

HONING PROCESS OPTIMIZATION IN ENGINE COMPONENT REMANUFACTURING: A SYSTEMATIC REVIEW OF METHODS, PARAMETERS, FUNCTIONAL PERFORMANCE METRICS AND CAM INTEGRATION

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ABSTRACT

Honing is the most precise abrasive finishing process used to achieve the dimensional accuracy, surface integrity and functional cross-hatch surface texture of the internal cylindrical surfaces of an engine. In engine remanufacturing it has an extra weight as a worn cylinder bore or relining sleeve will require a cylinder bore that is both back to standard and capable of sealing pistons, lubricating the engine and maintaining good piston ring performance. The present systematic review, which follows the PRISMA 2020 reporting guideline, gathers and summarizes 39 studies related to honing optimisation of cylinder sleeves, liners and similar bores, as well as contextual studies on design of experiments (DOE), condition monitoring and Industry 4.0 in a developing-economy context. It reviews conventional, multi-stage plateau, slide, variable-kinematics and non-conventional (electrochemical and magnetorheological) honing as well as the main variables that can be controlled (abrasive grain size and density, honing pressure, rotational and reciprocating speed, stroke, cross-hatch angle, time and tool expansion), and the performance criteria used to evaluate them (roughness, material-ratio and areal parameters, cylindricity, material removal rate, tool wear, energy and productivity). The results demonstrate that the influences of the parameters are related to the honing stages, the abrasive system, the material of the workpiece, and the texture of the object to be honed; so honing should be considered as a multi-response problem. The resolution of conflicting optima is a common feature of the Taguchi, ANOVA, grey relational analysis, desirability and neuro-fuzzy models, which is evident across the authors' experience in DOE in milling, injection moulding, additive manufacturing and wood machining. The Rk-family and the ISO 25178-2 parameters are more suitable to describe the function of cylinder-liners than the Ra alone. The review highlights eight research gaps, such as core-condition-aware parameter selection, functional-metrology-based objectives, energy and carbon accounting, stone-wear evolution and skills and proposes a CAM-integrated, data-driven framework for repeatable remanufacturing.

Keywords: Honing; Plateau honing; Engine remanufacturing; Cylinder liner; Surface texture; Taguchi method; Grey relational analysis; Computer-aided manufacturing; Industry 4.0

1 INTRODUCTION

Engine remanufacturing involves systematic disassembly, cleaning, inspection, dimensional restoration, machining, reassembly and verification (Sitcharangsie, Ijomah and Wong, 2019; Rizova, Wong and Ijomah, 2020) of used components to restore them to a serviceable condition as new or better than new. The process of remanufacturing starts with a core whose geometry and surface have been affected by the service-related loading, thermal cycling, lubrication conditions, and previous machining operations. Cylinder sleeves and cylinder bores are among the most challenging components for the surface treatment industry, as the surface finish must not only seal between the piston rings and prevent oil leakage but also minimise friction and wear and ensure the geometry is correct throughout the piston stroke (Pawlus and Reizer, 2022).

Honing is usually the last or near last processing step for these internal cylindrical surfaces and the combination of rotary and reciprocating cutting action creates the cross hatched surface finish needed for these functions. While the economic and environmental benefits of remanufacturing automotive parts have been documented, acceptance of remanufactured parts in the market relies on consumers' trust that remanufactured parts are as reliable as new parts (Milios and Matsumoto, 2019). In the case of engine parts, it's achieved during the honing process. It is common in Zimbabwe for remanufacturing and reconditioning workshops to still rely on visual assessment to determine if a bore has been honed, dial gauge readings and even 'finger feel' to determine the condition of the bore, with the conditions set through trial and error, and not taking into consideration energy use (Tayisepi et al., 2024).

This is also a reflection of the wider structural conditions in the local manufacturing sector: companies are subject to fluctuating demand and competition from lower cost imports, and most of the technologies enabling Industry 4.0 are only present as isolated technologies, not connected or optimised to substantially benefit the company. It is also a reflection of the wider structural conditions in the local manufacturing sector: Companies are exposed to volatile demand and competition from cheaper imports, and most of the enabling Industry 4.0 technologies are present in their companies, but not interconnected or optimised to benefit the company significantly. Meanwhile, the region suffers from a lack of engineers who have the practical skills necessary to productively meet industry expectations which learning factories have been suggested to address (Ndiyamba et al., 2026). Optimisation of honing is therefore a question of process knowledge, data and skills, and not a question of machining-science.

While there are a number of reviews that investigated honing kinematics and innovations (Sender and Buj-Corral, 2023), as well as the functional importance of honed cylinder-liner textures (Pawlus, Reizer and Wiecezowski, 2021a; Pawlus and Reizer, 2022), no one has summarized the evidence specifically from the perspective of engine-component remanufacturing and computer-aided manufacturing (CAM). This review fills this void. It has the following goals: (i) to categorize the different honing methods and the controllable variables reported in the literature; (ii) to summarize the different parameter–response relationships and the different optimisation methods that have been proven; (iii) to analyse the ability of current performance measures to reflect the function of a honed liner; (iv) to highlight the gaps inherent to the remanufacturing process; and (v) to propose a framework for condition-aware, function-oriented and energy-efficient honing that integrates CAM.

2 BACKGROUND AND THEORETICAL FOUNDATION

2.1 Honing fundamentals and process variants

Honing is a process that removes a small quantity of the bore by pressing bonded abrasive sticks radially against the bore as it is rotated and reciprocated (Figure 1). The intersection of the tangential velocity v_t and the axial (stroke) velocity v_a creates intersecting abrasive tracks, where the ratio of stroke to rotational speed directly controls the included cross-hatch angle θ , where $\tan(\theta/2) = v_a/v_t$ (Sender and Buj-Corral, 2023). Honings are adjusted for pressure by radial expansion of the sticks, which along with the grit size and the density of the grit determines the amount of stock removed. There are a number of different variants, which include conventional, plateau, variable-kinematics, ultrasonic-assisted and 3D-printed-tool honing (Sender and Buj-Corral, 2023). Adjusting the feed and rotational speed in each stroke, rather than maintaining a constant value, has been found to decrease deviation from cylindricity by as much as 12.77% and the temperature rise in the workpiece by as much as 35.2% compared with the standard honing of thin-walled liners (Sender, 2021).

