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Review

Recent Advances and Future Trends in Extending the Service Life of Injection Moulding Tools: A Comprehensive Review

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Abstract: Injection Moulding (IM) tools play a decisive role in high-volume manufacturing, particularly in the production of polymer components where dimensional accuracy, surface integrity, and process stability are paramount. The increasing adoption of fibre-reinforced polymers (FRPs), especially within the automotive and aerospace sectors, has substantially intensified the mechanical, thermal, and tribological demands imposed on tooling systems, thereby accelerating Tool Wear (TW) and surface degradation. Comparable challenges are encountered in related forming processes, including sheet-metal stamping and pressing, where abrasive contact, cyclic loading, and elevated temperatures contributepractical to premature tool failure. Extending tool service life has consequently emerged as a strategic priority for improving cost efficiency, reducing unplanned downtime, and ensuring consistent product quality across extended production runs. Against this background, the present review critically evaluates recent technological advances aimed at enhancing the durability and operational longevity of injection moulding tools, with a particular focus on solutions that have demonstrated practical relevance under industrial conditions. Advanced surface-engineering approaches, including electrodeposition, nitriding, and physical and chemical vapour deposition (PVD and CVD) coatings, are examined in terms of their effectiveness in mitigating wear, corrosion, and thermal-fatigue damage. Developments in tool material selection, encompassing high-performance alloys and engineered coating systems, are assessed with respect to friction reduction and thermal management, providing actionable insights for tool designers and manufacturing engineers. In addition, the integration of additive manufacturing for tool repair and refurbishment is discussed as a pragmatic and increasingly viable route to extending Tool Lifespan (TL), supporting more sustainable and cost-effective tooling strategies in modern manufacturing environments.

Keywords: injection moulding; surface treatments; coatings; additive manufacturing; PVD; CVD; electrodeposition; nitriding

1. Introduction

Injection moulding (IM) is one of the most widely adopted and economically significant manufacturing processes for polymer and composite components, underpinning production in sectors ranging from automotive and aerospace to medical devices, packaging, electronics, and consumer products [1,2]. Its capability to produce components of intricate geometry with exceptional repeatability, minimal tolerances, and short cycle times has established it as a cornerstone of modern mass production. Narowski and Wilczyński [3] tackled a global approach to model IM, demonstrating that real-time cavity pressure and temperature monitoring markedly improves understanding of melt behaviour, enabling more accurate detection of flow instabilities, improved part quality prediction, and enhanced optimisation of injection-moulding processing windows. As global demand for lighter, stronger, and more functionally advanced polymer components continues to grow, the operational performance and reliability of IM tools have become increasingly critical determinants of manufacturing efficiency, product quality, and overall cost competitiveness [4,5]. Figure 1 depicts an injection mould schematic.

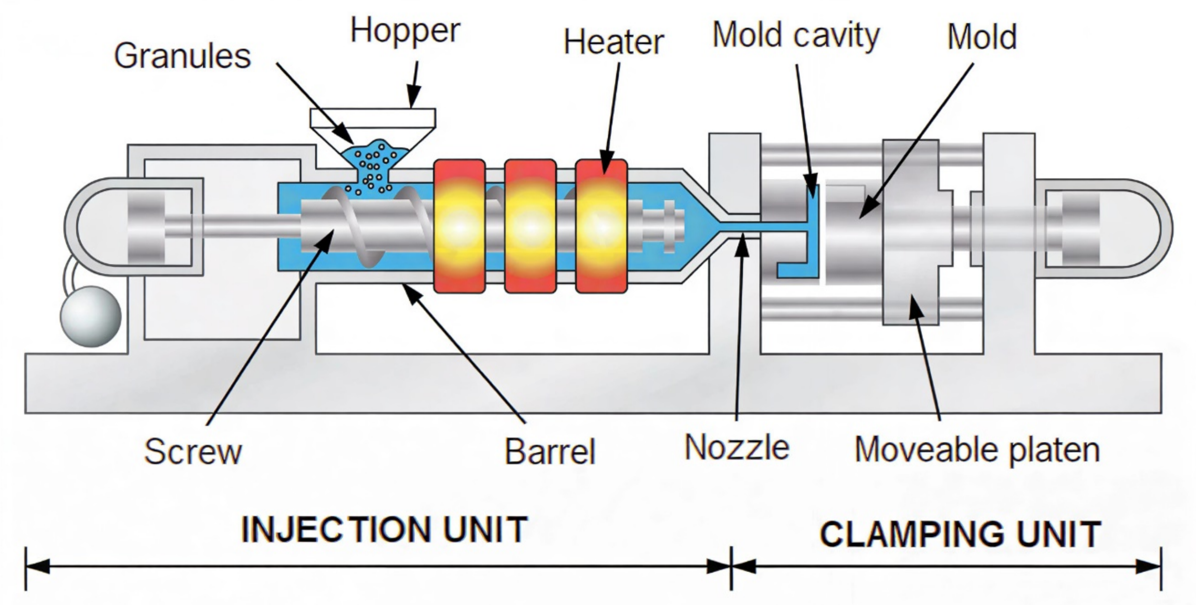

Figure 1. Illustration showing the operational layout and key functional units of an IM machine [6].

In recent years, the processing landscape has shifted markedly with the widespread adoption of fibre-reinforced polymers (FRPs), high-temperature engineering thermoplastics, and composite formulations designed to deliver superior mechanical, thermal, or chemical performance [7]. Figure 2 provides an insight into the glass and carbon fibre reinforced polymers (GFRP and CFRP, respectively) and some moulding processes applied, such as Resin Transfer Moulding (RTM), single lay-up (SLU), hand lay-up (HLU) and IM [8]. While these materials offer significant advantages at the component level, they impose far more aggressive service conditions on mould steels [9] and tooling systems. The presence of GFRP and CFRP introduces severe abrasive wear due to their hardness, angularity, and high velocity during mould filling, while high-viscosity, high-temperature melts increase thermo-mechanical stresses on cavity surfaces. Jhavar et al. [10] demonstrated that low-heat-input refurbishment techniques, particularly laser- and electron-beam deposition, significantly improve the restoration quality and service life of worn moulds by minimising distortion and ensuring superior metallurgical integrity, while years later, Podgornik et al. [11] demonstrated that the hardness and toughness of tool steels critically govern the performance of hard PVD coatings, showing that inappropriate substrate properties markedly accelerate cracking and spallation, whereas well-matched combinations significantly enhance wear resistance and coating durability.

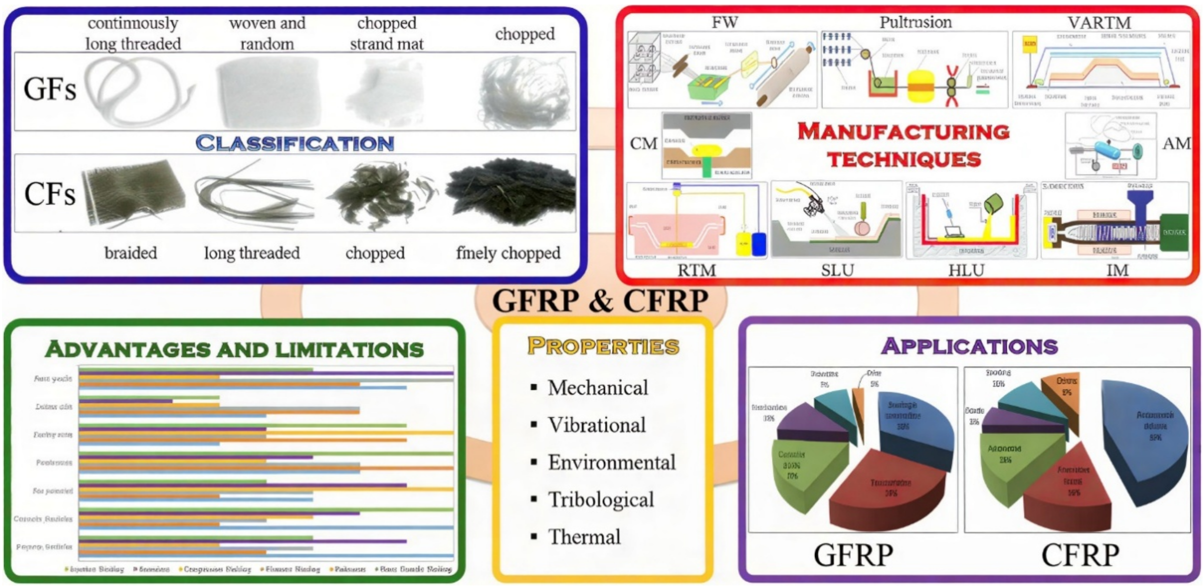

Figure 2. Integrated Summary of Material Classes, Fabrication Processes, Functional Properties, and Application Domains of glass or carbon fibre reinforced polymers (GFRP and CFRP, respectively) Systems [12].

In addition, many advanced polymers release chemically active degradation products during processing, such as hydrochloric acid (HCl), formaldehyde ($H_2C{=}O$) derivatives, or flame-retardant by-products, that can initiate corrosive attack [13]. Consequently, mould tooling is subjected simultaneously to abrasion, adhesion, erosion, corrosion, oxidation, and cyclic thermal loading. The synergistic interaction of these mechanisms accelerates tool degradation, undermines dimensional stability, reduces component surface quality, and ultimately shortens tool life (TL) [14].

The economic implications of these failure modes are substantial. In high-volume industrial production, mould tooling and maintenance-related expenditures may constitute up to 30% of total manufacturing costs. Gouveia et al. [15] studied the life-cycle assessment (LCA) of Direct Energy Deposition (DED)-based mould repair, showing that refurbishing damaged moulds can reduce environmental impacts by up to 76% in CO_2 emissions and 71% in particulate-matter formation compared with producing a new cast-iron tool. Premature tool wear not only necessitates costly refurbishment or replacement but also contributes to unplanned downtime, increased scrap rates, variations in product geometry, and higher energy consumption associated with process disruptions [16,17]. Figure 3 provides a comparative overview of four principal low- and zero-emission steelmaking routes for injection moulds, where CCS stands for Carbon Capture and Storage, DRI stands for Direct Reduced Iron and EAF stands for Electric Arc Furnace.

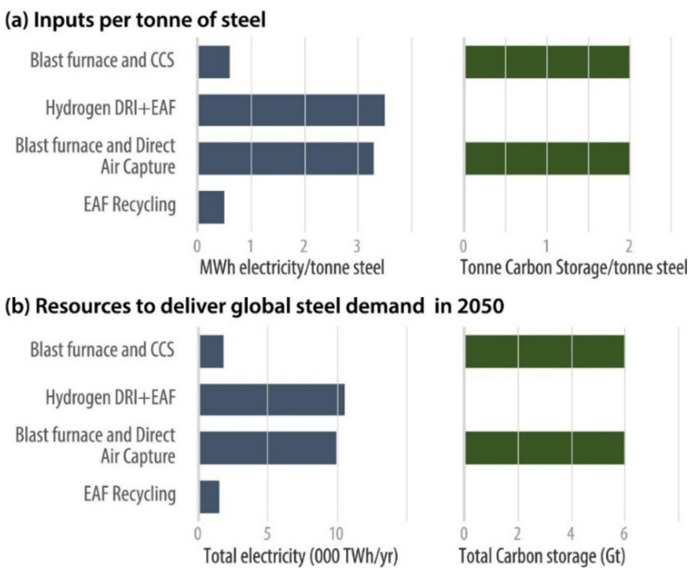

Figure 3. Overview of the four primary pathways for achieving zero-emission steel production, illustrating (**a**) the inputs required per tonne of steel and (**b**) how these input demands evolve under projected increases in global steel consumption [18].

