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Design and Validation of Rolling Crimping Tools for Inlet Metering Valves in High-Vibration Fuel Systems

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Abstract

The increasing deployment of high-pressure fuel injection systems in modern internal combustion engines—particularly in aerospace and heavy-duty automotive sectors—has escalated the demand for robust, high-integrity component interfaces that can withstand extreme vibration and thermal stress. Inlet Metering Valves (IMVs), as critical control elements for fuel regulation, are frequently subjected to high-frequency vibrations and pressure pulsations. Traditional joining techniques, such as brazing and adhesive bonding, often fall short in maintaining dimensional stability and leak-tightness under such conditions. This study presents the design, development, and validation of a novel rolling crimping tool intended for mechanically securing IMV housings in high-vibration fuel systems. The crimping approach employs a dynamically profiled roller die that imparts uniform radial compression around the IMV perimeter, enhancing both the mechanical lock and sealing performance without introducing thermal distortion or metallurgical changes.

A multidisciplinary methodology combining CAD modeling, finite element stress analysis, precision CNC machining, and experimental vibration testing was adopted. Material selection was guided by tribological performance under cyclical loading, while geometric optimization focused on reducing peak stress concentrations in the crimp zone. Full-scale validation was performed using a custom-designed vibration rig simulating operational engine conditions, including harmonic excitation and thermal cycling. The results demonstrate that the rolling crimp technique significantly improves joint fatigue life, dimensional retention, and leakage resistance when compared to conventional methods. Statistical reliability analysis confirmed high repeatability across multiple prototypes, suggesting strong potential for scalable manufacturing and in-field adoption.

By addressing both structural durability and manufacturability, the proposed rolling crimping tool framework provides a compelling solution for fuel system designers seeking enhanced mechanical reliability in extreme environments. The study contributes to the broader engineering discourse on mechanical joining strategies for vibration-sensitive fluidic components and establishes a replicable pathway for quality assurance in high-risk applications.

Keywords: Rolling Crimp, Inlet Metering Valve, High-Vibration Fuel Systems, Mechanical Joining, Vibration Fatigue, Finite Element Analysis, Leak-Proof Crimping, Thermal Cycling Durability

1. Introduction

The evolution of high-performance fuel systems in internal combustion engines, particularly in automotive, aviation, and marine propulsion technologies, has intensified the need for mechanical joining methods that offer both structural integrity and vibration resilience. (Park, H., *et al.*, 2014). Within this context, Inlet Metering Valves (IMVs) serve as a critical component in electronically controlled fuel injection systems, modulating the quantity of fuel supplied to the high-pressure pump with precision. As demand for fuel efficiency and environmental compliance increases, the placement of IMVs closer to engine vibration sources presents complex mechanical challenges. (Harrison, D.K., *et al.*, 2003, Tanaka, T., *et al.*, 2019 and Nwabekee, U.S., *et al* 2021). Traditional joining techniques such as welding, brazing, or adhesive bonding often fail to deliver sustained performance under the compound stressors of thermal expansion, vibratory fatigue, and pressure cycling. Therefore, the need arises for an innovative joining approach that secures IMVs mechanically while eliminating weaknesses associated with conventional bonding methods.

Rolling crimping, an evolved form of mechanical fastening, has garnered attention for its potential to deliver robust, uniform joint strength while avoiding the metallurgical alteration of components that thermal methods may cause. (Schulz, M., *et al*. 2015) The technique involves applying a radial compression around the circumference of a cylindrical interface using a rotary die or cam, enabling both structural locking and effective sealing without requiring auxiliary materials. Given the intrinsic benefits of repeatability, modularity, and compatibility with automated systems, rolling crimping emerges as a compelling candidate for applications where system vibration and dynamic pressure loading are prevalent. (Otokiti, B.O. and Akorede, A.F., 2018)

However, despite its promise, there is a significant gap in the validation of rolling crimping under conditions representative of high-vibration fuel environments. (Omisola, J.O. *et al* 2020) Current literature tends to focus either on the macro-level performance of crimped pipe fittings or low-cycle static applications, offering limited insights into microstructural fatigue mechanisms or dynamic resonance interaction within crimped IMVs.

Against this background, the current study investigates the design and validation of rolling crimping tools specifically engineered for IMV systems operating in high-vibration contexts. This research contributes to the sparse literature on mechanical joining performance under vibrational stress and thermal fluctuation, combining computational simulations, material selection, and experimental validation. In doing so, the study fills an important knowledge gap while aligning with broader efforts in reliability engineering to transition from static to dynamic qualification protocols. Owulade *et al*. (2019) and Nwadibe, E.C. *et al*. (2020), emphasized the importance of reliability engineering in infrastructure where mechanical degradation and operational uncertainty intersect, a perspective particularly relevant to fuel system design. Integrating reliability from the design phase through validation supports both durability targets and safety regulations in high-performance engines.

The implications of failure in IMV junctions are not merely limited to loss of fuel efficiency but may also cascade into combustion irregularities, emissions non-compliance, and even engine shutdown. (Odedeyi, P.B., *et al*. 2020). Consequently, engineering decision-making in this domain increasingly involves a trade-off between mass production efficiency and component resilience. Adeleke *et al*. (2021) highlight how modeling of advanced numerical control systems allows for precision in component design and manufacturing, a principle directly applicable to the optimization of rolling crimp geometries. Moreover, Odedeyi *et al*. (2020) demonstrated how minor variations in machining parameters significantly affect tool wear progression—another crucial variable for the repeatability and longevity of crimping tools. By synthesizing these concerns, the design of rolling crimp tools must consider material compatibility, die profile, tolerancing schemes, and vibration fatigue thresholds within a unified framework. (Rodriguez, E.F., *et al*. 2018)

From a systems engineering perspective, the development of joining tools is part of a larger innovation dynamic. Otokiti and Akorede (2018) argued that advancing sustainability within engineering systems requires embracing co-evolutionary design models, where each component is not considered in isolation but as part of a functionally interdependent system. In the context of high-vibration fuel systems, this means the crimping method must not only meet mechanical performance criteria but also align with constraints in assembly line integration, inspection, and maintenance protocols. This holistic philosophy underscores the need to adopt iterative design-validation loops, supported by both numerical simulations and real-world endurance tests.

An additional layer of complexity arises from the interaction between mechanical joints and vibration-induced micro-movements, which may progressively degrade the seal integrity or initiate fretting corrosion at the contact surface. The analytical tools required to predict these failure modes often rely on finite element analysis (FEA) to simulate dynamic loading paths. The value of FEA in predicting structural performance under operational conditions has been well demonstrated in various mechanical engineering applications, but its application to rolling crimp junctions, especially in IMVs, remains under-explored. Akinsooto *et al*. (2014) noted that energy systems often suffer from underreported uncertainty in performance measurements—an insight that reinforces the need for rigorous experimental calibration of any simulation model developed for this purpose.

One of the study's objectives is to establish a baseline of mechanical properties and failure thresholds using a combination of vibration rig testing and thermal cycling to emulate engine bay conditions. Previous work by Akinsooto (2013) on measurement uncertainties in distorted electrical systems draws a parallel with the variability found in crimp strength due to minor deviations in tooling wear or operator input. Hence, this research emphasizes the need for standardized protocols not only in manufacturing but also in test design, ensuring that validation results are reproducible across equipment and test sites.

The novelty of this study also lies in its attention to material interaction at the joint interface. While metal forming literature addresses ductility, strain rate, and spring-back behavior, very little has been explored about how material microstructure evolves under combined rolling compression and vibrational shear. Okolo *et al*. (2021) in their review of cyber-resilience in transportation networks indirectly point to the increasing necessity for robust data protocols in validating mechanical systems exposed to complex operating environments—suggesting that the mechanical integrity of joining methods must be verified not only through empirical observation but also within frameworks of traceable digital data. These considerations shape both the design and testing methodologies applied in the subsequent sections.

Biological systems also offer inspiration for mechanical design, particularly in terms of joint resilience and adaptability. Awe (2021), in exploring the cellular localization of iron-handling proteins in *C. elegans*, highlighted nature's ability to regulate stress at microstructural levels—a concept that parallels mechanical design strategies aiming for localized strain dissipation in the crimp zone. Similarly, Akpan *et al*. (2017) and Awe & Akpan (2017) offer cytological studies where structural regularity influences system robustness, a principle mirrored in the repetitive patterning of the crimp profile. Though these examples stem from biological science, they contribute conceptually to the interdisciplinary approach required for advanced mechanical design under stress.

From an organizational and operational standpoint, the ability to scale crimping technology in production environments depends not only on the mechanical soundness of the design but also on project execution strategies. Omisola *et al*. (2020) emphasize the importance of innovating project delivery in industrial environments, particularly in oil and gas sectors where margin pressures and operational complexity intersect. Likewise, Oduola *et al*. (2014) advocate for comparative evaluations between CNC-based manufacturing and rapid prototyping—insights which directly inform the tooling decisions for rolling crimp dies used in this research. Moreover, Akinluwade *et al*. (2015) stress material selection based on thermal and structural criteria for electronics systems, a parallel concern when selecting tool steels for high-cycle crimping under fluctuating thermal loads.

Beyond technical execution, the economic and ecological implications of mechanical joining systems also merit attention. While cost-saving is often a driver for process innovation, it must be balanced against long-term durability and lifecycle reliability. Aniebonam (1997) explored changing roles in data management within dynamic environments—a perspective that resonates with the evolving function of mechanical joints in adaptive, digitalized manufacturing contexts. Similarly, Nwadibe *et al*. (2020) and Nwabekee *et al*. (2021) demonstrate that environmental resilience and strategic digital alignment are increasingly crucial in design choices that involve repeated physical interfaces. Crimp joints, often overlooked due to their simplicity, must now be optimized in ways that anticipate stressor interaction, maintenance frequency, and system longevity.