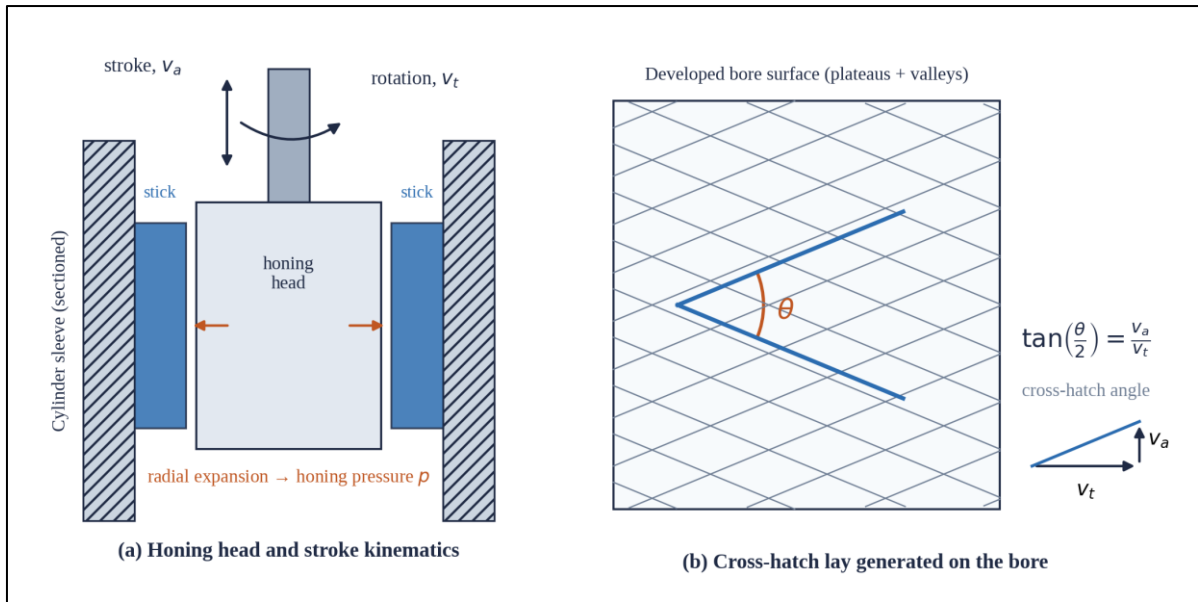


Figure 1: Honing kinematics: (a) expanding honing head with abrasive sticks performing rotation (v_t) and stroke (v_a) inside a cylinder sleeve; (b) the resulting cross-hatch lay and the relation between cross-hatch angle and velocity ratio. Original schematic prepared by the authors, based on the kinematic description in Sender and Buj-Corral (2023).

Abrasive-stone honing is not the only type of honing. Electrochemical honing (ECH) process is a combination of electrochemical dissolution and abrasive action which has been applied to restore the functional surface of the worn parts (Singh and Jain, 2016). For the cylindrical surfaces which are ferromagnetic, magnetorheological (MR) finishing can be used as a post-honing super-finishing process (Bedi and Singh, 2018). For rotational magnetorheological honing, the relative motion of abrasive particles was increased with the relative counter-rotation of the workpiece and a roughness reduction of 83.83% was achieved in 40 min as compared to 71.71% in 60 min for stationary workpiece (Paswan and Singh, 2020). Furthermore, abrasive material (sandpaper, alumina, white alumina or diamond) is one of the key factors affecting the volume removal of finish honing, and the rougher the finish material, the higher the volume removal. (Yudhistira et al., 2023)

2.2 Surface texture theory: from Ra to functional parameters

For multi-process surfaces – surfaces honed in a plateau process – Ra is not sufficient to describe surfaces because surfaces with the same Ra can have widely differing proportions of load bearing plateau and lubricant retaining valley. The material-ratio (Abbott–Firestone) curve defined in ISO 13565-2 (ISO, 1996) divides the profile into the reduced peak height Rpk, the core roughness depth Rk and the reduced valley depth Rvk, with Mr1 and Mr2 denoting the material ratios that are defined by the limits of the core. The areal equivalents in ISO 25178-2 (ISO, 2021) generalize this description into 3D and introduce hybrid, spatial and volume parameters more closely related to the function of texture (Pawlus, Reizer and Wiczorowski, 2021b). The functional parameters are correlated with friction, wear, oil retention and consumption, load capacity, seizure resistance and exhaust emissions (Pawlus, Reizer and Wiczorowski, 2021b).

The main design trade-off in the plateau honing (Pawlus and Reizer, 2022) for cylinder liners is deeper or rougher honing valleys, which enhance oil retention and reduce friction but also boost oil consumption and emissions. This has been confirmed in engine tests, where the higher the slope of the valley Rvk, the nearer the engine to producing higher power and CO and HC emissions (Woś and Michalski, 2011). A useful honing specification should therefore be able to place both peaks and core and valleys, not just core and valleys.

2.3 Remanufacturing as a distinct process context

The remanufacturing is a multi-stage decision making process encompassing core acquisition, inspection, disassembly, cleaning, reprocessing (includes surface finishing), and reassembly (Sitcharangsie, Ijomah and Wong, 2019; Rizova, Wong and Ijomah, 2020). Inspected cores are categorized as reusable, repairable, only for materials recovery and only for disposal, while parts that are repairable are assigned to the repair routings, and the outcome of the repairs determines if they are put back in the reassembly stream (Figure 3; Li et al., 2019). Surface-integrity remanufacturing technology is used to repair surface defects such as cracks, deformation, oxidation, corrosion, erosion, and microstructural degradation to restore the service life (Xiang, He and Hou, 2016). The repair procedure typically used

for engine blocks is to bore the worn out bore, insert a relining sleeve and then honing it to the proper size (Section 5.6). A more important difference between the route and new manufacture is the variable character of the incoming core which is a recurring theme in the review.

3 REVIEW METHODOLOGY

3.1 Objective and review protocol

The purpose of the review was to develop a clear, reproducible and objective approach to identifying, screening and synthesizing research after 2016 that focuses on process optimization, surface-topography optimization and functional surface integrity in manufacturing and remanufacturing. Reporting is done according to the PRISMA 2020 statement (Page et al., 2021).

3.2 Information sources and search strategy

Google Scholar was the main bibliographic engine used to retrieve the full texts of articles from the publisher databases, linked from Google Scholar (ScienceDirect, SpringerLink, MDPI, Taylor & Francis, SAGE and Atlantis Press). The following groups of keywords were used for search strings: “honing process”, “honing parameters”, “plateau honing”, “variable kinematics honing”, “cylinder liner”, “cylinder sleeve”, “engine block”, “remanufacturing” and “relining”, and “CAM” or “computer-aided manufacturing”. Backward and forward citation searching of included studies, and research group’s own publication record was carried out in order to identify relevant studies to the research questions related to condition monitoring or Industry 4.0 readiness in the context of DOE-based multi-response optimisation.

3.3 Eligibility criteria

Studies were evaluated against the predetermined inclusion/exclusion criteria listed in Table 1 to ensure that they were relevant to the theme, methods were rigorous and followed the time frame. Only works published prior to 2016 were included if they established concepts and/or measurement practice that were referenced in subsequent publications.

Table 1: Eligibility criteria.

