



**Università
di Brescia**

DIPARTIMENTO DI INGEGNERIA MECCANICA E INDUSTRIALE

DOTTORATO DI RICERCA IN INGEGNERIA MECCANICA E INDUSTRIALE

settore scientifico disciplinare
ING-IND/16 – Tecnologie e Sistemi di Lavorazione

XXXVIII CICLO

ADVANCED POLYMER COMPOSITES FOR AUTOMOTIVE ELECTRONICS:
DESIGN, PROCESSING AND TESTING

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“Education is what enables a nation to live as a free, independent, honorable and dignified community, or condemns it to servitude and misery.”

--Mustafa Kemal Atatürk

Abstract

The growing integration of electronic devices and digital architectures in vehicles has significantly increased the functional and thermal load on automotive electronic control units (ECUs). Their housings must simultaneously ensure electromagnetic compatibility (EMC), efficient heat dissipation and long-term reliability, while also supporting lightweight design and cost reduction. Traditionally, these requirements have been met with aluminium and steel enclosures. However, metallic housings are heavy, prone to corrosion, require additional finishing operations and impose constraints on compact, highly integrated geometries.

This thesis investigates whether filled polymer composites can realistically replace metal housings in selected automotive applications by combining material development, process optimisation and full system-level validation. Two key performance axes are addressed: thermal conductivity for LED headlamp housings and EMI shielding effectiveness for dashboard display modules. Twelve industrial polymer formulations were first screened by Moldex3D simulations on a standard plaque geometry to define robust injection-moulding process windows, then validated experimentally. The results show that highly filled, thermally conductive compounds can be moulded without short shots or excessive warpage when melt temperature, mould temperature, filling time and gate configuration are carefully tuned.

The selected materials were then characterised experimentally. Thermal conductivity was measured using both Hot Disk (TPS) and heat-flow meter techniques, while EMI shielding effectiveness was evaluated between 150 kHz and 3 GHz using a coaxial transmission-line setup. For the best formulations, thermal conductivity enhancements of up to about forty-fold and EMI shielding levels above 100 dB were obtained, confirming the dominant role of filler type and content. A down-selection process identified two PA6-based compounds for the headlamp housing and three PC/stainless-steel fibre compounds for the dashboard housing.

Industrial demonstrators were produced and analysed through combined simulation and testing. For the LED housing, Simcentre FloEFD simulations and climatic-chamber derating tests showed that conductive PA6 housings can keep component temperatures within acceptable limits under typical under-hood conditions, albeit with a narrower safety margin than aluminium. For the display housing, radiated emission, radiated immunity and ESD tests on complete modules demonstrated that two PC/SSF compounds significantly improve EMC robustness over the current ASA solution, particularly above 800 MHz and under high-voltage ESD stress, while all candidates remain within CISPR 25 limits.

Overall, the thesis demonstrates that polymer composites with tailored conductive networks, when combined with gate design and injection-moulding parameters that are engineered with equal care, can offer a viable, lighter and more cost-effective alternative to metal housings in automotive electronics. Because the proposed solutions are validated not only at material level but also on component and system demonstrators, the work moves beyond classical lab-scale studies and can be positioned in the intermediate Technology Readiness Level range (approximately TRL 4–6), with clear potential for integration into real vehicle applications.

Sommario

La crescente integrazione di dispositivi elettronici e architetture digitali nei veicoli ha aumentato in modo significativo il carico funzionale e termico sulle centraline elettroniche (ECU). I relativi contenitori devono garantire compatibilità elettromagnetica (EMC), efficace smaltimento del calore e affidabilità a lungo termine, contribuendo al contempo alla riduzione di peso e di costo. Tradizionalmente tali requisiti sono stati soddisfatti mediante involucri in alluminio o acciaio, che però risultano pesanti, soggetti a corrosione, richiedono trattamenti superficiali aggiuntivi e limitano la realizzazione di geometrie compatte e altamente integrate.

