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Experimental Investigation and Simultaneous Optimisation of Honing Parameters of Dry Cast Iron Cylinder Relining Sleeves of Motor Vehicle Engine Blocks for Surface Finish and Energy Use

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ABSTRACT

Machining based manufacturing industries consume significant amounts of electrical energy, to power the several modules constituting the machine tool, with low levels of efficiency. Honing operations, are vital machining manufacturing operations, utilised in the motor vehicles engine block cylinders internal surfaces super-finishing process, for improving many functional attributes of the machined cylinders. In an environment of diminished energy generation, bulk electrical energy users, like the machining industry, encounter many pressures to reduce consumption. Electrical energy consumption is a production driver of the ozone layer depleting carbon emissions, from the manufacturing sector. Governments' environmental legislation directives, in collaboration with environmental protection lobbyist groups, added to the ever soaring energy market prices, all exert mounting pressure on the machining industries, such as engine block manufacturers and repairers. Thus, compelling them to consider reducing energy consumption from their operations processes as well as increasing the efficiency of their machining processes. Machining productivity improvement and operation efficiency are influenced by the selection and setting of cutting parameters, during practical operation. In this present experimental study, honing parameters were investigated and optimised with focus on energy use conservation and surface quality enhancement during the machining operation. The L16 experiments were planned using Minitab 19. The three cutting parameters investigated were varied at four levels each. The study results showed the optimum honing parameters combination conditions, respectively, determined for surface roughness, power and total machining energy. The study results confirms that significant Energy could be saved by optimising process parameters at the machining planning stage.

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1. Introduction

Automobile cylinder liner sleeves are the important functional structural cylindrical members which are fitted into the engine blocks interior to constitute the cylindrical interplanetary in which the engine pistons smoothly reciprocate. The structural liner sleeve enables the internal combustion (IC) engine to contain and retain the working fluid enclosed only within this member bore where the piston moves [1]. The liner sleeve material experience and absorbs far higher stress loads (working pressure and thermal gradients) than the rest of the engine block. Hence, its constituting material have high resilience and its manufacturing processes are handled separately, by special operations, from the main casted engine block into which it will be assembled after the inner bore is smoothened by honing. Due to exposure to extreme working conditions, IC engine cylinder sleeve liners require to be replaced before the full life cycle and obsolescence of the engine block. The replacement sleeve liners, which are machined by internal boring and surface polished by honing, are what is termed reliner sleeves in this study.

Honing is a super-finishing micro-material removal machining operation, utilised to eradicate surface flaws such as out-of-roundness, indentations, sagging, tapering, etc, often on interior cylindrical surface components such as hydraulic cylinders; automobile engine cylindrical bores and sleeve liner bores of engine cylinders; bearings; gears; valves and gun barrels, inter alia. The honing operation process removes the surface finish waviness or cutting tool marks and traces during the finishing process of cylinder lining bores so as to size them with the desired surface quality [2,3]. Optimising the honing process had always been a big challenge confronting the automobile components reconditioning industry, particularly, for the mass production of cylinder blocks relining sleeves of internal combustion engines.

The current general practice in the Zimbabwe automotive industry involve application of visual inspection and dial test indicator (DTI) gauging of the surface honed to establish the surface quality feel obtained. In some instances the surface texture is tested by finger rubbing of the honed bore surfaces. This rudimentary testing method will influence the next course of action like having to rerun the honing process or stopping the operation if the expected result is achieved. These kind of activities are what can be considered as the actions approximating efforts to optimise the process in the industry. The cutting parameter conditions are manually estimated through trial–and–error process and the approximate results are realised through a costly process which do not consider the aspect of energy consumption.

During honing operation, excess material is removed from the cylinder bores by the abrading action of the honing sticks radially pressed against the surface to be machined whilst simultaneously experiencing linear reciprocating and rotational motion which generates the lubrication retaining cross-hatch surface texture quality in the honed cylinder inner bores [4,5].

This manufacturing operation constitutes a significant energy intensive machining process in the reconditioning business of motor vehicle engine block cylinder relining sleeves. Generally, the electrical energy powering the machine tool elements, during the components manufacturing process, represents a major source and driver contributing towards the increase in Greenhouse Gasses (GHG) - CO_2- emissions [6,7]. According to study findings [8], the metal cutting sector operations significantly contribute to the total amount of greenhouse gases (GHG) discharged into the surrounding environment. Privy of this fact, in an effort to protect and minimise acceleration of the environmental contamination from GHG emissions, nation state governments had put in place, and are implementing, stringent environmental legislation [9].

The legislation being developed in countries put the energy intensive machining based manufacturing sector under extreme pressure to minimise all environmentally hazardous practices and, inadvertently, avoid having to pay pollution penalties. Further compounding the energy related cost challenge for the metal honing industry is the ever soaring price of procuring electricity required for the machining process. Generation of the appropriate quality surface standard require several repetitive honing (grinding) cycles in the cylinder bore sleeve liners, and that represents significant amounts of electrical energy use per single component.

The surface finish quality of internal combustion engine cylinders have tremendous influence on the most significant functional properties of the engine performance, such as fatigue endurance, wear resistance between the cylinder lining and the piston rings as well as reduction of friction induced power losses [10]. Bad cylinder liner inner bore surface quality leads to premature rapturing of the oil films at the micro irregularity peaks of the cylinder bore interior during the engine operation. This leads to a state approaching dry friction within the combustion cylinders and resulting in the sliding surfaces decisive wear [11,12]. Thus, the honing process is employed to obtain very high surface finish standards in engine cylinder blocks.

