



Optimizing Piston Pin Bore Design for Enhanced Scuffing Resistance: Design & Statistical Approach

Vikrant Rayate

Powertrain Design Release Engineer

Stellantis

Abstract

This research effort brings to the forefront a very critical problem of scuffing in piston pin bores, which is one of the most common problems with automotive engineering scuff tests. Scuffing can be described by undesired surface damage between mating components due to inadequate clearance or failure of lubrication and has a big impact on internal combustion engine durability and performance. This paper focuses on the optimization of dimensions relating to the piston pin bore, with a view to enhancing the scuffing resistance of such a machine component to attain a balance between operational efficiency and component life.

One of the key areas for improvement had to be identified; this could be the piston pin bore, which is a feature designed to a targeted size to maintain minimal clearance from the piston pin. This project was aimed at developing a bore profile that is resistant to scuffing through statistical analyses and capability studies which consider long-term issues. It employed a detailed analysis of the manufacturing process of the bore, identification of critical process parameters influencing the resistance against scuffing, and optimization techniques for refining bore size and clearance specifications.

The revised minimum clearance guideline of the study was established by executing a statistically driven optimization process to ensure that produced parts meet and go beyond the required standards for scuff resistance. The results of this study are very informative with respect to the design of more reliable engine components and production and, therefore, offer significant contributions to mechanical engineering and automotive design. These findings underline the role of precision engineering and quality control in improving performance and durability of parts enroute to future advancements in internal combustion engine technologies.

Word count: 4,114

Keywords: scuffing, piston pin bores, scuff tests, surface damage, mating components, inadequate clearance, lubrication failure, internal combustion engine, durability, performance, piston pin bore optimization, scuffing resistance, minimal clearance, bore profile, statistical analyses, capability studies, critical process parameters, optimization techniques, clearance specifications, scuff resistance, statistically driven optimization, automotive design, quality control, performance, durability, internal combustion engine technologies.

1. Introduction

Scuffing, in automotive engineering, is one of the most serious durability and performance problems of internal combustion engines. It is described by undesirable surface damage between mating components, normally ascribed to insufficient clearance or failure of lubrication. This will have a very profound effect on the effectiveness and life span of an engine and hence is of interest to engineers and designers from a research viewpoint.

This paper seeks to optimize the design of piston pin bores for maximum resistance to scuffing. Since the piston pin bore is a fundamental subassembly of the engine and meets the piston pin under high-stress conditions, it is invariably subject to a phenomenon called scuffing. The objective will thus be to strengthen this interface by ensuring a minimum possible clearance between the piston pin and its bore; this will reduce the possibility of scuffing.

For this purpose, the current research followed the integrated approach of design optimization with a statistical analysis to refine bore dimensions and clearance specifications. This elaborate process consists of an in-depth analysis of the manufacturing process for defining the critical parameters affecting scuffing resistance and applying statistical methods for optimum bore size [1]. This should attain a just equipoise between operational efficiency and component longevity, all the while ensuring that the delivered engine parts are prompt to meet and exceed standards of scuff resistance.

The results to be envisioned from this research work would, therefore, be so much in design and production as regards more reliable engine components. Such works will greatly impact the disciplines of mechanical engineering and automotive design; setting the stage for further development in internal combustion engines, channeled towards precision engineering and quality control.

2. Literature Review

Knowland and Russell [2] underline predictive optimization of stability in pistons and rings, with respect to the balance between scuffing resistance and engine performance. This reiterates the requirement for a robust predictive tool during the development phase of an engine. Wang et al. [3] describe the scuffing resistance of coated piston skirts against numerous cylinder bores and demonstrate that some aluminum alloys and coatings improve resistance to scuffing, particularly in high-stress conditions within an automotive engine. According to Etsion, Halperin, and Becker [4] surface treatments like CrN and DLC coatings boost the scuffing resistance of piston pins. This paper focuses on the effectiveness of the mentioned treatment processes in order to retain their performances even under low-viscosity lubrication conditions. Tas et al. [5] demonstrated that both the mirror-polished surface and the DLC coating on the piston rings improved scuffing resistance of cast iron cylinder liners. Their findings showed that surface finish and coating play a key role in durability and engine performance under high loads. Wan et al. [6] present a comparison of different types of engineered coatings in automotive piston rings, while concluding that the integration of graphite-like carbon into traditional coatings offers significant improvement in their scuffing resistance and durability—the most important aspect within the strict consideration of automotive emission standards. Priest [7] provides a review of challenges in piston assembly tribology under higher operating temperatures and extended oil drain intervals, with emphasis on material-property optimization along with design optimization for further improvements in wear resistance within modern engines.