These impacts are magnified in sectors where production continuity and tight tolerances are imperative, reinforcing the need for more durable tooling solutions capable of withstanding extreme thermal, mechanical, and chemical conditions over extended service intervals, as studied by Ojeda et al. [19]. To meet these demands, research in the past decade has intensified around four major technological pillars: surface engineering [20], tool material innovation, advanced machining strategies [21], and additive manufacturing (AM) for tooling fabrication and repair. Veiga et al. [22] demonstrated that symmetry-based monitoring of the melt pool and bead geometry in Wire-Arc Additive Manufacturing (WAAM) fabricated INVAR-36® components enables far more stable deposition, improving wall accuracy and ensuring consistent layer formation through optimised process parameters. In Pedroso et al. [23] was comprehensively reviewed that contemporary injection-mould tooling demands rigorous evaluation of Cu–Be alloys [24], INVAR-36®, and heat-treated steels, emphasising their machinability constraints, process-dependent performance, and the need for improved manufacturing strategies to enhance durability and efficiency in high-precision mould making. Additionally Pedroso et al. [20] conducted an extensive review showing that milling hardened tool steels remains constrained by severe tool wear, thermal-mechanical loading, and surface-integrity challenges, while advances in coatings, cryogenic/MQL lubrication, and optimisation algorithms offer measurable improvements in machinability and TL.

Surface engineering has emerged as one of the most powerful approaches to enhancing tool longevity. Thermochemical treatments such as plasma nitriding [25] and carburising increase surface hardness, fatigue resistance, and load-bearing capacity by modifying near-surface microstructures [26]. Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD) coatings, including TiN, CrN, AlTiN, DLC films, and nanocomposite ceramic layers, which provide exceptionally hard, smooth, and chemically resistant surfaces. Silva et al. [27] showed that advanced PVD coatings substantially enhance the wear resistance of AISI P20 mould inserts during GFRP injection, with multilayer nanostructured systems, particularly CrN/TiAlCrSiN, achieving the greatest reduction in material loss and extending TL more than sixtyfold compared with uncoated steel. These coatings reduce friction, mitigate abrasive and adhesive wear, and substantially improve resistance to corrosive melt constituents. Continued research into multilayered, graded, or nano-architectured coatings offers opportunities to tailor surface performance to highly specific moulding environments [28].

Parallel advances in tool materials have further expanded performance capabilities. Modern tool steels and emerging alloy systems, such as high-entropy alloys (HEAs) [29], precipitation-hardened steels, and hybrid composites, offer improved combinations of toughness, thermal conductivity, and resistance to thermal shock [30]. Enhanced thermal conductivity is particularly advantageous in IM, where efficient heat dissipation can reduce thermal gradients, limit the formation of heat-affected zones, and minimise susceptibility to thermal fatigue or cracking. Such developments align with industrial requirements for both improved durability and reduced cycle times [31,32].

Additive manufacturing has become an increasingly influential technology in mould tool design and fabrication [33]. Powder-bed fusion processes such as Selective Laser Melting (SLM) enable the creation of complex three-dimensional cooling channels that conform closely to mould cavity geometry, achieving thermal management performance unattainable by conventional drilled channels [34]. Chalicheemalapalli Jayasankar et al. [35] focused on optimising injection-moulding tool design using additive manufacturing, integrating conformal cooling and lattice structures to enhance thermal control, as depicted in Figure 4. Their work demonstrated improved temperature regulation, reduced cycle times, and minimised material waste.

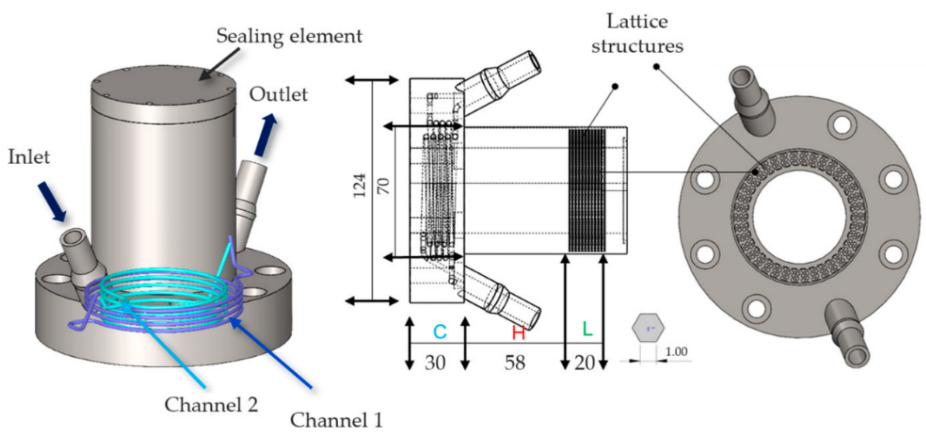

Figure 4. Design of the mould insert from Chalicheemalapalli Jayasankar et al. [35] work comprising Type 2 cooling channels (C), a dedicated heating element (H) to achieve localised temperature elevation, and a lattice structure (L).

These conformal cooling systems improve temperature uniformity, shorten cycle times, reduce warpage, and alleviate the thermo-mechanical stresses that contribute to tool degradation. Additive manufacturing also provides novel pathways for in-situ repair, local reinforcement, or partial reconstruction of worn mould features through Directed Energy Deposition (DED) and similar techniques [36], supporting more sustainable and cost-effective maintenance strategies.

Recent research has broadened further to encompass advanced machining techniques, residual stress optimisation, microstructural control, and polishing or texturing processes that influence tool performance at the micro- and nano-scale. Gustavo F et al. [37] demonstrated that optimised PVD-coated milling tools markedly improve the machining performance of AISI P20 steel, achieving lower cutting forces, reduced tool wear, and enhanced surface quality, thereby underscoring the importance of coating design in extending tooling reliability for mould manufacturing. The interplay between machining-induced subsurface damage, heat-affected zones, and coating adhesion has emerged as a critical factor governing TL. As a result, integrated approaches that consider the full tooling lifecycle, from material selection and heat treatment to surface finishing and final coating, are gaining prominence [38].

Despite significant progress, there remain notable gaps, as displayed in Table 1, in understanding the complex interactions between tooling materials, coatings [39], polymer melts, and process conditions. Variability in experimental methodologies, limited standardisation of wear or corrosion testing under moulding-specific conditions, and insufficient long-term industrial validation all pose challenges to the development of universally accepted design frameworks [40,41]. Moreover, as polymer systems continue to evolve, driven by functional additives, bio-based formulations, and increasingly stringent performance requirements, the demands placed on mould tools will intensify further.

Table 1. Summary of Principal Scientific and Technological Gaps in IM TL Research.

Key Research Gaps	Highlights
Tool–Polymer Interaction Mechanisms Not Fully Resolved	The coupled thermo-mechanical–chemical interactions between mould steels, coatings, and evolving polymer formulations (especially FRPs, high-temperature thermoplastics, and corrosive polymers) are still insufficiently characterised at realistic processing conditions.
Lack of Standardised Wear and Corrosion Testing for IM	Tribological and corrosion test protocols rarely replicate injection-moulding-specific conditions such as rapid thermal cycling, fibre impingement, melt chemistry, or fluctuating shear stresses. This limits comparability between studies.
Insufficient Long-Term Industrial Validation	Many coating, material, and AM-insert studies remain at laboratory scale, with limited real-world data on durability, fatigue, spallation behaviour, or tool failure modes over thousands or millions of cycles.
Limited Understanding of Multilayer and Nanostructured Coating Behaviour	Modern coatings involve graded interfaces, nano-architectures, and multilayers whose failure mechanisms (crack propagation, delamination, diffusion, oxidation) are not yet comprehensively modelled under cyclic moulding conditions.
Inadequate Integration of Thermal-Management Research with Material/Coating Design	Studies on conformal cooling, AM inserts, and heat-transfer optimisation are often disconnected from research on coating adhesion, tool-steel microstructure, or fatigue performance, despite strong interdependence.
Unresolved Issues in Additively Manufactured Tool Inserts	AM materials still face challenges regarding microstructural heterogeneity, anisotropy, residual stresses, coating compatibility, and predictability of wear behaviour under repeated thermal cycling.
Rapid Evolution of Polymer Systems Outpacing Tooling Research	Bio-based polymers, recycled blends, FRPs with new fibre treatments, and high-performance polymers introduce new chemical and abrasive environments that existing tool steels and coatings were not originally designed for.
Lack of Predictive Models Linking Process Parameters to Tool Damage	Existing models inadequately capture tool degradation as a function of melt flow behaviour, fibre orientation, injection kinetics, and localised thermal hotspots.

Against this backdrop, the present review aims to present a comprehensive and systematically structured examination of recent technological and methodological advances aimed at extending the service life of IM tools. It synthesises contemporary developments in surface treatments, tool material selection, machining and repair strategies, and associated performance-enhancement techniques. In doing so, the study identifies prevailing trends, emerging research directions, and future opportunities for improving tool durability and supporting the broader evolution of sustainable and high-performance manufacturing practices.

- Conceptual Clarification: To articulate the theoretical foundations underpinning tool wear, degradation mechanisms, and material failure in IM environments, while delineating the relationships between these mechanisms and the properties of commonly employed tool steels and alloys.
- Historical and Technological Mapping: To trace the development of surface engineering and tooling technologies, such as nitriding, carburising, PVD and CVD coatings, duplex treatments, and additive manufacturing, thereby contextualising their emergence as critical enablers of enhanced tool durability and manufacturing reliability.
- Technological Integration and Industrial Application: To examine how combinations of surface treatments, coating architectures, advanced machining practices, and improved thermal-management strategies contribute to reduced wear, enhanced corrosion resistance, improved demoulding behaviour, and prolonged operational TL within industrial moulding settings.
- Challenges and Future Directions: To identify the principal technical and practical limitations impeding the widespread adoption or optimisation of these technologies, such as coating adhesion, repairability, microstructural variability, and cost considerations, and to outline emerging research trends, including novel coating systems, hybrid manufacturing routes, and advances in tool-material design.

The structure of the paper is as follows. Section 1 provided an introduction to some state-of-the-art recent advances extending the service life of IM Tools, followed by Section 2, which provides the method of research. Section 3 offers a comprehensive and systematic review of the literature concerning tool degradation and surface engineering, outlining the principal wear and failure mechanisms that limit mould life and evaluating the full range of surface treatments, coating technologies, and manufacturing innovations reported in the selected studies. Section 4 discusses the industrial applicability and comparative performance of these technologies, and Section 5 identifies future research opportunities and summarises the broader implications of the review for researchers and industrial practitioners.

Ultimately, this paper aims to serve as an authoritative and comprehensive reference for academics, engineers, and industrial decision-makers engaged in improving the performance and longevity of IM tooling. By synthesising the current state of knowledge on materials, surface treatments, coating technologies, and manufacturing strategies, the study provides both conceptual clarity and practical direction for advancing tool durability, reducing operational costs, and enhancing production consistency within polymer processing industries. As tooling requirements become increasingly demanding, driven by abrasive polymer systems, complex geometries, and stringent quality expectations, mastery of these technologies will be essential for sustaining competitiveness and fostering innovation in modern manufacturing.

2. Method of Research

A systematic and comprehensive review of the literature was conducted, following a transparent and replicable research design [42,43], and grounded in the PRISMA 2020 framework, which ensures procedural clarity, methodological rigour, and reproducibility [44]. The assessment of candidate sources incorporated established quality indicators, including citation frequency and the academic standing of the publication outlets. Data collection was undertaken in September 2025, with primary records sourced from the Web of Science, Scopus, and CrossRef databases. To broaden the search scope and ensure consistency across metadata fields, supplementary indexing platforms, most notably Dimensions.ai, were also consulted. In addition, a bespoke MATLAB® algorithm [45] was utilised to automate record consolidation, harmonise cross-database outputs, and eliminate duplicate entries.

2.1. Study Selection (PRISMA)

The systematic identification and selection of studies adhered to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 framework, ensuring procedural transparency and reproducibility throughout the review process. The initial database query across Web of Science, Scopus and CrossRef yielded a total of 214,529 records spanning the 2015 to 2025 period. Following automated and manual deduplication using the MATLAB® routine, 116,194 unique studies were retained for preliminary screening. Drawing upon this structured framework, a coherent set of RQs was formulated to direct the systematic examination and synthesis of the selected body of literature. The systematic identification and selection of studies followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework, ensuring methodological rigour, transparency, and full reproducibility.