Criterion	Inclusion criteria (IC)	Exclusion criteria (EC)
Time period	Published 2016–2026 (foundational pre-2016 works admitted only for definitions and measurement practice)	Studies published before 2016 that are not foundational
Language	Full text available in English	Non-English publications without a verified English version
Document type	Peer-reviewed journal articles, doctoral theses and indexed conference proceedings	Editorials, book reviews, opinion pieces, patents and unindexed extended abstracts
Study focus	Experimental, numerical or optimisation studies of honing (conventional, plateau, variable-kinematics, ECH, MR honing); parameter–response relationships (Ra, Rz, Rk, Rpk, Rvk, MRR, tool wear, energy); surface integrity; cylinder remanufacturing; DOE-based multi-response optimisation and digital enablers directly transferable to honing	General machining studies with no bearing on internal cylindrical finishing, surface texture or metrology, or on the optimisation methods used for them

3.4 Data extraction and analytical framework

The data for each study included were extracted into a structured matrix of 13 standardised fields: bibliographic identifiers (authors, year, title, source); topic category (process parameters, cooling and materials, optimisation methods, performance metrics and research gaps); experimental set-up (component and material, e.g. cast-iron relining sleeves, St-52 steel, diesel cylinder liners; honing method and tool, e.g. plateau honing, variable kinematics, ECH, rotational MR honing, Sunnen CV-616E); parametric and analytical scope (parameters studied, optimisation method, such as Taguchi, response surface methodology (RSM), ANOVA, ANFIS or neural networks, and performance metrics, such as Ra, Rz, Rk, Rpk, Rvk, MRR, tool wear and energy); and synthesis outputs (key findings, parameter–response relationships, limitations and research gaps).

3.5 Study selection

The selection process is summarised in figure 2. After all the records were loaded into the database, 17 were duplicates and 24 were selected for screening by title and abstract and 26 full text articles were evaluated, of which 24 were included. Another 15 eligible studies were identified through citation searching and the publication history of the research group, which yielded 25 core studies on honing, surface function and remanufacturing, and 14 contextual studies on DOE-based optimisation, condition monitoring, human factors and Industry 4.0 adoption.

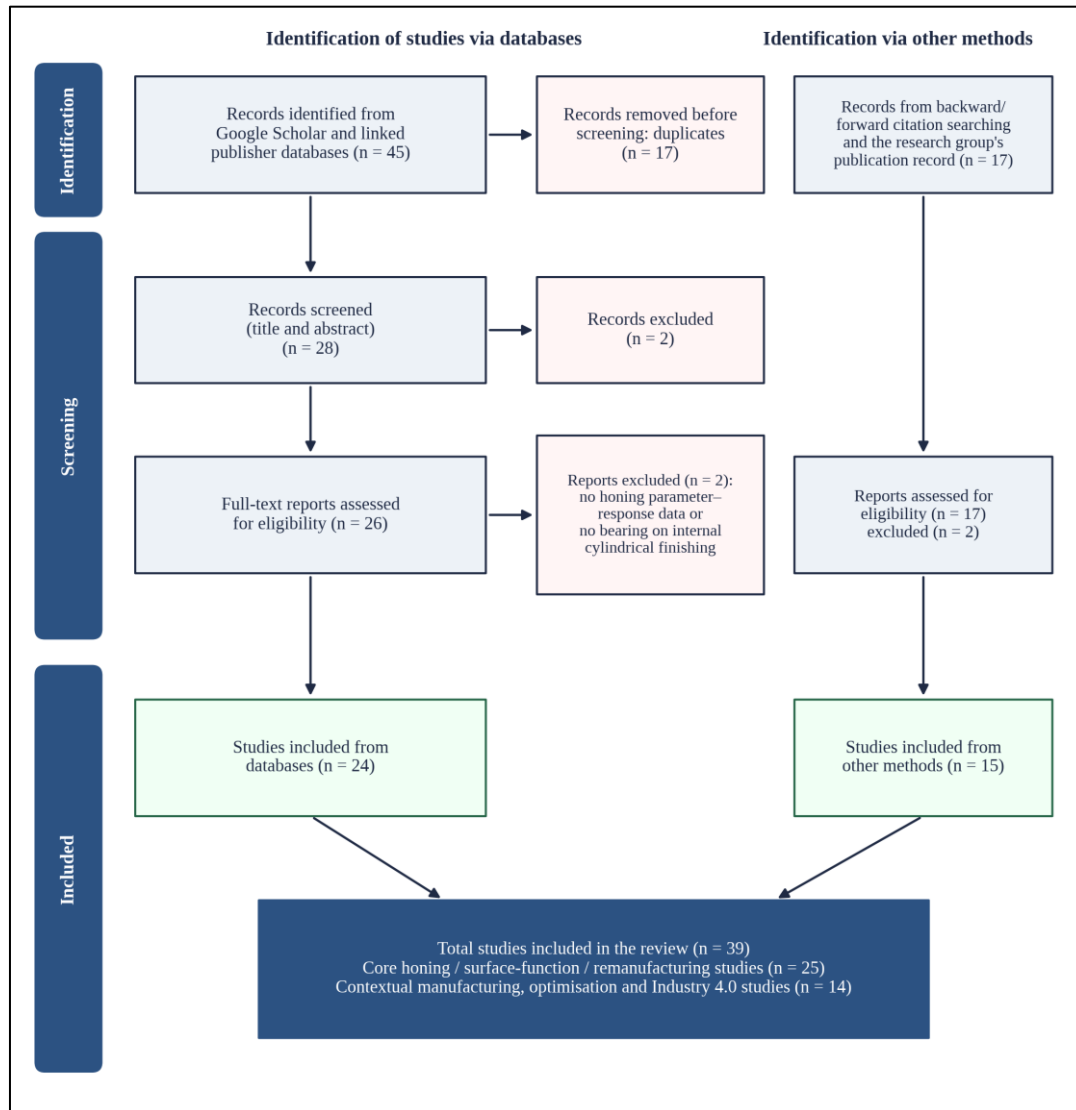


Figure 2: PRISMA 2020 flow diagram of study identification, screening and inclusion. Prepared by the authors using the PRISMA 2020 template (Page et al., 2021).

4 CLASSIFICATION AND TAXONOMY

The literature included was categorized in a taxonomy based on the main area of study of each research. Table 2 outlines the taxonomy that starts with the remanufacturing context of the honing problem and then progresses through honing methods, controllable parameters, optimisation approaches, outcomes of the honing and, finally, the digital and human enablers that depend on the industrial implementation.

Table 2: Classification of the literature by dominant research focus.