Malaczynski et al. [8] designed a bench test to measure the scuffing resistance of surface-modified piston and bore materials. The results of this study showed that some coatings can help in extending the wear resistance considerably, which is imperative for the elimination of iron liners from engine blocks. Zhang et al. [9] investigated the scuffing resistance of the piston rings when matched with different coated ring grooves, and the results showed that the anodized aluminum piston grooves give much better resistance to scuffing as compared with other tested materials. These have very important meanings for improving engine durability. Wang, Brogan, & Tung [10] conducted a study on the wear and scuffing characteristics of composite polymer and nickel/ceramic coated piston skirts in 2001. Some coating leading findings, which were quite provable, greatly enhance the scuffing resistance and durability when used with aluminum and cast-iron cylinder bores. Han et al. [11] made a comparison of the scuffing behavior between grey iron and 1080 steel, and it was found that while 1080 steel had higher scuffing resistance in reciprocating sliding, grey iron performed better under the same conditions of rotational sliding. Ma et al. [12] reported an investigation on the action of convexity position about the barrel surface of a Cr–Al₂O₃ coated piston ring and claimed that an optimal convexity position improves scuffing resistance, thus explicitly showing that the surface geometry is very important in the design process for piston rings. Galligan, Torrance, & Liraut [13] conducted a scuffing test with piston ring/bore combinations that used formulated motor lubrication and reported that surface finish has a significant effect on scuffing resistance in so far that a highly polished surface resulted in very scattered lifetimes compared to a standard finish.

3. Approach

3.1 Minimum Clearance Scuff Test

The first test phase of the research was conducted with a scuff test under conditions of minimum set clearance of 4.5 microns to be able to directly study the scuffing phenomena within the bore of an engine's piston pin. That choice of testing at the threshold of minimum clearance was backgrounded strategically by the recurrent history of scuff problems in previous versions of the same engine and in comparable models from this family line of heavy-duty engines. Conditions leading into scuffing in general were learned about by the study with an eye toward understanding operational and design margins that will tend to mitigate opportunities for it happening. In this study, the selection of running the engine deliberately under such highly constrained conditions was trying to do the replication of those scenarios most susceptible to scuffing, thereby setting a very robust platform for assessing just how successfully this piston pin bore design would stand up against this very widespread form of wear [14]. Such a study would deliver results valuable in insight and would therefore guide optimization processes by enhancing the durability and performance of such an engine.

The schedule comprises several stages, as follows:

1. Idle Phase:

The system or engine is initially set to idle, which is maintained for a period ranging from 30 to 300 seconds. This phase allows the system to stabilize before more demanding tasks.

2. Peak Power Phase:

After the idle phase, the system's activity increases to its peak power state, and it remains at this level for 60 minutes. This extended period tests the system's long-term operational stability under load.

3. Peak Power with the Secondary Coolant System ON:

The system maintains its power-production state with the Secondary Coolant System activated for 10 minutes. This phase evaluates the system's performance and cooling efficiency with additional cooling support.

4. Idle with the Secondary Coolant System ON:

The system operation is reduced back to idle, while keeping the Secondary Coolant System activated for 2 minutes. This allows for the observation of the system's stability and cooling efficiency without power stress.

5. Maximum Duration with Engine Off and Secondary Cooling System ON:

The engine or system is turned off, but the Secondary Cooling System remains running for a maximum of 10 minutes. This condition assesses the effectiveness of the cooling system without the engine's heat production.

6. Engine Off Phase:

The engine or system remains off for a brief period of 10 seconds, serving as a short buffer or transition period before the cycle is restarted.