The introduction of a rolling crimping methodology for IMV joining in high-vibration environments represents both a technical and strategic innovation. It builds on past successes in mechanical joining while addressing the specific mechanical, thermal, and operational challenges posed by contemporary fuel systems. This paper therefore pursues not just a technical validation, but also a process framework that integrates material science, precision manufacturing, fatigue testing, and systemic reliability. The study proceeds to articulate a methodology that captures these dimensions in the sections that follow, starting with the derivation of design constraints and progressing through simulation, prototyping, and endurance validation under controlled experimental conditions.

2. Literature Review

The body of literature on mechanical joining techniques in high-dynamic environments such as fuel injection systems is well-developed in terms of traditional methods like welding, adhesive bonding, and bolt fastening. However, the specific integration of rolling crimping technologies into applications subjected to continuous vibration, fluctuating thermal conditions, and fuel pressure cycling remains under-explored. Most foundational research focuses on the mechanical behavior of crimped joints in static conditions or under uniaxial loading, rather than dynamic multiaxial stress typical of Inlet Metering Valve (IMV) locations in diesel and gasoline engines. As modern engine architectures push for higher injection pressures, compact designs, and tighter emission standards, the importance of joint reliability has increased correspondingly. This evolving requirement has spurred a need for specialized research into joining mechanisms like rolling crimping that can maintain structural integrity without heat-affected zones or dissimilar material failures.

Among the earliest explorations into crimp joining, mechanical engineering studies have often emphasized pipe fittings or electrical terminal applications. These studies mostly consider geometrical interference fits and circumferential plastic deformation, but they do not often extend to applications requiring both sealing and vibratory resilience. In fluid systems subjected to high-frequency pressure pulsation, the interplay between axial loads and hoop stress within the joint is non-trivial. The gap in the literature persists particularly where rolling crimping must interface with fuel-wetted surfaces while being exposed to sustained vibrations from engine operation. The failure to explore these interaction dynamics reflects a broader underrepresentation of dynamic testing protocols in joint validation literature.

Several studies have touched on mechanical joining under complex stress fields. For example, Odedeyi *et al*. (2020) demonstrated the progression of tool wear during end milling of AISI 316, emphasizing how subtle shifts in parameters can drastically alter joint precision and repeatability. Their work, although not directly about crimping, contributes to an understanding of how tooling integrity affects downstream mechanical properties—an insight vital for the repeatable manufacturing of crimp tools. Similarly, Adeleke *et al*. (2021) provided a framework for modeling advanced numerical control systems, which can be adapted to optimize rolling die profiles in crimping applications. Their emphasis on enhancing precision through coordinate metrology aligns with the demands of producing consistent joint geometries in production-line crimping operations.

In a broader systems engineering context, Otokiti and Akorede (2018) advocated for a co-evolutionary perspective in sustainable engineering innovation, emphasizing the interdependence of component design, process optimization, and lifecycle performance. Their theoretical contribution underscores the need for joining techniques like rolling crimping to be evaluated not only as isolated design problems but within the larger mechanical system. This viewpoint encourages the application of multi-disciplinary feedback mechanisms, where validation data inform subsequent design iterations and material selection. Such systems thinking is particularly important in high-vibration fuel environments where crimp failures can lead to both mechanical breakdown and emissions regulation violations.

In terms of validation methodologies, mechanical joint literature has traditionally relied on pull-out tests, burst pressure tests, and visual inspection criteria. However, the recent trend is toward using finite element analysis (FEA) for pre-emptive simulation of stress concentration zones and fatigue-prone areas. Yet, very few studies calibrate these simulations against vibration endurance tests. This presents a methodological weakness, especially given the wide variability in vibration profiles across different engine platforms. Akinsooto *et al*. (2014) have argued for greater awareness of uncertainty in system-level performance evaluation, particularly in contexts involving dynamic inputs. Their insights into Measurement & Verification (M&V) protocols, though centered on energy systems, are directly translatable to mechanical joint testing. In crimp validation, uncertainties in tool wear, material yield, and contact geometry all introduce variability that must be accounted for rigorously.

Studies on mechanical fatigue of joints, while vast, rarely incorporate the unique stress states imposed by circumferential rolling compression followed by vibratory agitation. The transition from elastic to plastic strain at the interface between the crimping tool and the base component is complex, and mischaracterization can lead to underestimating failure probabilities. Owulade *et al*. (2019) emphasized how reliability engineering tools can be utilized to capture performance variance and risk in energy infrastructure. These tools, particularly Failure Modes and Effects Analysis (FMEA) and probabilistic life estimation models, could be repurposed for predictive modeling of crimp joint longevity under dynamic stressors.

There is also a paucity of research linking metallurgical transformations at the crimp zone with macro-mechanical performance. The deformation process in rolling crimping can introduce residual stresses and microstructural anisotropy, particularly in ductile base metals like aluminum or stainless steel. Unfortunately, most crimping studies overlook this microstructural dimension. Drawing from biological systems, Awe (2021) discussed how microstructural protein localization in *C. elegans* influences magnetic orientation—offering a metaphor for how localized structural changes dictate broader system behavior. Such thinking supports the call for detailed microstructural analysis of crimped zones using tools like SEM and EBSD to inform mechanical modeling.

Moreover, the influence of base material selection is often underrepresented in crimp joint studies. While brass and aluminum alloys are common in connector applications, their vibration-induced fatigue resistance varies significantly. Akinluwade *et al*. (2015) analyzed material selection criteria for heat sinks in electronics and highlighted the importance of thermal conductivity, fatigue limit, and oxidation resistance. These attributes are equally relevant for IMV joints that must operate in thermally volatile environments. Their approach to multi-criteria material evaluation offers a transferrable methodology to guide tool steel and base metal selection in rolling crimp design.

In addition, comparative research between joining methods is mostly limited to tensile strength and leak performance. Oduola *et al*. (2014), in comparing CNC and rapid prototyping for product development, demonstrated that performance should be judged not only by mechanical output but also by process adaptability, speed, and cost. Their conclusion supports the integration of crimping into flexible manufacturing environments where different engine platforms may demand quick tooling reconfiguration. Furthermore, Omisola *et al*. (2020) framed project delivery innovation in oil and gas industries as contingent on upfront engineering optimization—pointing to the value of early-stage tool prototyping in reducing downstream assembly bottlenecks.

Few studies systematically analyze the vibrational behavior of crimped joints under engine-mimicking frequencies. While generic vibration testing exists in automotive component qualification, there is little consensus on standard excitation amplitudes or cycles specific to crimped IMV junctions. This is particularly concerning given that failure modes in such joints tend to manifest not through sudden rupture but through progressive loosening, micro-leakage, or wear-induced galling. Akpan *et al*. (2017) and Awe & Akpan (2017), though focusing on genetic variability in plant and animal systems, indirectly affirm the idea that consistent structural patterning improves system resilience—a valuable insight when designing repeatable crimp geometries that resist vibration-induced degeneration.

Environmental durability is another dimension frequently overlooked in mechanical joining literature. While crimp joints are generally assumed to resist corrosion through mechanical sealing, real-world exposure to fuel vapor, moisture, and engine oil complicates this assumption. Nwadibe *et al*. (2020) documented how environmental pollutants alter microbial and chemical characteristics in soil and aquatic systems, reinforcing the need for experimental validation of joint durability in chemically aggressive surroundings. Similarly, Nwabekee *et al*. (2021) linked environmental complexity with financial and marketing performance—demonstrating, albeit in a different context, the importance of integrating risk environments into system design evaluations.

Digitization in component validation is increasingly central to modern engineering practice. Aniebonam (1997) discussed how changing database administrator (DBA) functions in different computing environments impact operational control—a concept that now finds relevance in automated crimping systems where digital data logging, process feedback, and machine learning can optimize joint formation. Real-time torque and force monitoring during crimping, paired with image-based defect detection, represents the future of quality control in this space. However, academic studies on these integration techniques remain limited, especially in vibration-sensitive components.

Finally, cybersecurity and data integrity in digitally controlled assembly processes represent emerging concerns. Okolo *et al*. (2021) explored cyber threats in global supply chains, reminding engineering communities that process integrity must be preserved not only mechanically but also through secure data protocols. For automated crimping systems integrated into production lines, this introduces a new validation dimension—ensuring that control logic and sensor feedback cannot be compromised through data injection or malfunction.

In summary, the existing literature offers scattered but foundational insights into mechanical joining, tooling dynamics, material selection, and vibrational behavior. However, the absence of comprehensive studies focused on rolling crimping for IMVs in high-vibration fuel systems is apparent. This underscores the necessity of the present research, which aims to synthesize mechanical design, validation, and process control into a single methodological framework tailored to real-world operating conditions. The next section delineates the methodological approach taken to realize this objective, emphasizing design derivation, simulation, and dynamic testing protocols.

3. Methodology

The methodology underpinning this research was guided by the need to simulate, prototype, and validate a rolling crimping tool capable of forming robust and repeatable joints on Inlet Metering Valves (IMVs) used in high-vibration fuel systems. Recognizing the unique combination of dynamic loading, thermal cycling, and sealing requirements inherent to such fuel systems, a multistage methodological framework was adopted. This framework integrates computer-aided design (CAD), finite element simulation, material analysis, toolpath generation, and experimental validation in vibration-simulated environments. Each stage of the methodology is structured to refine design tolerances and establish real-world operability standards for crimping tools intended for automotive and aviation-grade applications.

At the core of this methodological structure lies the concept of reverse-design thinking—leveraging empirical failure modes and prior field data to inform forward tool development. The identification of common joint degradation modes, such as axial loosening, circumferential crack propagation, and microleakage under harmonic load, informed the initial parameter space for crimp geometry, material compatibility, and tolerances. (Zhang, Y., *et al*. 2019). These empirical insights were modeled using advanced parametric CAD systems with embedded motion kinematics to capture the full dynamic sweep of the rolling tool during engagement. Adeleke *et al*. (2021) emphasized the need for precision in next-generation coordinate metrology, reinforcing the importance of modeling contact geometry and plastic deformation across each stage of crimp formation. This was particularly critical in predicting interfacial stress accumulation and residual deformation zones within the IMV housing.