Titles, abstracts, and keywords were then examined to assess their relevance to the durability, degradation mechanisms, and service life extension of IM tools. Works that lacked methodological adequacy, did not address mould performance, or fell outside the scope of surface engineering, tool steels, wear mechanisms, or mould maintenance were removed. This screening process resulted in 37,642 studies progressing to full-text evaluation. Following the application of clearly defined inclusion and exclusion criteria, focused on experimental robustness, industrial applicability, and theoretical coherence- a final set of 120 peer-reviewed publications was gathered. Since there are two journals with more than 50 articles, and to avoid bias, the most influential ones will be selected based on the number of citations. These constitute the empirical and conceptual foundation of this comprehensive review.

This multi-stage selection procedure ensured that only high-quality research addressing tool wear, surface treatments, coatings, machining strategies, thermal management, and tool material development was incorporated. The final collection of studies represents the most scientifically and industrially relevant contributions to the understanding of mould tool longevity over the last decade.

A recurring difficulty encountered during the literature review relates to the non-standardised way researchers reference tool steels. Despite the widespread use of internationally recognised nomenclature systems, identical steels may appear under multiple designations. For example, AISI H11**,** DIN 1.2343**,** and X38CrMoV5-1 refer to the same alloy, yet authors inconsistently adopt variations such as "X 38 CrMoV5-1" or "X38CrMoV5-1". Similar inconsistencies arise for other tooling alloys. This lack of uniformity necessitated careful cross-checking of compositions and standards during the selection and categorisation of studies to avoid misinterpretation of material behaviour. On the other hand, also there is the ambiguity of having authors writing in US English (e.g., "injection mold") versus the UK English (e.g., "injection mould"), introducing again unnecessary variations.

The formulation of precise Research Questions (RQs) is a central step in any SLR, as it establishes the conceptual boundaries and analytical direction of the investigation. To ensure internal coherence and to align the review with state-of-the-art developments in mould TL extension, the Population, Intervention, Comparison, Outcome, and Context (PICOC) framework was adapted as follows:

- Population: experimental, numerical, and review studies addressing the performance, degradation, surface engineering, or maintenance of IM tools, including those made of H-series steels, stainless tool steels, maraging steels, and additively manufactured tool materials.
- Intervention: surface treatments and modification techniques such as nitriding (gas, plasma, or ion), carburising, PVD and CVD coatings, duplex or multilayer systems, electrodeposition, HVOF-sprayed layers, advanced machining strategies for hardened tool steels, and thermal-management-enhancing approaches (e.g., conformal cooling channels).
- Comparison: comparisons between untreated and treated tool materials, between different coating systems, and between conventional and advanced machining or heat-treatment approaches (This domain is retained but broadened to materials and treatments, not digital methods.)
- Outcomes: improvements in wear resistance, corrosion resistance, friction behaviour, thermal stability, demoulding performance, fatigue life, dimensional stability, and overall, TL. In addition, emerging trends and technological gaps in contemporary mould tooling research.
- Context: Peer-reviewed academic and industrial publications on IM tooling, tool materials, surface engineering, manufacturing processes, and wear/corrosion phenomena published from 2015 to 2025.

Based on this framework, a coherent set of RQs was formulated to guide the systematic extraction, evaluation, and synthesis of knowledge from the retained literature. These RQs are presented in Table 2 of the manuscript.

Figure 5 depicts the three-stage literature screening and selection process conducted. The review examined peer-reviewed studies published between 2015 and 2025 to capture the most recent decade of research concerning the durability, performance, and service life extension of IM tools. The literature search employed the keyword combination "Injection Moulding" AND ("Surface Treatments" OR "Coatings" OR "Additive Manufacturing"), thereby targeting work directly relevant to material enhancement strategies and surface-engineering innovations.

Across the three repositories, a steady increase in research output is evident from 2015 to September 2025, with Scopus and CrossRef showing particularly consistent year-on-year growth, as may be seen in Figure 6. CrossRef reports considerably higher record counts overall, reflecting its broader indexing scope. The continuous growth in the subject demonstrates academic and industrial interest in surface treatments, coating technologies, and additive manufacturing approaches aimed at improving injection mould tool longevity and operational performance. Table 3 presents the studies retrieved from the Web of Science, Scopus, and CrossRef databases that met the inclusion criteria and were organised chronologically to illustrate publication trends.

Table 2. PICOC RQs.

ID	Research Question
RQ1	What are the predominant wear, corrosion, thermal-fatigue, and degradation mechanisms affecting the service life of IM tools?
RQ1.1	How do this degradation mechanisms differ across commonly used tool steels and alloys, including H-series steels, stainless tool steels, and advanced or additively manufactured tooling materials?
RQ1.2	What material properties and microstructural features most strongly influence susceptibility to wear, corrosion, and thermal damage during moulding operations?
RQ2	Which surface engineering techniques, such as nitriding, carburising, PVD/CVD coatings, duplex systems, electrodeposition, and HVOF-applied coatings, demonstrate the greatest effectiveness in extending TL?
RQ2.1	How do different coating architectures (e.g., multilayer, nanocomposite, duplex) compare in terms of wear resistance, corrosion protection, friction behaviour, and demoulding performance?
RQ2.2	What are the principal factors governing coating adhesion, failure modes, and long-term stability under industrial moulding conditions?
RQ3	How do advanced machining practices, heat-treatment strategies, and tooling fabrication methods influence surface integrity, thermal management, and durability of moulding tools?
RQ3.1	Which machining approaches (e.g., high-speed machining, cryogenic machining, MQL, trochoidal strategies) are most effective for hardened tool steels used in IM?
RQ3.2	How do fabrication approaches, including conventional machining, hybrid manufacturing, and AM-based insert production, affect tool longevity and maintenance requirements?
RQ4	What recent advances in cooling strategies, mould-insert design, and thermal-management solutions contribute to improving TL and reducing thermal fatigue?
RQ4.1	How do design innovations (e.g., optimised cooling layouts, conformal cooling channels) impact temperature distribution, cycle stability, and thermal-induced tool degradation?
RQ4.2	What limitations and practical challenges hinder the broader adoption of advanced thermal-management solutions in industrial mould construction?
RQ5	What are the emerging research trends, unresolved challenges, and promising future directions for improving the durability and operational performance of IM tools?
RQ5.1	Which novel materials, coating concepts, and surface-engineering methodologies show potential for next-generation high-durability tooling?
RQ5.2	What critical knowledge gaps remain in the current scientific understanding of tool wear, coating performance, and long-term mould tool behaviour?

Table 3. Summary of the articles gathered from each database and year.

Year of Publication	Web of Science	Scopus	CrossRef
2015	11	44	1595
2016	15	76	1711
2017	27	71	2027
2018	19	90	2405
2019	34	127	2949
2020	28	153	3257
2021	44	171	3740
2022	28	199	4016
2023	23	180	4255
2024	37	215	4686
2025 *	20	221	5168
Total	286	1547	35,809

* as of September 2025.

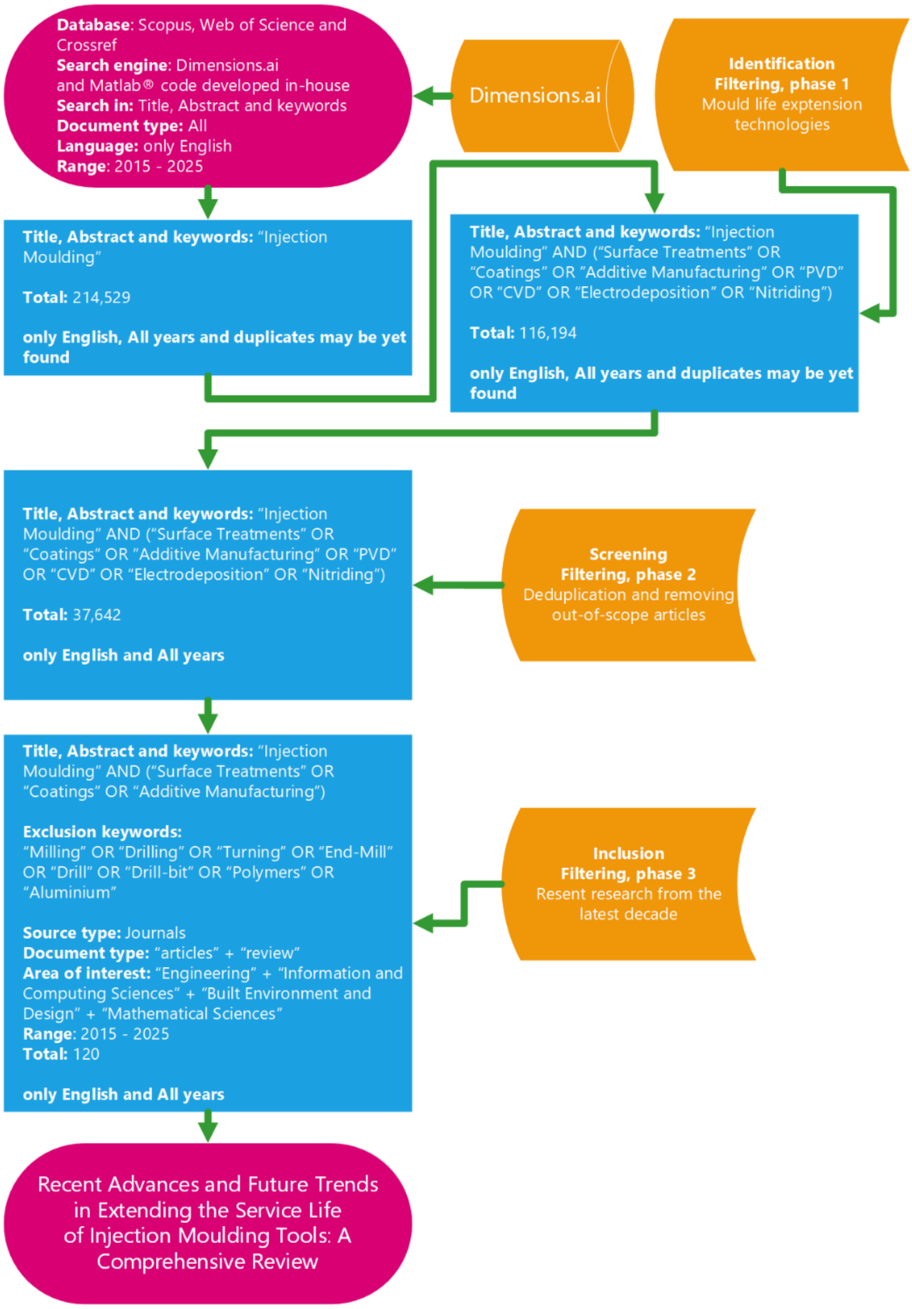

Figure 5. PRISMA-Based Three-Level Screening and Selection Protocol for IM searched articles.

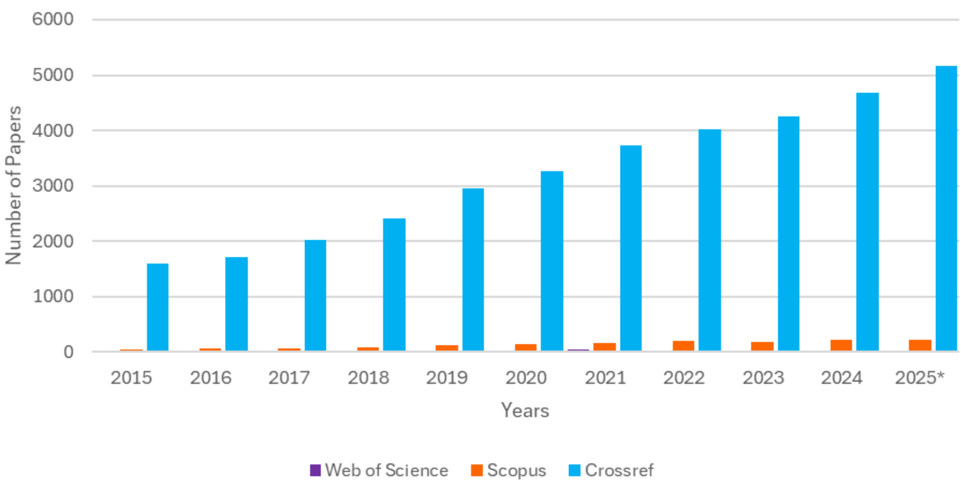

Figure 6. Web of Science, Scopus and Crossref.