7. Cycle Repetition:

The stages 1–6 is repeated five times in total. This repetition ensures comprehensive testing of the system's endurance and operational reliability under various conditions.

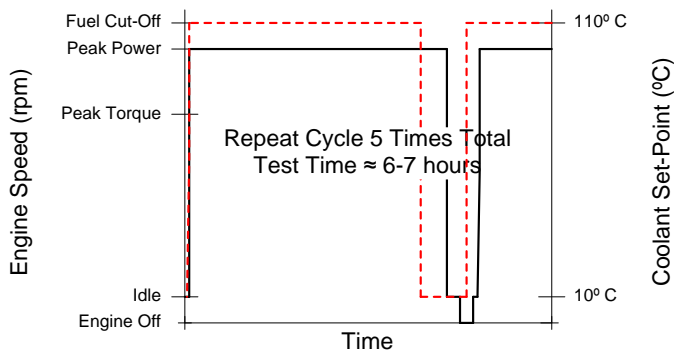


Figure 1: Scuff Test Schedule

The results of the scuff test showed that two of the piston pin bores had indeed suffered from some extent of the scuffing, thereby indicating that it is easily damaged when run at very small clearances. This damage would most likely have been caused by too little lubrication or spacings that were even too small. It is still noteworthy, though, that none of the rod bushings suffered from scuffing, therefore indicating that individual components within this engine could contain variable resistance to the same stresses encountered during operation. Finally, there was a light scuff on one end of the piston pin, indicative of uneven stress distribution. All these observations emphasize the need for understanding the interactions among design tolerances, lubrication, and operating practices to prevent scuffing and ensure that engine components have sufficient resilience to withstand wear over time.

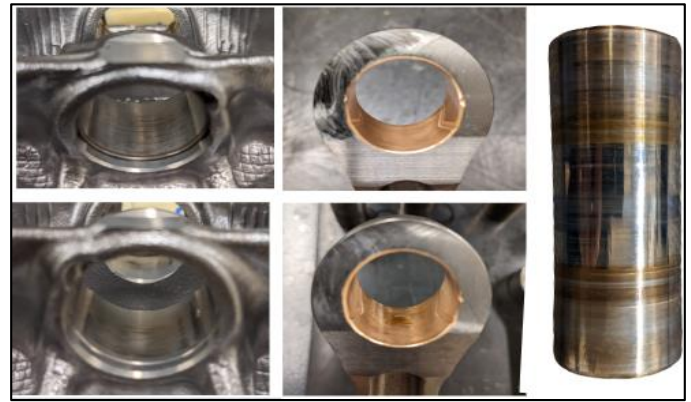


Figure 3: Piston, rod & pin post nominal clearance scuff test

3.3 Statistical clearance

Due to some problems encountered with the minimum clearance scuff test, a more pragmatic approach was deemed necessary, as the manufacturing process rarely goes to such extreme design limits. It was realized that the actual dimensions and capabilities achieved during the manufacture of these components needed examination, more so for those components that would critically affect the functionality of the piston pin joint. For this study, the surrogate component data were my synthesis of an earlier version of the engine to get a more realistic resultant minimum clearance value that would be reliably produced by the process.

The analysis for the diameter of the piston pin bore indicated that there was a leftover tolerance of about 1.5 microns on one side and 0.5 microns on the other side. This unused tolerance showed that the manufacturing processes were producing parts whose dimensions were more conservative than the maximum limits the design specifications permitted. The importance of this finding was in giving a more realistic understanding of the capabilities/limitations of the various manufacturing processes involved, thereby allowing design tolerances to be set in a more realistic vein with respect to the actual conditions under which the parts were being manufactured. By catching a design tolerance mismatch against the manufacturing reality, the team could recommend changes in clearance specifications that improve performance and reliability of the engine while staying within feasible manufacturing capability.