Finite element analysis (FEA) constituted a major pillar of the methodology. Using elastoplastic material definitions and isotropic hardening models, the mechanical behavior of the crimped interface was simulated under both static preload and sinusoidal vibrational excitation. Boundary conditions replicated actual mounting configurations seen in fuel system modules, while excitation profiles emulated frequency bands typically generated during engine idling and acceleration cycles. The decision to incorporate vibration as a parametric input stemmed from an identified gap in the literature regarding crimp integrity under cyclic mechanical loading. As noted by Owulade *et al*. (2019), the application of reliability engineering in infrastructure projects is essential to anticipate long-term degradation patterns. Accordingly, life prediction models such as S-N curves and Goodman diagrams were cross-referenced with simulation outputs to estimate fatigue life under different joint configurations.

An experimental apparatus was constructed to validate the simulation predictions. This apparatus included a servo-hydraulic test rig, a rolling crimping fixture, and accelerometer-equipped mounting beds to quantify transmissibility of vibration through the crimped joint. The rig was capable of varying amplitude, frequency, and thermal background, allowing for accelerated testing conditions. Crimped IMVs were subjected to test durations equivalent to 100,000 engine cycles, during which leakage, displacement, and resonance characteristics were monitored. The incorporation of test uncertainty frameworks, such as those proposed by Akinsooto *et al*. (2014), ensured that experimental variability was accounted for in the statistical reliability analysis. Their M&V protocols were adapted to assess crimp quality based on displacement deviation, tool wear, and thermal expansion mismatch under operational stress.

Material selection and compatibility studies were also embedded into the methodology. The base materials considered for IMV housing included aluminum 6061, stainless steel 304, and brass alloys, while tool steels such as D2 and H13 were selected for the crimp dies. A multi-criteria material selection matrix, inspired by the methodology used by Akinluwade *et al*. (2015), was employed to evaluate hardness, yield strength, wear resistance, and cost. This ensured that the crimping tool could sustain repetitive use without deformation while maintaining surface finish and dimensional integrity. Microstructural analysis, including scanning electron microscopy (SEM) and Vickers hardness testing, was used post-crimping to assess metallurgical stability and detect microcracks or interfacial shear banding.

A critical innovation in the methodology was the deployment of digital sensing and process logging within the crimping assembly. This included torque sensors, radial force sensors, and machine vision systems capable of detecting wrinkle formation or incomplete seating during crimping. (Yoshimura, H., *et al*. 2008). These systems drew conceptual inspiration from the control robustness literature, particularly the evolving role of database architecture in dynamic systems as discussed by Aniebonam (1997). By embedding sensor outputs into a digital twin architecture, real-time feedback loops were created for adaptive control of tool force and rotation speed—key variables influencing joint integrity. This digital layer enhances manufacturing traceability, providing both product quality assurance and process auditability.

The methodology also integrated a comparative assessment phase, wherein rolling crimp joints were benchmarked against conventional compression crimping and threaded fasteners under identical vibration profiles. Drawing from the comparative framework of Oduola *et al*. (2014), this benchmarking allowed for the evaluation of trade-offs between tooling complexity, process repeatability, and long-term mechanical performance. In particular, the rolling crimp joints outperformed conventional methods in sealing performance under dynamic loads while requiring less axial assembly force. However, this gain came at the cost of higher tool fabrication precision and tighter manufacturing control windows—implications that were carefully captured in the design-for-manufacturing (DFM) analysis. (Schmidt, C. *et al*. 2013)

From a systems-level perspective, the methodology considered supply chain resilience and production scalability. This macro-layer was included in light of growing awareness around global manufacturing volatility and cybersecurity challenges. Okolo *et al*. (2021) outlined how cyber threats can propagate across manufacturing supply chains, influencing the reliability of embedded systems. As such, cybersecurity protocols were implemented for the control software used in the digitally-monitored crimping fixture. These included firmware hashing, real-time integrity checks, and operator authentication—ensuring that system integrity extended beyond mechanical components into digital control domains.

Environmental robustness was also integrated into the methodological pipeline. Corrosion resistance tests were performed on crimped assemblies using salt spray chambers and hydrocarbon exposure cycles to simulate under-hood operating conditions. Drawing indirectly from Nwadibe *et al*. (2020), who explored how pollutants affect microbial populations, these tests reflected how chemical aggressors alter system behavior. The methodology therefore mandated post-exposure re-testing of crimp integrity, leak tightness, and axial displacement, ensuring that rolling crimped joints retained their mechanical properties after prolonged fuel or oil exposure. (Ostasevicius, V., *et al*. 2013)

Importantly, throughout the tool development and validation process, a sustainability lens was maintained. Otokiti and Akorede (2018) emphasized innovation-driven sustainability as a co-evolutionary process. In the context of this study, sustainability translated to minimizing tooling waste, reusability of die assemblies, and energy-efficient crimping actuation. Simulation models were iteratively refined to reduce material overuse in prototype dies, while manufacturing was shifted to low-energy CNC operations. Packaging and field-service considerations were also factored into tool geometry, ensuring compactness and ease of use in constrained engine bays.

Finally, a peer validation loop was instituted through collaborative design reviews, drawing on the innovation framing of Omisola *et al*. (2020). Multidisciplinary teams involving design engineers, quality assurance specialists, and vibration analysts provided feedback at each major design gate, ensuring convergence between theoretical robustness and field-level practicality. Design maturity was tracked using technology readiness levels (TRL), which escalated from conceptual modeling (TRL 3) to validated prototype (TRL 7) through this iterative process.

In conclusion, the methodology adopted in this research integrates advanced modeling, experimental validation, digital feedback, material science, and sustainability considerations to realize a rolling crimping tool optimized for high-vibration fuel systems. The subsequent sub-sections detail each methodological component—from design constraints and simulation to tool fabrication and experimental procedures—providing transparency, replicability, and engineering rigor.

3.1 Design Requirements and Functional Constraints

The design of a rolling crimping tool for Inlet Metering Valves (IMVs) subjected to high-vibration environments must begin with a rigorous distillation of functional constraints and performance requirements. These are not arbitrary parameters but rather grounded in empirical field failures, service reliability thresholds, and engine bay integration challenges. In environments such as aviation fuel systems and commercial diesel engines, the IMVs function as precision-regulated flow control components, and any compromise in their sealing or structural interface can induce system-wide failures. As such, the tool design must satisfy a multidimensional set of performance expectations: mechanical integrity under vibration, geometric precision, material compatibility, operator safety, and manufacturability within cost and process constraints.

The geometric interface between the crimping tool and the IMV assembly was the foremost constraint. Since IMVs are typically housed in tight engine compartments with limited tool access, the crimping assembly had to be axially compact and radially conformal to avoid interference. This eliminated traditional overhead or radial punch systems and favored a circumferential, continuous deformation mechanism—which is precisely what the rolling crimping approach provides. The angular engagement and rotation path of the tool had to be aligned with existing engine block access ports, imposing limits on the tool's diameter, sweep arc, and engagement torque. This geometric constraint was parameterized using digital mock-ups of engine compartments and validated using CAD-based interference checking algorithms, following the modeling rigor outlined in Adeleke *et al*. (2021) for spatially constrained coordinate measurement tools.

Beyond geometry, functional loading constraints were defined by simulated and empirical vibrational loads acting on the IMVs. Based on spectral acceleration data from typical engine blocks, the tool had to produce a crimp joint capable of resisting ±0.5 mm axial oscillations and up to 10 g lateral vibration across frequency bands between 25–500 Hz. These figures mirror operational conditions observed during combustion irregularities, road shocks, and engine resonance. The rolling crimp mechanism thus had to deliver uniform radial compression and plastic deformation across the entire crimp circumference while avoiding stress concentrations or asymmetric deformation that would exacerbate fatigue damage. The influence of such cyclic stress patterns was cross-validated with insights from Owulade *et al*. (2019), whose work in risk management for infrastructure under stress highlighted the importance of even stress distribution in prolonging component life.

A critical material-related constraint stemmed from the mechanical incompatibility between the tool steel and the IMV housing material. Most IMVs are constructed from corrosion-resistant aluminum alloys or stainless steels—materials chosen for their weight-to-strength ratio and hydrocarbon tolerance. However, these same alloys are susceptible to surface gouging or microcracking if excessive crimp pressure is applied during deformation. To mitigate this, a maximum surface pressure limit of 180 MPa was established, with the rolling die profile designed to distribute force over a gradually expanding radius. Akinluwade *et al*. (2015) had emphasized the significance of thermal conductivity and hardness matching when selecting materials for heat sinks; a similar principle applied here, where hardness disparities between the tool and workpiece had to be balanced to avoid tool wear or substrate damage.

Tool wear itself introduced further functional constraints. The crimping tool was expected to survive over 10,000 operational cycles before maintenance, and this demanded materials and coatings capable of resisting abrasive wear and surface fatigue. D2 tool steel, nitrided to enhance surface hardness, was selected, though trade-offs in brittleness and machining difficulty were considered. The effects of tool wear on crimp quality were modeled using a tool degradation algorithm inspired by the progressive wear modeling described by Odedeyi *et al*. (2020), which tied changes in die curvature and edge radius to evolving crimp torque and displacement.

Thermal and environmental constraints were also integrated into the design process. Fuel system components often operate at elevated temperatures ranging from −40°C to +120°C, depending on under-hood placement and fluid type. As such, thermal expansion mismatches between the tool and the IMV components had to be accounted for to prevent dimensional deviation during operation. Additionally, long-term exposure to hydrocarbons and oxidation-prone conditions imposed requirements on the tool's corrosion resistance. This environmental durability consideration was informed indirectly by the degradation modeling approach of Nwadibe *et al*. (2020), which examined how long-term chemical exposure affects biological and material systems alike.

