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Extending Bakelite Mold Lifespan: A Hybrid Metal Manufacturing Application

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Abstract:
Background: *The injection molding industry faces challenges with Bakelite thermosetting materials due to their rigidity and strength, which quickly wears out molds, generate excessive burrs, and require costly maintenance. This study aimed to enhance mold performance through the evaluation of Hybrid Metal Manufacturing (HMM) and its comparison with traditional systems*
Materials and Methods: *This study proposes using Hybrid Metal Manufacturing (HMM) to enhance the wear resistance of Bakelite molds. HMM integrates Metal Additive Manufacturing (MAM) with conventional machining, enabling more efficient and complex production. The research, which is exploratory and qualitative-quantitative, employed the Design Science Research (DSR) method to develop the artifact and used Focus Group (FG) evaluations to assess the solutions. DED of M2 steel was performed in the cavity of the AISI H13 steel mold and subjected to a total of 40,000 production cycles for further analysis.*
Results*: The mechanical properties, hardness, and wear resistance of the molds were analyzed after the tests.*
Conclusion: *The results aimed to improve future mold designs. HMM the potential to innovate the injection molding industry by increasing mold durability, reducing maintenance costs and ensuring the quality of injected parts.*
Keyword*: Hybrid Metal Manufacturing; Bakelite Injection Molds; Improving Mold Lifespan*

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I. Introduction

Bakelite is a thermoset material with high mechanical strength, used in various components. Its rigidity causes mold wear during injection, due to resistance to cutting and extraction. This wear increases maintenance costs and reduces the useful life of molds [1].

Additive Manufacturing (AM) technology is advancing and shows potential to reduce dependence on conventional processes, integrating well with Industry 4.0 through process hybridization [2]. Hybrid Metal Manufacturing (HMM), which combines 3D printing and CNC machining, presents new opportunities to overcome the limitations of traditional techniques, enabling the creation of more efficient and customized components.

The study focused on applying HMM to enhance the wear resistance of Bakelite molds and extend their useful life. The objective was to propose improvements for the molds, evaluating the performance of HMM, and compare it with existing systems. The specific objectives were:
- To research types of atomized steels and their properties.
- To evaluate metal deposition strategies.
- To assess the performance of HMM in the injection process.
- To compare HMM with current systems.
- To evaluate the technical and financial feasibility.

The research, which is applied and exploratory in nature, employs a qualitative-quantitative approach and utilizes the Design Science Research (DSR) method. This method seeks practical and prescriptive solutions by integrating theory with practice. Additionally, the Exploratory Focus Group method was used for incremental and collaborative improvements in the process.

II. Literature Review

Additive Manufacturing (AM)

Additive Manufacturing (AM) is the formalized term for what was previously known as rapid prototyping, and is more commonly referred to as 3D printing. Rapid prototyping (RP) is a term used across various industries to describe the process of quickly creating a system or representation of a part before its final commercialization. Essentially, the focus is on rapidly producing a prototype or basic model,, which serves as a foundation for developing additional models and ultimately culminating in the final product [3].

AM technology involves the direct manufacture of physical products from computer-aided design (CAD) models through a layered manufacturing process. Unlike traditional molding or material removal processes, 3D printed products are created by adding material layer by layer, eliminating the need for specific tools and fixtures. This approach enables the production of products with complex geometries [4].

As an innovative manufacturing technique, AM holds significant promise for social development. It optimizes product design, enhances functionality, and reduces energy and natural resource consumption during production processes, leading to considerable social benefits [5].

According to the American Society for Testing and Materials (ASTM) standard "ISO/ASTM 52900 - Additive Manufacturing", AM techniques are categorized into seven groups [6]: Vat Photopolymerisation; Material Jetting; Binder Jetting; Material Extrusion; Powder Bed Fusion; Sheet Lamination, and Directed Energy Deposition.

In 1981, Hideo Kodama invented a rapid prototyping system using photopolymers, which enabled the construction of solid models in layers. In 1984, Charles Hull invented stereolithography, a 3D printing technique that uses digital data to create tangible objects from photopolymers, which are transformed into solid plastic parts by a UV laser beam. This technology revolutionized prototyping by allowing projects to be tested more economically and quickly [7,8].

In 1992, Charles Hull, founder of 3D Systems, developed the first stereolithography (SLA) machine, enabling the production of complex layered parts. In the same year, the startup DTM introduced the first selective laser sintering (SLS) machine, which used powder as the printing material. Although initially expensive, these technologies were quickly recognized for their potential [9].

In 1999, a historic milestone was reached with the implantation of the first 3D printed organ in a human. Scientists at the Wake Forest Institute for Regenerative Medicine have printed a synthetic human bladder scaffold coated with patients' own cells, minimizing rejection by the immune system. This breakthrough was crucial for regenerative medicine, opening up new possibilities for the development of personalized organs [10].

In the 2000s, AM gained prominence for its ability to personalize products. In 2006, the startup Objet (now part of Stratasys) made the first selective laser sintering (SLS) machine commercially viable. This advancement enabled printing in multiple materials, facilitating the creation of more complex and customized objects [8,11].

In 2005, Dr. Adrian Bowyer launched the RepRap Project, an open-source initiative aimed at creating a self-replicating 3D printer. This project allowed users to freely modify and create designs without the need for commercial licenses, democratizing access to technology and boosting customized manufacturing [12].

Remarkable advances, progressing from rapid prototyping to the creation of 3D printed human organs, have marked the evolution of AM. The introduction of technologies such as stereolithography and selective laser sintering has revolutionized manufacturing, bringing this technology ever closer to the end consumer and significantly altering the supply chain [13].

Metal Additive Manufacturing (MAM)

Metal Additive Manufacturing (MAM) began in the 1990s with the introduction of Selective Laser Sintering (SLS), a Powder Bed Fusion (PBF) technique initially used to produce plastic parts. SLS uses a laser to melt and solidify thin layers of powder, creating three-dimensional objects and paving the way for the development of other MAM techniques[14].