Figure 2: Piston, rod & pin post min clearance scuff test

3.2 Nominal clearance scuff Test

A repeat scuff test with the components set to a nominal clearance of 10 μm was required to isolate any scuffing issues at minimal clearance conditions. The rationale for this change was to bring the conditions more in line with those for conventional running and to see how the components performed under those parameters. Significantly, all parts inspected—the piston, rod, and pin—after this testing cycle were completely scuff-free. That meant the tested run was successful without any scuffing at this increased clearance. This helped as the foundation on which effectiveness could be confirmed upon and components' resilience while working within the recommended tolerances for a pass indication.

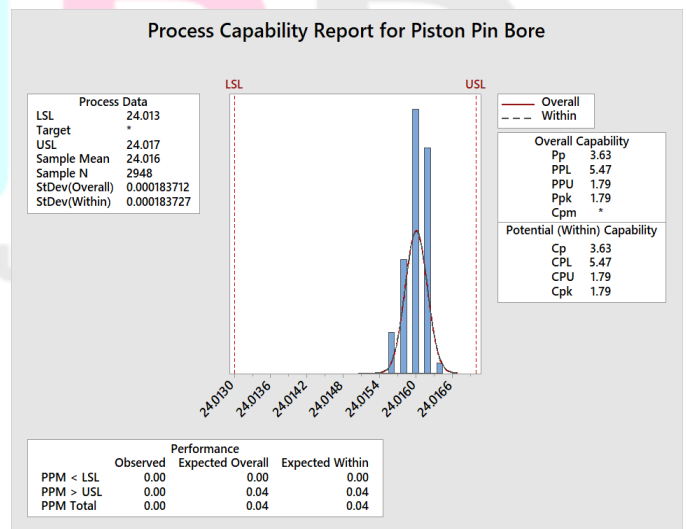


Figure 4: Piston pin bore 1-year capability

The production process for the pin's outer diameter (OD) revealed that a tolerance of 0.5 microns was not consistently applied on either side, suggesting a conservative approach. This indicates that the actual size of the pins was maintained slightly within the prescribed tolerance limits, without exceeding the design specifications.

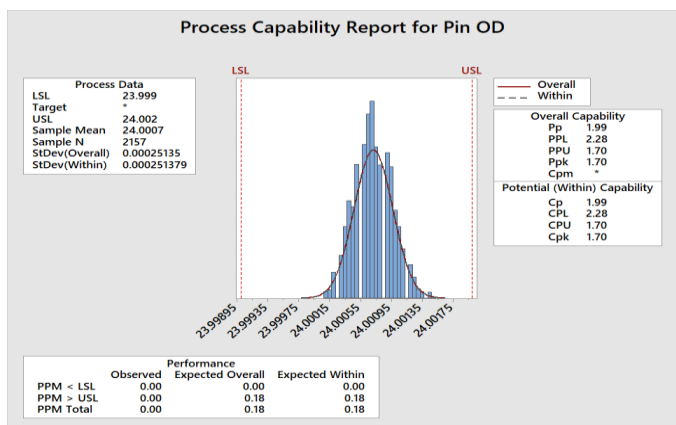


Figure 5: Pin 1 year capability

Here, the rod bushing bore has been manufactured with a margin of 2 μm from either side of the stipulated tolerance. It shows prudent manufacturing strategy where the dimensions of the bore are kept within the safer and narrower limits of design tolerance rather than maximum permissible limits.