2.2. Study Selection and Quality Assessment (QA)

Assessing the methodological quality of the selected studies constitutes a critical stage in any Systematic Literature Review, as it provides the evidential basis upon which the credibility, validity, and interpretative robustness of the subsequent synthesis depend. In this review, the Quality Assessment (QA) framework was designed to evaluate the rigour, transparency, and practical relevance of each study through a structured, multi-dimensional approach. The framework comprised four equally weighted categories, each addressing a distinct element of methodological soundness and scholarly contribution. The criteria were adapted from established systematic review protocols and operationalised using a three-point ordinal scale, whereby "Yes" = 1, "Partly" = 0.5, and "No" = 0. The four QA categories were defined as follows:

- Research Design and Theoretical Foundation (25%)—assessing the clarity of research objectives, the suitability of the methodological approach, and the coherence of the underlying theoretical framework.
- Technical Scope and Materials/Process Definition (25%)—evaluating the precision with which tool materials, surface treatments, coatings, or manufacturing processes are characterised, including the adequacy of experimental parameters.
- Methodological Soundness and Analytical Precision (25%)—examining the transparency of data collection procedures, the robustness of validation methods, and the consistency and accuracy of analytical interpretation.
- Practical and Industrial Relevance (25%)—determining the extent to which findings demonstrate applicability to real-world IM operations, including implications for tool performance, longevity, and industrial feasibility.

To ensure the integrity and reliability of the final synthesis, only studies achieving a QA score above 50%, equivalent to a total score greater than 5 out of 10, were retained, as illustrated in Figure 7. This threshold ensured that the final corpus comprised contributions of demonstrable methodological robustness, empirical significance, and conceptual clarity within the field of IM TL extension.

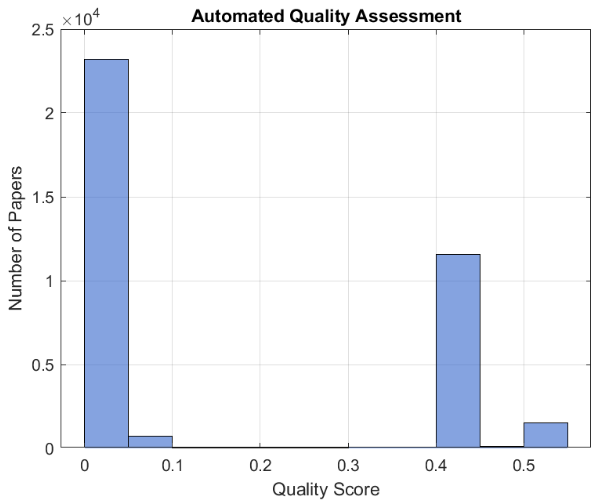

Figure 7. QA of the articles gathered.

The identification and selection of relevant studies followed a three-stage screening procedure consistent with the PRISMA 2020 framework, ensuring a systematic and transparent progression from initial retrieval to final inclusion. In the first stage, all search results were consolidated, and duplicate records were eliminated through both automated and manual verification using the MATLAB® routine. Table 4 presents the disseminated research on surface engineering, coating technologies, additive manufacturing, and other approaches relevant to extending the service life of IM tools, compiling a complete listing of publication venues together with the corresponding article counts. As conference proceedings were excluded from this review, all Lecture Notes series and similar outlets were omitted from the final dataset by design.

As shown in Figure 8, the geographical distribution of authorship and institutional affiliation across the reviewed studies reveals a pronounced concentration of research activity within Europe, with the United Kingdom emerging as a leading contributor to the scholarly literature on surface treatments, coating technologies, and TL extension in IM. A substantial proportion of publications also originates from the United States, reflecting the global relevance and widespread industrial engagement associated with improving mould tool performance and durability, followed by France and Italy.

Table 4. Core articles obtained from journals published by reputable academic institutions and publishing houses.

Journal Name	Count of Articles	Considered
International Journal of Advanced Manufacturing Technology	69	Y
Polymers MDPI	69	Y
Additive Manufacturing Elsevier	49	Y
Materials MDPI	46	Y
Rapid Prototyping Journal	33	Y
Lecture Notes in Mechanical Engineering	28	N
Progress in Additive Manufacturing	25	Y
Key Engineering	24	Y
Procedia CIRP	21	Y
Applied Sciences MDPI	18	Y

N—No, Y—Yes.

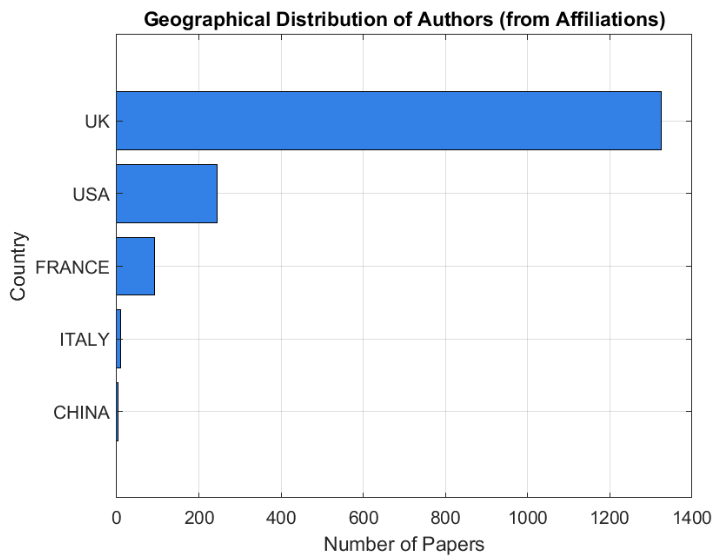

Figure 8. Geographical distribution of authors by institutional affiliation.

This spatial pattern is noteworthy, as it indicates that research leadership in this domain is distributed across multiple regions rather than centred exclusively within countries traditionally recognised for their historical influence in tooling, precision manufacturing, and materials engineering. This dispersion underscores the increasingly international character of contemporary research efforts aimed at enhancing the longevity and operational robustness of IM tools.

2.3. Descriptive Analysis and Taxonomic Synthesis

The descriptive synthesis of the final corpus reveals a diverse and rapidly advancing research landscape concerned with improving the durability and operational longevity of IM tools. Publications were categorised according to their technological focus, industrial application, and degree of methodological or experimental integration. The reviewed literature spans two principal domains:

1. Materials and Surface Engineering Technologies: including nitriding, carburising, PVD and CVD coatings, duplex treatments, electrodeposition processes, and other surface-modification techniques aimed at enhancing wear resistance, corrosion behaviour, demoulding characteristics, and thermal stability.
2. Manufacturing and Tooling Innovation Technologies: encompassing additive manufacturing (AM) for mould inserts, hybrid toolmaking strategies, advanced machining approaches for hardened steels, optimised cooling channel design, and process-induced thermal management solutions.

This classification underscores the multifaceted nature of contemporary research on mould TL extension, in which material science, manufacturing technology, and thermal–mechanical process optimisation converges to address complex degradation mechanisms. Application mapping across the literature identifies four dominant thematic areas:

1. Wear and Surface Degradation Mitigation: focusing on strategies to counteract abrasive wear, erosion, adhesive failure, and surface fatigue in tools exposed to fibre-reinforced polymers or high-temperature resins.

2. Corrosion and Chemical Stability Enhancement: addressing protective coatings and surface treatments capable of resisting corrosive gases, polymer degradation products, and chemically reactive melt constituents.
3. Thermal Management and Fatigue Reduction: examining conformal cooling channels, thermal-barrier coatings, and heat-treatment procedures designed to minimise thermal gradients and cyclic thermal loading.
4. Manufacturing Efficiency and Tooling Performance: exploring machining quality, surface finish, microstructural integrity, and the influence of tool fabrication pathways on subsequent service life.

Across the reviewed studies, several measurable benefits are reported:

- Significant improvements in wear resistance and corrosion protection, leading to extended TL and reduced maintenance frequency.
- Enhanced thermal stability and more uniform temperature distribution contribute to lower thermal fatigue and improved dimensional accuracy.
- Reduced demoulding forces and surface adhesion through low-friction or polymer-repellent surface treatments.
- Improved manufacturability and performance of complex tooling geometries through additive manufacturing and hybrid machining approaches.
- Commonly used performance indicators include hardness, coefficient of friction, wear rate, corrosion potential, thermal conductivity, fatigue life, and industrial TL measurements.

Despite significant progress, several challenges continue to limit the full effectiveness of contemporary coating and surface-engineering strategies. Variability in coating adhesion, heterogeneous microstructures, and complex interactions between coating layers and polymer melt chemistries remain critical technical obstacles. Practical constraints, including cost, process scalability, compatibility with common tool steels, and difficulties associated with repairing coated surfaces, are also widely reported. Additionally, inconsistencies in experimental design and the absence of standardised test protocols complicate meaningful comparison across studies.

The review's three-stage screening procedure began with an initial assessment of titles, abstracts, and keywords to identify research relevant to surface engineering, tool materials, and mould durability. Full-text evaluation then ensured compliance with predefined criteria prioritising empirical and review studies offering substantive technical or industrial insight into tool-wear mitigation and service-life extension. Only peer-reviewed journal articles were included; non-English publications, grey literature, and works lacking methodological rigour were excluded. The final dataset constitutes a carefully curated and scientifically robust body of literature underpinning the analyses presented in this review.

3. Literature Review

Contemporary advances in mould performance and the extension of tool service life are founded upon two interrelated technological domains: materials and surface engineering, and manufacturing-oriented innovations related to tool design, machining, and process optimisation. These domains collectively shape present-day strategies for enhancing durability, mitigating wear, and improving the thermal and tribological behaviour of injection-moulding tools.

The first domain comprises the selection and modification of tool materials, together with heat treatments and surface-engineering approaches that directly influence corrosion resistance, load-bearing capacity, and the stability of tools subjected to cyclic thermal and mechanical loading. Plasma and gas nitriding, carburising, PVD and CVD coatings, duplex systems, and polymer-repellent surface layers are central to improving near-surface microstructures and chemistries. These treatments reduce abrasion, adhesion, chemical degradation, and thermal-fatigue damage, thereby supporting tool performance under increasingly severe moulding conditions, particularly those imposed by fibre-reinforced polymers and high-temperature engineering thermoplastics.

The second domain encompasses developments in manufacturing technology, including additive manufacturing of inserts, high-performance machining of hardened steels, optimised cooling architectures, and predictive modelling of tool degradation. These innovations enhance thermal management, enable complex tool geometries, and improve microstructural control. When combined with advanced surface treatments, they offer significant improvements in robustness, dimensional stability, and overall tool longevity, forming the basis for next-generation injection-moulding systems.

3.1. Fundamentals of Tool Wear and Failure Mechanisms

The durability of IM tools is dictated by a highly coupled set of mechanical, thermal, chemical, and interfacial degradation mechanisms. Mechanical wear typically manifests through adhesive, abrasive, and erosive processes arising from elevated contact pressures, sliding motion, and the impingement of hard fillers or fibres within the polymer melt. Cyclic loading further promotes surface and subsurface fatigue, facilitating crack initiation and subsequent propagation. As summarised in Table 5, recent studies published between 2015 and 2025 have considerably advanced the understanding of these degradation pathways, clarifying the complex interactions between tooling materials, surface condition, melt rheology, and processing parameters. This collective body of research provides an increasingly robust framework for interpreting wear mechanisms and predicting failure in industrial moulding environments.

