the metal cutting Machineshop industry. The advent of optimisation techniques for processes enhancement have significantly contributed to these goals achievement, in a major way, in other industries, but not much so in the machining based manufacturing of EN 24 steel. EN24 material is a high utility chromium carbon steel broadly used in the tool and die manufacturing industry to make a range of high strength components for the aircraft, automotive and other industries, by machining operations in countries such as Zimbabwe. Most machining based manufacturing enterprises strive to produce components competitively –i.e. in reasonable time and resource efficiently. The selection of operating parameter settings is an important assessment metric of the effectiveness of the machining process. Observably, in a number of machine-shops the cutting parameters are estimated from the experience of the workmen, resulting in sub-optimal machining operations. As a result it becomes important to systematically determine how the machining, of EN 24 steel, can be carried out cost effectively on the CNC lathe machine. The objective of this Taguchi full factorial experimental study was to determine the optimum cutting parameter settings on the lathe machine in order to produce EN 24 components of better surface quality at minimum energy expenditure.

Full factorial design of experiments (FFDoE) was utilised in planning the three input factor (cutting speed, feed rate and depth of cut) machining iterative experiment runs of EN 24 material whilst three response factors - surface roughness, energy consumption and material removal rate - were monitored and analysed. According to Ahmed, Venkatesh & Shankrrya (2019) factorial design is the experimental planning platform of relevance when it is required to simultaneously determine the effect of various input factors on the response as well as consideration of the interaction of the factors. It is utilised in experimental instances where the effect of different factors or conditions on experimental results are to be explained.

Currently, the general practice, in machining industries, is that cutting parameter determination is done using the operative's past experience. This operation approach has limitations in the sense that it does not provide the optimum machining parameters that return the most desired surface finish, MRR and the least amount of electrical energy (power) use consumption. Machining production planning is not easy when using the good-guessing methodology of cutting parameter determination. Order fulfilment lead times cannot be met effectively owing to unknown total machining time for particular orders in an environment of estimated cutting conditions.

1.1 Related Literature

Machining is the process of removing excess material from a work part by means of a cutting tool, in the machine tool, to obtain a desired shape, size and surface finish. It is accomplished by selective removal of the work part surplus metal to produce the required shape. It can also be processes that consist of the removal of material and modification of the surfaces of a work piece after it has been produced by various methods. Machining is essentially done to impart required or specified dimensions, form and surface quality to enable the product to fulfill its basic functional requirements, provide better or improved performance, and render long service life, (Klorke, 2009; Tayisepi et al, 2023).

Turning, on a lathe, is one of the most common of all primary metal cutting operations by machining in the industry, (Singh, 2014). A work part is rotated about its axis whilst a single point cutting tool is being fed into it, shearing away unwanted material and creating the desired work part profile, as typically shown in Figure 1. The cutting tool is fed either linearly, in the direction parallel or perpendicular to the axis of rotation of the work piece, or along a specified path to produce complex rotational shapes (contouring). The primary and secondary motions of cutting in the turning operation are the rotation of the work piece and the feed motion respectively. Turning can be done on both external and internal surfaces of a work piece to produce an axially-symmetrical contoured part. The use of CNC lathe machines is assuming increased dominance in the metal machining industry today, Oosthuizen et al (2013). Surface finish of the turned components has greater influence on the quality and acceptability of the product by the customers. Reduction in the power consumption, during machining operations, also contributes in reducing the energy bill of a metal machining enterprise or machining workshop. Machining operation productivity, therefore, needs to be optimised in terms of cost/time and components quality. Optimisation of machining parameters improves the utility for machining economics. Increasing productivity and component part quality improvement are some of the main performance burdens of the metal machining industries. Improving the quality of the machined parts, cost effectively, during turning, is contemplated as one of the main hurdles distressing the metal machining industries. Good surface finish is a main requirement for the impression of the customers, (Gupta & Diwedi, 2014). Thus, quality of the machined products should be well within customer satisfaction. This should also be achieved with minimum electrical energy consumption. The affordability of a part is an important aspect, which means that the power consumption, during machining, should be reduced since it forms part of the main basis of product pricing.

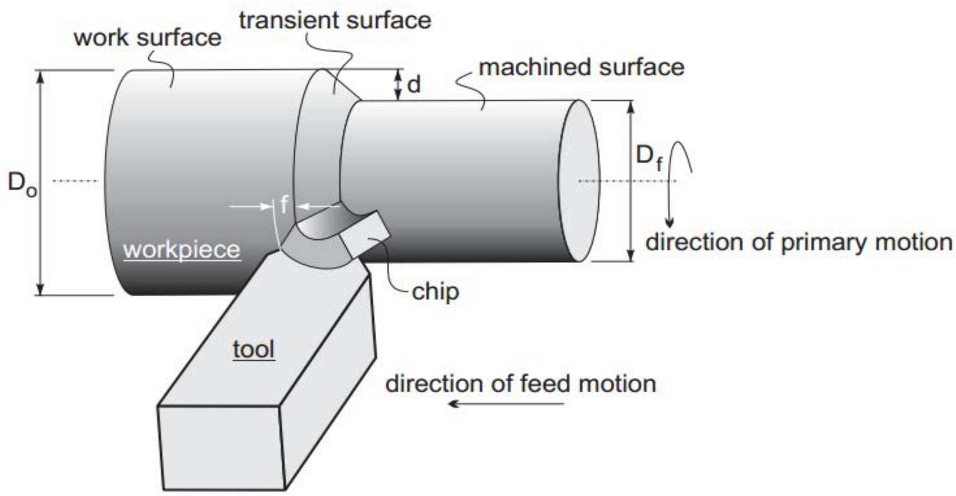

Figure 1. Turning Operation process

(Singh, 2014)

The higher the electrical energy use consumption, the higher the price of the machined product, (Tayisepi et al, 2023). Energy use reduction, thus, plays vital dual role during product machining manufacturing, i.e., reduction in the product cost as well as reduction in negative impact on the environment through reduction of the amount of carbon emissions released into the environment during the machining process, (Rajemi, Mativenga, & Jaffery, 2009).