La tesi indaga se i compositi polimerici caricati possano realisticamente sostituire gli involucri metallici in applicazioni automotive selezionate, combinando sviluppo del materiale, ottimizzazione del processo e validazione a livello di sistema. Sono stati considerati due assi prestazionali principali: la conducibilità termica per i corpi faro a LED e l'efficacia di schermatura EMI per i moduli display della plancia. Dodici formulazioni polimeriche industriali sono state valutate tramite simulazioni Moldex3D su una geometria standard per definire finestre di processo robuste per lo stampaggio a iniezione, quindi verificate sperimentalmente. I risultati mostrano che composti altamente caricati e termicamente conduttivi possono essere stampati senza short-shot o eccessiva deformazione, a condizione che temperatura di fusione, temperatura stampo, tempo di riempimento e configurazione di gate siano opportunamente tarati.

Le formulazioni selezionate sono state caratterizzate mediante misure di conducibilità termica (Hot Disk/TPS e heat-flow meter) e prove di schermatura EMI tra 150 kHz e 3 GHz con linea coassiale in trasmissione. Per le soluzioni migliori sono stati ottenuti incrementi di conducibilità termica fino a circa quaranta volte rispetto alle matrici nette e livelli di schermatura superiori a 100 dB, evidenziando il ruolo dominante del tipo e del contenuto di carica. Un processo di down-selection ha portato alla scelta di due gradi a base PA6 per il corpo faro e tre gradi PC/fibra di acciaio inossidabile per il contenitore del display.

Sono stati quindi realizzati dimostratori industriali e analizzati tramite simulazioni e prove sperimentali combinate. Per il corpo faro a LED, le simulazioni Simcentre FloEFD e le prove di derating in camera climatica hanno mostrato che gli involucri conduttivi a base PA6 mantengono le temperature dei componenti entro limiti accettabili nelle condizioni tipiche vano-motore, seppur con un margine di sicurezza più ridotto rispetto all'alluminio. Per il display, le prove di emissione irradiata, immunità irradiata ed ESD su moduli completi hanno evidenziato che due composti PC/SSF migliorano in modo significativo la robustezza EMC rispetto all'attuale soluzione in ASA, mantenendo tutte le configurazioni entro i limiti CISPR 25.

Nel complesso, la tesi dimostra che i compositi polimerici dotati di reti conduttive opportunamente progettate, combinati con una configurazione di gate e parametri di stampaggio ottimizzati, possono costituire un'alternativa praticabile, più leggera e più economica agli involucri metallici nell'elettronica automobilistica. Poiché le soluzioni proposte sono validate non solo a livello di materiale ma anche su dimostratori di componente e di sistema, il lavoro si colloca in una fascia intermedia di maturità tecnologica (circa TRL 4–6), con un chiaro potenziale di integrazione in applicazioni reali a bordo veicolo.

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Chapter 1

Introduction

The accelerating integration of electronics in modern vehicles has radically transformed the design and functional expectations of automotive components. Once dominated by mechanical assemblies, the automotive sector now relies on sensors, Electronic Control Units (ECUs), LED lighting modules, power electronics and connectivity systems that govern safety, comfort and driver-assistance functions. These devices must operate reliably under demanding thermal, electromagnetic and environmental conditions, so the housings that protect them are no longer passive shells, but key contributors to overall system performance. In particular, two functional requirements have become indispensable: effective heat dissipation to prevent overheating-related failures, and robust electromagnetic interference (EMI) shielding to guarantee electromagnetic compatibility (EMC) and trustworthy operation of vehicle electronics.

Traditionally, these combined functional requirements have been met using aluminium and steel housings. Metals offer high mechanical stability, excellent thermal transport and strong EMI shielding thanks to their intrinsic electrical conductivity. However, current automotive architectures are increasingly shaped by lightweight design, energy efficiency, sustainability targets and cost-sensitive manufacturing. Metal housings are relatively heavy, susceptible to corrosion and often require secondary finishing operations such as coating or anodizing, which increase both cost and environmental impact. In addition, the geometric constraints of casting and machining limit the adoption of compact, highly integrated designs that are now common in advanced lighting systems and electronic modules. These limitations motivate the search for alternative materials that can deliver comparable functional performance while aligning with modern mobility priorities.