The aim of this research was to generate, experimentally, clear understanding of the engine block cast iron cylinder relining sleeves honing process with the intent to identifying key adjustable process parameters which influence the desirable outcome of the cross-hatch surface finish quality (Figure 1) and reduced energy consumption. Further still the study aimed to establish the parameter optimum setting levels which would return these desired machining process outcomes (demanded sleeve inner bore surface texture and reduced energy use) efficiently, for the honing machining operation. Like most other machining operations, honing consumes significant amounts of energy which is attributable to the material separation activity operation and to the various machine tool modules constituting the integrated efficient machine tool running. Cutting parameters are the critical variables which the operatives manipulate and set on the machine tool in order to change the productivity rate during practical machining operations [13,14].

The cutting parameters are varied in accordance with the requirements of the workpiece material condition, machine tool condition [15] as well as the broader goal intention such as to obtain specified attributes on the component and say enhancing the energy efficiency of the machining operation or minimising production costs or maximising returns.

Many studies have been conducted with the intention to improve the performance of the internal combustion engine and enhancing its fuel economy, in a number of ways. For example Puoza et al [12], researched on post-treatment optimisation of honing parameters of the engine cylinder bores in an effort to eliminate slags generated by coarsening the laser treated surface and minimising the running-in period of engines and avoiding harsh rubbing wear. Risse et al

[13] investigated the impact of various abrading stone types and finish textures on the surface tribological running behaviour of internal combustion engines.

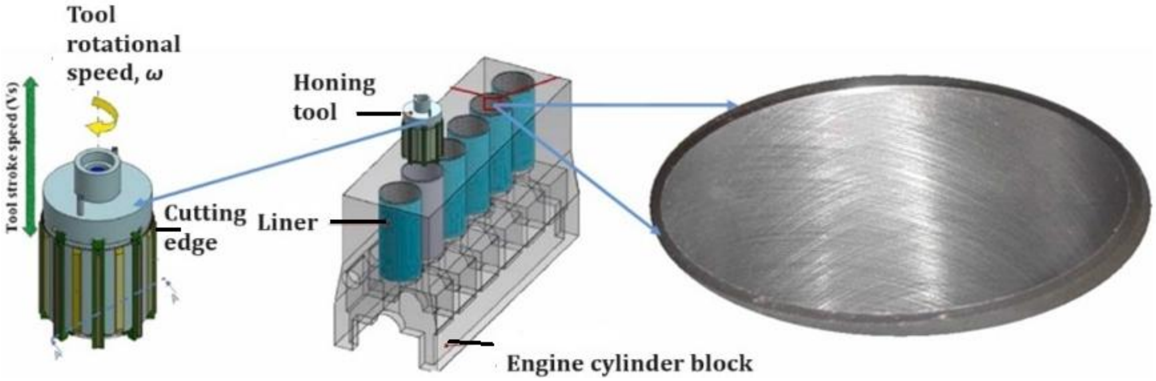

Fig. 1. Engine cylinder block honing process schematic view with cross-hatch surface quality.

Kang, et al [14] optimised cylinder surface topography with the intention to minimising engine oil and fuel expenditure by means of laser smoothening of internal combustion cylinder surfaces. In a study about honing process optimisation, Khang et al [14] and Saljé and von See [15] researched the effect of abrading stone topography impact on surface quality and cylinder surface texturing effect on on the sustenance of the cylinder surface roughness on oil expenditure respectively. The study determined cutting speed as a key influential factor of the process. Sadizade et al. [16] recommended applying advanced designed surface roughness texture in cylinder bores so as to promote oil retention and minimising wear and sliding friction as well as minimising oil consumption within the internal combustion engine cylinders as attempts to improve engine performance. Oda, et al. [17] proposed the enhancement of energy consumption minimisation through process improvement of machining operation. This is so because elevated electrical energy consumption is associated with escalated costs of products manufacturing particularly from energy intensive operations such as machining [10,17].

Therefore in an effort to minimise production costs, machining businesses such as honing operators strive to identify ways of reducing energy consumption anticipating to, inadvertently, reduce costs of their manufactured products. Costs reduction of manufactured products had given impetus to several recent studies. However, not many studies are readily available, published on the honing process costs containment through simultaneous operating parameters optimisation consideration with the intent to improve surface quality and energy use minimisation.

Typically, this study purpose is intent on determining the input parameters which impact the achievement of the desired surface quality standard energy efficiently, using the Analysis of Variance (ANOVA), as well as establishing the optimum setting levels which most likely yield the intended outcomes on the machined component by utilising the signal-to-noise (S/N) ratio main effects plot, available in Minitab 19 software. Determining the parameter settings which could return these responses from the experimental investigation is a deliverable outcome of this study. ANOVA and main-effects-plot optimisation process was performed at the 95% confidence level. The assumption adopted in carrying out this experimental investigation was that appropriate honing energy use levels and the attainment of good cylinder liner surface quality, essentially, hinges on the appropriate process parameter settings selection on the machine tool [18]. According to Tang et al [19] and Noordin et al [20], practical modelling could be required to provide clear understanding of the machining processes and estimate the character of its output. This derives from the realisation that understanding the behaviour of a manufacturing process influences the ability of stakeholders to continuously improve its operating efficiency and effectiveness.