As such this research sought to affirm on the optimum parameters which must be set on the Computer Numerical Control (CNC) lathe machine, in order to achieve good surface finish and energy use economical machining during EN 24 material cutting. Engineering Steel, EN 24, is a BS 970-1991 standard steel grade which is a through-hardened alloy steel, readily machinable in the "T" condition, designated as 817M40T, (Smiths-Metals, 2023). It is a high strength alloy steel with good tensile strength, decent ductility and abrasion or wear resistance characteristics, impact resistance, toughness, and torsional strength. EN24, a high chromium carbon steel, was selected for this study owing to its broad applications in tool and die manufacturing industry in Zimbabwe where it is appropriately suitable for the making of parts such as heavy-duty axles, gears, bolts, studs and shafts. Other application areas include manufacturing of aircraft, automotive and general engineering parts such as propeller or gear shafts, connecting rods, aircraft landing gear components and parts, gears and shafts, towing pins, load bearing tie rods, oil and gas industry applications. It is also suitable for producing parts for locomotives, cranes, rolling mills, coal cutting machinery etc., where good strength and fatigue resistance is required. It is extensively used in the plastic and rubber moulding industries for moulds manufacture.

EN24 alloy steel machining gives rise to problems such as escalated cutting forces, high cutting tool temperatures, poor surface finish and built up edge formation, (Baig et al, 2021). The low specific heat causes diffusion of the material between tool and work material and tendency to strain harden. In this present research study, the effect of depth of cut and cutting speed on surface roughness, power consumption, material removal rate and energy use were considered and optimum cutting conditions were determined. These factors influence, on the surface quality of the machined component as well on the cost of machining, were investigated. The study intended to establish the optimum set of cutting parameters for minimising component surface roughness, energy use and maximising material removal rate (MRR).

Variables that affect the cutting process include a plethora of factors which, inter alia, include - as independent variables: tool material and coating; tool shape and sharpness; work piece material and condition; cutting speed, feed, and depth of cut; cutting fluids; characteristics of the machine tool; and work holding and fixturing – and as dependent variables: type of chip produced; force and energy dissipated during cutting; temperature rise in the work piece, the tool, and the chip; energy/power consumption; tool wear and failure; and surface finish and surface integrity of the work piece, (Kalpakjian & Schmid, 2009) .

The surface texture, of machined components, is comprised of 3 components, which are roughness – the function of the main machining process; waviness – the component that is superimposed by roughness; and form/profile – the overall shape of the surface minus the contributions from roughness and waviness, (Dagnall, 2007). Surface roughness is a universal characteristic of all surfaces which can take many forms, (Suryawanshi & Inamdar, 2012) Figure 2.

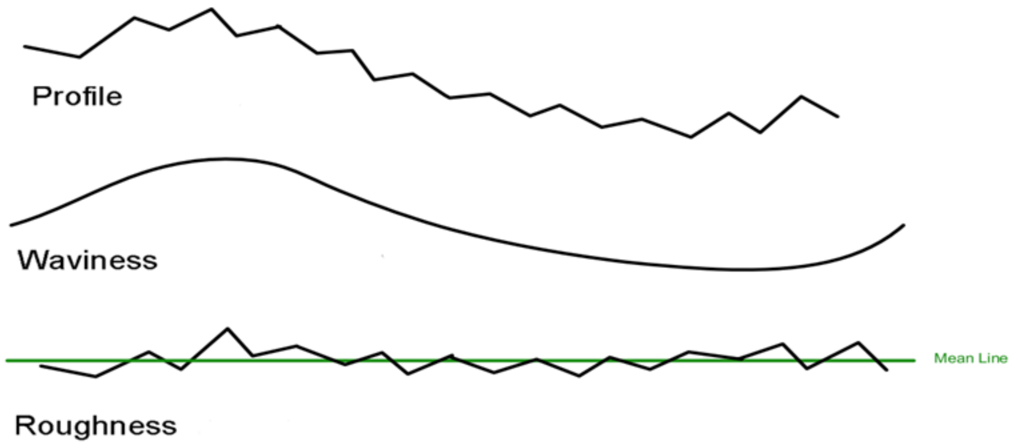

Figure 2. Elements of surface texture; waviness, profile and roughness

(MacKenzie, 2008)

High productivity is one of the most important requirements in the machining process, but high productivity at the cost of poor surface finish and high power consumption is not desirable. Surface topography is of great importance in specifying the functionality and acceptability of a machined component. A significant proportion of component failure starts at the surface due to either an isolated manufacturing discontinuity or gradual deterioration of the surface quality, (El-Hofy, 2013). Typical of the former is the laps and folds which cause fatigue failure, and of the latter is the grinding damage due to the use of a worn wheel resulting in stress corrosion and fatigue failure. The most important parameter describing surface integrity is surface roughness. In the manufacturing industry, surface quality must be within certain limits of roughness. Therefore, measuring surface roughness is vital to the quality control of machined work pieces. Assessment of surface roughness, of machined work piece components, can be carried out by different measurement techniques which constitute either direct or indirect measurement, (MacKenzie, 2008).