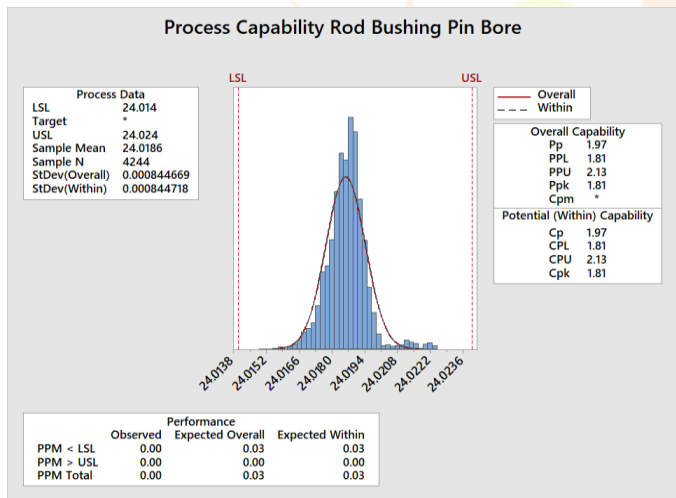


Figure 6: Rod bushing pin bore 1-year capability

An expert statistician was consulted, and a 1 Parts Per Million (PPM) fallout stack-up approach was implemented to determine a statistically optimal clearance between the engine components. This methodology was adopted since it is very accurate in giving the optimal value of clearance that minimizes risks of failure of components. This provided a critical role in recalibrating the specifications of clearance. The calculations gave an optimum piston-pin clearance of 8 μm, while that for the recommended rod in clearance was 13 μm. These fine-tuned clearance values were based on a rigorous statistical analysis to meet the objectives of this study: enhance engine reliability and performance by achieving the correct balance between the need for tightness to ensure efficiency and the requirement for sufficient space to avoid scuffing or other wear issues.

	Pin		Piston		Rod	
Production Stack Up	LSL	24.0055	LSL	24.0130	LSL	24.0190
	USL	24.0085	USL	24.0170	USL	24.0290
			Full Stack Max Clearance	0.0115	Full Stack Max Clearance	0.0235
			Ave Clearance	0.0080	Ave Clearance	0.0170
			Full Stack Min Clearance	0.0045	Full Stack Min Clearance	0.0105
	Mean	24.0070	Mean	24.0160	Mean	24.0236
1PPM Stack Up	Std Deviation	2.51E-04	Std Deviation	1.84E-04	Std Deviation	8.45E-04
			percentile	0.0010	percentile	0.0010
			Effective LSL	24.0062	Effective LSL	24.0154
			Effective USL	24.0078	Effective USL	24.0262
			1PPM Min clearance	0.008	1PPM Min clearance	0.013

Figure 7: Production Stack Up Vs. Static 1 PPM fallout Stack up

3.3.1 Statistical clearance scuff Test

Statistical clearances were estimated as prescribed, and then components making the required statistical clearances were made. The manufactured parts were subjected to rigorous testing by use of test plans for the scuff tests to establish their operation under oil-lubricating conditions. Statistical clearances brought improvement in all respects as far as scuff resistance was concerned. While most of the pistons performed well, one did exhibit some minor scuffing and indicated that further development in either the manufacturing process or the clearance specifications could be necessary to eliminate scuffing.



Figure 8: Piston, rod & pin post statistical clearance scuff test

3.4 Piston pin bore profile update

3.4.1 Design

Because the scuffed components were assessed, on average damage was mostly concentrated around the center while the inner edge of the piston bore remained clear; therefore, there was not a uniform mechanical stress distribution across the piston pin bore [15]. This pattern of wear can be viewed as reflective of a design problem more than a clearance variation. To address this, redesigning of the pin-bore profile will be introduced for a uniform distribution of load. The new component design ensures consistent contact along the entire length of the pin bore to ensure the robustness of the component and minimize localized scuffing. More importantly, it makes the engine operation more durable and efficient.

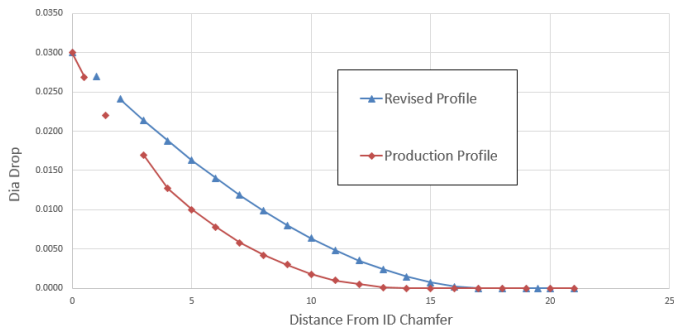


Figure 9: Piston pin bore profile designs

3.4.2 CAE

Finally, the pin-bore profile redesign was checked with the help of CAE methods. The redesign of the pin-bore profile was evaluated in detail. According to simulation results, the new geometry developed for the pin-bore reduced contact pressures considerably in its central region and resulted in balanced and effective distribution of loads along the bore. Thus, redesign improved the mechanical performance and durability of components.