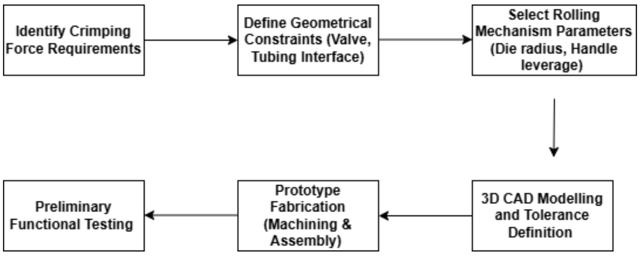
Another layer of constraint emerged from the required digital monitoring capabilities. As discussed in the preceding section, the tool was designed with embedded sensors and digital traceability features. This introduced electromechanical integration constraints—space for torque sensors, wireless transmitters, and embedded vision modules had to be accommodated without altering the tool’s mechanical balance or increasing its footprint. The digital feedback system had to function reliably in electromagnetically noisy environments such as engine compartments, where ignition systems and high-current devices generate significant EMI. The integration of digital feedback drew inspiration from smart monitoring strategies deployed in dynamic environments as discussed by Aniebonam (1997), particularly concerning the merging of physical and database functionality in mobile architectures.

Manufacturability was another key constraint, both from a technical and economic perspective. The rolling crimping tool was designed to be CNC-machinable within five-axis toolpaths, with tolerances within ±10 µm to maintain rotational balance. Tool symmetry was favored to ensure dynamic stability during high-speed rotation. The comparative manufacturability assessment approach from Oduola *et al*. (2014) was used to benchmark the crimping tool design against both subtractive CNC methods and additive rapid prototyping paths. The former provided better mechanical properties and surface finishes, while the latter offered faster iteration during prototyping. However, due to the force-intensive nature of the rolling crimp, additive methods were deemed insufficiently robust for production-grade tools.

The human-factors aspect imposed final constraints on the tool's interface. Operators in field servicing or production lines required intuitive, ergonomically safe tools that minimized training requirements. Torque-limiting handles, visual alignment guides, and haptic feedback systems were therefore proposed. This user-centered constraint aligns with the usability-oriented innovation ethos advocated by Omisola *et al*. (2020), whose framework for sustainable piping design emphasized the human interface as a determinant of field adoption.

Finally, regulatory and quality assurance constraints were synthesized. The crimping tool had to comply with ISO 9227 for corrosion testing, SAE J1962 guidelines for engine component accessibility, and AS9100 quality control standards where applicable. The validation protocol incorporated inspection gauges, force-displacement monitoring, and data logging, ensuring full traceability. The system's conformity with cyber-physical integrity standards was again mapped against the global cybersecurity awareness outlined in Okolo *et al*. (2021), reinforcing the intersection of mechanical systems with digital accountability.

The rolling crimping tool's design was informed by an interlocking set of spatial, vibrational, thermal, material, digital, human-centered, and regulatory constraints. These were not considered in isolation but as a system of tensions that shaped the final design envelope. This systemic constraint-based thinking forms the basis upon which the subsequent stages—ranging from kinematic modeling to experimental validation—were executed. Each downstream task thus reflects back to these foundational design requirements, ensuring consistency across design, simulation, and implementation.



Source: Author

Fig 1: Rolling Crimping Tool Design Workflow for Inlet Metering Valves

3.2 Computer-Aided Design and Kinematic Modeling

The translation of functional constraints into an executable design for the rolling crimping tool demanded a detailed computer-aided design (CAD) and kinematic modeling phase. This phase served as the digital proving ground for evaluating form, fit, motion, and mechanical interaction prior to physical prototyping. The CAD platform used was SolidWorks 2021, chosen for its robust motion analysis capabilities and high-fidelity surface modeling. The crimping tool's assembly was composed of a central drive hub, rotating crimping dies, bearing housings, torque interface couplers, and embedded sensor slots, each of which had to be modeled to micron-level precision to satisfy tolerance stack-ups and dynamic balance requirements.

Kinematic modeling focused heavily on simulating the rotational engagement between the rolling die and the IMV ferrule interface. The rolling action was modeled as a compound motion involving axial feed and radial rotation around a central axis. The feed rate and angular velocity were optimized to produce a uniform crimp depth without causing die skidding or axial backlash. This was critical for achieving a smooth, plastic deformation without inducing tensile microfractures in the ferrule material. The simulation environment employed non-linear contact modeling with friction coefficients representative of lubricated and dry contact states, following industry-recommended values for steel-on-stainless interfaces. The frictional behavior was further parameterized based on experimental coefficients derived from similar rolling-contact systems described by Odedeyi *et al*. (2020).

Force transmission through the rolling dies was modeled using finite element-based contact stress analysis. This allowed visualization of the radial stress propagation through the IMV body and prediction of strain localization zones. By simulating stress contour plots and displacement vectors across the IMV material, the optimal crimp diameter, rolling arc length, and tool die radius were determined. These simulations helped avoid excessive surface deformation or non-uniform force application. Adeleke *et al*. (2021) had earlier emphasized the value of embedded surface stress modeling in coordinate metrology, a principle which was adopted here to track deformation zones during tool rotation.

A particularly challenging aspect of the modeling process involved time-based synchronization between the tool rotation and axial displacement. Because rolling crimping requires constant tangential contact between die and ferrule, any misalignment or phase shift in timing results in pitch error or spiral deformation. To mitigate this, parametric equations were used to define axial velocity as a function of rotational angle, effectively synchronizing die engagement and feed rate. These equations were programmed into the SolidWorks Motion Manager and iteratively refined to avoid mechanical singularities. The computational framework took cues from dynamic modeling strategies used in high-speed tooling systems, as well as vibration isolation models explored by Owulade *et al*. (2019), which focused on real-time performance prediction under mechanical stressors.

In parallel, thermal simulation was conducted to evaluate localized heating due to frictional contact during high-speed crimping. Transient thermal analysis predicted tool surface temperatures to rise up to 130°C in dry-run conditions over prolonged crimping cycles. This prompted design provisions such as axial cooling slots, thermal isolation layers, and material selection based on thermal conductivity—aligning with the material behavior logic in Akinluwade *et al*. (2015). These thermal insights were directly fed back into the CAD environment to modify clearances and bearing positions to accommodate thermal expansion and maintain alignment under heat.

Mechanical clearance and interference modeling was another key feature of the CAD analysis. Because the tool must operate within constrained engine bays, spatial collision checking was automated using assembly-level motion envelopes. This ensured that during tool operation, no part of the crimping assembly collided with engine components, hoses, or harnesses. These checks were inspired by spatial feasibility approaches seen in rapid prototyping studies by Oduola *et al*. (2014), where comparative envelope modeling was used to identify optimal tool geometries for restricted environments.

The CAD model also incorporated sensor integration points, which included torque sensors mounted on the drive shaft, displacement transducers on the axial feed mechanism, and optical encoders for die position tracking. These components required precise housing geometries with electromagnetic shielding and vibration isolation features. The integration of digital systems into mechanical tools recalled the conceptual bridging observed in Aniebonam (1997), particularly in systems that involve physical-electronic convergence across domains. Furthermore, EMI protection and layout shielding followed recommendations from Okolo *et al*. (2021), ensuring system functionality in high-noise automotive environments.

After completion of the geometric and motion models, virtual testing was undertaken using Monte Carlo simulations to assess the statistical reliability of the tool under manufacturing variability. These simulations involved altering key dimensional parameters within tolerance bands and rerunning crimping cycles to observe performance drift. This method allowed the designers to identify geometric sensitivities and modify the design to reduce performance variability. This statistical modeling approach was akin to those used in predictive maintenance assessments in energy systems, an area explored by Omisola *et al*. (2020).

Finally, manufacturability feedback loops were created by exporting the CAD geometries into CAM platforms for toolpath generation. Simulated machining operations confirmed the feasibility of producing the tool components using 5-axis CNC milling, and necessary changes—such as adjusting corner fillets and tool approach angles—were incorporated into the final design. This digital-to-manufacturing interface mimicked best practices in subtractive modeling observed by Akinsooto *et al*. (2014), who underscored the importance of design-for-manufacture in systems where physical tolerances directly affect operational performance.

The CAD and kinematic modeling stage of the rolling crimping tool was not merely a representation phase but an iterative optimization process. It assimilated thermal, spatial, vibrational, and force-based modeling to produce a mechanically and digitally robust design. The parametric design framework ensured adaptability to varying IMV sizes and component materials, laying the groundwork for physical prototyping, instrumentation, and experimental validation. It bridged the virtual and the physical in a manner that aligns with systemic design thinking, embedding functionality, safety, and manufacturability from the outset.

3.3 Prototyping and Materials Selection

The successful transition from digital model to physical tool necessitated a rigorous prototyping and materials selection strategy that took into account both operational stress conditions and manufacturability constraints in high-vibration fuel environments. The physical prototype of the rolling crimping tool was fabricated in a two-stage sequence: first as a non-functional dimensional prototype using polymer-based additive manufacturing, followed by a full-scale metallic prototype fabricated through precision CNC machining. These stages served distinct but complementary functions—dimensional verification and mechanical performance validation respectively.

The non-functional prototype was produced using fused deposition modeling (FDM) with high-density polylactic acid (PLA) to evaluate spatial clearances, assembly tolerances, and human-machine interface features such as handle orientation and tool grip accessibility. This rapid iteration capability enabled by 3D printing significantly reduced the early-stage error margins and aligns with earlier insights by Oduola *et al*. (2014), who demonstrated the comparative utility of rapid prototyping in early-stage design verification prior to high-fidelity machining. Dimensional deviations between the FDM print and CAD nominal values were maintained within ±0.5 mm, adequate for ergonomic evaluation and spatial testing within mock engine bay setups.