Polymer-based solutions offer a promising route in this direction. Their low density enables significant mass reduction, supporting lower fuel consumption in internal combustion vehicles and extended driving range in electric vehicles. Injection-moulding technologies make it possible to produce thin-walled housings with complex geometries, integrated clips, sealing features and mounting points in a single step, reducing part count and simplifying assembly logistics. Polymers also provide inherent electrical insulation and chemical resistance, which are advantageous in under-the-hood and exterior environments. For these reasons, polymers are already widely used in interiors, exterior trims and various structural or semi-structural components.

Yet, neat thermoplastics such as polyamide 6 (PA6) and polycarbonate (PC) do not naturally provide the level of thermal management and EMI shielding required for housings of high-power or safety-critical electronics. Their stiffness and long-term dimensional stability decrease at elevated temperatures, and their intrinsic thermal conductivity and electrical conductivity remain too low to ensure efficient heat spreading or electromagnetic protection. As a result, using neat polymers alone quickly becomes a bottleneck when the goal is to replace traditional metal housings in demanding electronic applications such as LED headlamps, control units or power modules.

To overcome these limitations, recent developments have focused on reinforcing polymers with electrically and thermally functional fillers, creating lightweight composites with enhanced performance. Carbon fibres, graphite, stainless-steel fibres, metal powders and other advanced fillers can form continuous or semi-continuous networks inside the

polymer matrix, enabling both improved EMI shielding and more efficient heat transfer. Properly designed formulations have shown that it is possible to approach, and in some cases match, the functional performance of metals while retaining many of the manufacturing and design advantages of plastics. At the same time, experience from previous studies indicates that not all filler systems behave as initially expected: for example, some carbon nanotube-based composites show limited thermal gains and raise questions related to cost and sustainability. This reinforces the need for careful selection and optimisation of filler types and combinations rather than relying on a single “universal” solution.

From an industrial perspective, this work is embedded in a collaboration with COBO S.p.A. (Italy), a Tier-1 supplier of electronic systems and lighting modules for commercial and off-highway vehicles. Within this framework, representative components such as LED headlamp housings and electronic control modules were selected as case studies. COBO provided real geometries, boundary conditions, production constraints and performance expectations, ensuring that the materials and processes investigated in this thesis are not purely academic, but directly aligned with practical industrial needs.

The scope of this thesis is intentionally focused on application-oriented material and process integration for automotive housings. Rather than developing entirely new material chemistries, the thesis emphasizes the industrial implementation and validation of commercially available conductive polymer systems. Fundamental investigations on nanofiller physics, molecular-scale conductive mechanisms, or the development of new filler chemistries are outside the scope of this work. Instead, the study focuses on evaluating industrially relevant conductive polymer compounds under realistic manufacturing and operating conditions. The primary objective is therefore to establish the relationship between material formulation, injection-moulding process design, and functional thermal/EMC performance at component and system level.

Introducing conductive and thermally active fillers into polymers, however, also introduces new challenges. As filler content increases, the melt becomes more viscous and its flow behaviour departs from that of the neat matrix, making it more difficult to mould thin-walled, complex housings without defects such as short shots, weld lines, voids or excessive warpage. At the same time, the final EMI shielding and thermal behaviour are not determined solely by filler concentration: they also depend on filler orientation, dispersion and network connectivity, all of which are strongly influenced by the injection-moulding process. Parameters such as melt and mould temperature, injection speed, packing conditions and, critically, gate type and position shape the local shear fields inside the cavity and therefore the microstructure that develops during filling and cooling. This means that mouldability, dimensional stability, thermal performance and EMI shielding are tightly coupled and must be addressed together.

Against this background, Computer-Aided Engineering (CAE) tools, particularly three-dimensional injection-moulding simulation software such as Moldex3D, have become indispensable. These tools allow engineers to predict flow, pressure, temperature, shrinkage, warpage and even fibre or platelet orientation before any mould is manufactured. By exploring virtual process windows and gate configurations, it is possible

to identify promising solutions, avoid costly trial-and-error on the shop floor and reduce scrap and development time. For conductive polymer composites, CAE is especially valuable because the regions that are most difficult to fill are often the same regions where continuous shielding paths and efficient heat spreading are most critical.