Back in 2001, Bergstrom et al. [46] assessed the surface wear behaviour of die materials under full-scale IM of glass-fibre-reinforced polycarbonate, demonstrating that abrasive micro-cutting, ploughing and impact erosion dominate tool degradation, with wear severity strongly governed by fibre orientation, injection conditions, and the hardness and microstructure of the die material. Years later, Dimitriu et al. [47] reviewed advances in injection-mould remanufacturing, emphasising that TIG, plasma, and laser welding remain the principal repair routes, with laser welding offering superior precision, minimal heat-affected zones, and reduced hardness loss, making it particularly suitable for fine, localised moulding tool restoration.

Thermo-mechanical damage, particularly thermal fatigue, thermal shock, and spalling, emerges from rapid temperature fluctuations that impose localised tensile stresses beyond the fatigue strength of the tool steel. Chemical and electrochemical attack, driven by polymer degradation products, moisture, and reactive additives, contributes to pitting, oxide formation, and hydrogen embrittlement. Interfacial phenomena also exert strong influence: polymer adhesion, melt wetting characteristics, and surface chemistry affect demoulding forces and can intensify adhesive damage. Material–process factors, such as fibre orientation, filler hardness, and particle angularity, further modulate abrasion severity and thermal loading. Collectively, these mechanisms underscore the need for integrated strategies spanning material selection, heat treatment, surface engineering, and thermal management to achieve meaningful improvements in tool longevity.

Jameson et al. [48] conducted a comparative study demonstrating that variotherm moulding significantly enhances surface replication fidelity in polymer microstructures, with rapid heating–cooling cycles yielding markedly higher gloss, reduced flow marks, and improved feature definition relative to conventional processing. Also Yuan et al. [49] conducted an experimental analysis that systematically examined the strain-controlled thermo-mechanical fatigue behaviour of a novel Cr–Mo–V hot-work die steel, demonstrating that finely dispersed MC carbides markedly enhance microstructural stability, suppress crack propagation, and significantly extend thermal-mechanical fatigue (TMF) life compared with conventional AISI L6 (DIN 1.2714 or 55NiCrMoV7) tool steel.

Table 5. Studies carried out on the study of IM TW and failure mechanisms.

References	Technology	Highlights
Zabala et al. [50]	Wear & Corrosion Mechanism Modelling	Showed that TiN (PVD), nitrided layers, and electrodeposited Ni-PTFE coatings provide superior protection against abrasion, erosion, and corrosion in mould steels, with hardness above ~800 HV significantly improving predicted TL.
Martinho and Pouzada [51]	Hybrid moulds with AM-produced moulding elements	investigated hybrid tooling manufactured through additive manufacturing (vacuum epoxy casting, stereolithography, and ProMetal), demonstrating that material selection critically governs structural integrity, thermal behaviour, and ejection forces in IM tools.
Freitas et al. [52]	Tribological testing of mould steels inserts	Showed that Cu–Be alloy AMPCOLOY® 83 undergoes severe adhesive and abrasive wear during high-speed milling, with pronounced material transfer and tool–workpiece interaction, which the TiAlN/DLC multilayer coating significantly mitigated by reducing friction, adhesion, and wear progression
Gülçür et al. [53]	X-ray computed tomography (XCT) for predictive quality assessment of micro- IM	Demonstrated that XCT enables full 3D inspection of micro-moulded components, accurately quantifying feature replication and soft-tool deformation, and delivering predictive quality models with up to 92% filling-accuracy performance compared with conventional metrology.
Sebbe et al. [54]	Cu-Be inserts milling and mill-ends tool wear sustained.	Provided a complete comprehensive comparison among multiple investigations on Cu–Be machining, showing consistent evidence that TiAlN/DLC coatings substantially reduce adhesion-driven wear, flank deterioration, and surface damage relative to uncoated tools, confirming their superiority across different cutting conditions.

3.2. Surface Engineering and Coating Technologies: Strategies for Tool Life Extension

3.2.1. Thermochemical Treatments

Thermochemical surface treatments constitute a foundational strategy for extending the service life of IM tools, offering significant improvements in hardness, wear resistance, and thermal-fatigue performance through controlled modification of the near-surface microstructure.

Comparable challenges arise in tooling for micro- IM and for the processing of high-temperature polymers such as PEEK, PSU and LCP, where severe shear stresses, aggressive melt chemistries, and steep temperature gradients intensify wear, corrosion and thermal-fatigue mechanisms. Taken together, these material limitations highlight the necessity for optimised alloy selection, carefully controlled heat-treatment regimes, and the growing integration of surface-engineered solutions to counteract the complex degradation modes inherent to modern moulding operations. Wu et al. [55] researched how three ultrasonic plasticisation moulding technologies influence polymer melt fluidity, demonstrating that axial vibration markedly improves microscale filling behaviour, with ultrasonic pressing yielding the highest melt fluidity and most effective microstructure replication. On the other hand, Brettmann et al. [56] studied that processing highly filled polymers is limited by process-induced porosity, poorly characterised solid–liquid interfaces, equipment constraints, and insufficient in-situ monitoring, identifying these four areas as critical research gaps for advancing reliable forming and additive manufacturing of densely loaded polymer systems

As summarised in Table 6, which compiles the principal studies published between 2015 and 2025, thermochemical surface treatments remain among the most widely applied strategies for enhancing the durability of IM tools. Nitriding, whether conducted by gas, plasma, or ion-assisted processes, diffuses nitrogen into the steel matrix to form compound layers (ε-$Fe_{2–3}N$ and γ'-Fe_4N) and an underlying diffusion zone, thereby increasing surface hardness, enhancing resistance to abrasive and adhesive wear, and improving load-bearing capacity without inducing distortion. Plasma nitriding additionally enables precise control of case depth and phase composition, making it particularly suited to complex tool geometries. Scheuer et al. [57] reviewed that plasma-assisted thermochemical treatments fundamentally enhance the hardness, wear resistance and corrosion behaviour of martensitic stainless steels by enabling controlled interstitial diffusion, and proposed systematic property-processing maps to guide optimal treatment selection and performance prediction In Pedroso et al. [26] is briefly reviewed that advanced surface treatments, optimised machining strategies, and sustainable lubrication techniques markedly enhance mould durability, reducing tool wear and deformation while improving efficiency and extending service life in high-pressure injection-moulding applications.

Carburising and carbonitriding introduce carbon, or both carbon and nitrogen, into the surface layer, generating high-carbon martensitic structures upon quenching. These treatments markedly improve fatigue strength and wear behaviour, although excessive carbide precipitation or retained austenite may compromise toughness if not properly controlled. Boriding, in contrast, forms hard boride layers (FeB, Fe_2B) with exceptional resistance to abrasion and chemical attack, but the intrinsic brittleness of boride phases demands careful management of layer thickness to prevent cracking. Wang et al. [58] studied that carburizing–carbonitriding markedly elevates surface carbon and nitrogen uptake, refining martensite, increasing carbide precipitation, and reducing retained austenite, thereby enhancing microhardness and achieving up to ~33 % improvement in wear resistance relative to conventional carburizing.

Table 6. Studies carried out on Thermochemical Treatments.

References	Technology	Highlights
Dalibón et al. [59]	Low-temperature plasma nitriding	Demonstrated that duplex plasma-nitrided + DLC-coated PH stainless steel markedly improves corrosion resistance; the nitrided layer reduced mass loss by ≈100% in acid media and raised breakdown potentials, with the duplex system showing the most robust electrochemical performance.
Calderón et al. [60]	Electrodeposited Ni/NiO + PFOS Coatings	Used an electrodeposition-based multilayer Ni/NiO system with a PFOS top layer to improve tool surfaces, achieving up to 90% reduction in demoulding force and stable anti-adhesion performance over 150 injection cycles compared with uncoated and TiN-coated steel
Ye et al. [61]	Plasma electrolytic oxidation (PEO) surface treatment	PEO created a porous, mechanically interlocking oxide layer on AZ31B Mg, enabling significantly higher PPS–Mg joint strength than sandblasting. Optimal coating morphology (≈5 min PEO) maximised interfacial riveting and improved composite integrity.
Huang et al. [62]	Plasma Nitriding	Showed that plasma-nitrided S136 steel achieves ~1186 HV and a 92.6% reduction in wear rate, maintaining superior performance up to ~300 °C before oxidation effects dominate
Yang et al. [63]	Gas Nitriding + Laser Cladding (Iron-Based Coating)	Gas nitriding increased surface hardness to ~1214 HV, but an unstable ε/γ' phase balance caused microcracking, leading to greater wear depth and reduced corrosion resistance compared with the as-clad layer.
Sim et al. [64]	Laser-assisted nitriding (high-power diode laser)	demonstrated that diode-laser nitriding produced a nitrogen-rich AlN layer up to ~15 µm deep on AISI P21 steel, increasing surface hardness by approximately 40% through controlled nitride formation and significantly improving resistance to abrasive moulding conditions.
Krizsma et al. [65]	Gamma-irradiation post-treatment of material jetting-printed photopolymer moulds	Demonstrated that high-energy gamma irradiation markedly increases the stiffness, glass-transition temperature and creep resistance of material-jetting photopolymer mould inserts, halving operational deformation and significantly extending mould life during IM trials.
Lv et al. [66]	Plasma electrolytic oxidation (PEO) surface modification	The study demonstrates that sandblasting combined with PEO, enhanced by urea-derived amino and hydroxyl functionalisation, produces porous oxide layers enabling strong mechanical interlocking and chemical bonding, increasing Ti–PPS joint strength up to 17-fold.
Yan et al. [67]	Auxiliary-heating plasma nitriding of AISI H11 steel	The study establishes that auxiliary-heating plasma nitriding produces thicker, more uniform diffusion layers, markedly increases surface hardness, and substantially enhances wear resistance across varied loading, speed, and temperature conditions, outperforming traditional plasma nitriding approaches.

3.2.2. PVD Coatings

As outlined in Table 7, which collates key studies from 2015 to 2025, PVD coatings constitute one of the most effective surface-engineering routes for extending the service life of IM tools. PVD systems such as TiN, CrN, AlTiN, TiAlSiN, and more recent multilayer and nano-multilayer architectures offer substantial improvements in hardness, oxidation resistance, and tribological stability. Their performance derives from controlled thin-film growth mechanisms, typically involving energetic ion bombardment, adatom mobility, and preferential crystallographic orientation, which enable the formation of dense, fine-grained microstructures with excellent load-bearing capacity. Coating adhesion, a critical determinant of service performance, is governed by interlayer design, substrate pretreatment, and residual-stress management; optimised bias voltages and interlayer architectures are particularly important for preventing spallation under cyclic thermal and mechanical loading. For instance Bobzin et al. [68] studied the high performance of PVD hard coatings and how ultra-short-pulsed laser nanostructuring alters CrAl-based compounds, demonstrating that increasing pulse energy deepens structures but reduces hardness through thermally induced amorphization, informing optimal structuring parameters for mould applications.

Table 7. Studies carried out on PVD coatings.