Taxonomy category	Focus	Typical responses	Representative studies
Remanufacturing context	Bore restoration, surface-integrity restoration, remanufacturing decisions and routing	Cylindricity, roughness, restoration of damaged surfaces, core classification	Xiang, He and Hou (2016); Sitcharangsie, Ijomah and Wong (2019); Li et al. (2019); Rizova, Wong and Ijomah (2020); Qin et al. (2016)
Honing methods and materials	Conventional, plateau, slide and variable-kinematics honing; ECH and MR finishing; abrasive type	Roughness, MRR, temperature, geometry, finishing productivity	Sender (2021); Singh and Jain (2016); Bedi and Singh (2018); Paswan and Singh (2020); Yudhistira et al. (2023); Dimkovski (2011)
Process parameters	Grain size and density, pressure, speeds, stroke, depth of cut, tool-path radius, time, honing angle	Ra/Rz, Rk-family, MRR, cylindricity, tool wear, power and energy	Buj-Corral, Álvarez-Flórez and Domínguez-Fernández (2019); Buj-Corral and Sivatte-Adroer (2022); Tayisepi et al. (2024)
Optimisation methods	Taguchi, ANOVA, regression, GRA, desirability, ANFIS and multi-objective models	Optimum settings and compromise solutions	Lawrence and Ramamoorthy (2016); Sadizade et al. (2020); Buj-Corral, Sender and Luis-Pérez (2023); Yurdakul, Güneş and İç (2016); group DOE studies (Table 4)
Performance and function	Surface texture, geometry, metrology, friction, wear, oil consumption and emissions	Material-ratio and areal parameters, friction, oil retention, emissions	Woś and Michalski (2011); Pawlus, Reizer and Wieczorowski (2021a; 2021b); Pawlus and Reizer (2022)
Digital and human enablers	Condition monitoring, machine learning, Industry 4.0 readiness, human factors, skills	Fault detection, reliability, adoption barriers, safety, competencies	Mashava et al. (2026); Senda et al. (2026); Muhla et al. (2023; 2025a; 2025b); Tandi et al. (2025); Ndiyamba et al. (2026)

5 REVIEW OF THE LITERATURE

5.1 Honing of engine cylinder sleeves

Honing is a process that will remove a relatively small amount of material, correct or refine the geometry of the bore while creating a controlled surface finish. The typical sequence of engine cylinder operations is rough honing, finish (base) honing and plateau honing. Rough honing removes stock and corrects geometry, base honing sets most of the cross-hatch texture, and plateau honing truncates the highest asperities, leaving behind deeper valleys that retain oil. Lawrence and Ramamoorthy (2016) based their study of the cylinder bore on the assumption that the surface is a manufactured surface which has to meet a number of micro-geometrical requirements simultaneously. They applied the grey relational analysis (GRA) and varied the rotational speed, oscillation speed, pressure and time during three honing stages to satisfy seven surface targets, including the Rk-family parameters and the honing angle, all at once. The cross-hatch pattern influences the distribution of oil, the conformity of the rings and the frictional behaviour, hence it is included with the roughness parameters.

5.2 Conventional and plateau honing

Standard honing can create an even texture, but can also result in deep peaks. Plateau honing alters topography to remove the highest peaks but leave the valleys, resulting in a surface that is similar to partially run-in. The functional objective is a compromise between bearing area and oil retention ability and in material-ratio terms this is a low Rpk, a moderate Rk and a controlled Rvk (Pawlus, Reizer and Wieczorowski, 2021a). The feasibility of the cylinder with the desired special topography was demonstrated by Sadizade et al. (2020) who used the experimental design and desirability functions to optimise the plateau-honing sequence in a reasonable machining time using a diesel-engine cylinder.

5.3 Slide honing and advanced surface finishing

Slide honing and other multi-process finishing methods seek to directly control the surface. Slide honing can use fine diamond abrasives in the final finishing process; the tool life is long and the stable texture, but the tool loading and material smearing and the changed layers on the surface should be controlled. Dimkovski (2011) correlated the honed liner surface parameters with lubrication performance by modeling the contact and fluid mechanics between the measured honed liner surface topography and a twin-land oil control ring system under mixed lubrication. The friction mean effective pressure and oil passage rate calculated for each surface improved for surfaces with smoother plateaus and shallower valleys, which were produced with a low base-honing pressure and a longer plateau-honing time. The study provides a good example of the importance of a manufacturing, surface characterisation and functional analysis in a single loop.

5.4 Process parameters and parameter–response relationships

The variables that appear over and over in rough and finish honing are grain size and honing pressure. When referring to the grain size and density of the abrasive, there are no clear correlations between these aspects and the result of the roughing process (MRR and roughness) in rough honing, as can be seen, except in some cases of high density and small grain size, the abrasive may clog the stick and lead to less MRR and less surface roughness (Buj-Corral, Álvarez-Flórez and Domínguez-Fernández 2019). According to multi-objective regression models of rough honing, the MRR is mainly influenced by tangential speed, grain size and pressure, while tool wear is mainly influenced by abrasive density and pressure (Buj-Corral and Sivatte-Adroer, 2022). The combination of grain size, pressure and linear speed that minimises tool wear, roughness and MRR varies depending on the response being optimised by the adaptive neuro-fuzzy inference system (ANFIS) models developed (Buj-Corral, Sender and Luis-Pérez, 2023).

The use of Taguchi designs has also been studied in the improvement of surface quality in industrial honing (Yurdakul, Güneş and İç, 2016; Yurdakul, İç and Güneş, 2017). The most related evidence for remanufacturing is from Tayisepi et al. (2024) who honed a dry FG-260 pearlitic cast iron relining sleeve with #580 silicon-carbide vitrified stones on a Sunnen CV-616E vertical honing machine, using 96.00 mm bore sleeves. They employed a Taguchi L16 design, with spindle speed, tool-path radius and depth of cut at four levels, and identified spindle speed and tool-path radius as significant factors for Ra (at 95% confidence level) and the spindle power and energy (at 90% confidence level) but not as significant factors for roughness (at 90% confidence level). The optimum settings were found to be different for each response (310 rpm and 107.30 mm for surface finish; 125 rpm, 107.30 mm and 0.100 mm for minimum energy), with the difference between the actual and the predicted responses not exceeding 10% for the validation runs. The study demonstrates how a conflict exists between these parameters and how both parameters may be quantified in an inexpensive and shop-floor DOE.

Table 3 summarises the principal experimental studies on honing and related bore-finishing processes included in the review.

Table 3: Summary of key experimental studies on honing and related bore-finishing processes.

Study	Component / material	Method / design	Variables	Responses	Key finding
Lawrence and Ramamoorthy (2016)	Automotive cylinder liners	Three-stage plateau honing; robust design + GRA	Rotational and oscillation speed, pressure, time per stage	Seven targets incl. Rk-family and honing angle	All seven surface targets met simultaneously through multi-stage GRA optimisation
Qin et al. (2016)	Damaged hydraulic-cylinder bore	Staged honing for repair	Honing stages and conditions	Roughness, cylindricity	Staged honing restored a damaged bore for remanufacture
Singh and Jain (2016)	SS316 shafts clad by twin-wire arc	Developed ECH machine	Axial feed, processing time	Ra, geometry	Ra = 0.347 µm at 2.85 mm/min and 90 s; worn surfaces restored
Yurdakul, Güneş and İç (2016)	Industrial honed bores	Taguchi design	Honing parameters	Surface quality	Taguchi method improved honed surface quality