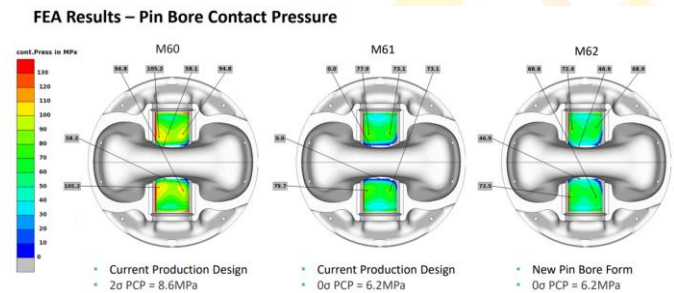


Figure 9: Piston pin bore contact pressure FEA

This new profile design considerably improved the wear patterns on the pin bore compared to the previous configuration and, hence, substantially improved its durability and operational life with the modified design parameters.

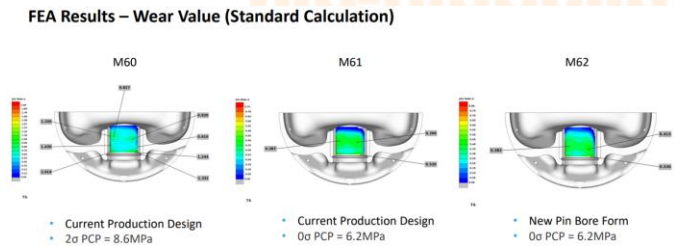


Figure 10: Piston pin bore WEAR FEA

3.4 Statistical clearance scuff Test with profile Update

The research team incorporated the successful simulation outcomes and the enhanced resistance to scuffing achieved through statistical minimum clearance adjustments into the final stages of design refinement and validation. By employing these improved design principles, the components underwent extensive hot-scuff testing. Notably, the testing results demonstrated the absence of scuffing, confirming that the piston pin bores, rod bore, and pins were in excellent condition. This outcome effectively showcased the effectiveness of the combined design improvements in elevating the component's resilience and performance.

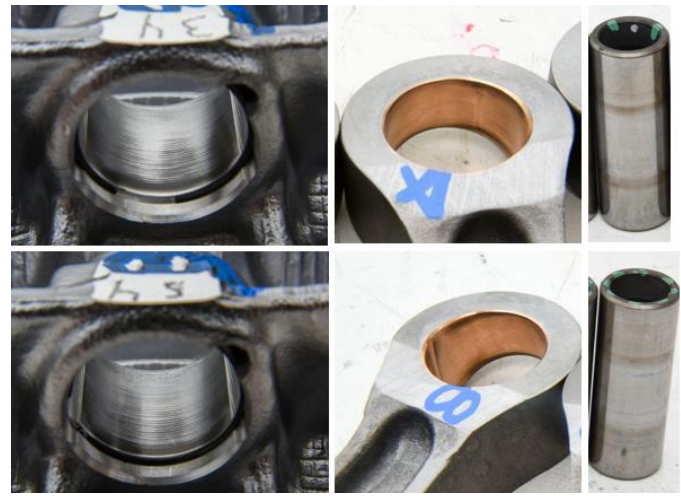


Figure 11: Piston, rod & pin post nominal clearance scuff test

4. Conclusion

It is a comprehensive and innovative solution to this age-old problem of scuffing in the piston pin bores, which has been giving tough times to automotive engineers. The project Refine meticulous design and uses advanced statistical analysis to make improvements in the scuffing resistance of critical engine components dramatically better. The following is a synopsis of the study: It has been possible to effectively reduce the occurrence of scuffing, hence increasing the life and reliability, through focusing on the optimization of piston pin bore dimensions and revising the recommended clearances.

The treatment was underpinned by a comprehensive understanding of the manufacturing processes and identification of key controlling parameters influencing scuffing resistance. Advanced understanding has also opened the development and utilization of optimization techniques to fine-tune bore size and clearance specifications to such levels beyond imagination by traditional standards. In the processes, it introduces a revised profile for the piston pin bore that distributes loads around the component more uniformly—an imaginative innovation in component design.