This thesis builds on these motivations and aims to demonstrate that advanced polymer composites can realistically replace metal housings in selected automotive electronic applications, provided that material formulation and processing are designed in an integrated way. The work combines the development and characterisation of PA6- and PC-based composites with conductive fillers, the optimisation of injection-moulding parameters and gate layouts, and the use of Moldex3D simulations to understand how processing-induced microstructures influence EMI shielding and thermal behaviour. By linking material design, process design and functional performance, the thesis seeks to contribute to a more lightweight, efficient and sustainable generation of automotive electronic housings.

1.1. Original Contributions of the Thesis

This thesis contributes to the field through the following aspects:

- Establishing an integrated material–process–function framework for conductive polymer housings used in automotive thermal-management and EMC applications.
- Investigating the coupled influence of conductive filler systems, injection-moulding parameters and gate design on thermal conductivity, EMI shielding effectiveness and mouldability.
- Demonstrating how processing-induced microstructural anisotropy influences both in-plane and through-thickness thermal behaviour as well as EMI shielding performance.
- Combining CAE-based injection-moulding optimisation with experimental validation using Moldex3D simulations and industrial manufacturing trials.
- Validating conductive polymer composites at component and system level through climatic-chamber tests, infrared thermography, radiated EMC testing, GTEM immunity measurements and ESD evaluations.
- Providing industrial design guidelines for metal-to-polymer substitution in automotive electronic housings.

Chapter 2

Automotive Electronics: Demand, EMI & Thermal Challenges

This chapter translates the general motivations introduced in Chapter 1 into concrete thermal and electromagnetic requirements for automotive electronic housings. Particular attention is given to the increasing functional demands placed on electronic enclosures, especially regarding electromagnetic compatibility (EMC), heat dissipation, lightweighting, and long-term operational reliability.

2.1. Automotive Electronics: Demand & New Challenges

The transformation of the automotive industry in the last two decades has fundamentally reshaped the role of electronics inside vehicles. What were once predominantly mechanical systems have now evolved into highly digital, software-defined platforms, driven by advanced connectivity, autonomous functions, electrified powertrains, and smart lighting interfaces [1]. As illustrated in *Figure 1*, modern vehicles integrate a wide array of electronically controlled features ranging from adaptive cruise control and emergency braking to cybersecurity and over-the-air software updates all of which require robust networks of electronic control units (ECUs).

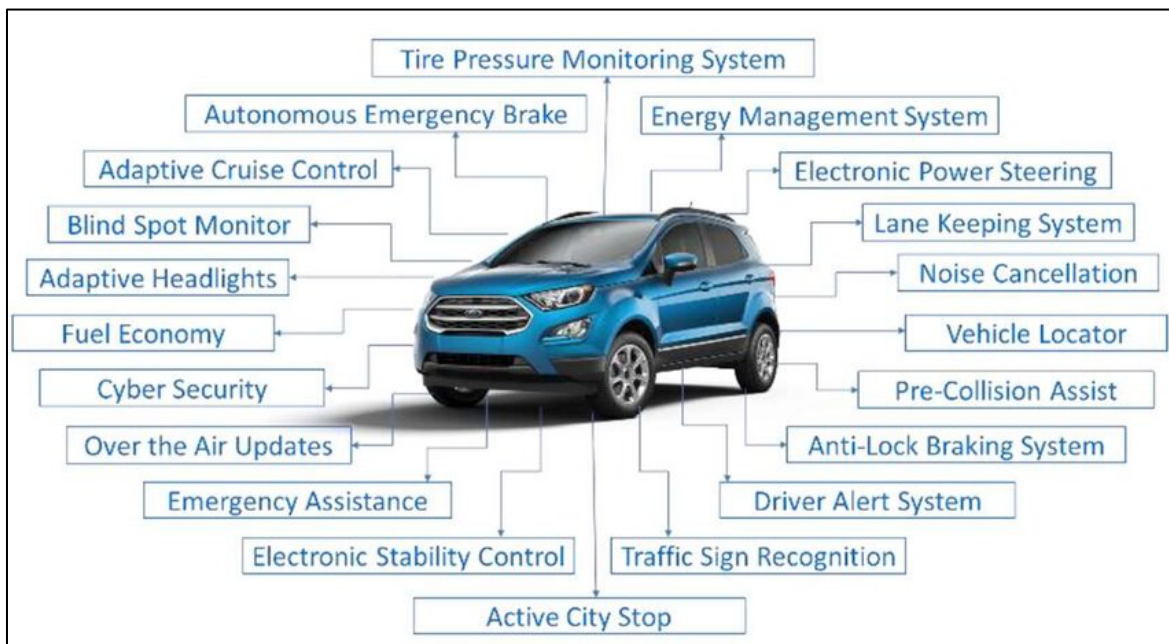


Figure 1. Electronic functionalities enabled by ECU-based architectures in modern vehicles [2].