References	Technology	Highlights
Sorgato et al. [69]	PA-CVD DLC and CrTiNbN coatings	Examined how PA-CVD DLC and CrTiNbN coatings influence ejection friction in micro- IM. Coatings reduced adhesion-driven friction, with performance strongly dependent on polymer type; CrTiNbN increased friction due to higher roughness, while DLC enabled lower demoulding forces.
Sorgato et al. [70]	Thermally insulating mould-surface coatings (CrN, Al_2O_3, DLC, a-C:H:Si)	Demonstrated that thermally insulating coatings, particularly DLC, substantially reduce cavity pressure and frozen-layer formation during filling. The optimised thermal boundary enabled up to 12% wall-thickness reduction and significant material and cycle-time savings.
Jaud et al. [71]	ZrO_2 Thermal Barrier Coating	Showed that PVD magnetron-sputtered ZrO_2 produced a dense, uniform microstructure that improved thermal insulation efficiency with increasing thickness, offering strong heat-transfer reduction for tooling applications.
Yiu et al. [72]	Cr-based thin-film metallic glass	Verified that CrCoNbB thin-film metallic glass produced by DC magnetron sputtering exhibits markedly higher hardness, lower friction, reduced surface energy, and weaker polymer adhesion than PVD Cr, indicating strong suitability for mould-wear reduction.
Tillmann et al. [73]	CrN / CrAlN coatings	The study demonstrates that mechanically post-treated CrN and CrAlN PVD films substantially reduce ejection forces in polypropylene moulding by mitigating roughness-induced mechanical interlocking, achieving ~23% force reduction relative to uncoated H11 tool steel.
Santos et al. [74]	Pulsed DC magnetron sputtering (pDCMS)	The study demonstrated that pDCMS-deposited amorphous carbon coatings on Cu–Be alloys require engineered Ti/Si or Ti/TiN/Si interlayers to achieve adequate adhesion. Thicker TiN interlayers markedly enhanced hardness, adhesion strength, and wear resistance under scratch loading.
Ruehl et al. [75]	ta-C and CrN coatings	Noted that hard coatings, such as those produced by CVD, can modulate filling and demoulding behaviour in micro IM; their study emphasised the relevance of coating morphology and integrity for successful submicron replication.
Sütőová et al. [76]	PVD nitride hard coatings (TiN, TiAlN, CrAlSiN)	Examined TiN-, TiAlN-, and CrAlSiN-coated AISI H11 inserts in HPDC and demonstrated that nitride PVD coatings markedly extended TL by reducing erosion, soldering, and roughness evolution, with TiN delivering the longest operational lifetime under industrial conditions.

Comparative studies consistently demonstrate that these coatings markedly outperform uncoated tool steels in environments characterised by fibre-reinforced polymers and chemically aggressive melts. CrN and AlTiN exhibit superior resistance to abrasion from glass and carbon fibres, while TiAlSiN and nano-multilayers provide enhanced oxidation and corrosion resistance, maintaining structural integrity under elevated temperatures. Collectively, PVD coatings represent a strategically important class of technologies capable of mitigating the dominant wear, corrosion, and thermal-fatigue mechanisms encountered in modern injection-moulding operations.

3.2.3. CVD Coatings

Chemical Vapour Deposition (CVD) coatings constitute a pivotal surface-engineering route for enhancing mould durability, offering exceptional hardness, thermal stability, and chemical resistance, particularly in high-temperature or corrosive injection-moulding environments. Sun et al. [77] stated that CVD enables the controlled synthesis of high-quality inorganic and polymeric thin films, offering precise structural tuning, excellent conformality, and scalability, while identifying key challenges in reproducibility, process control, and industrial scale-up.

As summarised in Table 8, Chemical Vapour Deposition (CVD) coatings represent a crucial class of surface-engineering technologies for extending the operational life of IM tools, particularly in high-temperature or chemically aggressive processing environments. Conventional CVD processes enable the deposition of dense ceramic layers, most notably SiC, Al_2O_3, and ZrO_2 [78], together with diamond and diamond-like carbon (DLC) films, each offering distinct advantages in hardness, chemical inertness, and thermal stability. Diamond and DLC coatings provide exceptionally low friction coefficients and outstanding resistance to abrasive wear, making them highly effective in moulding applications involving fibre-reinforced polymers. Ceramic CVD layers, by contrast, maintain structural integrity at elevated temperatures and exhibit strong resistance to corrosive melt constituents. Neto et al. [79] demonstrated that hot-filament CVD diamond coatings, supported by a CrN interlayer, exhibited excellent adhesion and negligible morphological degradation after HDPE moulding cycles, significantly enhancing wear resistance and reducing polymer adhesion

A distinguishing feature of many CVD coatings is their intrinsic porosity, which influences thermal transport through enhanced phonon scattering. Studies indicate that such microstructural features can significantly reduce thermal gradients across the coated surface, thereby lowering thermo-mechanical stresses and mitigating thermal-fatigue damage during repeated heating and cooling cycles. High-temperature CVD systems additionally promote excellent adhesion through diffusion-controlled interfacial bonding, although the thermal stresses generated during deposition require careful management. Collectively, the diverse family of CVD coatings, diamond, DLC, and ceramic films, offers robust and highly adaptable solutions for improving wear resistance, thermal stability, and chemical durability in demanding injection-moulding environments.

Table 8. Studies carried out on CVD coatings.

References	Technology	Highlights
Dalibón et al. [59]	PACVD DLC coating on PH steel	Showed that PACVD-deposited DLC films offer excellent inertness and low friction but suffer from defect-induced permeation and coating detachment, limiting their corrosion protection, particularly in acidic environments, unless combined with an appropriate supporting layer.
Yang et al. [80]	One-step CVD graphene thin-film heater	Exhibited that a one-step CVD graphene coating forms a rapid-response, wear-resistant thin-film heater enabling fast variothermal moulding, uniform heating, and significantly improved surface quality in fibre-reinforced polypropylene components.
Sorgato et al. [70]	Thermally insulating mould-surface coatings (CrN, Al_2O_3, DLC, a-C:H:Si)	demonstrated that thermally insulating coatings, particularly DLC, substantially reduce cavity pressure and frozen-layer formation during filling. The optimised thermal boundary enabled up to 12% wall-thickness reduction and significant material and cycle-time savings.
Jaud et al. [71]	ZrO_2 Thermal Barrier Coating (CVD)	Demonstrated that DLI-MOCVD ZrO_2 formed porous, columnar structures that enhanced thermal-gradient reduction per micron via increased phonon scattering, yielding highly effective lightweight thermal barriers.

3.2.4. Duplex and Hybrid Treatments, and manufacturing processes

Duplex and hybrid surface treatments have emerged as increasingly significant strategies for mould-tool durability, integrating diffusion-based hardening with advanced coating architectures to deliver superior load-bearing capacity, wear resistance, and tribological stability. Xiao et al. [81] reviewed advances in tribological materials, emphasising surface-engineering strategies, coatings, texturing, and hardening, and matrix strengthening to enhance wear resistance, friction reduction, and structural reliability across diverse mechanical and industrial applications. As summarised in Table 9, recent work published between 2015 and 2025 demonstrates that duplex and hybrid surface treatments have become increasingly prominent as strategies for extending the operational life of injection-moulding tools. These approaches combine complementary hardening mechanisms within a single layered architecture, most commonly by pairing a thermochemical diffusion treatment, such as gas or plasma nitriding, with a subsequent PVD coating. The nitrided diffusion zone enhances load-bearing capacity and suppresses plastic deformation, while the outer PVD layer (e.g., TiN, CrN, AlTiN) provides superior hardness, oxidation resistance, and tribological performance. This synergy greatly improves resistance to abrasive and adhesive wear, particularly in the processing of fibre-reinforced polymers. Tacikowski et al. [82] study demonstrates that a hybrid electrochemical pre-treatment with subsequent gas nitriding can generate diffusion iron-nitride layers on aluminium substrates produced by hybrid method, though magnesium-induced oxide formation severely limits adhesion, hardness, and tribological performance, necessitating Mg-free alloys for practical applicability

Table 9. Studies carried out on Duplex and Hybrid Treatments.

References	Technology	Highlights
Dalibón et al. [59]	Plasma nitriding + PACVD-deposited DLC (duplex treatment)	Demonstrated that duplex plasma-nitrided + DLC-coated PH stainless steel markedly improves corrosion resistance; the nitrided layer reduced mass loss by ≈100% in acid media and raised breakdown potentials, with the duplex system showing the most robust electrochemical performance.
Bobzin et al. [83]	PVD (Cr,Al)N hard coating via mf magnetron sputtering	The study demonstrated that mfMS-deposited (Cr,Al)N coatings on laser-structured H11 moulds significantly reduced friction, melt wettability, and adhesion to PC and PMMA, enabling up to 30% higher replication ratios and markedly improving demoulding behaviour
Kuo et al. [84]	Hybrid additive–rapid tooling–micro-milling	Developed a hybrid process integrating AM, rapid tooling, and CNC micro-milling to fabricate injection-mould inserts with micro-features. The method achieved high dimensional accuracy (10–60 µm) and excellent surface quality, enabling low-cost, rapid production of precision moulds.
Bobzin et al. [85]	Hybrid dcMS/HPPMS PVD oxy-nitride coatings	Demonstrated that (Cr,Al)N/(Cr,Al)ON coatings deposited by hybrid dcMS/HPPMS significantly reduced wetting and adhesion of polycarbonate, improved demoulding behaviour, and maintained high hardness, offering clear advantages over uncoated tool steel
Török et al. [86]	Hybrid L-PBF steel–copper mould insert	Established that a hybrid maraging-steel/copper insert, produced by combining laser powder bed fusion with casting, significantly improved heat extraction, reduced residual cooling time by ~15%, and enhanced cooling uniformity compared with a monolithic L-PBF steel insert
Marin et al. [87]	Hybrid machining–SLM conformal cooling manufacture	The study demonstrated that hybrid machining–SLM fabrication enabled defect-free bonding, significantly reduced SLM volume and manufacturing time, and produced conformal-cooled mould inserts that improved thermal homogeneity, reduced warpage sevenfold, and shortened cycle time by 36% compared with conventional baffle cooling.
Carrupt and Piedade [88]	Laser surface texturing + DLC coating	Investigated laser-textured AISI H13 surfaces subsequently coated with DLC, demonstrating significantly reduced friction and adhesive wear through micro-dimple geometries that enhanced lubricant retention and improved coating durability under reciprocating sliding.
Meng et al. [89]	HVOF/PVD duplex coating (NiCr-30Cr_3C_2 + TiSiN)	Studied that the HVOF/PVD duplex system markedly outperforms single HVOF or PVD layers by mitigating pit initiation, interfacial corrosion and coating delamination, delivering superior resistance to aggressive HCl-induced degradation in mould steels.
Aktaş Çelik et al. [90]	Nitriding + CAPVD AlTiN/CrN–AlTiN coatings	The study demonstrates that gas nitriding combined with CAPVD AlTiN and CrN/AlTiN coatings substantially enhances AISI H11 steel's load-bearing capacity, lowers tensile and shear stress concentrations, and significantly reduces wear loss under dry sliding
Maskavizan et al. [91]	Cathodic arc PVD CrN + plasma nitriding	The study demonstrated that duplex plasma nitriding combined with cathodic-arc CrN markedly enhances adhesion, reduces friction and wear, and increases corrosion resistance in both chloride and acidic media, outperforming single treatments.
Burdin et al. [92]	Plasma micro-etching + Cr/CrN coating	Developed a [Cl_2/Ar] plasma-etching protocol for AISI H11 (X38CrMoV5) mould steel and demonstrated that an H_2 post-treatment plus Cr/CrN bilayer effectively prevents corrosion and withstands 1000 injection cycles with excellent micro-texture replication.

Hybrid systems incorporating high-velocity oxy-fuel (HVOF) thermal-sprayed interlayers followed by PVD coatings have also gained prominence. The HVOF layer offers a tough, well-anchored substrate with reduced porosity, thereby improving adhesion and mitigating residual stresses within the superimposed hard coating. Multilayer and nano-multilayer architectures further refine stress distribution and crack-arrest behaviour, enabling tailored resistance to thermal fatigue and corrosive melt chemistries.

Despite these advantages, duplex systems remain susceptible to specific failure modes, including interfacial delamination, tensile residual-stress accumulation, and crack propagation across brittle ceramic layers. Consequently, the optimisation of interlayer design, diffusion depth, and stress management remains essential for fully realising the benefits of duplex and hybrid treatments in demanding moulding environments.