Surface roughness is considered as an index of product quality which makes it the most desired outcome along with productivity. A good quality, turned component, surface can lead to improvement in strength properties and functional attributes of parts like friction, wearing, light reflection, heat transmission, coating and ability of distributing and holding a lubricant. Various process parameters have an effect on the ability to obtain the desired surface quality, according to reported studies, (Ranganath & Vipin, 2014). Typically, according to experimental study findings by Kumar & Sharma, (2014) and supported by Gupta & Diwedi , (2014), feed rate was determined as the most dominant factor in influencing surface roughness quality of a component and material removal rate. In concurrence, Thakkar et al, (2014) also established feed rate as the most dominant cutting parameter influencing the surface roughness and material removal rate response parameters. Whereas, research by Digvijay et al, (2017) determined depth of cut as the input factor which most influence surface roughness.

On the other hand, electrical power consumption during machining is of vital importance as it reflects the energy cost effectiveness, or lack thereof, of the machining process. Minimising energy consumption on one machine is of less significance to the whole national power grid, but implementing a technique to minimise the power being consumed during machining on all the machines in the nation state industrial sector is of very high significance, (Liu, Wang , & Liu, 2013). Figure 3 shows the breakdown of the energy use for the Zimbabwe economy in 2009, (Chikoko, Ngundu, & Kupeta, 2018). It is apparent that most of the energy generated was used for Industrial purposes. The energy utilisation partitioning structure had not much changed, observably in the nation to date. Thus, minimising the use of energy in this sector would contribute, considerably, towards reducing energy demand from the national electricity grid by machining-based manufacturing industry.

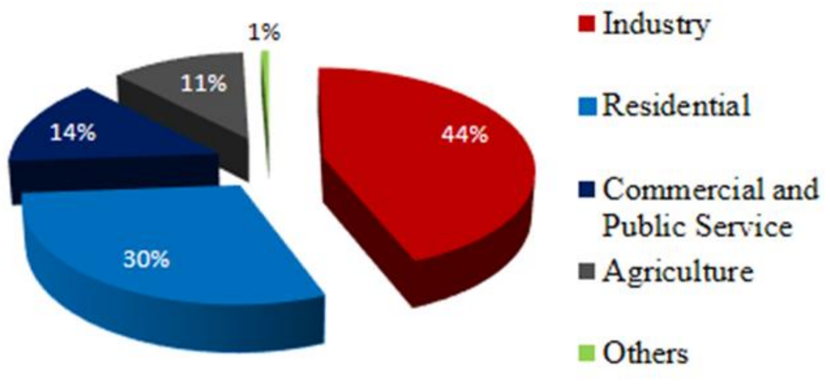

Figure 3. Energy use partitioning for Zimbabwe

(Chikoko, Ngundu, & Kupeta, 2018)

High power demand from the industrial sector means that electricity production should also increase at the power stations. The generation of electric power produces more pollution than any other single industrial sector in many countries, (Rajemi, Mativenga , & Jaffery, 2009). The resource most commonly used for electricity production is coal, which is a fossil fuel and is a non-renewable resource. Almost all of the power plants in developing countries such as Zimbabwe, generate electricity from coal, except one or two Hydro-electric Power plants that uses water, (Stiles & Murove, 2016). Burning of coal creates unpleasant by-products that are not environmentally friendly, changing the planet's climate and harming the ecosystem. Carbon monoxide and nitrous oxides emissions contribute to ground-level ozone, particulate matter pollution, haze pollution in national parks and wilderness areas, causing brown blanket covering clouds in major cities, acid deposition in sensitive ecosystems across the country. Elevated ozone levels persisting throughout the nation states territories could also lead to adverse health effects of smog and millions of dollars in losses through agricultural damage, (Dahmus & Gutowski, 2004).

This research main objective was to experimentally investigate the effect of machining parameters (cutting speed and depth of cut) on surface roughness, MRR, power consumption and energy use as well as to optimize the cutting parameters during the CNC lathe machining of EN24 alloy steel. Taguchi full factorial DOE approach was utilised, in planning the experimental study. Input process parameters – cutting speed and depth of cut – were analysed for their effect on the response parameters of EN24 alloy steel machining – surface roughness and energy use, with the intent to determining optimum input parameter settings which minimise the resultant energy use, surface roughness and maximising MRR of the components from the cutting process.

1.1.1. Material Removal Rate (MRR)

MRR, also termed Metal Removal Rate, by other authorities, refers to the rate at which excess material is removed from a component part, by machining, in a given period of time of the manufacturing operation, (Pouras, 2019). This explains how fast material can be removed by the machining process. Thus, it constitute an important metric of the cutting process, and by which the operation can be optimised. Material Removal Rate constitute one of the metrics very important for any machinist or machining operation to consider optimising (Oosthuizen et al, 2013). This is so noting the fact that the intent of almost any machining activity operation is to subtract material in the generation of the desired component shape. Thus, how fast the material can be removed, without causing other unintended consequences, presents a critical measurement therefore.

According to Oosthuizen et al, (2013) and Isakov (2013), the formula for computing material removal rate (MRR), during turning operation on the lathe machine, is given by equation (1), thus:

$$MRR = D \times S \times F_r. \qquad (1)$$

Where D is the depth of cut (mm), S is the cutting speed (m/min) and F_r is the feed rate (mm/rev).

This study considered the dependence of power consumption, material removal rate (MRR), specific cutting energy (SEC) and surface integrity (as responses) of the cutting speed and depth of cut as input parameters.