2. Research significance

The study importance is vested in the research intention to establish the optimum operating conditions for the energy efficient honing of engine block cylinder sleeve liners to the desired surface quality standard. The determined optimum honing parameters are expected to provide additional technical information solution to enhance the machining industries productivity through, consistently and reliably, achieving the intended surface quality results energy efficiently from the finishing honing process. In research terms, this small contribution, builds up onto the existing knowledge body about the machining science of engine block cylinder relining sleeves [10].

3. Experimental process

The research experimentally investigated the possibility of maximising the opportunity for good surface quality generation on internal combustion (IC) engine block cylinder sleeve liners and simultaneously minimising the production cost by utilising minimum amount of electrical energy in executing the honing super-finishing operation. Cutting parameter optimisation was employed in an attempt to attain this twin set of goals. The experimental study is intended to generate information which fosters understanding of how the honing process input variables (tool radius of rotation, cut depth and spindle speed) affect the output performance outcomes of process energy consumption and surface quality, by respectively characterising them. It was deemed essential to establish the extent to which input process parameters influence the response parameters and in what way they do so.

In this current research, honing machining experiments were carried out on FG-2601, a close grained pearlitic cast iron alloyed with chromium; molybdenum; vanadium; phosphorous; Nickel; Sulphur; Silicon and Manganese. The cylinder liner sleeve material inner surface was heat treated - normalized and shot blasted - in order to achieve smooth and hardened surface. The graphite content available in the cast iron helps with lubrication whilst the alloying elements helps with corrosion resistance and wear resistance improvement at elevated temperature [19]. The sleeve liner dimensions were bore diameter 96.00 mm and linear length, 86.41 mm. The specimens material composition is presented in Table 1.

The honing experiment runs design plan was created by utilising the Taguchi L16 orthogonal array experiments design plan (DOE), available on Minitab 19 software which also was applied in analysing the gathered primary data. Table 2 show the parameters and the setting levels considered. 16 out of the possible 64 experimental space were carried out. The process involved varying the three input parameters as the output responses - energy use and surface roughness quality, of the liner sleeves - were being monitored and recorded. The experiment process flow chart is presented in Figure 2.

Table 1
Element components configuration of cylinder liner sleeve specimens.

Component	% Content
Carbon	3.14
Silicon	2.1
Manganese	0.62
Phosphorous	0.49
Chromium	0.22
Molybdenum	0.13
Sulphur	0.06
Nickel	0.05
Iron	balance

Table 2
Experiment parameter conditions and level settings.

Process parameter	Setting levels variation			
	1	2	3	4
Spindle speed (rpm)	125	170	230	310
Tool path diameter	87.6	88.4	100.85	107.3
Cut depth (mm)	0.05	0.025	0.075	0.1

The honing tool used, in this study, is a finishing stone number EHU 525-FY. Castrol Honilo 981 honing oil was used as the coolant. The experiment operation was carried out on the 310 rpm maximum spindle speed Sunnen CV-616E Cylinder King vertical honing machine shown in Figure 3.

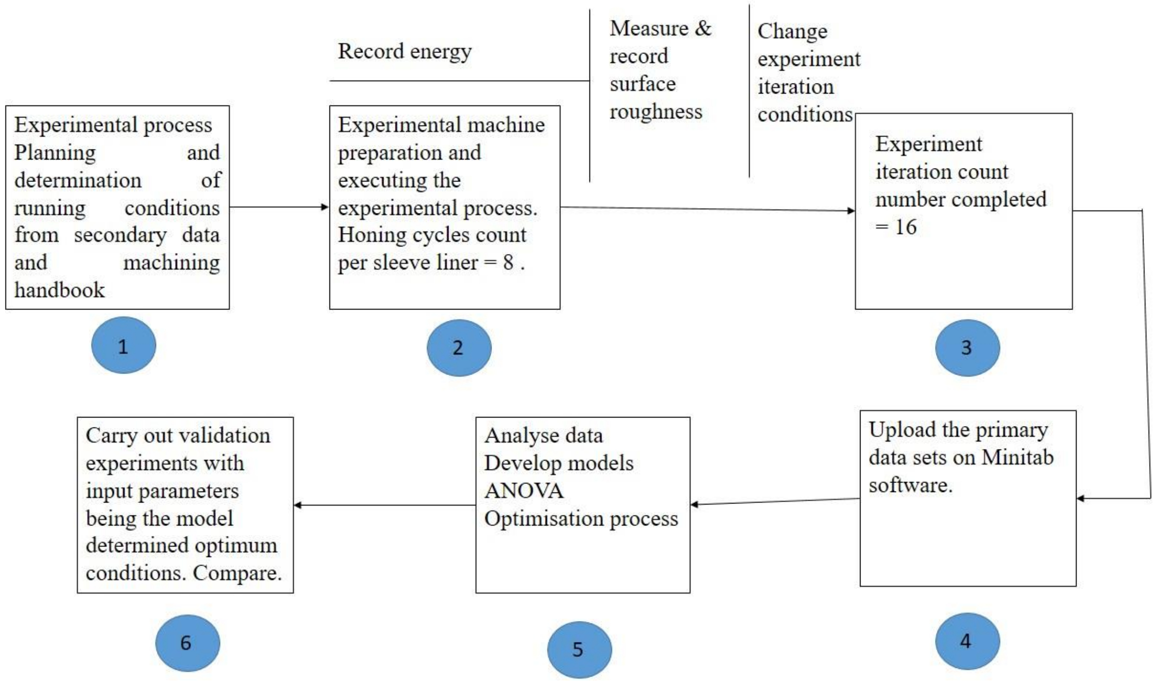

Fig. 2. Research process experiment flow chart.