In PBF, powder is spread over a platform, and an energy source, such as a laser, selectively melts the powder according to the digital design of the part. After melting one layer, the platform lowers, and a new layer of powder is applied and melted, repeating the process until the object is complete. PBF techniques include SLS, which sinters the material, as well as Selective Laser Melting (SLM) and Electron Beam Melting (EBM), which completely fuse the metal powder to produce dense parts[15].

Directed Energy Deposition (DED) is another MAM technique that deposits metal powder or wire through a nozzle and melts it with a focused thermal energy source. Unlike PBF, DED feeds the material directly during deposition, eliminating the need for binders and offering greater control over the part-building process.

DED is ideal for repairs, coatings, and large part builds due to its ability to add material precisely and in real time. It provides flexibility in creating complex geometries and allows for the use of different metal materials simultaneously, expanding the possibilities of 3D metal fabrication[15].

MAM has evolved rapidly, enabling the production of increasingly complex parts with advanced mechanical properties. Today, it is utilized across several industries, including aerospace, automotive, medical and jewelry [16]. To ensure successful adoption of MAM in different sectors, it is essential to invest in qualification and certification, as well as to promote process standardization[17].

MAM processes are categorized into two main types according to the ISO/ASTM 52900 standard: DED and PBF. They are further distinguished by their primary heat source, which include laser, electron beam, plasma arc and gas metal arc [18].

Hybrid Metal Manufacturing (HMM)

The evolution of MAM culminated in the development of Hybrid Metal Manufacturing (HMM), which integrates AM and machining into a single platform. HMM emerged in the 1990s through the combination of Directed Energy Deposition (DED) and CNC machining. Initially developed for manufacturing tools and molds, HMM has since been explored by various institutions for its potential to produce complex, high-performance parts [19,20].

HMM integrates additive and subtractive processes in a single platform, allowing the manufacture of parts with complex geometries and customized features[21]. This process has been increasingly adopted in industry, particularly for producing parts that require high precision [22].

The combination of AM with CNC machining is particularly attractive because it allows the production of complex geometries from materials that are difficult to machine. However, challenges remain regarding finishing and dimensional accuracy [23]. HMM offers significant benefits, especially in the remanufacturing and repair of existing parts, and shows promise in the tooling industry by allowing the combination of different materials in molds to meet specific needs [24,25].

In Brazil, HMM began to be adopted in the 2000s, primarily within research and development institutions. Although still little disseminated, its potential to transform manufacturing and impact the global economy is evident [26,27]. The advancement of HMM in Brazil is closely tied to investment in research and innovation [17].

Thermosetting Bakelite

Bakelite is a thermosetting material, a type of plastic that does not soften under high temperatures. It was one of the first synthetic resins developed, discovered by the American chemist Leo Baekeland in 1907 [28]. This phenolic resin is produced from the reaction between phenol and formaldehyde. Once this reaction occurs, the molded resin is hardened under high pressure and temperature, resulting in a hard, resistant and durable material. Due to its high electrical resistance and thermal insulation properties, Bakelite has been widely used due to its thermal insulation properties in handles and pot handles. However, its rigidity and brittleness limit its use in certain applications, and it is also a toxic substance during the production process [29].

Bakelite is a highly cross-linked phenolic resin with excellent mechanical properties, resistance to heat and humidity, and low flammability. During the curing process, the resin becomes highly cross-linked, acquiring its thermosetting characteristics. For each specific application, it is crucial to select the correct type of Bakelite, as there are several variations, each with different properties and suitable for particular applications [30].

Bakelite is commonly used in electrical and electronic parts, especially in insulators, capacitors and connectors [30]. Table 1 lists the main characteristics, advantages and disadvantages of this material.

Characteristics	It is a hard, resistant and durable material;
	It has high electrical resistance and thermal insulation;
	It is resistant to most chemicals, acids and solvents;
	It is a self-extinguishing material, that is, it does not propagate flames;
Advantages	Low production cost;
	Excellent dimensional stability, even when exposed to high temperatures;
	High mechanical strength, even at high temperatures;
	Resistance to most solvents, acids and bases.
Disadvantages	It cannot be recycled or reprocessed after molding and curing;
	It is a relatively fragile and brittle material, with low impact resistance;
	Low resistance to UV radiation and aging in external environments;
	Low resistance to UV radiation and aging in external environments;

Table 1 - Characteristics, advantages and disadvantages

The main molding processes for thermoset Bakelite include compression, transfer, and injection molding. In compression molding, as illustrated in Figure 1, the material is placed in a heated mold and subjected to high pressure. The heat and pressure promote the curing of the material, resulting in the formation of the final product. In the transfer molding process, the material is preheated in a separate chamber before being transferred to the mold. The mold is then closed, and the resin is forced into the mold under high pressure with the applied heat promoting the curing of the material [28].

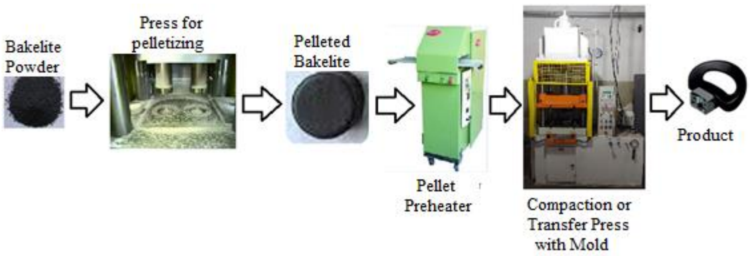

Figure 1- Schematic representation of the compression and transfer molding process

Despite being a thermoset, Bakelite can also be injection molded using a modified process. In this process, the resin is placed in the machine's hopper, plasticized in the injection cylinder and screw assembly, and preheated to 60°C with heating elements before being injected at high pressure into a mold heated to 170°C. The heat promotes the curing of the resin, forming the final product, as illustrated in Figure 2 [31].