1.2 Taguchi Design of Experiments - Factorial Design

Taguchi‘s full factorial design of experiments methodology was employed in planning the experiments in this study. The methodology stresses on the identification and selection of the most optimum set of the operating input parameters which lead to the realisation of reduced costs and enhanced quality of the response parameters of the operation. Design of experiments (DOE) is explained as an efficient and systematic, methodology of investigation that enables researchers to study the relationship between output or response variables as they are influenced by the multiple input factor variables, (Motorcu, 2010). It is a structured technique for collecting data and making findings, in applied statistics, which deals with planning and conducting research, analysing research results, and interpreting controlled trial runs to determine the factors which affect the value of a parameter or group of studied parameters. The DOE which is a technique of defining and investigating all feasible conditions in an experimental setting involving multiple factors is the technique which, in literature, is also referred as factorial design, (Roy, 2010). This concept had been successfully applied in several disciplines such as in optimising agriculture factor inputs to (maximise yields), in the chemical and pharmaceutical industries with positive results, in the hospitality industry for recipe formulations and recently, to a not so very significant extent, in the engineering industry. This research utilised the technique in organising experiments to study and optimise the machining parameters of EN 24 steel material.

2.0 EXPERIMENTAL PROCESS, SET UP AND DESIGN

Typically, in this machining research, cutting speed and depth of cut were optimised to realise advantageous returns on surface roughness and power or energy use consumption. The investigation process involved carrying out external longitudinal cutting tests on EN 24 round billet material specimens of initial diameter 51mm and length 250 mm using coated insert tipped turning tools. The process entailed firstly removing a cleaning layer of 0.5 mm from the top surface of each test specimen as a process of removing potentially problematic exterior surface imperfections on the billet as well as ensuring running concentricity of the specimens during the experiments. The cleaning run, intended to remove eccentricity imperfections, was implemented using a tip which would not be involved in the experiments. An experiment iteration run involved taking a cut of 200 mm long on the specimen linear length at the set depth of cut of 0.4 mm. Energy consumption was monitored and recorded online whilst surface roughness measurements were taken at the end of each cutting run. An experiment iteration was terminated and changed over when the turning tool tip wear had reached flank wear, V_B = 300 μm, in conformity with the ISO standard 3685-1993 (E) - for single point cutting tools, (Oosthuizen, 2013). As such, the tool change and rejection criteria (experiment change) was to reach a localised flank wear greater than 300 micrometers or sudden excessive chipping or fracturing as the tool wear progression was measured at the end of each machining pass of 200 mm length. A new tool tip was used for each experiment. The sensitive Ohaus GA200 mass measurement digital scale, with a measuring accuracy of 0.1 mg, was utilised to measure tool wear after calibration. Material removal rate was computed from considering the cutting parameters set and actual machining time used for each pass. Cutting time was recorded using a digital stop watch on an A60 Itel cellular phone. A total of 16 experiments were conducted and data conducted.

The specimens material chemical composition and mechanical properties, according to the supplier’s certificate, were as shown in Table 1(a) and (b)

Table 1(a) Chemical Composition of EN 24 (weight %)

Material	C	Si	Mn	P	S	Mo	Cr	Ni
Weight %	0.38	0.21	0.51	0.035	0.04	0.25	1.2	1.52

Table 1(b) Mechanical Strength Properties of EN 24

Condition	Tensile (N/mm2)	Yield (N/mm2)	Elongation %	Izod (kCVJ)	Hardness Brinnell
T	870	650	13	35	265

The desired optimal solution is the one which would see the cutting process being least affected by exterior disturbances such as the noise or other environmental conditions, (Vijayesh, Jasvinder , & Gaurav , 2015). Taguchi approach is utilised in a wide variety of applications, including in manufacturing, to design assured quality into a product by optimising input parameters of the generation process, (Ganesan & G. Mohankumar, 2013) due to its easiness in the different fields because of its tolerance. The experiment process control factors variation and levels are shown in Table 2. The dependent variables were energy use or power consumption, material removal rate and surface roughness.

Table 2. Process parameters and their levels

			LEVELS

PARAMETERS	SYMBOL	UNITS	L_1	L_2	L_3	L_4
Cutting Speed	*v*	*m/min*	100	150	200	250
Depth of Cut	*f*	*mm*	0.1	0.2	0.3	0.4
Feed	*d*	*mm/rev*	0.4	0.4	0.4	0.4
Cutting Environment			Dry Turning			

The feed rate was held at a constant value of 0.4mm/rev.

Figure 4 shows the experiment set-up and the lathe machine on which the primary data was generated.

Figure 4. Experiment rig set-up

The turning tool used was an ISO coded right hand tool holder, PSBNR 2020K12,with a PVD method coated right handed insert.The insert type was SNGA 120408. The KY4400 grade tool tip is constituted of the substance for coating the tip, which included mixed ceramic substrate and PVD-TiN coated mixed ceramic with a matrix of Al2O3 (70%):TiC (30%) +TiN,(Kennametal, 2008). The summary details of the cutting tool tip type, used in the experiments, is presented in Table 3. The tool inserts, used in the machining tests are commercially available in accordance with the ISO code and were supplied by Kennametal Inc, as distributed by Sandvik Hardware Distributors in Zimbabwe.