This correction has been proved to reduce contact pressure near the center of the bore, hence contact pressure in general, reducing wear and increasing the life of engine components.

In particular, the application of statistical clearance models and capability studies that were used in this study provide a very strong and reliable framework for the prediction and improvement of engine component performance under real-world conditions. The results of this research provide not only a practical guide for future engineering projects; it also illustrates the need to combine statistical analysis with engineering design to solve complex mechanical problems. That combination of those methodologies made a difference in both mechanical engineering and the car designs. This research demonstrated that a data-driven approach could deliver large improvements in the performance of engine components. While it has turned out to be one of the success stories, more exciting successes from internal combustion engine technology are yet to come forth with such promising engines as more hard-wearing, fuel-efficient, able to stand rigors of high performance. This forms a landmark study in our continued quest to develop engine technologies that address the ever-changing demands of an increasingly innovative automotive industry,

where precision engineering and quality control become highly indispensable for excelling in automotive design and manufacturing.

5. Future Work

Research in the optimization of the cylinder bore design of a piston pin for improved scuffing resistance brings a solid platform for future study, focusing on some key areas. Durability testing under various realistic conditions is required to properly understand the long-term performance and scuffing resistance of the component. To achieve this goal of improving the life and reliability of components by reducing friction and wear, new materials or coatings need to be investigated. Advanced simulation techniques such as multi-physics modeling and machine learning are needed to significantly improve understanding of scuffing mechanisms and effectiveness for designed components. The manufacturing process needs to be improved to have more control on the bore dimensions and surface finish, which could be achieved through precision machining or additive manufacturing. In addition, it sets up real-time monitoring systems through sensors for early signs of scuffing detection that will help preventive maintenance for reliability. Finally, such cooperation across the boundaries of narrow expertise could give birth to innovative solutions for scuffing resistance, oneself contributing to sustainability and reduced environmental impact within the automotive industry with more durable engines, efficient, and reliable.

References

- [1] Wakuri, Y., Soejima, M., Kitahara, T., Maeda, T., Xu, S., & Fujisaki, K. (1991). Experimental Studies on Friction and Scuffing Resistance of Ceramics for Cylinder Linear and Piston Ring. *JSME International Journal Ser 3 Vibration Control Engineering Engineering for Industry*, 34(2), 271–277.
- [2] Knowland, C. G., & Russell, C. J. (1996). Predictive Optimization of Piston and Ring Stability. *SAE Technical Papers on CD-ROM/SAE Technical Paper Series*. <https://doi.org/10.4271/960873>
- [3] Wang, Y., Yao, C., Barber, G. C., Zhou, B., & Zou, Q. (2005). Scuffing resistance of coated piston skirts run against cylinder bores. *Wear*, 259(7-12), 1041–1047. <https://doi.org/10.1016/j.wear.2004.12.005>
- [4] Etsion, I., Halperin, G., & Becker, E. (2006). The effect of various surface treatments on piston pin scuffing resistance. *Wear*, 261(7-8), 785–791. <https://doi.org/10.1016/j.wear.2006.01.032>
- [5] Tas, M. O., Banerji, A., Lou, M., Lukitsch, M. J., & Alpas, A. T. (2017). Roles of mirror-like surface finish and DLC coated piston rings on increasing scuffing resistance of cast iron cylinder liners. *Wear*, 376-377(Part B), 1558–1569. <https://doi.org/10.1016/j.wear.2017.01.110>
- [6] Wan, S., Li, D., Zhang, A., Tieu, A. K., & Zhang, C. (2017). Comparison of the scuffing behaviour and wear resistance of candidate engineered coatings for automotive piston rings. *Tribology International*, 106, 10–22. <https://doi.org/10.1016/j.triboint.2016.10.026>
- [7] Priest, M. (2003). Optimisation of piston assembly tribology for automotive applications. *Tribology Series*, 41, 739–748. [https://doi.org/10.1016/s0167-8922\(03\)80187-6](https://doi.org/10.1016/s0167-8922(03)80187-6)
- [8] Malaczynski, G., Qiu, X., Hamdi, A., & Alaa Elmoursi. (1996). Bench Test for Scuff Evaluation of Surface Modified Piston and Bore Materials. *SAE Technical Papers on CD-ROM/SAE Technical Paper Series*. <https://doi.org/10.4271/960013>