Bedi and Singh (2018)	Ferromagnetic cylindrical honed surfaces	MR finishing after honing	MR process parameters	Surface finish	MR finishing is a viable super-finishing step after honing
Buj-Corral, Álvarez-Flórez and Domínguez-Fernández (2019)	Steel cylinders, rough honing	Experimental design with acoustic emission	Grain size, abrasive density	Roughness, MRR, AE signal	Roughness and MRR rise with grain size and density; clogging at high density with fine grain
Sadizade et al. (2020)	Diesel-engine cylinder	DOE with desirability functions	Rough- and plateau-stage pressure, speed, stroke	Rk-family targets, machining time	Two-stage plateau honing met specification with reduced honing time
Paswan and Singh (2020)	Internal cylindrical surfaces	Rotational MR honing (counter-rotating workpiece)	Workpiece rotation, finishing time	Ra reduction	83.83% Ra reduction in 40 min vs 71.71% in 60 min for stationary workpiece
Sender (2021)	Thin-walled cylindrical holes	Variable-kinematics honing	Feed and rotational speed varied within the stroke	Cylindricity, temperature	Cylindricity deviation reduced by up to 12.77% and temperature rise by up to 35.2%
Buj-Corral and Sivatte-Adroer (2022)	Rough honing	Regression models; multi-objective optimisation	Grain size, density, pressure, tangential and linear speed	MRR, tool wear	MRR driven by tangential speed, grain size, pressure; wear by density and pressure
Buj-Corral, Sender and Luis-Pérez (2023)	Finish honing	ANFIS models; multi-objective optimisation	Grain size, pressure, linear speed	Tool wear, Ra, MRR	Preferred settings depend on the response; compromise needed
Yudhistira et al. (2023)	Finish-honed bores	Comparative experiments	Abrasive material type	Volume removal, roughness	Abrasive type is a main driver of removal and roughness
Tayisepi et al. (2024)	FG-260 cast-iron relining sleeves, Ø96 mm	Taguchi L16; ANOVA; S/N ratio	Spindle speed, tool-path radius, depth of cut	Ra, power, energy	Speed and radius significant for Ra; depth of cut only for power/energy; validation error < 10%

5.5 Optimisation methods and their transferability

All the honing studies above involve the same small family of statistical tools: orthogonal-array DOE, signal-to-noise (S/N) analysis, ANOVA, regression, desirability functions, GRA and, more recently, tools such as the neuro-fuzzy and machine-learning surrogates. Evidence of the efficiency of these tools in addressing competing goals in other processes is directly applicable in remanufacturing workshops, as those workshops do not typically have the resources to conduct a large factorial experiment. The research group's DOE studies for various processes (Table 4) reveal a consistent pattern. First, a small orthogonal array (L9-L16) with replications is sufficient to rank factors and identify the significant effects. Second, the optima for quality and productivity or cost responses are nearly always in opposition. Third, GRA or an equivalent compromise method is needed to produce a single, verifiable operating recommendation.

Table 4: Transferable evidence from the research group's DOE-based multi-response optimisation studies.

Study	Process material /	Design and analysis	Responses	Dominant factor(s)	Insight for honing optimisation
Tayisepe et al. (2023)	Planing of teak, saligna and pine	Taguchi L9; ANOVA; S/N	Cutting energy, cutter-mark surface quality	Depth of cut (energy, saligna and pine); knives (teak)	Optimum settings are material-specific; energy and surface quality conflict
Tayisepe et al. (2024)	Honing of cast-iron relining sleeves	Taguchi L16; ANOVA; regression	Ra, power, energy	Spindle speed and tool-path radius	Separate optima for finish and energy; direct remanufacturing evidence
Jansen et al. (2025)	Vacuum bleaching of edible oil	Taguchi L12 two-level; regression; ANOVA	Colour, free fatty acids, soap	Oil temperature (FFA)	Screening DOE with six factors guides process-system design
Mapindu et al. (2026a)	Injection moulding of PP plaques	Taguchi L9(3 ⁴), 3 replicates; ANOVA; GRA	Shrinkage, warpage	Injection pressure (67.25%; 60.55%)	Additive predictions at untested combinations require confirmation runs
Mapindu et al. (2026b)	CNC milling of mild steel	Taguchi L9(3 ³); ANOVA; GRA	Ra, flank wear	Feed (Ra, 82.81%); spindle speed (wear, 63.40%)	Quality and tool-life optima conflict; GRA gives a verified compromise
Mapindu et al. (2026c)	FDM printing of PLA	Taguchi L9(3 ⁴), 3 replicates; ANOVA; GRA	Tensile strength, print time	Infill (strength, 68.99%); layer height (time, 51.77%)	Dominant factor switches between quality and productivity responses

Honing is based on three lessons. However, the dominant factor may be different for different responses in fused deposition modelling (FDM) (Mapindu et al., 2026c) and in CNC milling (Mapindu et al., 2026b) where the factors were infill density governed strength, and feed rate governed roughness, and spindle speed governed tool wear respectively. This is the same behaviour that is seen for grain size, pressure and density for all honing responses. However, the optimum also varies with the material of the workpiece, as shown by the comparative optimisation of teak, saligna and pine (Tayisepe et al., 2023) and recommends re-optimisation of the honing recipe when it is changed from one liner alloy to another. Lastly, an untested level combination for the additive Taguchi prediction needs to be tested before it is applied (Mapindu et al., 2026a). This same DOE concept has found uses outside of machining, such as optimising a vacuum-bleaching process for edible-oil quality (Jansen et al., 2025) and also in the optimization of welding parameters to maximize weld strength (Mapindu et al., 2026d).

5.6 Remanufacturing process routing and the role of CAM

Figure 3 shows a generic remanufacturing routing for engine cores. Where a cylinder is worn beyond oversize limits or cracked, the repairable route typically involves relining, and CAM supports each step of that route:

- **CAD import and model preparation:** import or create the 3D geometry of the cylinder sleeve and the modified block bore, including the register step and deck datum.
- **CAM programming:** define cutting parameters, feeds, speeds and tool selection for turning the sleeve and boring the block.
- **Simulation and verification:** run virtual tool paths to detect collisions with chucks, fixtures or block decks before cutting metal.
- **Sleeve machining:** turn the outer diameter to the interference allowance specified by the liner manufacturer and cut the retention lip or bottom register step that stops the sleeve from moving under thermal cycling.
- **Block boring:** set up the block on a CNC boring or multi-axis milling machine, perform rough and finish passes to match the sleeve outer diameter, and leave a precise register ledge as a positive stop.
- **Installation and deck finishing:** press or thermally shrink-fit the sleeve, then resurface the deck so that sleeve protrusion meets the specification for the chosen head-gasket type.
- **Final honing:** hone the sleeve bore to size, geometry and the specified cross-hatch and material-ratio targets, because installation distortion makes pre-installation honing insufficient.