Fig. 3. The Cylinder King, Sunnen CV-616, vertical honing machine.

The abrading stone used was #580 grit silicon carbide vitrified bonded abrasive. Surface quality measurement were conducted using the internal bore measuring hommel etamic perthometer – calibrated in accordance with the ISO 12179 standard - and electrical energy measurements were recorded by employing the three phase digital Lutron Power meter/analyser (Figure 4). The average surface roughness parameter (R_a) was measured as the surface quality attribute in this research. The surface measurement tool used had a 2 µm diameter diamond stylus in conformity with the IS0 3274:1996(E) standard. The tool have a resolution of, respectively, 0.5 µm in length and 7 nm in height. Measurements were done at a speed of 0.5 mms^{-1} accordingly in line with the standard [21]. The ISO 4288 standard was applied in guiding the measurement process. Accordingly, the measurement length was 5.6 mm whilst the evaluation length was 4 mm. Each experiment iteration run comprised eight (8) honing cycles at the end of which an average of five (5) surface texture measurements was recorded for each parameters setting. Thereafter which the settings would be adjusted for the next experiment. Electrical energy measurements were recorded live online as the honing was being carried out.

Fig. 4. Lutron three phase digital power analyser.

3.1 Modelling and optimisation process: ANOVA and S/N ratio

Statistically, examining variation between the data means, ANOVA, was employed to assess the substance of the impact of the variable input process factors - after a sequence of experiment results - on the response factors, in the design of experiments research plan [22].

In researches, ANOVA scrutiny is used to examine and establish the influence of the independent variable factor inputs on the dependent factors. ANOVA determination is utilised assess the significance of the disparity between data group averages, the discrepancy subsisting is utilised to establish if the averages are not the same. Variance analysis of examines the proposition that averages of atleast 2 grouped data averages are similar. The null supposition hypothesise similarity of all the population averages (level of factors), whereas, the alternate proposition assert that at minimum one is dissimilar. The significance of the parameters is evaluated through making comparison of the response factor means at distinct levels [20].

The adjustable input process factors were utilised to develop the mathematical representation models of the respective required process. Analysis of variance examinations can be either one-way or two-way. The former assesses the characteristic of population averages when categorisation is by singular factor variable which, generally, have atleast 3 levels. The levels denote applied treatment. Assessment of dissimilarities of the averages, utilising several resemblances stands feasible with the procedure of the one-way. A single-way analysis of variance using dual levels is comparable with a t-test [22]. When categorisation in handling population average is through dual factor variation, then, a two-way ANOVA is employed in performing the characteristic assessment. The data must be balanced in a two-way ANOVA. There must be similar number of cell observations as the number of fixed factors, in balance. The variable input parameters in this research were tool radius of rotation, spindle speed and cut depth. The confidence level at 95% was considered, wherein factors were considered significant if the p value subsisted at five hundredth or less, in the assessed range.

S/N proportionate relation articulates the affiliation between the average value (signal) and the standard variation (commotion setting disturbance). This subsists as the numerical performance gauge utilised to choose the preeminent levels of control which most likely endure the noise factors with lowest discrepancy consequence or influence on the process results. Elements of control that minimises the unpredictability in the operation activity are determined by way of measuring the robustness that is realised in abating the impact of the uninhibited disturbance factors. It is more convenient to control noise factors during the planning than attempting to control it during processing. Elevated S/N ratio readings signal control factor locations where the factors noise effect is minimised. The signal-to-noise ratio determines, in what way, the response changes comparative to the nominal value or target under distinctive noise conditions. By and large, three groupings of performance characterisation employed in analysing the S/N ratio are the smaller-the-better, nominal-is-best and the larger-the-better [22]. The different feasible S/N ratios contemplated in this investigation were [20]:

(a) Characteristic, biggest-is-best quality, provided by computation formula (1), thus:

$$SN_B = 10log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_1^2}\right] \tag{1}$$

Wherein, y_i represents the significance of the i^{th} attribute feature and the experiment test numbering is represented by n .

(b) The Quality characteristic, nominal is the best, is presented in Equation (2):

$$SN_T = 10log\left[\frac{y^{-2}}{S^2}\right] \quad (2)$$

(c) The smallest is best quality factor, as given in Equation (3)

$$SN_S = 10log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (3)$$

Signal-to-noise ratio data examination should establish the unsurpassed optimal settings of the operational strategy (tool radius of rotation, cut depth and spindle speed) in the mandate towards achieving the anticipated honed cylinder liner sleeve surface quality at smallest amount of energy expenditure. The optimal operational settings condition are attained by choosing the conditions that provides the greatest scale readings of the S/N proportionate relation. This stands achieved by employing the graphical plot of the main effects, S/N relation ratios [22]. In the present research, the performance excellence is amplified through minimalising the surface feel texture roughness along with energy expenditure prerequisite of the polishing process. Accordingly, the smallest is best quality attribute was utilised.

4. Results and discussion

Results collation presented in Table 3 summarises the experiment process record. The response factors - Surface texture roughness quality, electrical power and energy were recorded by utilising the respective measuring instrumentation indicated in the experimental process.

Table 3
Experiment results summary.