[9] Zhang, W., Becker, E., Wang, Y., Zou, Q., Zhou, B., & Barber, G. C. (2008). Investigation of Scuffing Resistance of Piston Rings Run against Piston Ring Grooves. *Tribology Transactions*, 51(5), 621–626. <https://doi.org/10.1080/10402000802044316>

[10] Wang, Y., Brogan, K., & Tung, S. C. (2001). Wear and scuffing characteristics of composite polymer and nickel/ceramic composite coated piston skirts against aluminum and cast iron cylinder bores. *Wear*, 250(1-12), 706–717. [https://doi.org/10.1016/s0043-1648\(01\)00679-2](https://doi.org/10.1016/s0043-1648(01)00679-2)

[11] Han, J. M., Zhang, R., Ajayi, O. O., Barber, G. C., Zou, Q. L., Guessous, L., Schall, D., & Alnabulsi, S. (2011). Scuffing behavior of gray iron and 1080 steel in reciprocating and rotational sliding. *Wear*, 271(9-10), 1854–1861. <https://doi.org/10.1016/j.wear.2010.11.061>

[12] Ma, S., Chen, W., Li, C., Jin, M., Huang, R., & Xu, J. (2018). Wear Properties and Scuffing Resistance of the Cr–Al₂O₃ Coated Piston Rings: The Effect of Convexity Position on Barrel Surface. *Journal of Tribology*, 141(2). <https://doi.org/10.1115/1.4041215>

[13] Galligan, J., Torrance, A. A., & Liraut, G. (1999). A scuffing test for piston ring/bore combinations: *Wear*, 236(1-2), 210–220. [https://doi.org/10.1016/s0043-1648\(99\)00277-x](https://doi.org/10.1016/s0043-1648(99)00277-x)

[14] Ahn, T.-S., Cho, D.-H., Oh, C.-S., & Lee, Y.-Z. (2007). Friction Wear and Scuffing Life of Piston Rings With Several Coating for Low Friction Diesel Engine. *Tribology and Lubricants*, 23(4), 170–174. <https://doi.org/10.9725/kstle.2007.23.4.170>

[15] Olander, P., & Jacobson, S. (2015). Scuffing resistance testing of piston ring materials for marine two-stroke diesel engines and mapping of the operating mechanisms. *Wear*, 330-331, 42–48. <https://doi.org/10.1016/j.wear.2015.01.074>

Definitions/Abbreviations

Scuffing: Unwanted surface damage between mating components due to insufficient clearance or lubrication failure.

Piston pin bore: The hole in the piston where the piston pin is inserted, crucial for maintaining minimal clearance to prevent scuffing.

Clearance: The gap between the piston pin and its bore.

NVH: Noise, Vibration, and Hardness.

CAE: Computer-Aided Engineering.

POC: Proof of Concept.

Optimization: The process of making a system or design as effective as possible.

Statistical analyses: Use of statistical methods to analyze data and draw conclusions.

Capability studies: Assessments to determine the capability of a manufacturing process.

1 Parts Per Million (PPM) fallout: A statistical approach used to determine optimal clearance values to minimize component failure.
Minimum Oil Film Thickness (MOFT): The thinnest layer of oil that provides lubrication between components.

Idle Phase: The initial phase where the system or engine is set to idle.

Peak Power Phase: The phase where the system's activity increases to its peak power state.

Secondary Coolant System: An additional cooling system to enhance the cooling efficiency.

Cycle Repetition: Repeating the stages of a test cycle to ensure comprehensive testing.

Finite Element Analysis (FEA): A computerized method for predicting how a product reacts to real-world forces.

Hot-scuff testing: Testing to assess the performance of engine components under high-temperature conditions.