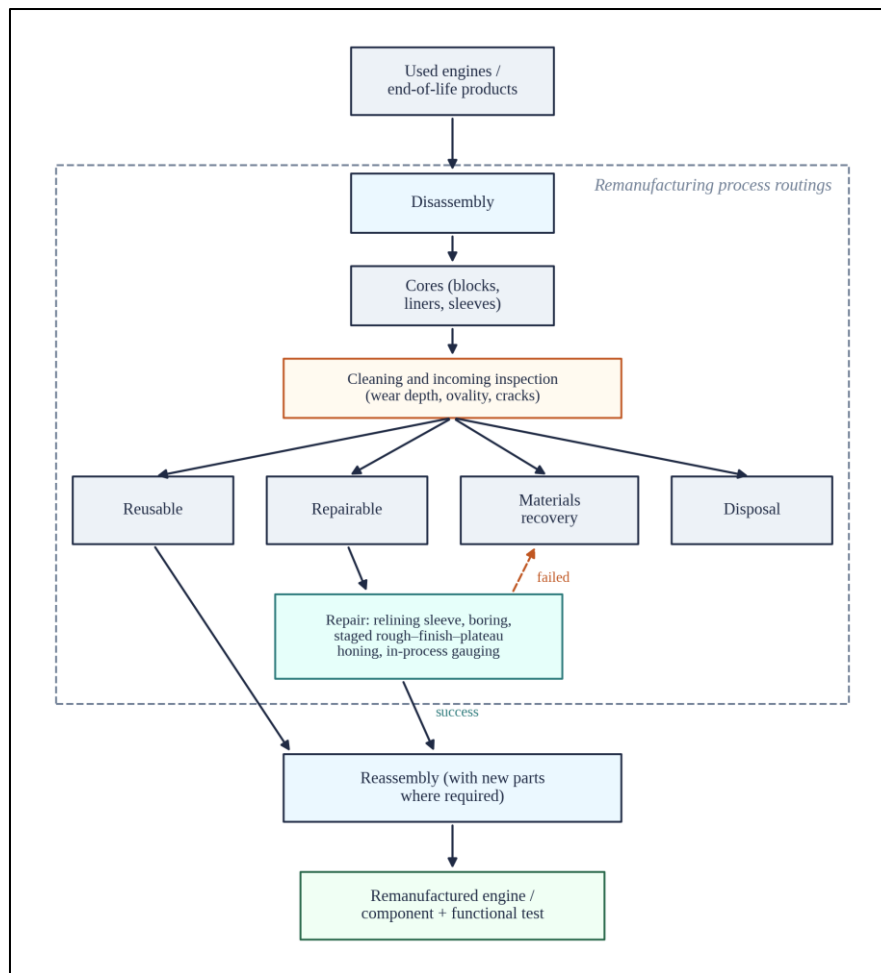


Figure 3: Remanufacturing process routing for engine cores, showing core classification after inspection and the bore-relining and honing repair route. Adapted from Li et al. (2019), with the repair route specialised for cylinder bores.

Today, the main aspect of honing that is usually programmed on CAM is stroke length, dwell, spindle speed and feed-out on CNC honing machines. Common to the state of remanufacturing is the lack of these capabilities that would be most useful in this process, including condition dependent parameter selection, variable-kinematics strokes (Sender, 2021) and in-process gauging with closed-loop feed-out. Qin et al. (2016) successfully repaired a defective bore of a hydraulic-cylinder with a staged honing process and Singh and Jain (2016) repaired worn stainless-steel shafts applying twin-wire-arc cladding followed by ECH, with a R_a of $0.347\ \mu\text{m}$ and an axial feed rate of $2.85\ \text{mm/min}$ for 90 s. These are both case studies and not systematic parameter studies.

5.7 Digital enablers: condition monitoring, data-driven maintenance and Industry 4.0

The repeatability of honing is not only related with the parameters selected but also with the machine and the stones. There are two strands of recent work relevant. Firstly, agent-based architectures have been proven to enable real-time, self-diagnostic condition monitoring of production equipment in developing economies: a FIPA-based multi-agent system that connects sensors, a PLC and an OPC server with a rule-based expert system managed all five injected fault classes in an induction furnace without any false positive during 72 hours of nominal operation, with a payback period of 3 months (Mashava et al., 2026). This sensor-PLC-agent scheme could be used to monitor load, stone expansion, coolant condition and power on a honing machine. Second, with the relatively small historical data that is common in local plants, it is possible to establish a region of optimum reliability based on a data-driven model: a random-forest model is trained on data from 13 months of monthly boiler measurements, and a region of optimum reliability was identified and associated with plant availability, cost and failure frequency (Senda et al., 2026).

Analogous models might help forecast stone-dressing times and the window for honing machine health on honing cells. Adoption, however, is limited. Mobile devices, sensors, PLCs and internet connectivity are widely adopted during production within the Zimbabwean manufacturing industry, while simulation, mathematical modelling, and additive manufacturing are not commonly used; the major problems in the industry are lack of an Industry 4.0 roadmap, cost of solutions, and insufficient government support (Muhla et al., 2025a). As per a related study, local companies' agility is

constrained more by the integration and optimisation of the technologies than by the availability of individual technologies (Muhla et al., 2023). Therefore a CAM-integrated honing system for remanufacturing should prefer the low cost, modular and locally maintainable parts. It also resulted in the development of an arduino based dual mode smart wheelchair with ultrasonic obstacle detection system at an estimated 60-70% lower cost as compared to commercial system (Munotyaani et al., 2026).

5.8 Human factors and skills in the honing cell

In reconditioning workshops, honing and relining are still labour-intensive processes, in which the operators have to handle heavy blocks and sleeves, press-fit liners and in many local workshops, assess hone quality by hand (Tayisepi et al., 2024). Unsafe work practices, fatigue, cognitive overload and inadequate ergonomic design are the biggest causes of work accidents in manufacturing sector in Zimbabwe while human factors engineering (HFE) interventions most widely adopted include enhanced training and ergonomic workstation design (Muhla et al., 2025b). Passive upper-limb exoskeletons, or systems that use levers, springs, and pulleys to assist the user with arm elevation and tool manipulation, have been designed to alleviate fatigue in the user after prolonged use, and a prototype upper-limb exoskeleton for this purpose was found to cost approximately US\$387 (Tandi et al., 2025). These devices might facilitate manual handling when replacing liner in cells. Standardized, instrumented honing would also eliminate the need for the tacit operator judgment, however, it does require the technicians to be trained in metrology, DOE and CAM. Ndiyamba et al (2026) have suggested that learning factories that allow students to design, manage and test the actual process can be used to develop these skills in Southern Africa.

6 CRITICAL ANALYSIS AND SYNTHESIS

From the literature reviewed, it is clear that there is a consistent correlation between the abrasive properties, honing pressure, material removal and surface roughness. The larger the grains, the higher the MRR and the higher the roughness, and the higher the pressure, the more material is being removed and the deeper the valleys (Sender and Buj-Corral, 2023). The influence of abrasive density is more complex: an increase in abrasive density will increase roughness and MRR until it causes clogging (mainly at high density and small grain size, Buj-Corral, Álvarez-Flórez and Domínguez-Fernández, 2019), and density is also a main factor that influences tool wear (Buj-Corral and Sivatte-Adroer, 2022).