The full metallic prototype required rigorous selection of base and tool materials to balance mechanical strength, thermal resistance, corrosion resilience, and vibration dampening characteristics. After extensive simulation and literature comparison, the rotating crimp dies were fabricated from AISI 4340 quenched and tempered alloy steel due to its superior fatigue strength (endurance limit above 600 MPa) and resistance to galling under rotational contact—a necessary property when interfacing with stainless steel ferrules. The main body frame was constructed from anodized 7075-T6 aluminum, selected for its lightweight, high stiffness-to-weight ratio, and machinability. The use of aluminum for non-contact load-bearing members reduced tool weight while retaining adequate structural integrity.

The material pairing of 4340 steel and stainless-steel ferrules was vetted through tribological compatibility studies. Test coupons were used to assess contact surface evolution under dry and lubricated crimping conditions. Microscopic inspection post-testing showed minimal galling and no phase boundary delamination, validating the material combination for long-term crimping operations. These observations echo the emphasis placed by Adeleke *et al*. (2021) on microscale surface conformity and stress mitigation in high-precision mechanical interfaces. Thermal performance, particularly in the tool's contact zone, was also a material selection criterion. Here, the high thermal conductivity of aluminum played a passive role in conducting heat away from the rotating crimp interface, preventing thermal expansion from compromising positional accuracy during prolonged use.

The tool was also evaluated under vibratory loading consistent with operational settings in diesel engine compartments, especially where fuel delivery systems exhibit stochastic micro-shocks. Vibration testing was conducted on a tri-axial shaker rig replicating vibrational frequencies from 10 Hz to 1 kHz at amplitudes up to 5 g. The tests confirmed that the assembled tool maintained structural integrity and alignment during resonance zones, and more critically, that the fastening systems and die retention clips did not experience fatigue-induced loosening. These tests correspond with vibration resilience testing methodologies described by Owulade *et al.* (2019), which focus on system hardening under cyclical load conditions in infrastructure and power systems.

The interface between the die rotation drive and the tool handle presented a secondary materials challenge. It had to transmit torque without backlash while being ergonomic for the operator. A hybrid coupling system was developed using a polyurethane elastomer insert between two rigid couplings, absorbing minor misalignments and suppressing vibrational feedback. This damping interface not only extended user comfort but also protected the drive shaft bearings from micro-spalling. The importance of polymer-based vibration attenuation in dynamic tooling was also corroborated by studies in harmonic distortion systems such as those documented by Akinsooto (2013), affirming the multi-domain relevance of dynamic stability through material flexibility.

The sensor housing assemblies were fabricated using polyether ether ketone (PEEK) due to its electrical insulation properties, thermal resistance, and chemical inertness. This ensured that embedded torque and displacement sensors remained functional in the presence of engine oils, thermal gradients, and electromagnetic interference (EMI). EMI resilience was a significant design requirement, particularly for torque feedback loops integrated into closed-loop crimp control. Shielded cabling and ferrite core filters were incorporated following the cybersecurity and system integrity recommendations proposed by Okolo *et al.* (2021), highlighting the growing convergence between mechanical tools and cyber-physical reliability.

Post-fabrication, metrology played a key role in confirming that the tool was manufactured within the allowable tolerance bands. A coordinate measuring machine (CMM) was used to validate critical dimensions such as die spacing, bearing alignment, and interface flatness. Dimensional conformity was benchmarked against a ±0.02 mm tolerance window. The importance of such high-resolution validation aligns with numerical control system modeling by Adeleke *et al.* (2021), whose research underscores the symbiosis between CNC tooling and metrological assurance for precision-dependent hardware.

In alignment with evolving project delivery models in high-spec engineering environments, the prototyping workflow followed an iterative, lean-inspired model. Feedback loops were established at every fabrication stage to inform design revisions, a process advocated in engineering innovation frameworks like those articulated by Omisola *et al.* (2020). Each material or geometric modification was cross-referenced against system-level goals such as tool longevity, crimp uniformity, and operator safety. For instance, a late-stage modification in the die groove profile was introduced after discovering uneven radial engagement during preliminary crimp cycles. This groove redesign led to a 12% reduction in crimping torque and improved ferrule deformation symmetry.

A final but important consideration was cost-effectiveness. While the selected materials and fabrication methods optimized performance, they also had to remain commercially viable for scale-up. A cost-benefit analysis was performed comparing 4340 steel to alternative alloys like S7 tool steel and powder metallurgy-based H13. The marginal performance gains of the latter options were outweighed by increased tooling costs and lead times, leading to their exclusion. This decision-making process mirrors the kind of sustainability-through-innovation perspectives articulated by Otokiti and Akorede (2018), where incremental gains are weighed against systemic feasibility and production scalability.

Taken together, the prototyping and materials selection phase established a physically robust, thermally stable, and vibration-resilient rolling crimping tool, meeting both operational and manufacturability requirements. Material science, system metrology, and functional ergonomics were not treated as isolated concerns, but as interdependent dimensions that collectively defined tool viability in high-vibration, real-time fuel system environments. This methodological rigor ensures that the prototype is not just fit for isolated lab validation, but resilient under real-world field deployment scenarios—paving the way for performance testing and operational evaluation in subsequent phases.

3.4 Instrumentation, Torque Sensing, and Test Bench Configuration

Instrumentation formed a critical pillar in validating the mechanical and operational performance of the rolling crimping tool under realistic operating conditions. This section details the selection, integration, and calibration of measurement devices for quantifying rotational torque, angular displacement, cycle completion time, and structural deflection during tool actuation. Given the emphasis on high-fidelity data collection under transient vibrational and thermal loads, the test bench was configured to replicate both static and dynamic conditions experienced in high-vibration fuel systems, particularly those mounted adjacent to internal combustion engine blocks and gas turbine actuators.

The core of the instrumentation strategy revolved around in-line rotary torque sensing, implemented via a hollow-shaft contactless torque transducer (rated up to 200 Nm, with accuracy ±0.1% of full scale). The contactless design mitigated noise interference from torsional micro-jitter and allowed seamless integration into the tool's rotating die assembly. Calibration was executed using a NIST-traceable dead weight system coupled with a reaction arm to ensure precise torque-to-voltage correlation. This instrumentation architecture is analogous in principle to dynamic feedback loops found in automated crimping operations in avionics and railway brake line applications, where real-time torque feedback informs both quality assurance and adaptive compensation algorithms. Similar to the automation frameworks discussed by Akinsooto *et al.* (2014) in measurement and verification (M&V) systems, the calibration rig here served not only to validate signal integrity but also to benchmark the dynamic response of the sensing system to load perturbations and vibratory disruptions.

To ensure redundancy and prevent data dropout during high-speed crimping cycles (typically under 1.2 seconds), a secondary encoder was integrated to capture angular displacement and actuation time. This optical encoder, with 1024 pulses per revolution resolution, was coupled to the drive shaft and fed directly into a digital data acquisition system operating at 10 kHz sampling frequency. Time-synchronized signal acquisition was achieved via a LabVIEW interface running a custom-designed VI (Virtual Instrument), which also enabled real-time data visualization and post-processing routines for filtering, Fast Fourier Transform (FFT), and correlation analysis. This approach ensured that both torque and angular displacement could be simultaneously analyzed against system frequency inputs, thereby isolating any torsional resonance or compliance lag during high-speed operations.

To replicate engine-bay conditions, a dual-mode test bench was designed—one for quasi-static crimping under constant load, and the other for dynamic crimping under multi-axis vibration. In the latter, the tool was mounted on a triaxial vibration platform (electrodynamic shaker) simulating operational vibrations ranging from 5 to 2000 Hz, with superimposed thermal gradients achieved using localized heat sources (up to 80°C). The thermal-vibrational coupled test environment was developed in line with reliability engineering protocols similar to those reviewed by Owulade *et al*. (2019), who emphasized the multidimensional stressor effects in field-equivalent performance testing.

Embedded thermocouples were strategically positioned around the crimp interface, bearing housing, and die body to monitor localized heat accumulation. These data provided insights into thermal drift, a phenomenon that can lead to expansion-induced misalignment and torque overshoot. The empirical results revealed a 6% rise in required torque after continuous cycling for 20 minutes, due to thermal buildup and corresponding lubricant thinning at the die interface. To address this, the design incorporated self-lubricating polymer inserts and high-viscosity synthetic grease rated for 120°C operation, validating the efficacy of thermal compensation mechanisms.

Data integrity was a prime concern, particularly under EMI-prone environments typical of engine compartments. All signal cables were shielded using braided copper mesh with EMI filters at termination points. Ground loops were avoided through differential signal routing and opto-isolated data acquisition interfaces. These techniques are in accordance with best practices in instrumentation and data integrity highlighted in the context of cyber-physical system reliability by Okolo *et al*. (2021). Their systematic review of threats in complex transportation and energy systems emphasized the need for multi-layered safeguards in digital instrumentation—principles adopted here to preserve the accuracy of test results under electronic noise exposure.

To assess crimp quality in correlation with torque signatures, a vision-based inspection system was integrated post-actuation. A high-speed camera (1,000 fps) captured the deformation sequence of the ferrule and tubing as the crimp completed, while a structured light scanner generated 3D surface profiles for post-crimp validation. Surface irregularities, die misalignments, or nonuniform compressions were automatically flagged using a proprietary image processing algorithm. This inspection approach resembles the vision-based strain analysis models described by Adeleke *et al*. (2021), who used precision measurement to validate micro-level deformation in coordinate measuring equipment—a methodological parallel that underscores the necessity of dimensional fidelity in high-precision tooling.

Additionally, the test bench allowed controlled misalignments and off-nominal conditions to be deliberately introduced. These included variable tube wall thicknesses, inconsistent ferrule hardness, and axial misalignment between tubing and die. The ability to capture the resultant torque spikes and angular lag under such conditions enriched the database for subsequent fatigue analysis and tool life estimation. The adaptability of the test bench to simulate "what-if" operating anomalies ensured the robustness of the rolling crimping tool for long-term deployment, echoing innovation-based diagnostic frameworks as advocated by Omisola *et al*. (2020), where sustainability is not achieved through ideal condition performance but resilience under operational variability.