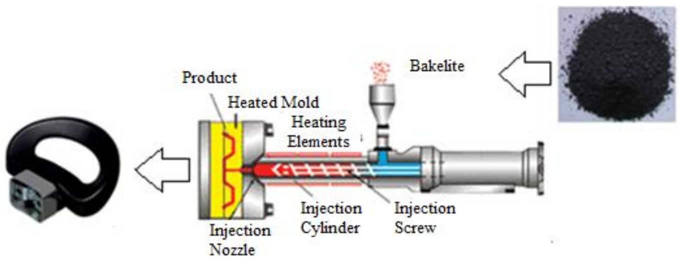

Figure 2- Schematic representation of the injection molding process

Due to its rigidity and high mechanical strength, Bakelite can cause wear in injection molds during the molding process. This is because high pressure is require to fill the mold cavity and allow the part to be extracted, which can result in wear marks on the molds [1].

To mitigate the impact of wear, several techniques can be adopted, including the application of wear-resistant coatings on the molds, adequate lubrication, and precise adjustments of the injection parameters. Additionally, the choice of steel for the injection mold, the configuration and conditions of the injection process, and the specific properties of the Bakelite material used are crucial factors that can significantly affect the mold life and the quality of the molded parts [32].

Bakelite Injection Molds

Injection molds are essential tools in the production of compact plastic parts, whether made from thermoplastic or thermoset materials. These molds are widely used in large-scale production, enabling consistent repeatability of the final product. The mold structure can accommodate one or more cavities, which determine the quantity of parts produced per hour in conjunction with the cycle time [33].

The mold consists of two parts: a movable part and a fixed part, which come together to form the mold cavity, as shown in Figure 3. The material is injected into this cavity and solidifies to form the final part. The design of the injection mold involves selecting appropriate materials for its construction and designing the cavity, which directly influences the quality and properties of the final part. Factors such as the geometry of the part, the orientation of the material flow, the position of the injection channels, and the location of the injection points are crucial to the success of the mold design [33].

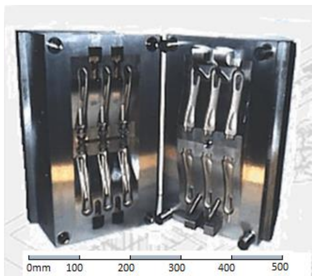

Figure 3 - Representation of the fixed and movable part of the mold

In the specific case of Bakelite injection, the mold must be designed considering the particular characteristics of this thermosetting material, which has high viscosity. This high viscosity hinders flow in the mold cavity and prolongs cycle time. Additionally, Bakelite is highly abrasive, which can cause premature wear in the mold, requiring the use of wear-resistant and temperature-resistant steel [34].

Zhao, Mattner and Drummer [35] recommend that Bakelite injection molds be made of hardened steel and coated with hard chrome to ensure wear resistance. The mold must be designed with wide feed channels and an optimized cavity geometry to ensure complete and uniform filling of the part.

The choice of material used in manufacturing the mold significantly impacts its service life. Among the most common materials is AISI H-13 tool steel, which receives a double-layer application of Physical Vapor Deposition (PVD) coatings, including chromium nitride (dark gray) and titanium nitride (golden). These coatings form a ceramic microlayer that reduces the coefficient of friction, increasing the mold's durability and allowing it to withstand a greater number of injection cycles, as illustrated in Figure 4 [36].

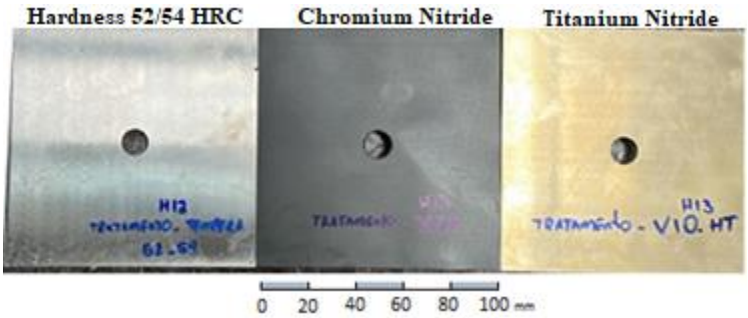

Figure 4 - Representation of AISI H-13 steel with double PVD layer

AISI H-13 steel is a hot work tool steel known for its excellent toughness, heat resistance, and thermal fatigue resistance. It maintains its mechanical properties at high temperatures and is suitable for applications where heating is continuous, such as in plastic injection molds, forging dies, and casting tools [37].

The choice of AISI H-13 steel is made due to its high strength and durability, while the application of the PVD coatings aims to enhance wear resistance. These decisions are intended to improve the performance and quality of the molds used in the Bakelite injection process [38].

M2 steel is a type of high-speed steel known for its high hardness and wear resistance due to the presence of hard carbides formed by alloying elements. It maintains its hardness even at high temperatures, and although it is hard, it has moderate toughness that allows it to withstand mechanical shocks during use [37].

The higher Mo content and lower Si content in M2 steel help to balance the compositional differences with AISI H13 steel. Thus, the combination of M2 and AISI H13 appears promising for use in DED repair experiments [37].

Preventing or reducing wear in mold cavities is crucial to maximizing their useful life, minimizing maintenance costs, and reducing interruptions in the production process, thereby ensuring the quality of the injected parts [33]. Proper design of injection molds for thermosets, combined with strict control of the injection process, significantly contributes to the overall efficiency and effectiveness of the production system.

III. Material And Methods

This chapter outlines the project methodology, detailing its stages, objectives, research tools, and data collection and analysis methods. The development within both academic and business contexts is emphasized, aiming to generate valid knowledge for informed decision-making [39].

The research is applied, focusing on solving practical problems related to the performance of the injection process and mold wear [40]. Classified as exploratory, it seeks to clarify the problem and generate hypotheses [41]. The chosen methodology was Design Science Research (DSR), which is suitable for proposing improvements in mold design and evaluating its performance in production [42].