3.2.5. Polymer-Repellent and Low-Friction Coatings

Polymer-repellent and low-friction coatings have emerged as an increasingly important strategy for extending the service life of injection-moulding tools, particularly in applications where adhesion, sticking, and demoulding forces impose significant operational constraints. Saikia et al. [93] emphasise in their study the development of polymer-repellent corrosion-protection coatings, highlighting how hydrophobic and low-surface-energy polymer formulations, particularly functionalised epoxy systems, impede polymer adhesion, minimise ionic ingress, and enhance long-term resistance through improved barrier performance and passive-layer formation. As summarised in Table 10, recent studies between 2015 and 2025 demonstrate the effectiveness of fluorinated surface chemistries, most notably perfluorinated compounds such as PFOS and fluorinated self-assembled monolayers (SAMs), in reducing polymer–tool adhesion through the formation of ultra-low-energy surfaces. These monolayers promote weak interfacial interactions by suppressing polar and dispersive bonding mechanisms, thereby facilitating easier demoulding and reducing surface damage.

Complementary advances have been achieved through amorphous metal films such as CrCoNbB, which exhibit inherently low surface energy alongside excellent thermal stability and corrosion resistance. Diamond-like carbon (DLC) coatings, including fluorinated DLC variants, offer exceptionally low friction coefficients and high hardness, providing an effective barrier against abrasion while simultaneously minimising melt adhesion. Their performance derives from tailored hybridisation states and surface terminations that disrupt chemical bonding with polymer chains.

Table 10. Studies carried out on Polymer-Repellent and Low-Friction Coatings.

References	Technology	Highlights
Dalibón et al. [59]	Plasma nitriding + PACVD-deposited DLC (duplex treatment)	Demonstrated that duplex plasma-nitrided + DLC-coated PH stainless steel markedly improves corrosion resistance; the nitrided layer reduced mass loss by ≈100% in acid media and raised breakdown potentials, with the duplex system showing the most robust electrochemical performance.
Kern et al. [94]	Organosilane anti-adhesive coating with fluorescent marker	The study demonstrates that a fluoro-organosilane anti-adhesive coating incorporating a naphthalimide-based fluorescent silane enables rapid, non-destructive visual monitoring of coating presence, uniformity and wear during IM, while maintaining low surface energy and stable demoulding performance.
Guan et al. [95]	Electroforming of Ni-based moulds	Electroformed nickel nanocomposites incorporating WS_2, MoS_2 or PTFE significantly enhance hardness, reduce friction, and improve hydrophobicity. WS_2 offers the greatest tribological and wear-performance gains, enabling defect-free demoulding and extended mould lifetime in polymer micro-replication.
Guan et al. [96]	Electrodeposited nano-PTFE reinforced Ni mold	This study demonstrates that incorporating nano-PTFE fillers into electroformed nickel markedly reduces adhesion, friction, and demoulding forces, enabling >1500 defect-free micro-injection-moulding cycles with enhanced wear resistance and no polymer contamination.
Wang et al. [97]	Heat treatment + hot-water treatment (Heat + HWT) for Injection Molded Direct Joining (IMDJ) pretreatment.	Investigated a chemical-free Heat + HWT pretreatment for Al–Mg alloys in injection-moulded direct joining, demonstrating nano-scale surface texturing via Mg-enrichment mechanisms and achieving shear strengths up to 22 MPa.
Gateman et al. [98]	Thermal spraying with compression-moulded PTFE composites	The study demonstrates that Fe_3Al HVOF thermal-spray coatings, combined with compression-moulded PTFE/PI composite layers, produce thick, solid-lubricating coatings with low friction, substantially reduced wear rates, and strong mechanical adhesion enabled by the high substrate roughness.

3.3. Advanced Manufacturing and Tooling Innovations: Additive and Hybrid Manufacturing for Tool Longevity

3.3.1. Additive Manufacturing for Mould Inserts

Additive manufacturing (AM) has become an increasingly important route for producing high-performance mould inserts, offering design freedoms and functional capabilities that are unattainable through conventional subtractive methods. As summarised in Table 11, studies published between 2015 and 2025 highlight the transformative potential of AM in enabling moulds with conformal cooling channels. These complex, curved channels significantly enhance thermal management, reducing cycle times, improving dimensional stability, and mitigating thermal-fatigue stresses at critical regions of the mould tool. Hussin et al. [99] comprehensively reviewed recent advances in Representative Volume Element modelling for photopolymerization-based additive manufacturing, demonstrating its effectiveness in predicting microstructural behaviour, enhancing mechanical reliability, and improving dimensional and thermal performance in mould production. On another note, Masoudi et al. [100] synthesised recent advances in conformal cooling channel design, modelling, and simulation, emphasising the superior thermal efficiency, reduced cycle time, and enhanced part quality achievable through AM-enabled complex cooling geometries. It also identifies unresolved challenges and outlines future research directions for optimising channel topology, manufacturability, and thermal–mechanical performance.

Enabling technologies for thermal management have become increasingly central to the advancement of permanent mould casting, where precise control of heat flow critically influences solidification behaviour, defect formation, and overall casting quality. Recent developments in hybrid manufacturing have been particularly influential in this regard. Ahn et al. [101] critically reviewed enabling thermal-management technologies for permanent mould casting, identifying key heat-transfer mechanisms, evaluating heating and cooling strategies, and highlighting limitations in modelling, data availability, and benchmarking, while outlining opportunities for improved process control and mould performance.

Table 11. Studies carried out on Additive Manufacturing for Mould Inserts.

References	Technology	Highlights
Weise et al. [102]	Carburising & carbonitriding (thermo-chemical case hardening)	Case-hardening by carburising or carbonitriding produced a martensitic surface layer and tripled the bending strength of MIM-processed syntactic iron foams, demonstrating that standard gear heat-treatment cycles can be directly applied to foam-filled components
Bogaerts et al. [36]	Additive Manufacturing of Digital ABS Inserts	Showed that Digital ABS inserts produced by AM fail mainly due to thermal hotspots rather than shear loading, with cracking occurring after ~60–90 cycles, highlighting temperature as the key durability constraint.
Kanbur et al. [103]	Metal additive manufacturing of conformal cooling channels	Direct Metal Laser Sintering enabled fabrication of complex conformal cooling channels that closely follow part geometry, achieving markedly reduced cooling time and improved thermal uniformity compared with straight-drilled channels, while maintaining acceptable pressure-drop performance
Vetter et al. [104]	Material Extrusion Additive Manufacturing (MEX/M) for multi-material tool inserts	Worked that MEX/M enables multi-material injection-moulding inserts combining AISI H11, 420, and A2 steels. The study evaluated co-sintering compatibility, shrinkage behaviour, and interfacial diffusion, highlighting challenges related to densification, shrinkage mismatch, and surface quality.
Barragan De Los Rios et al. [105]	Hybrid DED–HSM remanufacturing process	Hybrid deposition and machining enabled remanufacture of a bimetallic AISI 1045/316L component with low dilution, refined dendritic microstructure, improved hardness, and over 90% roughness reduction, delivering enhanced corrosion resistance and reduced process time.
Fernandez et al. [106]	Hybrid moulding with AM polymer inserts	Evaluated hybrid moulding using polymeric AM inserts, demonstrating that Digital ABS and MJF-printed PA11 significantly influence mechanical durability and cooling efficiency, with PA11 offering superior sustainability and reduced cooling times.
Krizsma et al. [65]	Material jetting with gamma-irradiation post-curing	Enhanced material jetting -printed photopolymer mould inserts through controlled gamma-irradiation, which significantly increased T_g, stiffness, and creep resistance while markedly reducing operational deformation and extending mould life during injection-moulding trials.
Wilson et al. [107]	Hybrid LP-DED and CFD/FE thermal analysis	The study evaluates hybrid LP-DED manufacturable self-supporting channel geometries through validated CFD/FE thermal simulations, demonstrating superior heat extraction for triangular profiles and establishing a regression-based method for equivalence between circular and non-circular cooling channels.
García-Cabezón et al. [108]	Fused filament fabrication, MIM, and PM comparison	The study compares FFF, MIM, and PM processing routes for 17-4 PH stainless steel, demonstrating that FFF achieves near-full density, superior tribocorrosion resistance, and a more stable passive layer, outperforming PM and matching or exceeding MIM counterparts.
Marqués et al. [109]	Wire Arc Additive Manufacturing (WAAM)	The study demonstrated that WAAM enables large-scale moulds with fully integrated conformal-cooling channels, improving heat extraction, cycle-time efficiency, and temperature uniformity compared with conventionally machined channels, while substantially reducing material consumption and buy-to-fly ratio.
Solís et al. [110]	Metal-FFF with conformal cooling channels (validated using CFD–FE simulations)	The authors applied combined CFD and finite-element analyses to optimise conformal cooling channel geometry for Metal-FFF inserts, demonstrating significantly improved thermal uniformity, reduced cycle time, and enhanced dimensional accuracy compared with conventionally machined cooling designs.
Wang et al. [111]	Laser cladding of $Al_xCrMnFeCoNi$ HEA coatings	The study showed that increasing Al content altered FCC–BCC phase balance, refined microstructure, and markedly enhanced hardness and wear resistance. Optimal performance occurred at x = 1–1.5, producing up to 2.9-fold hardness improvement over H13 steel.
Zhao et al. [112]	Laser-Directed Energy Deposition (L-DED) with Ni buffer layer	The study demonstrates that depositing H13 onto Cu–Be using L-DED and a pure Ni buffer effectively suppresses solidification cracking, establishes a stable compositional gradient, and enhances load-bearing capacity, providing crack-free, high-hardness claddings suitable for injection-mould tooling.

By integrating AM with conventional machining, it is now possible to produce moulds with highly complex internal geometries tailored for enhanced thermal regulation, while maintaining the surface integrity and dimensional accuracy required for industrial casting operations. AM enables the incorporation of tailored cooling features, such as conformal channels, lattice structures, or thermally engineered cavities, whereas subsequent machining ensures the functional precision of working surfaces. Maraging steels and related alloys, when processed additively, are especially advantageous; their precipitation-hardening response allows for robust, lightweight internal architectures that deliver improved heat extraction without compromising mechanical strength. Collectively, these hybrid approaches form a foundational set of enabling technologies for next-generation thermal management in permanent mould casting. Despite these advantages, AM-produced inserts face several limitations. Surface roughness, intrinsic porosity, lack-of-fusion defects, and anisotropic mechanical properties remain persistent challenges, often necessitating extensive post-processing or heat treatment. Collectively, these findings demonstrate that AM offers substantial opportunities for TL extension, provided that material integrity, quality assurance, and hybrid processing approaches are carefully managed.

3.3.2. Digital Twins and AI-driven Predictive Maintenance

Digital Twins (DTs) and AI-driven predictive maintenance have emerged as powerful tools for enhancing mould reliability and extending TL, providing capabilities that extend well beyond traditional empirical monitoring. Nasiri et al. [113] proposed a knowledge-based DT framework for IM, integrating IoT-enabled sensing, case-based reasoning fault detection, additive manufacturing, and enterprise system integration to enable real-time monitoring, predictive maintenance, and process optimisation aligned with I4.0 principles. As summarised in Table 12, studies published between 2015 and 2025 demonstrate that DT frameworks, integrating real-time sensing, high-fidelity simulations, and data-driven analytics, enable continuous tracking of key process variables, including cavity pressure, melt temperature, cooling efficiency, and characteristic wear signatures on critical mould surfaces. These data streams support the development of virtual replicas capable of replicating the thermo-mechanical behaviour of the mould throughout its operational life.

Machine-learning models increasingly complement these frameworks by predicting tool wear (TW), thermal-fatigue accumulation, and the onset of Tool Failure (TF). Algorithms trained on historical production data, sensor inputs, and operational trends can identify precursors to surface degradation, cracking, or loss of dimensional fidelity, enabling maintenance interventions to be scheduled proactively rather than reactively. In this regard, Ahmmed et al. [114] comprehensively reviewed the integration of DT, modular artificial intelligence, and cybersecurity in additive manufacturing, highlighting their combined role in enabling real-time monitoring, predictive optimisation, enhanced process reliability, and improved resilience against cyber-physical threats.

Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) further enhance DT accuracy by identifying hotspots, shear-stress concentrations, and cooling inefficiencies that accelerate damage. These simulations provide predictive insight into the evolution of residual stresses, temperature gradients, and localised fatigue, thereby guiding redesign or process adjustments.