Iteration No.	Spindle speed	Depth of cut	Tool path radius	Ra (μm)	Electrical Power (kW)	Run Time(Sec)	Energy (x10-3kWh)
1	125	0.050	87.60	0.933	2.681	3.73	2.78
2	125	0.025	88.40	0.947	2.626	7.60	5.54
3	125	0.075	100.85	1.158	2.981	16.41	13.59
4	125	0.100	107.30	1.268	3.311	21.88	20.13
5	1702	0.050	88.40	1.132	2.638	3.73	2.73
6	1702	0.025	87.60	1.118	2.571	7.46	5.33
7	1702	0.075	107.30	1.453	3.122	16.41	14.23
8	1702	0.100	100.85	1.343	2.975	21.88	18.08
9	230	0.050	100.85	1.590	2.981	5.47	4.53
10	230	0.025	107.30	1.700	3.318	10.94	10.08
11	230	0.075	87.60	1.365	2.632	11.19	8.18
12	230	0.100	88.40	1.378	2.669	14.92	11.06
13	310	0.050	107.30	2.028	3.189	5.47	4.85
14	310	0.025	100.85	1.919	3.122	10.94	9.49
15	310	0.075	88.40	1.707	2.571	11.19	7.99
16	310	0.100	87.60	1.694	2.571	14.92	10.65

4.1 Taguchi DOE results analysis

4.1.1 Surface roughness texture quality, Ra

The surface roughness texture quality response outcome was investigated by applying the ANOVA analytical tool, using the mean differences examination, in order to establish the critical input factors influencing the response parameter, surface roughness, measure achieved from the experimental process. The ANOVA, at 95% assurance level, results, with regard to the surface ruggedness are, indicated, presented in Table 4. The p value results reveal that, both, the spindle speed and tool path radius of rotation, are less than 0.05 - being 0.000, which indicate that both these input factors significantly influence the surface roughness response parameter. However, the p value of 0.740 for the cut depth, imply that this input factor has insignificant influence on the work piece surface finish.

Table 4
Surface roughness ANOVA.

Source	DF	Adj SS	Adj MS	F Value	P Value
Spindle speed	3	1.29916	0.433052	2969498.71	0.000
Cut depth	3	0.000000	0.000000	0.43	0.740
Tool path radius	3	0.32284	0.107615	737928.43	0.000
Error	6	0.00000	0.000000		
Total	15	1.62200			

The regression model expressing the mathematical dependence affiliation of the surface coarseness, Ra, to the variable input factors was developed in Minitab 19, statistical software. The regression model, is presented in Equation (4):

$$\text{Surface roughness, Ra} = 0.087438\ \text{Spindle speed} - 0.000062\ \text{Depth of cut} + 0.081687\ \text{Tool path radius} \quad (4)$$

Table 5 presents the summary model, results, of surface roughness. It is apparent, from the 100% coefficient of determination (r^2), that the model effectually represent the modelled data. Results presented in Figure 5 show the surface roughness normal probability plot. It is apparent that the data points approximate symmetrical distribution, of the data, about the diagonal line, which fact points to near normal distribution.

Table 5
Summary model of surface ruggedness (R_a).

S	R sq	R sq(adj)	R sq(pred)
0.0003819	100.000%	100.000%	100.000%

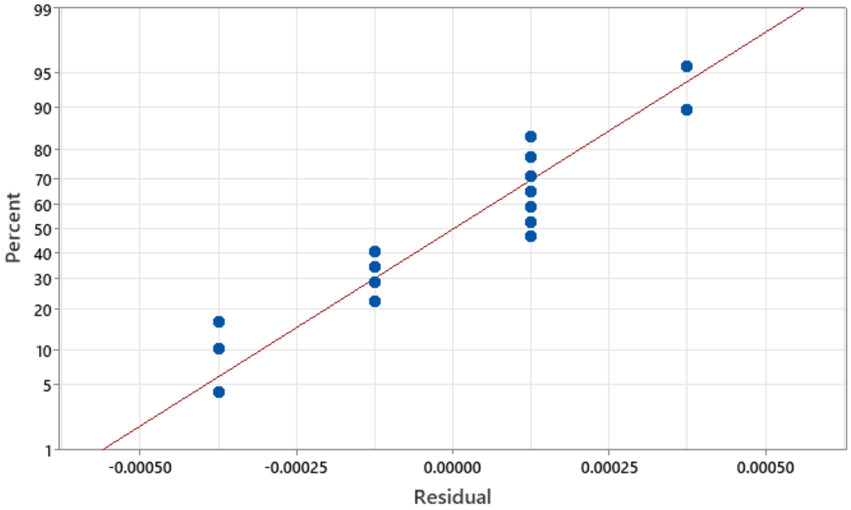

Fig.5. Ra normal probability plot of the response parameter.

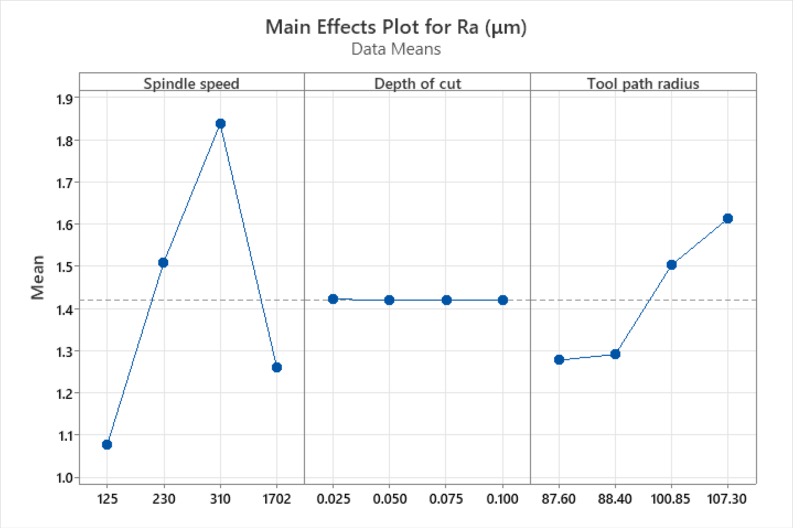

Fig. 5. Surface texture quality S/N ratio main effects plot.