The Focus Group (FG) methodology was used to validated and refine the artifacts, while the Design of Experiments (DoE) method assessed the impact of HMM on mold improvement [43]. The research followed a flowchart, guiding the process from problem identification to the creation, validation, and evaluation of solutions, including a bibliometric analysis and a systematic literature review.

DSR was applied in six stages to improve the performance and service life of injection molds, focusing on solving problems like wear on the cavity closing line, or parting line, is the plane where the mold halves meet and close during molding. Its accuracy is crucial to the quality of the final part, influencing the presence of burrs and dimensional accuracy. The methodology involved conducting tests, simulations, and experiments using Minitab® software, alongside analyzing limitations and lessons learned for future improvements [44].

The initial phase of problem awareness aimed for a deep understanding of the issue, using FG to gather data from participants from companies and HMM experts. The systematic literature review supported problem identification and the formulation of research questions.

In the ideation stage, ideas were generated and refined to address the problem. The Exploratory FG provided valuable insights into HMM applications, contributing to the development of a functional prototype and the assessment of the technical and economic feasibility of the proposed solutions.

The development phase transformed ideas into a concrete artifact, with review and testing cycles ensuring a functional final product. The FMEA technique was applied to identify and mitigate risks during the DED process, and the prototype was tested in practical scenarios at the BAQUELLITES company.

A demonstration of the prototype was planned, including practical simulations and data collection to evaluate its performance. Adjustments and improvements were made based on user feedback, ensuring the solution's effectiveness.

The evaluation aimed to validate the prototype applicability, using GF and DoE to analyze the effectiveness of the new process compared to the traditional method. Minitab® was used for statistical analysis, and the response variables included the thickness of the flashing on the injected parts.

IV. Result And Discussion

This chapter presents the main results of the research and their analyses, relating them to the existing literature and the research objectives. Problem identification was essential for this work, highlighting the need for improvements in the manufacturing of injection molds. The GF analysis at BAQUELLITES revealed injected samples with excessive flash (Figure 5) due to the wear of Bakelite thermoset after approximately 80,000 production cycles.

Figure 5 - Injected part with excessive flash

The current maintenance process takes 7 to 10 days, reduces wear resistance by 35%, increases costs, and interferes with the scheduling of other products. The systematic literature review (SLR) of the Feriotti, et al.[14] , highlighted gaps and helped avoid repetitive solutions. This review led to research on HMM applications and characteristics, as well as types of steels and mechanical properties**.**

Feriotti, et al. [14] emphasize that laser deposition is crucial for refurbishment and restoration, but requires detailed analysis of mechanical properties. Hybrid manufacturing reduces the need for post-processing and enhances wear resistance, particularly in steels like AISI H13 and M2. The RSL highlighted growing academic interest in HMM, leading to the decision to focus on this technology for the research.

To address the challenges identified, a solution was developed and tested through prototyping. 3D mathematical modeling and CAD were used, as illustrated in Figure 6, with AISI H-13 steel being deposited onto a SAE 1045 steel prototype shown in Figure 7.

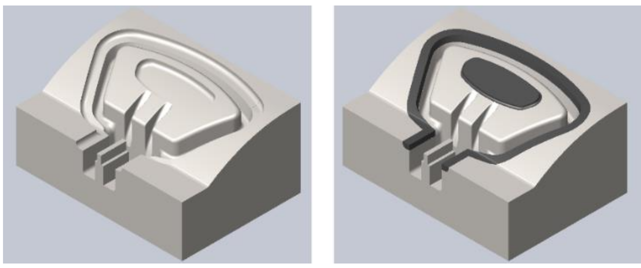

Figure 6- 3D CAD® mathematical modeling

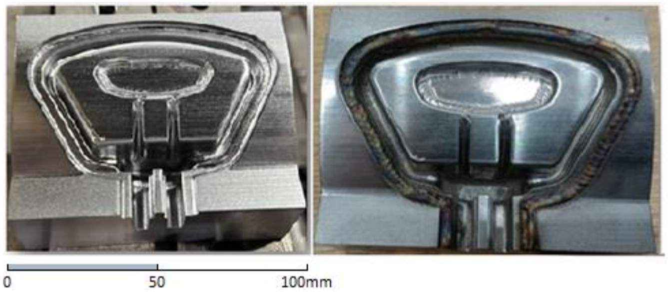

Figure 7- SAE 1045 steel prototype with AISI H-13 powder steel deposition

The prototype development focused on design, testing, and practical implementation, including microstructural characterization with HMM to determine the prototype's properties and effectiveness. The deposition tests with OERLIKON® 1030A and 1040A materials involved samples of AISI H13 steel, a tool steel suitable for hot work, and SAE 1045, a carbon steel suitable for mechanical construction, supplied by BAQUELLITES (Figure 8).

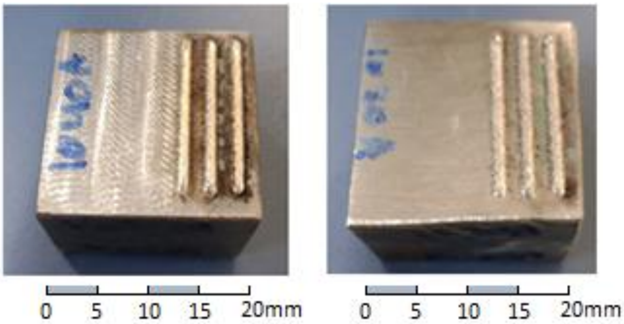

Figure 8 - Samples with deposition of 1030A and 1040A materials

The depositions illustrated in Figure 9, revealed cracks in the SAE 1045 samples with 55% overlap and increased velocity with 45% overlap. Additional tests showed cracks and spalling in samples with 55% overlap on AISI H13 substrate, as illustrated in Figure 10.