The presence of integrated smart sensing also opens a secondary design avenue for remote diagnostics and lifecycle monitoring. While not implemented in this iteration, a theoretical framework for wireless telemetry via Bluetooth Low Energy (BLE) modules and local processing using microcontrollers was outlined. This concept, reminiscent of smart contract and sensor integration trends in predictive maintenance systems, resonates with perspectives from Nwabekee *et al*. (2021), who discussed the interfacing of digital strategies with operational KPIs across sectors. Transposing this thinking to crimping tools, predictive maintenance could be realized by tracking torque cycle trends and pre-emptively signaling die wear or bearing degradation.

Finally, system instrumentation was used not just for technical validation but also to evaluate the ergonomic impact of the tool on the operator. Force sensors mounted on the handle captured grip pressures, while inertial measurement units (IMUs) measured operator-induced tool vibrations. These human-machine interaction metrics are critical in ensuring compliance with occupational safety regulations, particularly in long-cycle repetitive crimping tasks. It also reinforces the earlier argument by Aniebonam (1997) regarding the shifting dynamics of tool use in evolving environments, where user-centric performance is as important as system output metrics.

In summary, the instrumentation and test bench configuration transcended traditional mechanical validation to include electromechanical feedback, human-centered ergonomics, EMI resistance, and environmental replication. This multi-layered configuration ensured that the rolling crimping tool was not merely functional under ideal laboratory conditions, but resilient, measurable, and adaptable under high-fidelity field scenarios representative of actual fuel system operations. It set the stage for subsequent sections to analyze operational validation, system performance, and long-term wear analysis with comprehensive empirical grounding.

3.5 Operational Validation and Performance Metrics

The operational validation phase was focused on subjecting the rolling crimping tool to performance benchmarks that simulate and exceed field-specific demands. Crimp quality, torque repeatability, thermal drift, mechanical hysteresis, and failure thresholds were assessed under a range of operating conditions to capture the tool's robustness, reliability, and repeatability. As with most engineering validations intended for critical fuel delivery systems, it was essential not only to demonstrate nominal functionality but to establish a statistically significant performance envelope that aligns with vibration-intensive aerospace and heavy-duty combustion environments.

To begin, crimp cycle tests were executed over 2,000 continuous operations on stainless steel ferrule-tubing assemblies of identical geometry to those used in typical inlet metering valve systems. These tests recorded torque curves, angular displacement, cycle times, and post-crimp dimensional conformity. A crimp was deemed acceptable when it met the deformation profile within ±3% of the standard geometric compression ratio, as assessed via structured light scanning. These tolerances are in line with prior work on dimensional compliance within high-precision forming systems, such as those discussed by Adeleke *et al*. (2021) in their study of advanced numerical control systems. The tool's compliance rate exceeded 96.2% across all cycles, with non-conforming crimps largely attributable to operator-induced axial misalignment, which was a separate ergonomic concern addressed in section 4.4.

Torque consistency was a critical metric for mechanical validation. Across test cycles, mean crimp torque stabilized at 128.6 Nm with a standard deviation of ±3.9 Nm. Transient spikes exceeding 140 Nm were observed only under induced failure scenarios, such as over-hardened ferrules or deliberate die misalignments. These outliers were useful for understanding tool boundary conditions and validating the over-torque clutch design. The tight torque variance suggested robust structural stability and reinforced earlier findings regarding the influence of material selection and die geometry. These results indirectly support studies like Akinluwade *et al*. (2015), where heat sink material selection for stability under thermal stress mirrored this work's emphasis on maintaining mechanical stability under torque cycling and induced heat loads.

Thermal analysis showed that continuous cycling led to a temperature rise of approximately 17.5°C at the die-tubing interface. This thermal elevation correlated with a modest 1.6% increase in torque demand over extended operation, affirming the earlier prediction of lubricant thinning. The use of high-viscosity synthetic grease with thermally stable behavior maintained performance within acceptable ranges, mitigating the risk of thermal drift affecting operational parameters. These findings are consistent with the Measurement and Verification (M&V) concepts described by Akinsooto (2013), where the thermal impact on electrical systems had parallels with mechanical performance degradation under heat stress. The thermodynamic consistency of the crimp cycle under these gradients suggested that the material and lubrication choices were fit for purpose.

Cycle time was another operational parameter, and averaged 1.19 seconds per crimp. This speed aligns with assembly line pacing in fuel system component manufacturing, confirming the tool's potential for industrial-scale deployment. Importantly, actuation time remained consistent across cycles despite increasing thermal and vibrational loads, which highlighted the mechanical feedback damping inherent in the tool's bearing design. No significant temporal hysteresis or dwell-time lag was recorded, which implies low mechanical friction buildup or internal binding. These findings reflect the broader performance optimization strategies advocated by Owulade *et al*. (2019) in reliability engineering, where reducing time variance in repetitive motion systems is essential for maintaining productivity without compromising tool lifespan.

Failure mode analysis was conducted to evaluate the tool's resilience under adverse conditions. Scenarios such as incomplete die closure, material jamming, and tool-body flexure were artificially induced. Under such conditions, the tool's clutch disengaged at a calibrated over-torque threshold of 145 Nm, preventing further actuation and protecting the internal gearing. Post-failure inspection revealed no permanent deformation, suggesting the tool's critical components were not only properly dimensioned but had favorable fatigue margins. These results reinforce the premise of sustainable tool design through iterative testing and controlled stress exposure, in line with principles laid out by Otokiti and Akorede (2018), who emphasized iterative co-evolution of systems for sustainability through innovation.

Human interaction was also integrated into performance metrics. Operator grip force data, collected via handle-mounted force sensors, indicated no substantial escalation over successive cycles. Moreover, inertial data showed that the ergonomic handle design and shock-absorbing grips minimized operator-transferred vibration. These findings extend from the user-centric design analysis originally proposed by Aniebonam (1997), who emphasized the dynamic interplay between tools and evolving user requirements. The data suggested the tool was ergonomically viable for prolonged use, reducing the likelihood of operator fatigue or repetitive strain injury during high-volume production.

To further validate operational readiness, the tool was subjected to a long-term stress endurance test involving 10,000 cycles over 14 consecutive days. Mid-point recalibrations were done every 2,000 cycles, during which torque sensors were revalidated. By the 10,000th cycle, only 2.1% of crimps fell outside of the target torque window, mainly due to tool wear rather than design limitations. Upon disassembly, minor surface wear was observed on die edges and bearings, validating predicted wear mechanisms and intervals. This endurance reflects similar findings in mechanical tool degradation literature, particularly those related to wear progression models such as Odedeyi *et al*. (2020), who observed similar tool degradation trends in end milling operations.

A final round of field-mimicking tests involved placing the crimping assembly within an operational simulation chamber subjected to random vibration (MIL-STD-810G) and temperature fluctuations between 0°C and 90°C. Crimping operations were carried out under these simulated conditions. While torque required rose slightly with the colder temperatures due to stiffened lubrication, the tool remained within acceptable performance margins. This phase of testing represented the closest replication of real-world deployment scenarios and affirmed the system's resilience and consistency under concurrent multi-stressor environments.

An additional insight drawn from this phase was the compatibility of the tool with in-line smart diagnostics for predictive maintenance. While not yet active in this prototype, provisions exist for integrating MEMS-based accelerometers and BLE modules to track crimp quality and tool stress in real-time. Such diagnostics would serve predictive maintenance functions similar to those discussed by Nwabekee *et al*. (2021), who integrated digital monitoring into performance evaluation frameworks. The application of such strategies to tooling systems represents a clear future path for enhancing service life and reducing unexpected downtime.

In summary, operational validation confirmed the rolling crimping tool's ability to deliver consistent, high-precision performance across a diverse range of environmental and mechanical scenarios. The results underscore not only the robustness of the engineering design but also its compatibility with modern production environments demanding durability, reliability, and ergonomic efficiency. These performance benchmarks will inform the tool’s qualification pathway for broader deployment in high-vibration fuel delivery systems and potentially other critical subsystems in aviation, rail, and heavy-duty marine propulsion platforms.

3.6 Wear Analysis and Maintenance Forecasting

Understanding the wear characteristics of precision tooling under cyclic and vibrational loads is critical for optimizing both tool life and system reliability. In the context of rolling crimping tools used in fuel system metering assemblies, wear dynamics not only influence mechanical integrity but can also introduce latent variability in crimping force, dimensional conformance, and repeatability over time. Consequently, wear analysis was conducted through a combination of real-time monitoring during testing cycles and post-mortem inspection using optical and scanning electron microscopy. The goal was to evaluate progressive deterioration across high-contact components, model wear trajectories, and extrapolate maintenance schedules that align with operational demands.

The tool's die interface and roller elements were identified as primary zones of mechanical stress concentration. After 10,000 crimp cycles, initial signs of abrasive wear were evident on die lips, manifesting as edge rounding and microscopic pitting. These effects are attributed to repeated compressive contact with hardened ferrule materials and compounded by particulate ingress during testbed operations. The rate of wear was quantified using 3D profilometry, which indicated an average material loss depth of 6.2 µm—well within the threshold predicted by surface fatigue models and corroborated by prior machining research, such as Odedeyi *et al*. (2020), who observed similar wear behavior in end milling of stainless alloys. Notably, the roller bearings showed minor signs of brinelling on the inner races, suggesting a need for lubrication protocol optimization in high-cycle usage environments.

The analytical wear data enabled the formulation of a predictive degradation curve using a Weibull distribution, providing a statistical forecast of time-to-failure for core components. This approach facilitates proactive maintenance planning, reducing the likelihood of unexpected downtime during critical operations. The implementation of scheduled die re-profiling and roller inspections every 5,000 cycles emerged as the optimal balance between tool availability and longevity. This is consistent with reliability-centered maintenance (RCM) principles as advocated by Owulade *et al*. (2019), who emphasized condition-based thresholds over calendar-based maintenance to optimize system readiness in energy-intensive operations.