A more aggressive honing tool does not necessarily provide more overall performance. Tooling must be designed to consider the interactions between grain size and pressure and density. This is confirmed by multi-response studies. The optimum grain size, pressure and linear velocity will depend on the result to be optimized, while the optimum conditions for roughness does not necessarily correspond to the optimum conditions for the minimization of cylindricity deviation and/or tool wear (Buj-Corral, Sender and Luis-Pérez, 2023). There are different optimal surface finishes and power settings for remanufacturing applications, also different settings for total energy (Tayisepi et al., 2024). Over time, the literature is increasingly referring to honing as a multi-criteria process and selecting settings based on the function of the component and the relative importance of the responses.

The cross process DOE evidence for the group reveals that a set of compromise conditions can be found and checked using less than 30 runs, an achievable number of runs in small workshops. A second development is the move from fixed to variable honing kinematics. While conventional optimisation methods seek to find the best combination of spindle speed, feed and pressure, varying the feed and rotational speed while holding the other fixed parameters constant resulted in a reduction of the cylindricity deviation by up to 12.77% and temperature rise by up to 35.2% (Sender, 2021). The optimum machining condition is then not necessarily a fixed condition for the whole process and the difference between a “best recipe” and a process controlled dynamically is methodologically significant. Another case of process sequencing is that an optimised two-stage plateau-honing process is able to meet the required surface specification, while also considerably reducing the honing time compared to the conventional three-stage process (Sadizade et al., 2020).

The order in which operations are performed can be as important as the numerical values of the operations. One of the drawbacks of this quality of honing has yet to be addressed: how to measure that quality. In the literature on process optimization, especially the remanufacturing literature, Ra is the main indicator of finish, while the surface-metrology literature reveals that Ra does not represent the functional character of a honed liner (Pawlus, Reizer and Wieczorowski, 2021a; 2021b). The valley shape with deeper valleys can lead to less friction, but larger volume of the valleys causes more oil consumption and emissions (Woś and Michalski, 2011; Pawlus and Reizer, 2022). This lower roughness is not always desirable for cylinder liners, however, because a process may be able to deliver the low Ra but not the plateau-valley structure required for the engine. When optimizing parameters for remanufacturing, optimize Ra, Rk-family and areal parameters, not just one numerical roughness value. The evidence is much thinner when it's limited to remanufacturing. However, the studies of honing parameters for new manufacturing of hydraulic-cylinder bores do not compare with the studies conducted on damage repair of hydraulic-cylinder bore (Qin et al., 2016) or optimisation of honing parameters for cast-iron relining sleeves (Tayisepi et al., 2024).

The amount of variation in cores received is still not incorporated as a controlled input parameter in any optimisation study; this includes; wear depth, out-of-roundness, scratch distribution and residual surface condition. The pattern is the same for non-conventional processes. Both ECH (Singh and Jain, 2016) and MR-based honing and finishing (Bedi and Singh, 2018; Paswan and Singh, 2020) have shown significant improvement in the finish. However, they have not yet been exposed to the same depth of Taguchi, RSM or multi-objective optimisation compared with the conventional abrasive honing; therefore, there is no generalisation regarding their performance yet in the field of different types of liners, different geometries and different core conditions.

In general, the literature illustrates a trend from only fixed-parameter honing to the adaptive and multi-objective honing. Grain size, pressure and density are still the primary factors affecting material removal and roughness. Variable kinematics and optimised sequencing demonstrate that the process can be controlled to enhance the geometry, thermal performance and productivity, and that the surface metrology is changing the old concept of the continued use of Ra. The best potential is to integrate these elements: condition-aware parameter selection, dynamic tool-path control, functional metrology, multi-objective optimisation and machine-condition data in a CAM system that can be afforded and operated by local workshops.

7 RESEARCH GAPS AND FUTURE DIRECTIONS

Existing studies establish relationships between honing parameters, surface roughness, material removal, energy consumption and tool behaviour, but mostly under controlled conditions that do not represent the variability of used or relined components. Eight gaps follow.

7.1 Core-condition-aware parameter selection

In most experiments, the workpiece is used as a fixed input, while remanufactured cores are received with varying amounts and kinds of damage. The amount and location of stock to be removed depends on how worn the wheels are (wear depth), the out-of-roundness of the wheels, and the bore distortion or scratch depth and location. Qin et al. (2016) found that damage condition must be taken into account for repaired bores in relation to the honing process, but this has not been studied yet as a controlled design variable. The initial condition of each core should be measured as well as a wear depth, initial cylindricity, ovality, scratch characteristics, and remaining allowance, which should be entered alongside spindle speed, pressure and specification of abrasive so that an adaptive model can be developed to suggest conditions for each core.

7.2 Functional surface parameters as optimisation objectives

The studies on re-manufactured products have dealt with Ra, power or energy (Tayisepi et al., 2024) or roughness and cylindricity (Qin et al., 2016), but not the plateau–valley structure that determines function (Pawlus, Reizer and Wieczorowski, 2021a; Pawlus and Reizer, 2022). Future experiments should employ the Rk, Rpk, Rvk, Mr1, Mr2, and appropriate ISO 25178-2 parameters as responses in order to optimize the surface for a combination of ring contact, lubricant retention, friction and wear, not just a roughness value. There is a ready template for multi-stage GRA formulations available for new liners (Lawrence and Ramamoorthy, 2016).

7.3 Multi-objective optimisation under remanufacturing constraints

ANFIS based (Buj-Corral, Sender and Luis-Pérez, 2023) and desirability based (Sadizade et al., 2020) multi-objective methods have been used to develop and optimize under controlled condition. The future should take advantage of optimisation of functional texture, dimensional accuracy, MRR, cycle time, energy and tool wear, all of which should be taken into consideration, while considering the variation in core condition. From the cross process results, shown in Table 4, it is seen that the Taguchi–GRA workflows are an economical starting point, followed by RSM, ANFIS or machine-learning surrogate when there are interactions.

7.4 Energy and carbon-emissions assessment

It is assumed that re-manufacturing will save resources, although the overall benefit of a particular route will depend on the amount of resources used in the machining process. Tayisepi et al. (2024) measured power and energy in the honing of relining sleeves and suggested that this work might be expanded to include greenhouse-gas accounting. This trade-off between surface quality and cutting energy has also been shown in the wood planing process (Tayisepi et al., 2023). The situation is less benign where the supply of grid electricity is fossil-based, and this has led people to seek alternatives like vertical-axis wind turbines powered by slipstream (Muyambo et al., 2025). Future studies should attempt to replace electricity, abrasive and coolant usage, and tool replacement with a carbon or life-cycle indicator and assess whether small finish improvements are worth their environmental costs.

7.5 Evolution of stone wear over repeated remanufacturing cycles

The performance of tools is typically determined from a limited number of trials, but in industrial re-manufacturing the same stones are applied repeatedly to cores under varying conditions. Tayisepi et al. (2024) found that the impact of stone wear and reconditioning on energy and roughness was a priority for future studies. For long-run experiments, abrasive wear, loading, dressing frequency, energy and texture of a number of components should be monitored, and the information provided to predictive tool-life models, which may employ the condition-monitoring and machine-learning architectures described in Section 5.7 (Mashava et al., 2026; Senda et al., 2026).