The MEP S/N ratio, of the surface roughness texture quality, -was by smaller is better, according to Equation (3). The optimum surface roughness texture quality of the cylinder sleeve liner honing was attained on cutting parameter settings, respectively, spindle speed of 310 rpm, tool path radius of 107.30 mm whilst depth of cut had no significant impact. See results presented in Figure 5, the MEP of the S/N relation for the surface roughness texture quality.

4.1.2 Electrical Power

Results presented in Table 6 show the, Minitab 19, ANOVA statistical analysis of the average power consumed during the honing process. The three input variables comprise p values below 0.05. Thus, implying that the entered variable parameters hold considerable sway on the dependent parameter, power consumption. The levels of dominance of the factors influence are different, however, as shown by the different p-values, respectively as follows: tool path radius of rotation appear the most dominant influential factor showing a p-value of 0.000. This is followed by the spindle speed factor with a p-value of 0.0426 whilst the cut depth bears the value of 0.0442, as presented in the experiment results indicated in Table 6.

Table 6
Total operating Power ANOVA.

Source	DF	Adj SS	Adj MS	F Value	P Value
Spindle speed	3	0.01480	0.004934	14.03	0.0426
Cut depth	3	0.01419	0.004730	14.08	0.0442
Tool path radius	3	1.11742	0.372473	81.42	0.000
Error	6	0.02745	0.004575		
Total	15	1.17386			

The regression model of electrical power consumption mathematical relationship with the variable independent parameters is shown in computation formula (5).

$$\text{Electrical Power (kW)} = 0.0276 \text{ Spindle speed} + 0.0249 \text{ Depth of cut} - 0.2464 \text{ Tool path radius} \quad (5)$$

The power consumption regression equation model summary is shown in Table 7, and the model summary coefficient of determination of 97.66 score attests to the fact of the model's firm representativeness of the data considered.

Table 7
Electrical energy rate of transfer (power) model summary.

S	R-sq	R-sq (adj)	R-sq (pred)
0.0676363	97.66%	94.15%	83.37%

Results of the S/N ratio main effects plot for the electrical energy rate of transfer (power) are shown in Figure 6, where-from the optimum cutting conditions for power are read as 107.30 mm tool radius of rotation, 0.025 cut depth and 230 rpm spindle speed.

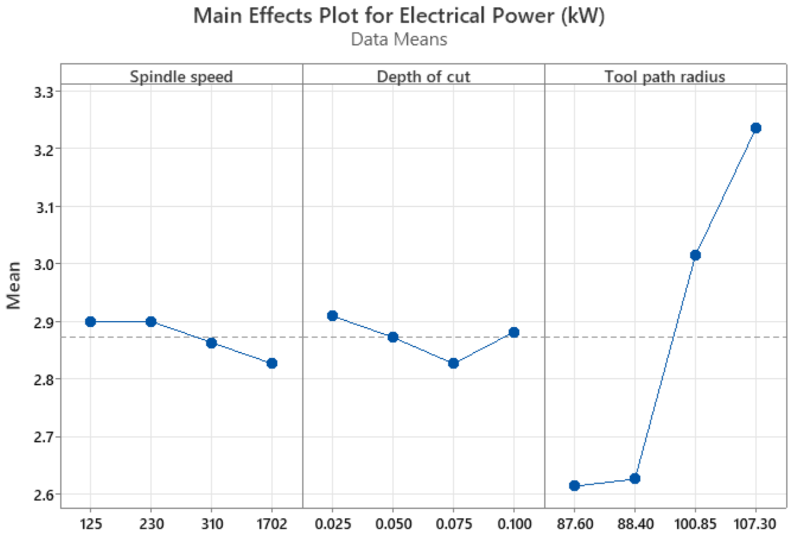

Fig. 6. Electrical energy transfer rate S/N ratio main effects plot.

4.1.2 Electrical energy

Electricity energy embodies the aggregate quantity of expended energy. It is quantified in kilowatt-hours or joules. During the experiment process, electrical energy was, online recorded, using the three phase digital energy meter. Results of the ANOVA for electrical energy expenditure are indicated in Table 8. It is apparent, from the ANOVA results that all three input factors have significant influence on the response parameter.

Table 8
Analysis of Variance for Electrical Energy expenditure (kWh).

Source	DF	Adj SS	Adj MS	F Value	P Value
Spindle speed	3	15.614	5.205	4.86	0.048
Depth of cut	3	276.422	92.141	85.95	0.000
Tool path radius	3	105.270	35.090	32.73	0.000
Error	6	6.432	1.072		
Total	15	403.738			

Equation presented in (6) is the mathematical modelling of the electrical energy consumption of the honing process activity, whilst the 98.41% coefficient of determination value (Table 9) confirms the strong representativeness of the data by the model.

Energy (x10-3kWh) = 1.182 Spindle speed - 1.718 Depth of cut -1.718 Depth of cut - 2.592 Tool path radius (6)

Table 9
Electrical Energy expenditure model summary.