Table 3. Details of the cutting tool, used in the experiments

Type of cutting tool	Coated ceramic tool (KY4400)
Designation	SNGA 120408
Chemical composition of coating materials	Ti(C,N)+TiC+Al_2O_3+TiN
Tool Geometry Feature	Size value specification
Principal cutting edge included angle	80^o
Auxiliary cutting edge angle	10^o
Inclination angle	-6^o
Orthogonal rake angle	-6^o
Orthogonal clearance angle	6^o

In this research paper, the Taguchi methodology of statistical analysis for investigation of the cutting parameters and minimising surface roughness and energy use had been utilised. The effect of the input parameters, depth of cut and cutting speed, were assessed to establish the nature of influence each parameter produce on the response parameter - surface roughness, material removal rate and energy use or power consumption. The Analysis of Variance (ANOVA), in statistics, is the collection of verifiable models and their associated systems, in which the observed vacillation, in a particular variable is apportioned into subdivisions, inferable from diverse fountains of variety, (Thakkar, et al, 2014). Significance of each input parameter (cutting speed and depth of cut) on the response parameters was analysed using the analysis of variance to see which factor had the most effect. The signal to noise (S/N) ratio main effects plot and analysis of variance (ANOVA) techniques of analysing data were utilised in this research. According to Suryawanshi & Inamdar, (2012), the optimum cutting conditions, for a parameter, is indicated at the point where the S/N ratio main effects plot have maximum value while the p-value shows the level of influence of the input parameter on the response parameter.

The machining experiments were carried out on a Sinumeric controller run computer numerically controlled Lathe Machine model, Econo CNC 26. The work piece material used was cylindrical diameter 51 mm EN24 billet. The specimens were prepared into 250 mm length round bars. The cutting conditions are shown in Table 2. The influence of input cutting parameters on the surface roughness and machining power consumption, as response parameters were experimentally investigated and analysed. Optimisation of the process conditions was carried out by applying the ANOVA and the main effects plot S/N ratio to determine the cutting conditions which minimise energy use and surface roughness of the machined components.

3.0 RESULTS AND DISCUSSIONS

Table 4 present a summary of the experiment results. Surface roughness and power use were recorded utilising the measuring instruments whilst material removal rate (MRR) and specific cutting energy (SEC) were computed from the recorded results.

Table 4. Experiment results summary

Expt. No.	Cutting Speed	Depth of Cut	Feed	Surface roughness, Ra	Power	MRR	SEC
	m/min	mm	Mm/rev	Microns	kW	mm^3	mm^3/sec
1	100	0.1	0.4	12.77	2.265	534.04	3.864
2	100	0.2	0.4	19.8097	1.646	1070.3	14.79
3	100	0.3	0.4	21.083	1.835	1589.2	32.063
4	100	0.4	0.4	25.5	2.009	2149.26	59.751
5	150	0.1	0.4	13	2.021	805.86	8.368
6	150	0.2	0.4	13.25	2.284	1607.9	33.751
7	150	0.3	0.4	15.25	2.719	2514.78	82.317
8	150	0.4	0.4	26.933	3.002	3230.42	139.845
9	200	0.1	0.4	11.25	2.591	1034.82	13.873
10	200	0.2	0.4	18.05	3.028	2087.07	55.618
11	200	0.3	0.4	20.3333	3.471	3167.94	132.218

12	200	0.4	0.4	21.5333	3.854	4266.48	232.189
13	250	0.1	0.4	4.27	4.124	1321.41	22.357
14	250	0.2	0.4	17.2667	4.396	2624.84	89.053
15	250	0.3	0.4	24.9167	4.651	3805.54	186.638
16	250	0.4	0.4	26.5	8.995	4784.56	307.096

3.1 Taguchi Analysis of Results

Taguchi techniques, ANOVA and S/N ratio main effects plot, were respectively utilised to determine individually for the response factors, which input parameters have more effect on the response factor and show the individual optimum corresponding input parameter settings in order to obtain the identified performance characteristics on the desired response factor. Both the variability and the mean are considered by the S/N ratio. The Taguchi approach proposed several different S/N possible ratios utilised in order to obtain the optimum operating parameters settings. Two of them were selected and utilised in the present work. These are Smaller the better type S/N ratio for Surface roughness and Energy consumption whilst the Bigger is better S/N ratio for MRR was utilised. The individual parameter optimisation results are presented in the ensuing sections.

3.1.1 Surface Roughness

ANOVA investigative tool was applied to examine the surface roughness response outcome, using the differences examination, in order to distinguish the critical input factors influencing the response parameter measures achieved from the experimental process. The ANOVA results for the surface roughness, at 95% confidence level, are presented in Table 5. The results show that, the p-value of both cutting speed and depth of cut, are less than 0.05, which indicate the input factor significant influence on the surface roughness response parameter. However, the p-value of 0.0421 for depth of cut compared with 0.0501 for the cutting speed, imply that the largest contribution, to the work piece surface finish, is attributed to the depth of cut input factor.

Table 5. Analysis of Variance for Surface, Ra

Source	DF	SS	MS	F	P
Cutting speed	3	11.51	3.835	0.33	0.0501
Depth of cut	3	35.85	11.950	1.04	0.0421
Error	9	103.41	11.490	-	-

Total	15	150.77	-	-	-

The main effect plot for S/N ratio for surface roughness - Signal to noise ratio was by smaller is better. The optimum surface roughness of the EN 24 material machining was attained on cutting parameter settings, respectively, cutting speed of 150 m/min and depth of cut of 0.3 mm as shown on Figure 5, on results of the main effects plot of the S/N ratio. The figure curve profile further confirm the fact that depth of cut is the more significant factor influencing surface roughness during the machining process.