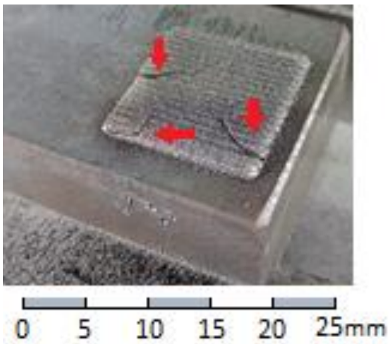

Figure 9- Samples with deposition on SAE 1045 substrate with cracks

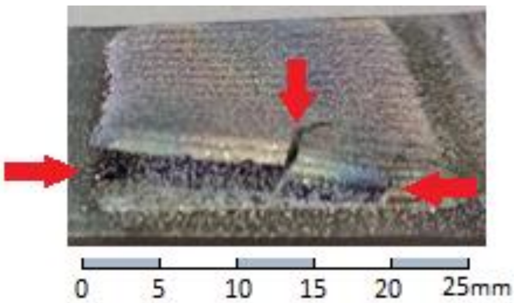

Figure 10- Samples with deposition on AISI H-13 substrate with cracks and spalling

The suggestion to test heated substrates led to the decision to discontinue the use of OERLIKON® material. Subsequent tests were carried out with HÖGANÄS® M2 steel on an AISI H13 substrate, with varied parameterizations to validate the adequacy of the material for DED.

The tests on "Sample A1" (Figure 11) and "Sample A2" (Figure 12) demonstrated hardness values ranging from 55 HRC (substrate) to 62.7 HRC (top with 100% M2). "Sample A3" (Figure 13) showed similar hardness, with values between 59 and 62.8 HRC.

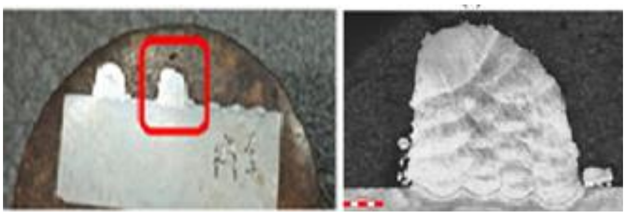

Figure 11- Hardness and metallographic test sample A1

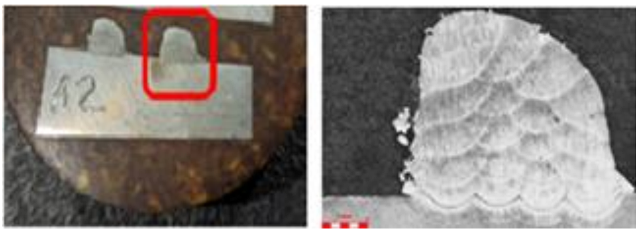

Figure 12- Hardness and metallographic test sample A2

Figure 13- Hardness and metallographic test sample A3

A comparative hardness and fusion test was conducted between DED, Figure 14, and traditional TIG welding process, shown in Figure 15. This test aimed to evaluate the differences in material properties, particularly hardness and fusion quality.

Figure 14- Fusion tests of DED sample

In the DED test, the hardness of the ZTA was 17 HRC, the first layer 61.8 HRC and the top layer 62 HRC

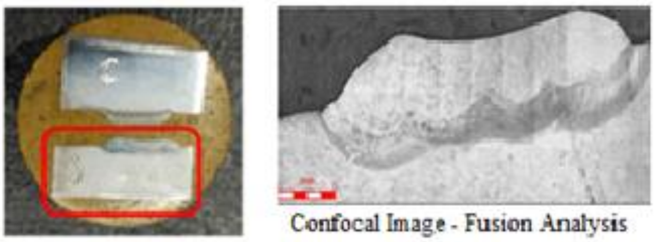

Figure 15- Fusion tests of TIG welding sample

In the sample with TIG welding performed with AISI H-13 wire on the AISI H-13 steel substrate, heat-treated, the hardness was 52/54 and in the weld region, the hardness was 55.5 HRC.

The parameterization used in test A1 was selected for the recovery process, achieving a surface hardness of 62.5 HRC and demonstrating good fusion quality. BAQUELLITES supplied the mold for recovery, which exhibited wear in the closing line cavities, as identified in Figure 16. A recess was machined in the closing line region, based on the geometry of the tests performed on the prototype, as shown in Figure 17.