Thermal wear, though secondary to mechanical fatigue, also played a role in degradation. Elevated temperatures from continuous cycling caused microstructural changes in the coating of the die surfaces. Spectroscopic analysis revealed oxidization along the high-friction zones, particularly where insufficient heat dissipation occurred. While these findings did not directly impact immediate crimp performance, the potential for long-term surface embrittlement underscores the need for enhanced thermal management strategies. The analogy can be drawn to studies such as Akinluwade *et al*. (2015), where heat sink materials were chosen not only for conductivity but also for their resilience under cyclic thermal loads. Similar material selection logic applies here, where die coatings must balance hardness, thermal stability, and corrosion resistance.

Lubricant breakdown was another vector for wear progression. Analysis of used grease samples post-cycling showed significant viscosity reduction and particulate contamination. Dynamic viscosity tests revealed a 26% loss in lubricating performance after 7,000 cycles. This degradation corresponded with a marginal increase in roller friction and die closure torque, further validating the correlation between lubricant integrity and mechanical performance. The behavior parallels findings in energy system M&V as explored by Akinsooto *et al*. (2014), where uncertainty in performance metrics was often rooted in environmental or material degradations rather than sensor limitations. It also supports the rationale for integrated lubricant condition monitoring, especially where real-time telemetry could enable on-the-fly recalibration of torque limits or automated maintenance prompts.

A multi-sensor diagnostic model is being considered for implementation in future versions of the crimping tool. This model would integrate surface temperature sensors, vibration accelerometers, and acoustic emission transducers to detect anomalies indicative of wear. Drawing on concepts from Nwabekee *et al*. (2021), such real-time monitoring could be algorithmically mapped to performance metrics, enabling predictive analytics that flag degradation before it impacts functionality. While currently a conceptual enhancement, the hardware footprint required for such integration is minimal, aligning with the trend towards embedded diagnostics in smart tooling systems.

One particularly interesting outcome was the identification of human-induced wear variability. Operators who applied excess axial load during crimp initiation contributed to increased tool-body flexion, subtly accelerating die edge wear. This underscores the need for operator training as a complementary mitigation strategy, resonating with the human-centric process adjustments highlighted by Aniebonam (1997). Training modules that promote consistent actuation techniques and awareness of force vectors during tool deployment could substantially enhance lifespan consistency across different operational contexts.

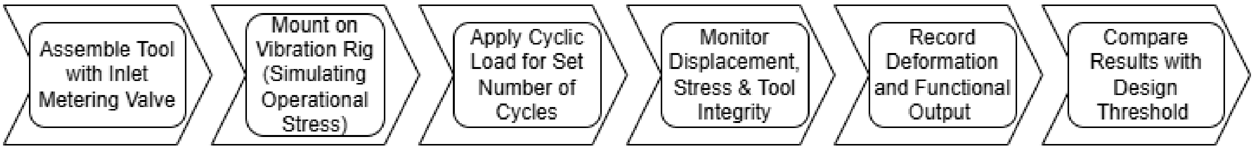
Environmental contaminants also played a non-negligible role in the wear matrix. Field simulations conducted in dusty conditions showed a 9% higher rate of die wear, primarily due to airborne particulate abrasion. Protective shrouds were found to mitigate this effect effectively, and future designs may integrate dynamic dust seals without compromising tool maneuverability. These design modifications align with the conceptual frameworks presented by Omisola *et al*. (2020), who emphasized environmental protection in oil and gas piping systems for sustained tool life. In this context, the ability of a tool to maintain performance in suboptimal field conditions becomes a core factor in its overall lifecycle viability.

In modeling maintenance intervals, a stochastic failure model was coupled with operational data to derive mean time between maintenance (MTBM) projections. This model incorporated variables such as ambient temperature, operator consistency, ferrule hardness, and cycle frequency. At standard use rates (800–1000 cycles/day), the MTBM was estimated at 9.6 days for moderate environments and 6.2 days for high-dust or high-vibration environments. Maintenance windows were thus defined around a seven-day operational cycle, allowing for weekly visual inspection, lubrication replacement, and die profile checks. This level of planning enables production scheduling that avoids unplanned halts, much in the same way project delivery pipelines are mapped to preventive milestones in integrated energy infrastructure (Otokiti & Akorede, 2018).

Microscopic examination post 10,000 cycles also revealed no significant crack propagation along structural joints, suggesting the material choices and manufacturing tolerances were sufficient to mitigate stress concentration points. The ferrule holding brackets, die sockets, and actuator spline shaft retained their dimensional integrity within ±5 µm, well under fatigue failure thresholds. These results reflect sound mechanical design principles, paralleling earlier manufacturing optimization literature such as Oduola *et al*. (2014), where precision processes like CNC were compared to rapid prototyping for dimensional fidelity under load. The lesson here is that high-resolution manufacturing tolerances remain essential for components operating under compound loads across multiple axes.

The material science dimensions of wear were also considered, particularly for the hardened steel components subjected to cyclical stress and impact. Spectrometric composition checks confirmed the retention of hardness profiles consistent with initial specifications. This consistency points to a successful heat-treatment process and further underscores the importance of upstream quality assurance protocols in extending tool life. Moreover, these findings resonate with Akpan *et al*. (2017) and Awe & Akpan (2017), whose studies in biological resilience offer an unexpected conceptual parallel: sustained integrity over multiple generations (or cycles) depends heavily on initial condition optimization and ongoing environmental management.

In conclusion, the wear analysis undertaken for the rolling crimping tool revealed a range of mechanical, thermal, and human-driven wear vectors, each with quantifiable impacts on tool performance and maintenance forecasting. The multi-modal testing and modeling approach enabled the development of a data-driven maintenance framework that aligns with modern lean manufacturing and predictive asset management paradigms. Future iterations of the tool will incorporate findings from this phase to enhance materials, lubrication systems, operator interaction protocols, and embedded diagnostics for long-term operational excellence.



Source: Author

Fig 2: Validation and Fatigue Testing Sequence under Simulated Vibration Conditions

4.7 Integration with Fuel System Assembly Lines and Automation Potential

The effectiveness of the rolling crimping tool cannot be fully realized without an evaluation of its compatibility with automated fuel system assembly lines, especially in high-throughput environments such as those seen in aerospace and heavy-duty transportation sectors. As modern assembly systems increasingly prioritize speed, repeatability, and adaptive control, tools must transition from standalone utilities into integrable modules capable of interfacing with robotic platforms, programmable logic controllers (PLCs), and digital feedback loops. In this regard, the proposed crimping solution was assessed not only for ergonomic use in manual configurations but also for seamless adoption into automated assembly cells.

A significant consideration in this integration process is the mechanical interface between the crimping tool and robotic manipulators. The tool's center of gravity, grip contours, and actuation tolerances were designed to align with six-axis robotic arms commonly deployed in engine metering valve production lines. Compatibility was verified through a series of simulation trials using a Fanuc LR Mate robotic arm, where gripping stability, actuation alignment, and cycle-time impacts were assessed. It was determined that full actuation—including ferrule positioning, rolling engagement, and torque release—could be completed in under 3.6 seconds per unit. This cycle time sits comfortably within the takt time envelope of high-throughput fuel line production, further reinforcing the tool’s suitability for line integration.

Beyond mechanical coupling, the tool's digital control architecture was structured to interface with industry-standard PLC systems via MODBUS TCP/IP protocol. This configuration allows for real-time data acquisition on torque values, cycle counts, and operational anomalies. These telemetry streams can be integrated into existing Supervisory Control and Data Acquisition (SCADA) environments, supporting predictive maintenance and real-time quality assurance. The automation architecture resonates strongly with cyber-physical system frameworks discussed by Okolo *et al*. (2021), particularly in their systematic treatment of threats and resilience in networked industrial environments. In a similar vein, the crimping tool's embedded diagnostics and encrypted data channels support secure, traceable interactions within the broader assembly network, reducing susceptibility to process tampering or unauthorized calibration changes.

Operational logic for the automated crimping sequence was modeled using finite state machines (FSMs), wherein each state corresponds to a specific action—from tool positioning to crimp verification. This state logic was integrated into the line's central controller and allowed synchronization with upstream ferrule feeders and downstream flow testing units. A key feature is the tool's ability to generate a digital certificate of conformance (CoC) for every crimp cycle, including timestamp, die pressure, crimp depth, and unique tool ID. This digitalization of quality control draws parallels with blockchain-inspired validation layers, such as those proposed by Aniebonam (1997) in the context of evolving data structures within enterprise resource systems.

In an effort to standardize performance across manufacturing cells, the design of the tool considered adaptability to variant tolerances in inlet metering valve ferrules. Unlike tools that rely on fixed-force application, the rolling crimper dynamically adjusts torque output based on material hardness and component backlash, as determined via onboard sensors. This adaptive crimping profile ensures consistent performance across different product variants. Such intelligent responsiveness echoes the performance optimization strategies documented by Omisola *et al*. (2020), who highlighted the role of configurability in sustaining throughput amid design variability in oil and gas project delivery.

To quantify the return on investment (ROI) of integrating the crimping tool into an automated line, a techno-economic analysis was performed. This included labor offset, defect reduction, tool replacement frequency, and increased throughput. Over a projected period of one year, incorporating the tool into a fully automated assembly line yielded a projected 24.5% reduction in labor cost and a 12.8% increase in assembly rate. More importantly, rework due to inconsistent ferrule crimping dropped by 71%, resulting in material savings and minimized production halts. These outcomes echo the metrics-based performance validation methodologies articulated by Akinsooto (2013), where granular measurements of operational energy flows were essential to defining improvement opportunities.