The mathematical expression - modelling relationship the of surface roughness, Ra, with the variable input parameters - was explained and approximated from the Minitab 22 statistical software generated, regression equation, and the result is presented in equation Eq2:

Surface, Ra = 9.71 - 0.0034 Cutting speed + 0.05 Depth of cut (2)

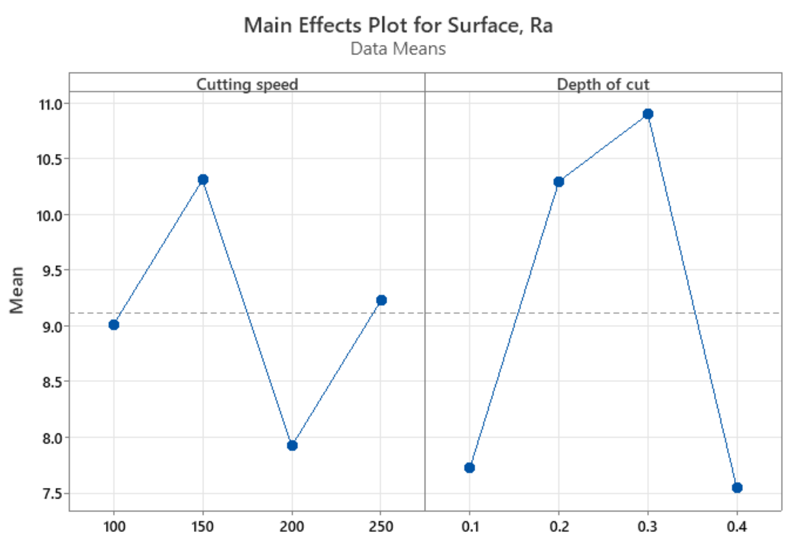

Figure 5. S/N Ratio main effects plot for surface roughness

The surface roughness model summary for is presented in Table 6, where it is apparent from the 71.41% coefficient of determination (r^2) that the model effectively represent the data modeled.

Table 6. Ra Model Summary

S	R-sq	R-sq(adj)

3.38974	71.41%	0.00%

3.1.2 Power Consumption

Results presented in Table 7 is the ANOVA statistical analysis of average power consumption. The ANOVA results show that depth of cut rate is the more dominant factor for power use indicated by a p- value of 0.0362 whilst cutting speed is indicated to be also significant with a p-value of 0.0486.

Table 7. Analysis of Variance for Average Power

Source	DF	SS	MS	F	P
Cutting speed	3	8.292	2.764	0.68	0.0486
Depth of cut	3	11.316	3.772	1.21	0.0362
Error	9	28.156	3.128	-	-

The regression equation modelling average power as a function of the variable input parameters is shown in equation Eq3.

Average power = 4.93 + 0.00130 Cutting speed - 7.41 Depth of cut Eq3

The power consumption regression equation model summary is presented in Table 8, and the model summary coefficient of determination attests to the fact that the model fairly represent the data being modeled with a 58.25% score.

Table 8 Power consumption model summary

S	R-sq	R-sq(adj)
1.76876	58.25%	1.75%

Residual analysis of the developed model was further checked with diagnostic analysis as presented in the residual plots in Figure 6, for power consumption. The residual plots generally lie around the respective straight line which imply near normal distribution of the errors. Thus, from the plot results it can be adduced that the values lie within control range, and not displaying any obvious patterns and unusual structures to insinuate any inadequacy of the model. Thus, therefore these values produce reliable results in the future. These results findings are consistent with the findings by Ranganath & Vipin, (2014).

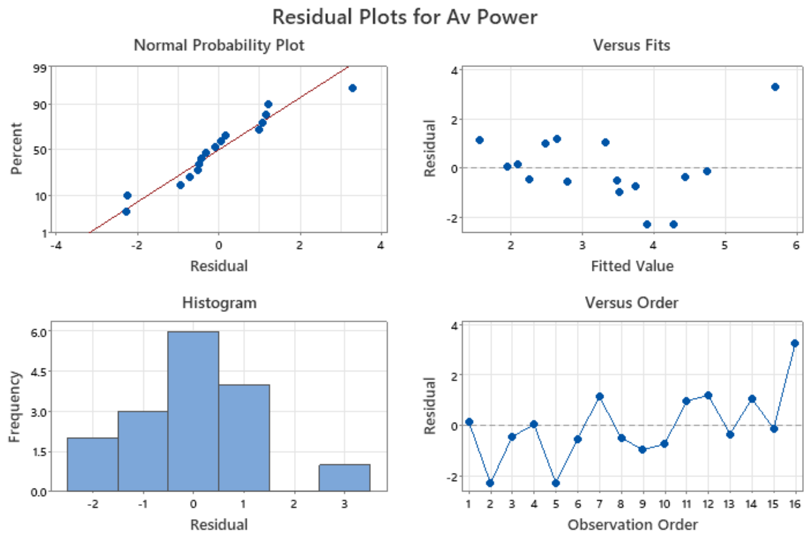

Figure 6. Residual analysis for power use

Figure 7 results present the S/N ratio main effects plot for power use during the machining process. The result display the variation of the power consumption response parameter with the input parameters separately – cutting speed and depth of cut. Shown in the plot x-axis is representation of the value of each input process parameter whilst the y-axis value represent the response parameter. The horizontal line denote the mean of the response. The main effect plots are used to determine the optimum operating parameters in order to assure achievement of the intended response parameters, (Ranganath & Vipin, 2014). According to the main effects plot in Figure 7 using Signal-to-Noise ratio of interest for optimisation for power use - smaller the better, the optimal conditions for minimum power consumption are depth of cut of 0.1 mm and cutting speed of 150 m/min.