S	R sq	R sq(adj)	R sq(pred)
1.03536	98.41%	96.02%	88.67%

The S/N proportionate relation main effects plot of electrical energy expenditure is indicated in Figure 7. Readable from the plot are the optimum honing process input parameters which are cut depth setting of 0.100 mm, tool radius of rotation of 107.30 mm and spindle speed of 125 revolutions per minute.

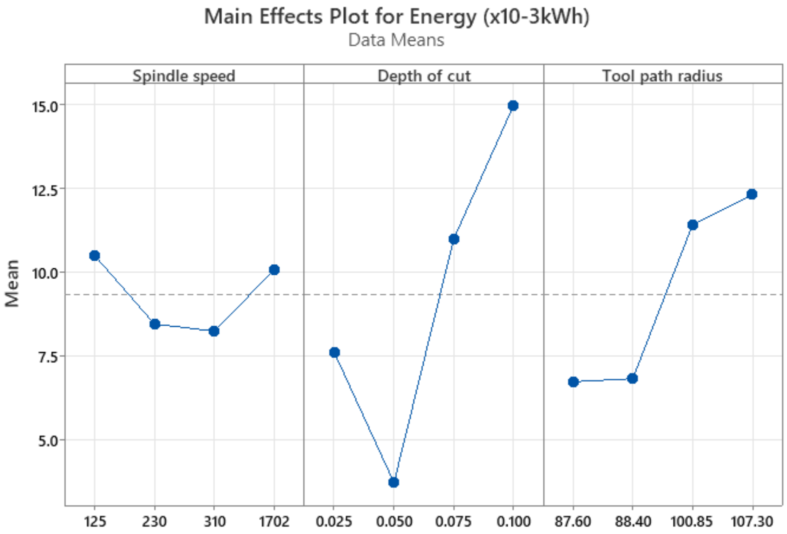

Fig. 7. Electrical energy expenditure S/N ratio main effects plot.

4.1.4 Validation test

Once the optimum cutting conditions were established, from the computational models, the determined cutting parameters were set on the machine and test runs were conducted. The obtained validation test results are presented in Table 10. The variability level of less than 10% for all the measured response parameters confirm functionality of the model in predicting, effectively, the cutting variable factors to set on the honing machine.

Table 10
Validation experiment results summary representation.

Driving performance parameter	Optimal process parameter settings and responses						Analytic Model and Validation experiment result variability
	Optimum input parameters			Response	Optimal value		
Surface roughness	S (rpm)	TRR (mm)	D (mm)		Model	Confirmation Experiment	
	310	107.30	0.075	Microns (µm)	1.582	1.628	2.91%
Power consumption	230	107.30	0.025	kW	2.71	2.93	8.12%
Energy expenditure	125	107.30	0.100	kWh	8.21	7.89	3.9%)

5. Conclusion

The study presented results of the design of experiments methodology based investigation in the optimum cutting parameters determination, for energy conservation and surface quality enhancement during the dry honing of Cast Iron sleeve liners for motor vehicle engine blocks. Taguchi DOE L16 orthogonal array experiments planning, was employed in organising the abrading experiments. Analysis of variance (ANOVA) and signal to noise (S/N) ratio main effects plot techniques were ustilised in analysing the experiment data to, respectively, establish most influential process input factors and determining the optimum cutting conditions. Validation tests were further carried out by setting the analytically established optimum honing parameters on the honing machine. Subsequent to the experimental investigation and evaluation conducted, the following conclusions were gotten in the exploration:

The input factors, spindle speed and tool path radius of rotation are the more dominant variable input parameters impacting the three response factors – power and energy consumption as well as surface texture quality. Whilst depth of cut, input fact, had insignificant influence of the response factor – surface texture quality whilst significant impact on power and energy. The determined optimum cutting parameters for the cost effective energy efficient honing process of the engine block cylinder reliner sleeves are, respectively, 310 rpm spindle speed, 107.30 mm TRR – for enhanced surface texture quality; 230 rpm spindle speed, 107.30 mm TRR and 0.025 mm depth of cut – for optimum power consumption; and 125 rpm spindle speed, 107.30 mm TRR and 0.100 mm depth of cut – for optimum energy utilisation during the honing process. Validation results show that the determined optimum operating (cutting) strategy can be applied, by the automotive manufacturing communities, in the honing process of engine block sleeve liners machining on machines of a compatible nature beyond the experimental machine.

Future research involves:

- Integration of these findings with an environmental impact assessment, such as computation of the associated reduction in greenhouse gas emissions in an effort to further contextualise the study's significance in addressing broader environmental concerns.

- Investigating the stone wear evolution and reconditioning influence of the honing tool on surface texture quality and energy consumption.

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Conflicts of Interest

The researchers were not conflicted in any way in this study.

Authors contribution statement

Nicholas Tayisepi: Idea conceptualisation, data analysis, research experimental planning and implementation, authentication, research methodology interpretation, report development and reviewing of the process and detail.

Lameck Mugwagwa: Research methodology expergoration, process coordination, draft proof reading and final references structuring.

Takudzwa M Muhla: Data analysis, project administration, graphics generation, draft editing.

Albert N Mnkandla: Data preparation for easy of readability, experimental process, resources mobilisation, proof reading draft.

Innocent Mapindu: Softwares procurement and management, drafting, experimental process.

References

[1] Dzyura V, Maruschak P. Optimizing the formation of hydraulic cylinder surfaces, taking into account their microrelief topography analyzed during different operations. Machines 2021;9:116. https://doi.org/10.3390/machines9060116.