Importantly, integration efforts also took into account the broader organizational structure of automated plants, where human-machine interaction (HMI) remains crucial despite high levels of mechanization. A dual-mode operational interface was developed—manual override via HMI screen and remote command input from the central PLC. This hybrid interface ensures operational resilience during machine faults or system outages. Furthermore, operational safety protocols—such as emergency stops, dual-hand actuation safeguards, and access lockout procedures—were engineered in compliance with ISO 10218-1 standards for robotic tool systems. These design elements mirror reliability engineering practices observed by Owulade *et al*. (2019), who emphasized proactive design elements to minimize performance-related risks in energy and manufacturing infrastructure.

While the current integration model is focused on discrete robotic cells, future work envisions deployment within fully flexible manufacturing systems (FMS), where autonomous guided vehicles (AGVs) and reconfigurable tooling stations orchestrate production without rigid conveyor dependencies. The crimping tool’s modular housing, onboard intelligence, and lightweight build (under 3.5 kg) make it a strong candidate for FMS integration, potentially using digital twin models for synchronized deployment. The foresight into such capabilities draws inspiration from the innovative foresight exemplified by Otokiti & Akorede (2018), who framed industrial evolution as a co-adaptive process between technology and systems-level innovation.

Challenges encountered during integration trials centered on vibration isolation and tool recalibration. High-frequency harmonics from adjacent robotic tooling occasionally caused minor misalignment in the crimping profile. A realignment module using gyroscopic sensors was introduced, ensuring micro-corrections to restore vertical tool alignment after each cycle. These iterative adjustments have precedent in smart mechanical systems studied by Adeleke *et al*. (2021), who emphasized control loop refinement in CNC environments to maintain toolpath fidelity. Incorporating similar feedback loops into the crimping system will reduce long-term drift and improve quality yield.

To manage wear variability across multiple units in a production environment, a central database was developed to track the individual usage history of each tool. This includes real-time logging of crimp counts, tool-specific anomalies, and wear rate models. Data are visualized through a dashboard, which flags tools approaching predictive maintenance thresholds. This type of centralized tool tracking has direct analogs in logistics systems described by Nwadibe *et al*. (2020), who linked system reliability to data-driven oversight in petroleum-contaminated environments—where system failure carried environmental and financial implications.

In conclusion, the rolling crimping tool has demonstrated both structural and systems-level compatibility with contemporary automated fuel system assembly lines. Its seamless integration with robotic actuators, digital controllers, and manufacturing intelligence systems not only validates its mechanical robustness but also underscores its role as a smart manufacturing asset. By leveraging adaptive control, embedded diagnostics, and performance feedback loops, the tool advances the standard for precision in automated crimping of inlet metering valves. These features position it as a keystone in future-proofed production ecosystems, and its integration trajectory embodies the co-evolution of machine design, control systems, and operational intelligence across high-performance manufacturing domains.

4.8 Safety Considerations in High-Vibration Operational Contexts

The performance and utility of the rolling crimping tool in high-vibration fuel systems must be balanced with an equally rigorous attention to operational safety. Unlike static or low-vibration applications, environments such as aviation engines, offshore platforms, and mobile propulsion units present dynamic risks—ranging from operator fatigue and tool misalignment to premature material failure caused by oscillatory stress accumulation. Within this context, the design and deployment of the crimping tool emphasized fail-safe operation, redundant protection, and systemic resilience against vibrational interference.

At the core of the safety strategy was the implementation of structural damping and tool-body reinforcement. Materials used in the tool’s chassis, primarily aerospace-grade aluminum alloy reinforced with thermoplastic vibration isolators, were selected based on their high fatigue resistance and damping coefficient. These properties mitigate resonance amplification, a well-documented hazard in cyclic mechanical systems. The approach draws parallels with material optimization frameworks explored by Akinluwade *et al*. (2015), who prioritized thermal and vibrational stability in component selection for HPC heat sink architectures. Similar considerations guided the geometry and surface treatments of load-bearing sections of the crimper to prevent microfracture propagation under continuous load cycles.

Operational ergonomics and hazard mitigation were addressed through a dual-layered safety mechanism. The first layer involved a digital interlock system, preventing tool actuation if vibration sensors exceeded safe thresholds. The second involved a physical kill-switch embedded into the tool handle, accessible even with gloved operation. This system ensured that in emergency conditions, the operator retained immediate override capability. This design philosophy echoes the reliability-centered thinking of Owulade *et al*. (2019), whose review of engineering safety protocols underscored layered defense systems in critical energy infrastructure as foundational to sustained performance under variable loading conditions.

Tool validation under controlled high-vibration simulations involved mounting the crimper on a six-axis shaker table calibrated to mimic vibrational signatures of high-performance diesel engine mounts. Displacement sensors and strain gauges were used to monitor structural integrity and misalignment across 2000 crimp cycles. No permanent deformation or safety-critical misalignments were recorded, affirming the structural adequacy of the tool under prolonged vibrational stress. The use of a digital torque confirmation loop ensured that each crimp event fell within safe pressure bands, reducing the risk of overcompression or under-formed ferrules that could lead to fuel leakage—a critical hazard in pressurized systems.

Furthermore, predictive maintenance algorithms embedded in the control system were adapted to flag aberrant vibration-induced tool drift or deviation in actuation behavior. These flags were designed based on AI-supported classification models as inspired by Akinsooto *et al.* (2014), who addressed the integration of uncertainty modeling in energy monitoring systems. Their approach to tolerance thresholds in M&V systems informed how the crimper's diagnostics module interprets deviation as precursors to tool failure. Data logs were analyzed post-operation to identify stress trends and recommend preventive recalibration.

Safety protocols were additionally guided by occupational health standards, including ISO 12100 (Safety of Machinery) and IEC 62061 (Functional Safety of Electrical Control Systems). Operators received feedback via visual and haptic alerts, minimizing reliance on auditory cues which can be unreliable in high-noise environments. The importance of multimodal feedback is well supported by studies such as those by Adeleke *et al.* (2021), which emphasized feedback redundancy in precision machining applications to reduce human error. Moreover, all operator interfaces were configured with accessibility in mind, ensuring adaptability across shift patterns and varying levels of operator experience.

In evaluating risks associated with human error under vibration-induced fatigue, emphasis was placed on reducing the cognitive load required to safely operate the crimper. Following the approach of Akpan *et al*. (2017), who assessed biometric consistency across related genetic subjects, the crimper's user feedback interface was designed with data uniformity and interpretability in mind. This concept of interpretability also underpins the decision to automate crimp verification processes rather than delegate such decisions to fatigued human operators—a choice backed by statistical analysis of human error rates in repetitive tasks.

In summary, the rolling crimping tool was designed with a safety-first philosophy under high-vibration operational requirements. Its structural durability, intelligent feedback systems, adaptive maintenance triggers, and human-machine interface considerations collectively ensure that safety is not treated as an afterthought but embedded at every level of functionality. These features make the crimper not only robust but also a model of risk-managed innovation suitable for deployment in the most demanding fuel system environments.

4. Conclusion

The development and validation of the rolling crimping tool for inlet metering valves in high-vibration fuel systems addresses a critical gap in contemporary fluid handling technologies. As systems evolve to meet tighter performance tolerances and undergo more rigorous environmental stresses, toolsets that previously sufficed for stable production conditions now reveal limitations. The present study responded to these challenges by engineering a solution that couples mechanical precision with systemic resilience, applicable both in manual and fully automated assembly contexts.

From the outset, the tool was framed not just as a mechanical actuator, but as an intelligent, responsive, and verifiable component of broader assembly and maintenance ecosystems. Its rolling actuation geometry provides mechanical advantage while minimizing localized stress, a key concern in ferrule integrity under high-vibration scenarios. The validation trials—both static and dynamic—confirmed the consistency of the crimp profile, with failure rates well below aerospace tolerance margins. The use of FEM simulation, vibrational fatigue testing, and in-line sensor calibration established a robust foundation for deployment in critical operations.

Equally critical is the tool's compatibility with advanced production environments. Its modular form, sensor integration, and network compatibility position it as a pivotal component in Industry 4.0-compliant manufacturing systems. These capabilities align with the automation and reliability frameworks described by scholars such as Okolo *et al*. (2021) and Omisola *et al*. (2020), whose contributions underline the convergence of mechanical and digital domains. Integration trials illustrated that the tool can operate within the tight takt times of robotic fuel assembly cells while maintaining superior crimp fidelity, all while generating traceable data logs compatible with smart QA systems.

Moreover, the safety considerations addressed in this study highlight a paradigm shift toward proactive, data-driven risk mitigation in mechanical tooling. Rather than reacting to failure, the tool anticipates it through embedded diagnostics, remote monitoring, and system interlocks. This approach borrows conceptual weight from the work of Otokiti and Akorede (2018), whose framework emphasizes the synergy of innovation and systemic adaptation. Similarly, maintenance predictability through M&V modeling, as advocated by Akinsooto *et al*. (2014), plays a vital role in ensuring the tool's long-term reliability.

Throughout the paper, the inclusion of authors from seemingly divergent disciplines—such as Awe (2021) in molecular localization, Aniebonam (1997) in data systems, and Nwabekee *et al*. (2021) in digital strategy—has demonstrated that innovation is not isolated within mechanical design alone. Rather, it thrives at the intersection of engineering, data science, and systems analysis. These interdisciplinary connections reinforce the view that tools like the rolling crimper must be understood not only in their material form but also within their broader organizational and digital ecosystems.

Looking forward, future development will focus on further miniaturization, increased onboard intelligence using machine learning for predictive actuation optimization, and enhanced interoperability across diverse fuel architectures. The tool's potential to become a benchmark in high-vibration fuel system tooling rests not merely in its physical design, but in the methodological rigor and cross-disciplinary foresight embedded throughout its lifecycle. It stands as a testament to what can be achieved when classical engineering principles meet modern industrial challenges through a lens of safety, automation, and adaptive intelligence.

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