This rapid expansion has dramatically increased both the number and the functional importance of ECUs. While a typical passenger car in the early 2000s contained approximately 20–30 ECUs, current mid-segment vehicles commonly exceed 70–100 units, and premium or highly automated vehicles can surpass 150 ECUs due to the reliance on distributed sensing, high-performance computing, and real-time actuation capabilities [1]. Consequently, the housings that enclose these modules have become mission-critical components that must ensure continuous thermal safety, immunity to electromagnetic disturbances, and mechanical reliability under harsh environmental loads.

The economic weight of automotive electronics has risen in parallel with this architectural evolution. As shown in Figure 2 the share of electronics in total vehicle cost was below 10% in the 1980s, but exceeded 35% by 2020 and is projected to approach 50% in battery-electric vehicles by 2030 [3]. This shift clearly indicates that electronics are no longer supplementary subsystems, but the primary enablers of safety, comfort, efficiency, and digital mobility services.

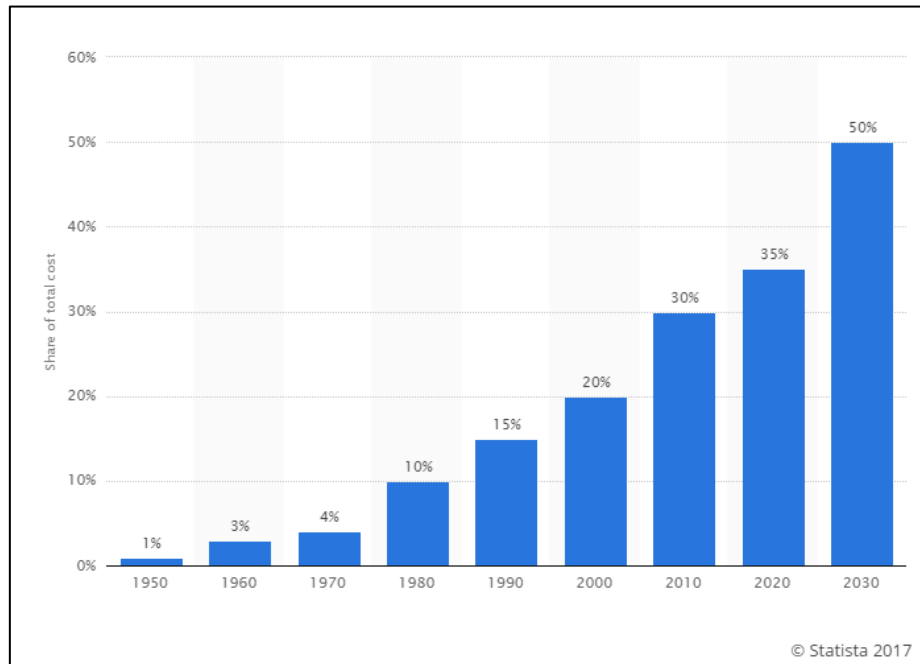


Figure 2. Increase in electronic content share in total vehicle cost over time [3].

As a direct result, the expectations placed on electronic housings continue to intensify. They must maintain electrical integrity in high-frequency environments, dissipate heat from power-dense components, enable compact and lightweight packaging, and adapt to increasingly complex part geometries. These evolving demands form the core motivation of the present research: to evaluate whether conductive polymer composites, engineered for improved electromagnetic shielding and thermal transport can serve as viable industrial alternatives to conventional metal housings in next-generation automotive electronics.