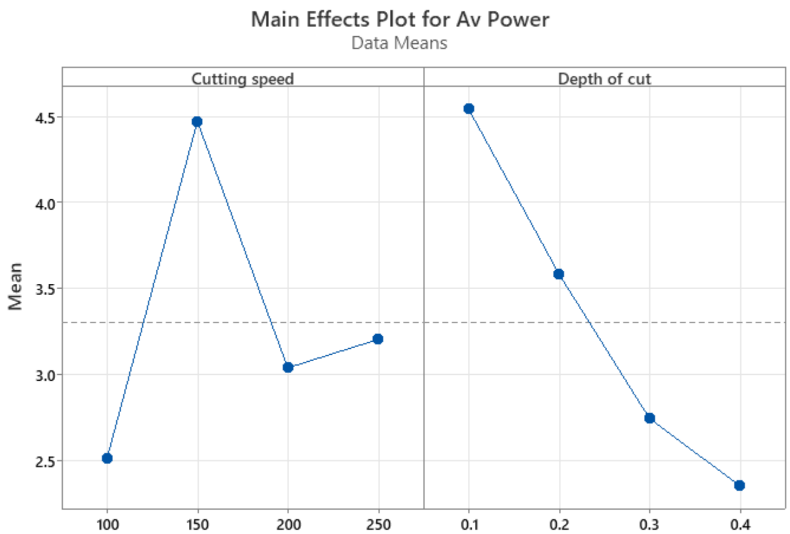

Figure 7. S/N Ratio Main effects plot for power consumption

3.1.3 Material Removal Rate (MRR)

Statistical analysis of material removal rate - through ANOVA as shown in Table 9 - show that both factors – depth of cut and cutting speed significantly influence material removal rate as their p-values are less than 0.05.

Table 9. Analysis of Variance for MRR

Source	DF	SS	MS	F	P
Cutting speed	3	2166061	722020	0.37	0.0578
Depth of cut	3	4716058	1572019	0.80	0.0424
Error	9	17666499	1962944	-	-
Total	15	24548618	-	-	-

The Regression equation, mathematically modelling the relationship of the response parameter, MRR, with the input variable parameters is presented in equation Eq4.

MRR = 2723 + 1.29 Cutting speed - 2648 Depth of cut Eq4

The model summary (Table 10) shows the r^2 value of 78.03% which confirms strong representativeness of the data by the model.

Table 10 Material removal rate model summary

S	R-sq	R-sq(adj)
1401.05	78.03%	0.00%

The residual plot diagnostic checking of the MRR model data, shown in Figure 8, confirmed the normality of the experiment. According to the residual plot graph, the data points are distributed along and near the normal line, which implies a normally distributed result.

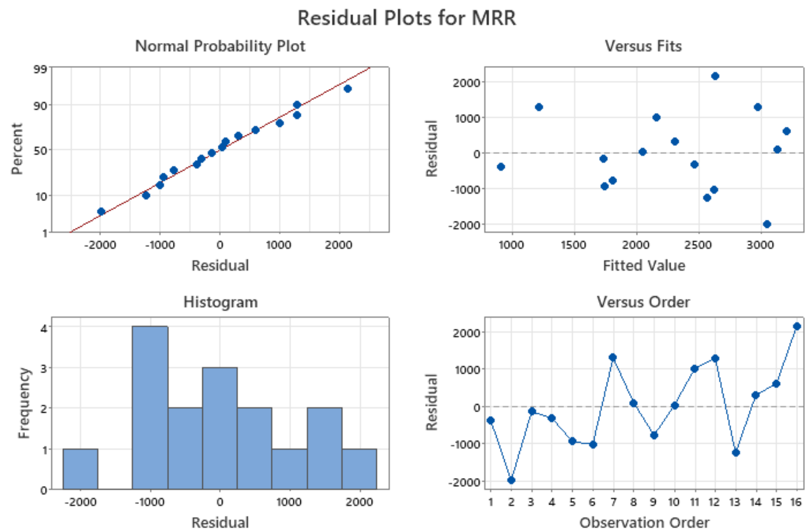

Figure 8. Residual analysis for Material removal rate (MRR)

According to Figure 9, presenting the S/N ratio main effects plot of MRR, the optimum cutting conditions are, respectively, depth of cut of 0.2 mm and cutting speed of 150 m/min.

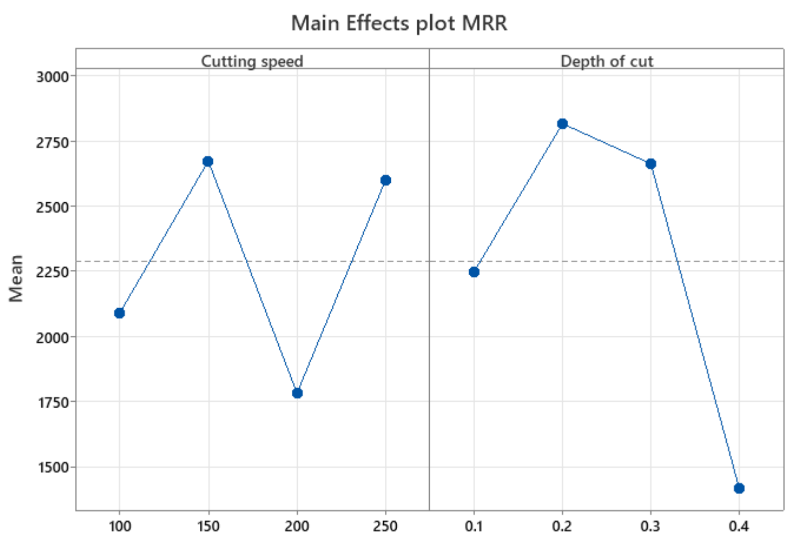

Figure 9. S/N Ratio Main effects plot for Material removal rate

3.1.4 Specific Cutting Energy

Specific cutting energy explain the amount of energy required to remove a unit volume of material. Investigation of the analysis of variance (ANOVA) and the S/N ratio main effect plot were applied, as part of the Statistical analysis process to optimising the cutting parameters in this research. ANOVA results, presented in Table 11, indicate that both cutting parameters – cutting speed and depth of cut - are statistically significant factors in positively influencing specific cutting energy (SEC).