7.6 Validation of non-conventional honing technologies

The structured parameter optimisation and statistical validation for conventional honing are also applicable to magnetorheological and electrochemical approaches (Singh and Jain, 2016; Bedi and Singh, 2018; Paswan and Singh, 2020). A series of controlled tests, comparing all the various liner materials and geometries and against the conventional abrasive honing method, would determine when these techniques are truly beneficial technically or environmentally for the remanufacturing of the liner.

7.7 Digital thread and CAM integration

There have been no studies on the connection of incoming inspection data, parameter-selection models, CNC honing programs and in-process gauging and final functional metrology in a single digital thread. Considering the observed gap between the availability of individual Industry 4.0 technologies and their integration in the local industry (Muhla et al., 2025a), low-cost, modular architectures like the sensor–PLC–agent pattern (Mashava et al., 2026) are a viable approach to the honing digital twin.

7.8 Skills, human factors and technology transfer

Technicians need to be trained in metrology, DOE and CAM, and workstations need to be designed to harness the human capacities to make the transition from tacit, touch-based judgement to data-driven honing. Remanufacturing process improvement should not be considered as a standalone agenda but should incorporate learning factories (Ndiyamba et al., 2026), HFE interventions (Muhla et al., 2025b) and assistive devices for manual handling (Tandi et al., 2025).

7.9 Proposed framework

These directions are summarized in Figure 4. The Core-condition data used to populate a parameter-selection layer generated by DOE surrogate models. Then, CAM performs staged and possibly variable-kinematics honing cycles, followed by functional verification of material-ratio and areal parameters, closing the loop. The in-process sensing, stone and machine condition monitoring and energy and CO₂ accounting are integrated into a data layer, and the data layer updates the models as production data is gathered. The system is made possible by skills development and human-factors engineered work stations, and the objectives look to function, accuracy, tool life, time, energy and emissions. The purpose of the framework is to help to close this gap between controlled lab-based studies and the practical conditions of engine remanufacturing.

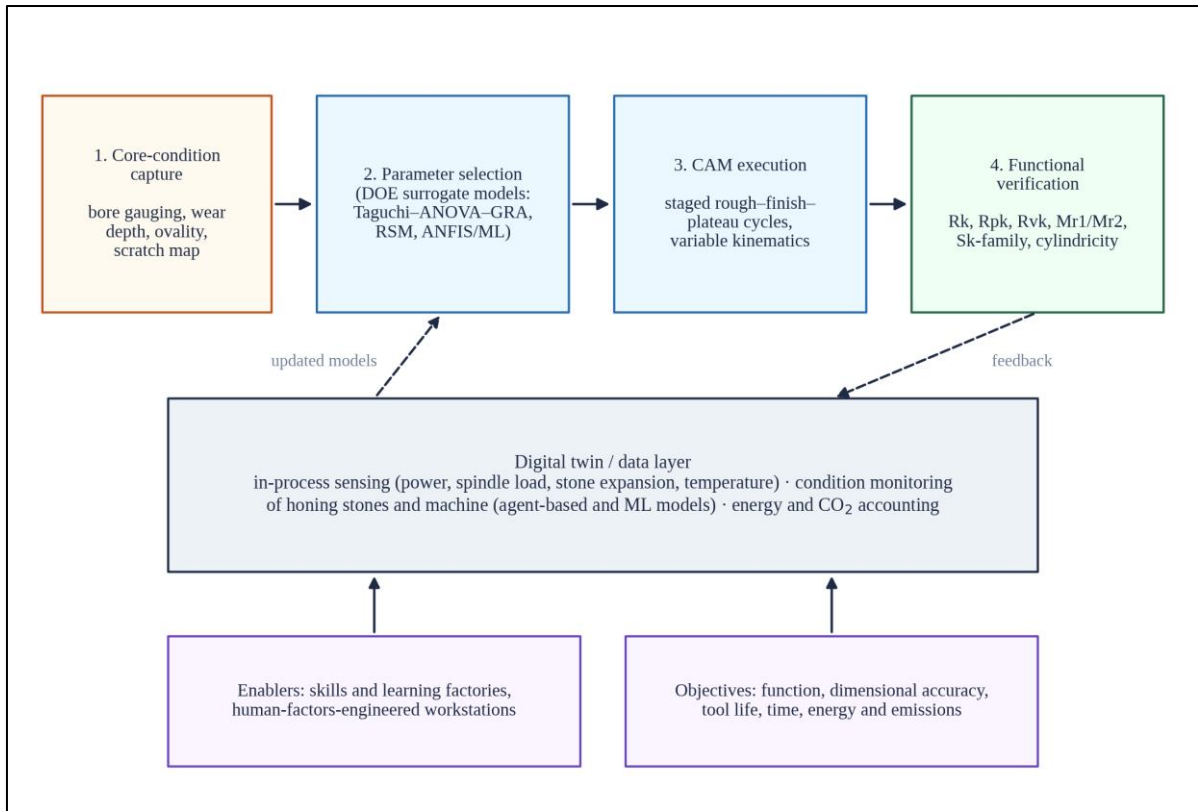


Figure 4: Proposed CAM-integrated, condition-aware framework for honing in engine-component remanufacturing. Original figure prepared by the authors.

8 CONCLUSIONS

This review focuses on the effects of tooling, material and process parameters on honing performance, especially for engine-component remanufacturing. Abrasive grain size, density, pressure, spindle speed and tool-path conditions were consistently found to be the dominant factors affecting MRR and roughness, while pressure, feed, and spindle conditions also impact cylindricity and thermal behaviour. Variable-kinematics and optimised multi-stage honing can be superior in controlling the removal and finish separately at each stage of the process, but the optimum can be different depending on the material of the workpiece and the desired performance goal.

The surface of a cylinder-liner can only be evaluated by using Ra. The parameters of the plateau and valley (rk-family and areal) are more closely associated with the functional requirements of the liner. Optimisation of honing should therefore consider the desired surface condition for function rather than just a set Ra value. Abrasion honing, or staged abrasive honing can restore damaged bores and the parameters for abrasive honing of cast-iron relining sleeves can be optimised for both surface finish and energy. However, the evidences about the effect of initial core condition, post-installation distortion, evolution of stone-wear and functional surface parameters under realistic conditions are still limited.

The DOE methods applied in this study, especially Taguchi designs and ANOVA and GRA, have been shown to be efficient and applicable in different fields of manufacturing such as remanufacturing in resource-limited workshops, which is suitable for both machining and moulding/AM and process industries. Core-condition-aware optimisation, functional metrology as the goal of process control, multi-objective optimisation (including energy and emissions) and condition monitoring of stones and machines are all the main priorities for future work. These should be embedded in an affordable CAM based digital thread supported by skills development and human-factors engineering. Their treatment would enable optimized tool paths and process parameters, enable the observation of surface and tooling behaviour during production and provide quantitative information about the sustainability aspects of the process decisions.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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