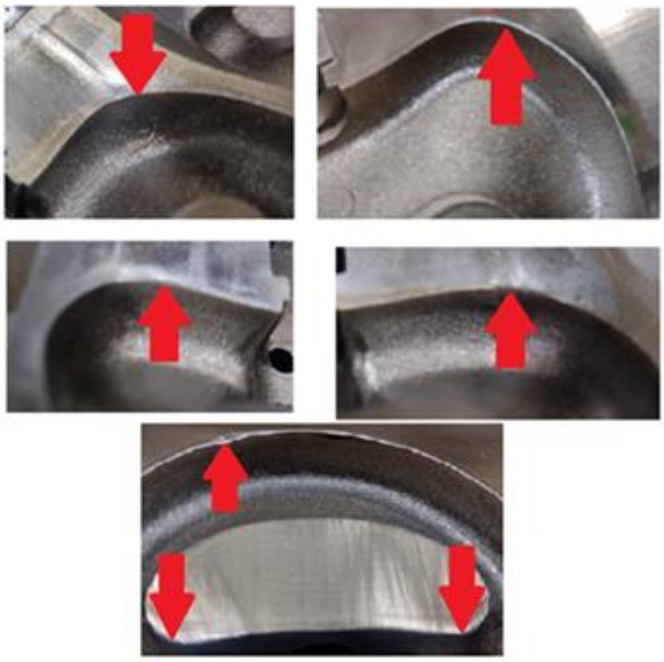

Figure 16- Cavities with wear on the closing line

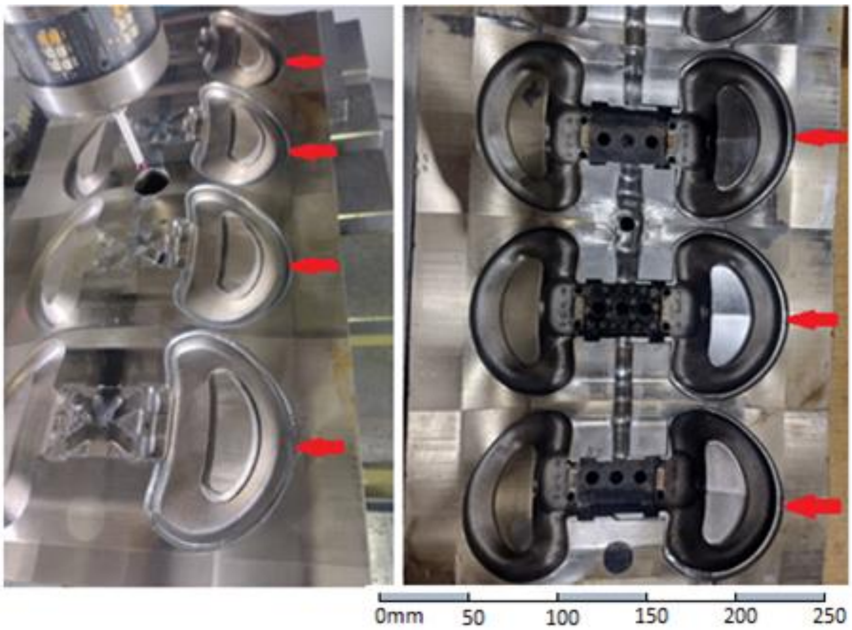

Figure 17- Perimeter with recess for repair Matrix and Core

Subsequently, deposition was carried out using the ROMI HYBRID machine from LAPRAS at the São Carlos School of Engineering; the repair approach was based on relevant articles and expert guidance.

The data collected during the tests were essential to determine the optimal deposition strategy for recovering the artifact's closing line. The adopted parameterization involved alternating between cavities 15-20 minute intervals, leading to significant improvements in DED, and successfully preventing cracks, as shown in Figures 18 and 19.

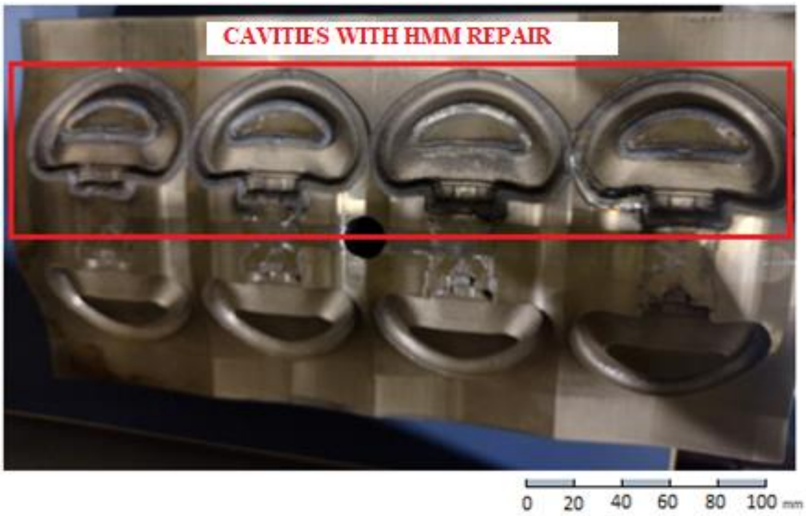

Figure 18- Matrix completed with DED in the cavities

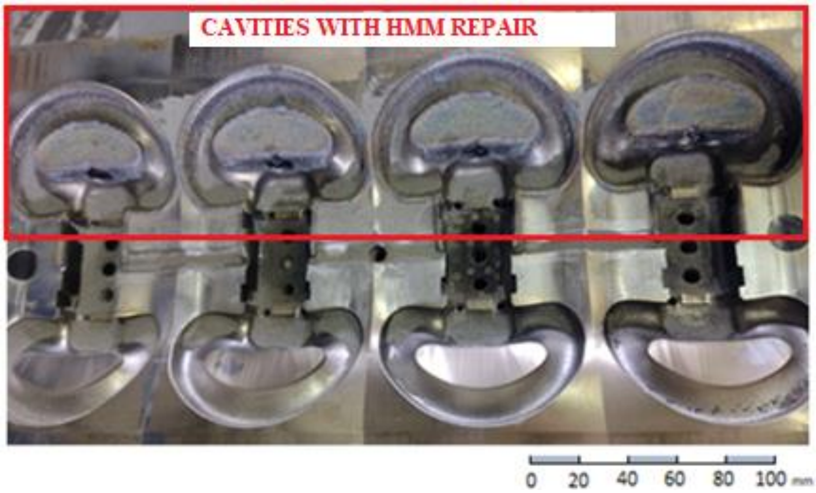

Figure 19- Complete deposition on the Core

After DED application, the artifact was sent for additional post-processing and Electrical Discharge Machining (EDM), as shown in Figure 20. The repair strategy proved effective and efficient in restoring critical regions of the mold. Once the die and core sides were assembled, the mold's functionality was successfully recovered (Figure 21).

Figure 20- EDM operation in reworking cavities

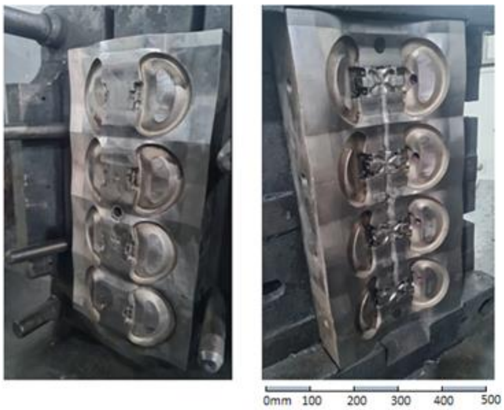

Figure 21-Mold assembled on the die and core side

The results demonstrate the effectiveness of HMM in reducing maintenance time and increasing wear resistance of injection molds. The microstructural characterization highlighted the importance of selecting appropriate materials and optimizing deposition parameters to prevent cracks and material displacements, as observed in the early tests. The decision to discontinue the use of OERLIKON® material due to the cracks identified reinforces the need for rigorous testing and adjustments in the parameterizations to guarantee the quality and durability of the artifacts produced.