[2] Günay M, Korkmaz ME. Optimization of honing parameters for renewal of cylinder liners. Gazi Univ J Sci 2017;30:111–9.

[3] Vates UK, Sharma S, Mittal VK. Optimisation of honing process parameters for reducing surface roughness and power consumption on grey cast iron (FG-260I). Int J Addit Subtractive Mater Manuf 2017;1:67–81. https://doi.org/10.1504/IJASMM.2017.082987.

[4] Jayasimha SLN, Lingaraju KN, Raju HP. Modelling of as bored surface of Inconel-625 alloy using unidirectional extrusion honing process. Mater Today Proc 2022;52:993–7. https://doi.org/10.1016/j.matpr.2021.10.464.

[5] Tayisepi N. Towards Goal Programme optimisation of machining parameters during the production of Ti-Alloy components. Zimbabwe J Sci Technol 2020;15:101–15.

[6] Lu F, Zhou G, Zhang C, Liu Y, Chang F, Xiao Z. Energy-efficient multi-pass cutting parameters optimisation for aviation parts in flank milling with deep reinforcement learning. Robot Comput Integr Manuf 2023;81:102488. https://doi.org/10.1016/j.rcim.2022.102488.

[7] Pervaiz S, Deiab I, Rashid A, Nicolescu M, Kishawy H. Energy consumption and surface finish analysis of machining Ti6Al4V. Int J Ind Manuf Eng 2013;7:535–40.

[8] Sarkar S, Kumar CS, Nath AK. Effects of different surface modifications on the fatigue life of selective laser melted 15–5 PH stainless steel. Mater Sci Eng A 2019;762:138109. https://doi.org/10.1016/j.msea.2019.138109.

[9] Bolander NW, Steenwyk BD, Sadeghi F, Gerber GR. Lubrication regime transitions at the piston ring-cylinder liner interface. Proc Inst Mech Eng Part J J Eng Tribol 2005;219:19–31. https://doi.org/10.1243/135065005X9664.

[10] Zhou L, Li J, Li F, Meng Q, Li J, Xu X. Energy consumption model and energy efficiency of machine tools: a comprehensive literature review. J Clean Prod 2016;112:3721–34. https://doi.org/10.1016/j.jclepro.2015.05.093.

[11] Lee B., Tarng Y. Cutting-parameter selection for maximizing production rate or minimizing production cost in multistage turning operations. J Mater Process Technol 2000;105:61–6. https://doi.org/10.1016/S0924-0136(00)00582-3.

[12] Puoza JC, Zhang T, Uba F, Kuusana Y, Ibrahim A. Optimization of post-treatment honing parameters of laser textured engine cylinder bore and engine performance. J Eng Res 2023;11:478–87. https://doi.org/10.1016/j.jer.2023.100100.

[13] Risse K, Schorgel M, Bartel D, Karpuschewski B, Welzel F. Resource-efficient piston ring/cylinder liner pairing. Ind Lubr Tribol 2019;71:154–63. https://doi.org/10.1108/ILT-06-2018-0250.

[14] Kang Z, Fu Y, Zhou D, Wu Q, Chen T, He Y, et al. Reducing engine oil and fuel consumptions by

multidimensional laser surface texturing on cylinder surface. J Manuf Process 2021;64:684–93. https://doi.org/10.1016/j.jmapro.2021.01.052.

[15] Saljé E, von See M. Process-Optimization in Honing. CIRP Ann 1987;36:235–9. https://doi.org/10.1016/S0007-8506(07)62594-3.

[16] Sadizade B, Araee A, Bavil Oliaei SN, Farshi VR. Plateau honing of a diesel engine cylinder with special topography and reasonable machining time. Tribol Int 2020;146:106204. https://doi.org/10.1016/j.triboint.2020.106204.

[17] Oda Y, Kawamura Y, Fujishima M. Energy consumption reduction by machining process improvement. Procedia CIRP 2012;4:120–4. https://doi.org/10.1016/j.procir.2012.10.022.

[18] Tayisepi N, Mnkandla AN, Tigere G, Gwatidzo O, Mutenhabundo W, Ndala E, et al. Taguchi Full Factorial Design of Experiments Optimisation of Cutting Parameters for Energy Efficiency and Surface Roughness during the Dry Turning of EN19 Material. World J Eng Technol 2024;12:438–54. https://doi.org/10.4236/wjet.2024.122028.

[19] Tang Y, Feng F, Guo Z, Feng W, Li Z, Wang J, et al. Integrating principal component analysis with statistically-based models for analysis of causal factors and landslide susceptibility mapping: A comparative study from the loess plateau area in Shanxi (China). J Clean Prod 2020;277:124159. https://doi.org/10.1016/j.jclepro.2020.124159.

[20] Noordin M., Venkatesh V., Sharif S, Elting S, Abdullah A. Application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel. J Mater Process Technol 2004;145:46–58. https://doi.org/10.1016/S0924-0136(03)00861-6.

[21] Pal D, Bangar A, Sharma R, Yadav A. Optimization of grinding parameters for minimum surface roughness by Taguchi parametric optimization technique. Int J Mech Ind Eng 2012;1:74–8. https://doi.org/10.47893/IJMIE.2012.1051.

[22] Mahendra K, Neeraj A. Optimization of different machining parameters of EN24 alloy steel in CNC turning by use of Taguchi Method. Int J Emerg Technol Adv Eng 2012;2:160–4.