Collectively, DTs and AI-based predictive maintenance represent a decisive shift towards condition-based tool management, improving operational reliability, reducing unplanned downtime, and extending mould service life through informed, data-driven decision-making.

Table 12. Studies carried out on Digital Twins and AI-driven Predictive Maintenance.

References	Technology	Highlights
Qi et al. [115]	Rapid Heat Cycle Moulding (RHCM)—electric heating-rod optimisation	Optimised electric heating-rod layouts improved RHCM performance, reducing the temperature uniformity coefficient by 44.6%, halving the maximum cavity temperature difference, and lowering energy consumption by 12.5%
Gaspar-Cunha et al. [116]	Process optimisation / Conformal cooling design	Demonstrated that multi-objective optimisation and conformal cooling strategies markedly improve mould thermal performance, reducing cycle time and enhancing tool efficiency.
Redeker et al. [117]	Mould surface texturing / Wetting control	Showed that laser-induced surface textures significantly reduce polymer–mould adhesion during ejection, improving demoulding performance and enhancing mould durability.
Šakalys et al. [118]	Additive manufacturing with embedded surface acoustic wave (SAW) sensing	The study demonstrates that LPBF enables reliable embedding of a wireless SAW temperature sensor and print-in-place venting within stainless-steel mould tools, enabling accurate in-mould thermal monitoring and effective venting where conventional machining cannot achieve such features
Silva et al. [119]	2D transient FEM and MATLAB–ANSYS optimisation	Developed a 2D transient heat-transfer optimisation framework coupling ANSYS FEM with MATLAB simulated annealing to refine conformal cooling channel placement, significantly reducing thermal gradients and enhancing cooling uniformity in injection-mould design.
Wilson et al. [120]	Generative design with AM conformal cooling.	Established an automated generative-design methodology integrating CAD, Moldex3D multiphysics simulation, and evolutionary optimisation to produce conformal cooling channels for hybrid-manufactured moulds, achieving markedly improved thermal uniformity, reduced cooling time, and superior part quality
Storti and Sobotka [121]	Laser cladding of high-entropy alloys	Al-content variation alters FCC/BCC phase balance, refining microstructure and enhancing hardness and wear resistance. Maximum hardness occurs at x=1, while friction and abrasion performance improve further at x=1.5 due to increased BCC phase.
Wagner and Nóbrega [122]	Thermal-fluid modelling and PCM-enhanced cooling	The authors employed coupled CFD–FE analysis to model transient heat transfer in permanent-mould casting, demonstrating improved prediction of thermal gradients and enhanced optimisation of cooling strategies for stabilising mould temperature fields.

4. Discussion

The findings of this review demonstrate that contemporary strategies for extending the service life of injection-moulding tools have evolved towards increasingly integrated, multi-mechanism approaches that combine material optimisation, surface engineering, and enhanced thermal management. The literature consistently indicates that conventional single-treatment solutions, such as isolated nitriding or monolithic PVD coatings, are no longer sufficient to withstand the thermo-mechanical and chemical severity introduced by modern polymer systems, particularly fibre-reinforced and chemically aggressive formulations. Instead, duplex and hybrid treatments, multilayer and nanostructured coatings, and carefully tailored near-surface microstructures emerge as the most effective means of mitigating simultaneous abrasion, adhesion, corrosion, oxidation, and thermal fatigue.

A recurrent theme across the reviewed studies is the critical importance of substrate condition and microstructure in determining coating performance and long-term durability. The interplay between steel grade, heat treatment, machining-induced subsurface damage, and coating adhesion remains insufficiently resolved, and several researchers highlight premature failure due to incompatible hardness–toughness balances or residual stresses. Likewise, the influence of evolving polymer chemistries, particularly the release of corrosive degradation by-products, is only partially understood, with a limited number of studies addressing realistic moulding environments that combine chemical attack with fibre-induced abrasion. These gaps highlight the need for more representative test protocols that capture the cyclic, transient, and multi-factor nature of tool degradation during industrial moulding cycles.

Thermal-management research also shows considerable progress, especially with the advent of conformal cooling channels enabled by additive manufacturing. Improved temperature uniformity demonstrably reduces thermal stresses, shortens cycle times, and alleviates fatigue-related damage. However, research on thermal management often remains decoupled from studies on coating design, adhesion, and substrate behaviour, despite strong interdependencies. The performance of multilayer coatings, for example, is inherently sensitive to thermal gradients, yet few studies integrate thermal-mechanical modelling with coating failure analysis.

Additive manufacturing continues to broaden its influence, both in the fabrication of advanced cooling geometries and in the repair or reinforcement of worn tooling. Nevertheless, concerns persist regarding AM-induced heterogeneity, anisotropy, residual stresses, and long-term wear predictability. These limitations hinder widespread industrial adoption, especially where high-volume production requires sustained dimensional and mechanical stability over millions of cycles.

Taken together, the reviewed literature underscores the increasing need for comprehensive design frameworks that unify material selection, machining quality, surface engineering, and thermal management within a coherent, lifecycle-oriented methodology. Such an integrated approach is indispensable for addressing the complex and synergistic degradation phenomena characteristic of contemporary injection-moulding environments.

In addition to the technical insights derived from the reviewed literature, it is important to critically reflect on the methodological implications of employing AI-assisted screening tools within the review process. While the AI-based filtering framework enabled the efficient identification of thematically relevant studies from a large and heterogeneous body of literature, its application is not without limitations. In particular, reliance on keyword frequency, abstract structure, and semantic similarity metrics can bias selection towards well-established terminology and explicitly articulated methodologies, potentially disadvantaging exploratory or interdisciplinary studies that employ unconventional nomenclature or emphasise qualitative industrial insights. For example, several studies addressing tool degradation indirectly through case-based manufacturing optimisation or proprietary industrial reports were excluded during automated screening due to insufficient explicit reference to surface engineering or TL metrics, despite offering potentially valuable contextual evidence. This highlights the risk that AI-assisted filtering, if applied without critical oversight, may inadvertently narrow the conceptual scope of a review. Consequently, while AI-based tools represent a powerful aid for managing scale and consistency in systematic reviews, their outputs must be interpreted as decision-support mechanisms rather than definitive arbiters of relevance. Transparent reporting of exclusion rationales and selective manual reassessment remain essential to ensure methodological robustness and to preserve the breadth of perspective required in complex, multi-disciplinary domains such as injection-moulding TL research.

As for future research prospects, the convergence of surface engineering, digital manufacturing, and data science will define the next decade of tooling innovation. Key directions include:

- Smart coatings with self-healing or adaptive friction behaviour.
- Nanocomposite films incorporating graphene, TiBN, or MoS_2 nanoparticles for ultra-low friction.
- In-situ diagnostics and closed-loop control within injection machines for real-time wear mitigation.
- Sustainable hybrid processes, combining green coatings, energy-efficient machining, and additive repair.

- Integration of digital twins and AI for life prediction and autonomous maintenance scheduling.
- Holistic design frameworks linking tool design, coating selection, and production simulation to optimise performance and sustainability.

5. Conclusions

This review has synthesised recent advances in TL extension for IM, highlighting the scientific principles, technological innovations, and persistent challenges that shape current research and industrial practice. The key conclusions may be summarised as follows:

- Overall Advances
    - Surface engineering remains the most influential strategy for enhancing tool durability, with nitriding, carburising, PVD/CVD coatings, duplex treatments, and polymer-repellent layers demonstrating significant improvements in wear, corrosion, and thermal-fatigue resistance.
    - Additive manufacturing has transformed thermal-management design, enabling conformal cooling channels and hybrid manufacturing approaches that reduce cycle time, stabilise temperature fields, and mitigate thermo-mechanical degradation.
    - Material innovations, including advanced tool steels and engineered microstructures, provide improved hardness, toughness, and thermal stability, particularly for demanding applications involving fibre-reinforced or high-temperature polymers.
- Key Observations on Degradation Behaviour
    - Tool wear is inherently multi-mechanistic, involving coupled abrasive, adhesive, corrosive, and fatigue processes that evolve dynamically with polymer chemistry, fibre morphology, and processing conditions.
    - Coating performance is strongly dependent on substrate preparation, residual stress management, and interfacial adhesion, underscoring the need for integrated material–surface system design.
    - Thermal gradients remain a dominant driver of failure, reinforcing the importance of cooling architecture, heat-transfer control, and thermo-mechanical modelling.
- Persistent Challenges
    - Lack of standardised tribological and corrosion testing limits comparability across studies and weakens the translation of laboratory coatings into industrial tooling.
    - Insufficient long-term industrial validation results in uncertainty regarding coating fatigue, thermal cycling stability, and wear evolution over millions of moulding cycles.
    - Additive-manufactured inserts still face limitations, including porosity, anisotropy, residual stresses, and variable microstructural quality.
    - Evolving polymer formulations—with aggressive additives, fillers, and reactive chemistries—outpace current tool-coating strategies, demanding more targeted material–process compatibility studies.

Contemporary research collectively indicates a clear transition from isolated material enhancements towards holistic, multi-scale engineering strategies that integrate microstructural optimisation, advanced surface treatments, and innovations in thermal management. Sustained interdisciplinary investigation remains essential for addressing the increasing mechanical, thermal, and chemical demands imposed by next-generation injection-moulding operations, while simultaneously advancing sustainability, durability, and overall manufacturing efficiency. As for limitations of the present review:

- The review is inherently constrained by the availability and quality of published studies, with a strong reliance on peer-reviewed journal articles, which may underrepresent negative results or unpublished industrial findings.
- Considerable heterogeneity in experimental methodologies, wear-testing conditions, and performance metrics across the reviewed studies limits direct quantitative comparison and hinders meta-analytical synthesis.
- Many studies evaluate technologies under laboratory-scale or short-duration conditions, which may not fully capture long-term tool degradation mechanisms encountered in industrial injection-moulding environments.
- The interaction effects between material selection, surface engineering, process parameters, and thermal management are often investigated in isolation, restricting the ability to draw fully integrated lifecycle conclusions.

While the reviewed studies demonstrate substantial progress in extending injection-mould TL, their collective findings also indicate a clear shift in the challenges faced. Incremental optimisation of individual materials or coatings is increasingly insufficient to address the tightly coupled mechanical, thermal, chemical, and interfacial degradation mechanisms inherent to modern moulding operations. Future research must therefore prioritise system-level design frameworks that integrate material selection, surface engineering, machining quality, and thermal-management strategies into a unified lifecycle methodology.

A critical priority lies in the development of standardised, application-representative testing protocols capable of reproducing combined wear, corrosion, and thermal-fatigue conditions over industrially relevant timescales. The absence of such frameworks currently limits cross-study comparability and constrains effective translation from laboratory performance to industrial durability.

Further advances are also required in predictive modelling and digitalisation, particularly through the coupling of finite-element and computational fluid-dynamics simulations with data-driven approaches for wear and failure prediction. Such tools offer a pathway towards anticipatory maintenance and failure prevention, rather than reactive tool replacement.

Finally, the rapid evolution of polymer formulations necessitates a stronger focus on material–process compatibility, demanding closer integration between polymer science, surface engineering, and tool design. Addressing these priorities will be essential for achieving resilient, sustainable, and high-performance tooling systems capable of meeting the demands of next-generation injection-moulding applications.

Author Contributions

Conceptualisation: A.F.V.P. and R.J.D.A.; methodology: A.F.V.P., L.M.D. and R.P.M.; validation: M.B. and A.P.M.; formal analysis: A.F.V.P. and R.J.D.A.; investigation: A.F.V.P.; data curation: L.M.D. and M.B.; writing—original draft preparation: A.F.V.P.; writing—review and editing: L.M.D., R.P.M., M.B. and A.P.M.; visualisation: R.J.D.A.; supervision: R.P.M. and M.B.; project administration: R.J.D.A.; funding acquisition: F.J.G.S. All authors have read and agreed to the published version of the manuscript.

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No new data was created.

Conflicts of Interest

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Use of AI and AI-Assisted Technologies

The authors declare that they have no AI tools were utilized for this paper.

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