3D modeling using CAM® software was essential for the practical implementation of the artifact, enabling the generation of G-code from IGES files to define detailed deposition trajectories for various regions of the artifact. This process is illustrated in Figures 22 to 25.

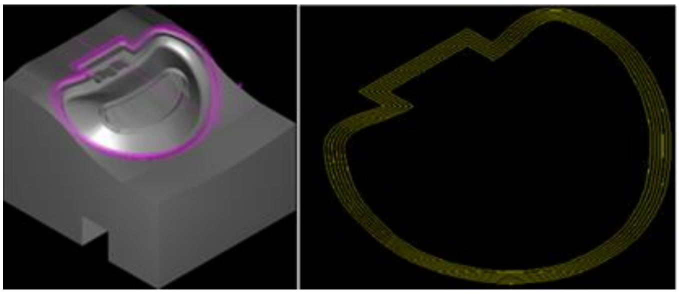

Figure 22 - Deposition Trajectory in the external region of the Matrix

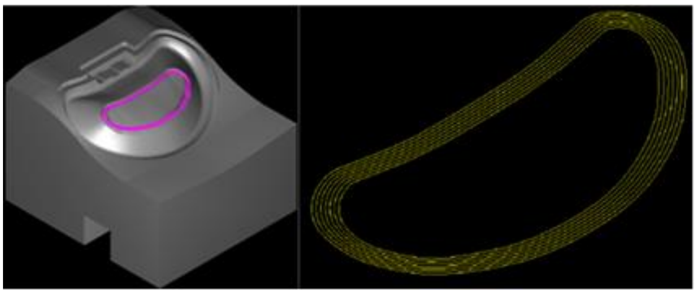

Figure 23 - Deposition Trajectory in the internal region of the Matrix

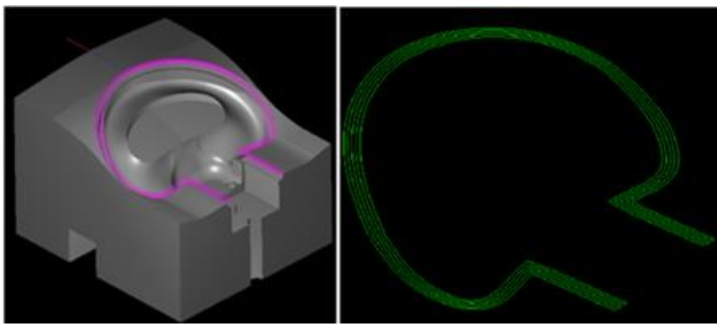

Figure 24 - Deposition Trajectory in the external region of the Core

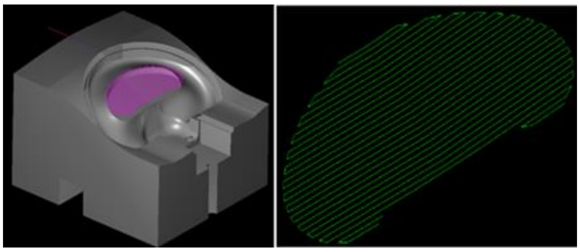

Figure 25 - Deposition Trajectory in the internal region of the Core

The HMM was performed in an interleaved manner to avoid cracks. However, difficulties were observed in some regions. Due to the proximity of the nozzle to the deposition surface (Figure 26), issues arose with burning of the laser lens caused by material splashing in a molten state. (Figures 27).

Figure 26 - Nozzle region close to the geometry

Figure 27 - Burning region identified on the lens

The need for improvements in software and deposition strategies was identified, with subsequent adjustments. After the completion of the HMM, the device was assembled and tested at BAQUELLITES, where it underwent practical tests to evaluate its effectiveness.

The device demonstration involved detailed planning of the test methods and the evaluation, using the DoE methodology and the MINITAB® tool to measure the device's efficiency.

The results showed variation in the level of burrs, with necessary adjustments in the injection volume and time, as shown in Figure 28.

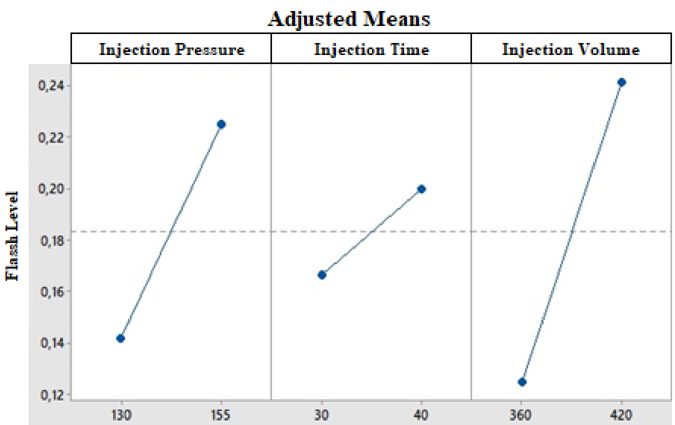

Figure 28 - Effect factors for burr levels

To achieve the minimum burr in the product, adjustments were made to the injection volume to 360g, the injection pressure to 130 bar, and the injection time to 30 seconds. It was noted that the maximum tolerable burr of 0.2mm is within the average of the injection volume of 390g, injection pressure of 142 bar and injection time of 35 seconds. Exceeding these parameters results in an increase in the level of burrs, signaling the need to stop production and submit the mold for repairs.

The comparison between HMM and traditional TIG welding methods indicated significant advantages in terms of cost reduction and increased mold durability. The financial analysis, based on average machine-hour costs and steel prices in Brazil, confirmed the economic viability of HMM, highlighting both technical and economic benefits (Tables 2 to 5).