Table 11. Analysis of Variance for Specific cutting energy (SEC)

Source	DF	SS	MS	F	P
Cutting speed	3	15787	5262	0.54	0.0481
Depth of cut	3	16771	5590	0.58	0.0502
Error	9	87142	9682	-	-
Total	15	119700	-	-	-

Regression mathematical model, explaining the relationship of the response parameter – specific cutting energy - and the independent input variable parameters, is presented in equation Eq5.

SEC = 112.1 + 0.148 Cutting speed - 199 Depth of cut Eq5

The model coefficient of determination, 76.96%, shown in the model summary in Table 12, confirms effective representativeness of the data being modeled.

Table 12. Model Summary for SEC

S	R-sq	R-sq (adj)	R-sq (pred)
38.3257	76.96%	75.39%	72.59%

The residual analysis plot diagnostic check, performance results presented in Figure 10, show most of the points generally falling along or scattered around the straight line with no apparent particular pattern, which attests to the fact the errors are normally distributed. Thus it can be concluded that all the values lie within control range. Therefore, consequently, the residual analysis result confirms the model adequacy which mean that these values yield reasonable results in future predictions.

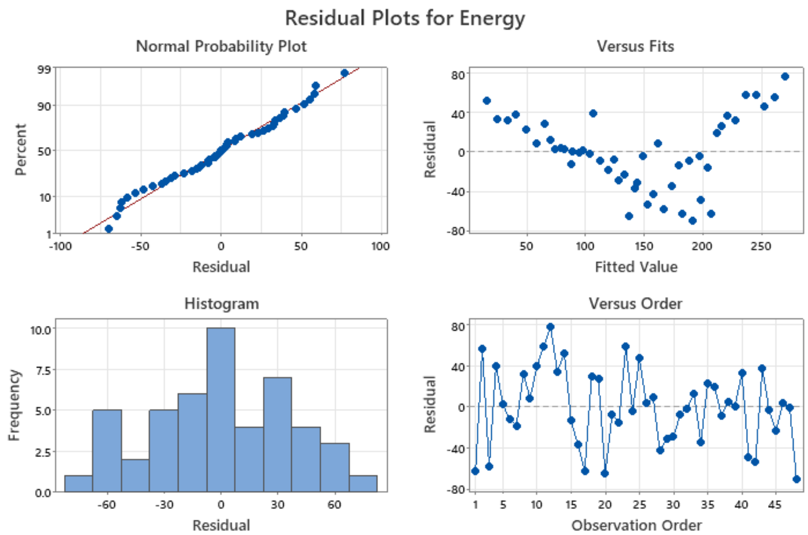

Figure 10. Residual analysis for Material removal rate (MRR)

The optimum operating parameters for SEC are presented the signal to noise S/N ratio main effects plot in Figure 11. A cutting speed of 150 m/min combined with a depth of cut of 0.2 mm would yield optimum specific cutting energy during the cutting operation of EN 24 alloy steel on the lathe machine.

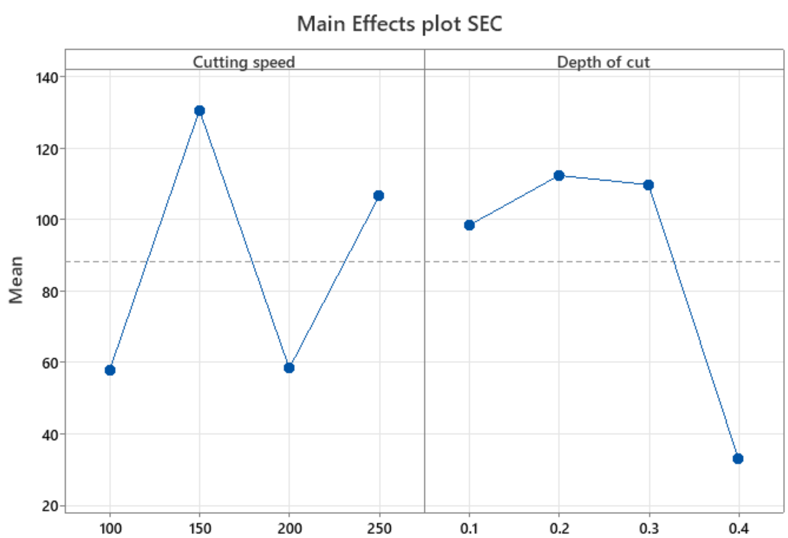

Figure 11. S/N Ratio Main effects plot for specific cutting energy

4.0 CONCLUSIONS

The research work presented an experiment methodology based study on the optimisation of machining parameters for surface roughness and power use during the dry CNC Lathe

machining of EN24 Alloy Steel. Taguchi DOE full factorial design approach was employed to design and planning the machining experiments, whilst the analysis of variance (ANOVA) and signal to noise (S/N) ratio main effects plot techniques were used in analysing the experiment data to determine the optimum cutting conditions. Confirmation experiments were further employed to validate the optimum operating parameters determined by the statistical analysis process.
Pursuant to the experimental investigation and analysis carried out the following conclusions were reached in this research:

Depth of cut is the more dominant variable input factor influencing the surface roughness and material removal rate (MRR) response parameters and the optimum cutting parameters affecting surface quality are 150 m/min cutting speed and depth of cut of o.3 mm/rev. Minimum power consumption is at depth of cut of 0.1 mm and cutting speed of 150 m/min. A cutting speed of 150 m/min combined with a depth of cut of 0.2 mm would yield optimum specific cutting energy. The result from the data analysis have close fidelity with the results derived from the confirmation experiments further validating the effectiveness of the research findings and the regression models generated.

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