EVENT	WELDING	HMM	UNIT
Service life	40.000	68.800	Nº Cycles
Production downtime	15	8	days
Total maintenance cost	1.500,00	1.297,00	US$
Number of cavities	4	4	cav.
Number of injected parts	160.000	275.200	Pcs
Maintenance cost/pc	**0,009**	**0,005**	US$

Table 2 - Comparison of downtime between processes

WELD RECOVERY 04 CAV			
Event	**Unit**	**US$**	**Cost US$**
H-13 Wire (kg)	3,200	9,00	28,80
Welding Time (h)	20,0	18,20	364,00

HMM RECOVERY 04 CAV			
Event	**Unid**	**US$**	**Cost/pc**
Atomized M2 (kg)	1,072	82,00	87,90
DED Programming (h)	2,0	27,00	54,00
MHM Time (h)	3,35	68,20	228,47

POST PROCESSING (ADJUSTMENT/ FINISHING)			
Event	**Hs**	**Cost/ h**	**US$ Total**
CNC Machining Cost	4,0	27,00	108,00
EDM Machining Cost	15,0	18,20	273,00
Bench (Adjustments)	20,0	18,20	364,00
		Sub Total	1.137,80
		PVD Application	363,00
		Cost Total	**1.500,80**

POST PROCESSING (ADJUSTMENT/ FINISHING)			
Event	**Hs**	**Cost/ h**	**US$ Total**
CNC Machining Cost	4,0	27,00	108,00
EDM Machining Cost	5,0	18,20	91,00
Bench (Adjustments)	20,0	18,20	364,00
		Sub Total	933,37
		PVD Application	363,64
		Cost Total	**1.297,01**

Table 3 - Comparison of mold recovery costs

EVENT	WELDING	HMM	UNIT
Nº of Cycles x Hour	80	80	Cycles/h
Monthly shift 22h x 22 days	38.720	38.720	Cycles/month
Estimated production time until maintenance shutdown	31	54	Days/year
No. of Interventions x year	12	7	Unit.
Number of days stopped for intervention x year	174	53	Days/year
Number of parts not produced x year	306.581	93.867	Pcs/year
Number of Injected Parts x year	1.551.979	1.764.693	Pcs/year
Maintenance cost x year	17.440,00	8.646,00	US$/year
Annual maintenance cost/pc	**0,011**	**0,005**	US$/pc

Table 4 - Comparison of predicted maintenance costs between processes x injected part (annual projection)

EVENT	RESULT
Number of annual interventions	**-42,6%**
Number of days stopped for annual intervention	**-69,4%**
Annual productivity	**13,7%**
Annual maintenance cost	**-50,4%**
Annual maintenance cost/pc	**-56,4%**

Table 5 - Annual projection of predicted impacts with the use of HMM

The evaluation included weighing the parts and comparing the methods, monitoring wear data during the process to predict durability up to 40,000 cycles, as shown in Figure 29.

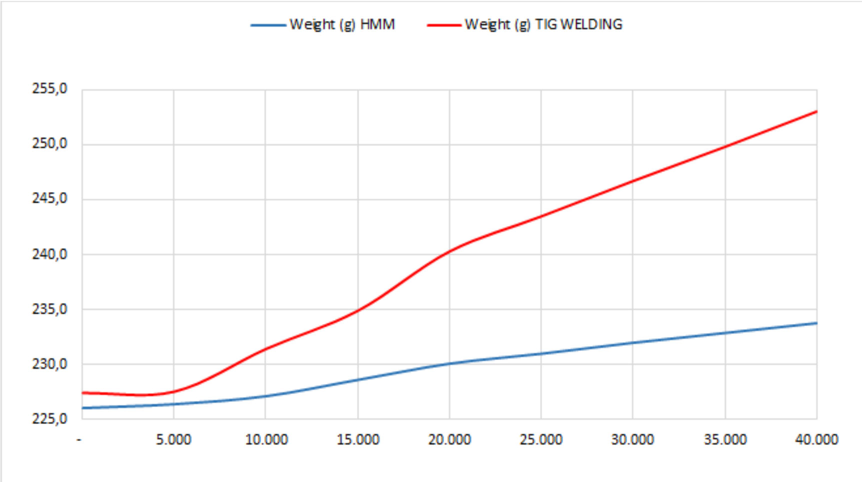

Figure 29 - Comparison of weight variation HMM x TIG Welding

In addition, the injection volume was carefully monitored, recording the variations that occurred during the injection cycle, and a large variation was observed between the weights of the cavities recovered with welding compared to those recovered with HMM. These quantitative data were documented in detail and provided a solid numerical basis for the analysis.

V. Conclusion

The transition from MAM to HMM marks a significant advancement in injection molding, combining the advantages of additive and traditional manufacturing to create more versatile and cost-effective solutions. As the technology evolves, it is expected to bring more innovations to the industry.

The researcher's experience in the tooling sector was essential, providing in-depth insight into the challenges and opportunities in mold construction. His knowledge of Bakelite injection molding allowed him to develop more efficient geometries, improving wear resistance and process efficiency.

The application of HMM, combined with technical expertise, illustrates how practice and technology can transform industrial processes, promoting efficiency and innovation. This study promises positive impacts on mold manufacturing, with the potential to reduce maintenance costs and extend the service life of Bakelite molds.

However, the study identified some gaps in HMM:

i. Lack of Specific Software: The lack of adequate tools to integrate 3D printing and machining may limit adoption.
ii. Skilled Personnel Shortage: A shortage of skilled personnel can impede effective implementation.
iii. Need for Norms and Standards: The lack of consistent guidelines can affect quality and reliability.
iv. High Costs: High equipment costs can restrict access to smaller companies.
v. Data Integration: Challenges in integrating CAD and CAM data can impact efficiency.
vi. Sustainability: Waste management and environmental impact require further attention.

These areas represent both challenges and opportunities for future research, development and capacity building. Collaboration between practical experience and technological innovations will be essential to overcome these barriers and ensure the continued success of HMM in the industry.

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