2.1.1. Electromagnetic interference (EMI) & compatibility (EMC)

As vehicles increasingly rely on electronic sensing, computing, and control functions, ensuring electromagnetic compatibility has become one of the most critical design requirements in automotive electronics [1]. Electromagnetic interference (EMI) refers to unintended electromagnetic disturbances that can disrupt the operation of adjacent circuits, whereas electromagnetic compatibility (EMC) defines the ability of a system to operate reliably without emitting or being affected by harmful electromagnetic noise [4].



Figure 3. Schematic illustration of typical electromagnetic interference (EMI) sources affecting electronic systems, adapted from [Newhaven Display Technologies](http://newhavendisplay.com)

In modern ECU networks [1], high-speed communication buses, power converters, radar/communication modules, and switching semiconductor devices often operate in close proximity, creating a high-energy electromagnetic environment inside the vehicle [4,5]. Inadequate shielding can lead to signal corruption, functional instability, or unexpected shutdown of safety-critical systems, such as advanced driver-assistance functions (ADAS), braking or steering controllers [6]. These risks directly threaten functional safety and system trustworthiness, particularly as autonomous and electrified vehicles demand error-free real-time performance [7].

Table 1. Typical EMI shielding effectiveness classifications and representative application ranges adapted from [8].

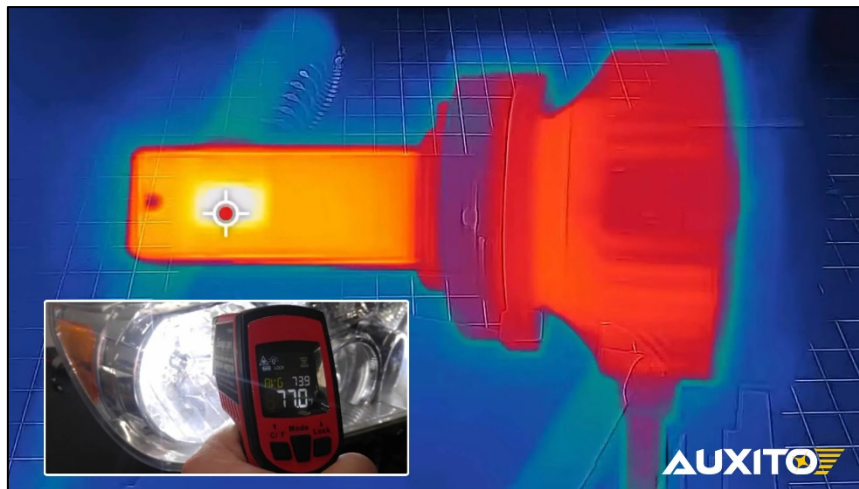
EMI SE/dB	LEVEL	APPLICATION
0–10	1	–
10–30	2	Low EMI SE to meet some industrial and commercial needs
30–60	3	General EMI SE to meet some industrial and commercial needs
60–90	4	High EMI SE to meet aerospace and military needs
>90	5	Special requirements for high accuracy and sensitivity

These shielding targets (Table 1) demonstrate that enclosure materials are no longer required to provide only mechanical protection, but must also actively contribute to electromagnetic reliability and compliance with automotive EMC standards. To protect consumer safety and avoid EMC-related recalls, automotive regulations such as CISPR 25 (emissions) and ISO 11452 (immunity) typically require minimum shielding effectiveness levels in the range of 30–60 dB, depending on module function and installation location [4,5]. Consequently, the EMC performance of electronic housings is now treated as a first-order design requirement, essential for ensuring long-term reliability, regulatory compliance, and market acceptance of next-generation vehicle electronics. In this context, lightweight conductive polymer composites are increasingly investigated as

multifunctional alternatives capable of combining structural integrity with EMI shielding performance.

2.1.2. Thermal management requirements in automotive electronics

Thermal performance represents the second fundamental reliability constraint for automotive ECUs [9]. The high switching frequencies, compact packaging, and continuously increasing processing power of power electronics and control units result in localized heat generation that must be effectively dissipated through the enclosure and surrounding system [9,10].



*Figure 4. Local heat accumulation and hotspot formation in LED headlamp electronics.
Adapted from AUXITO [11].*

If excessive heat is not removed efficiently, junction temperatures in semiconductors may exceed safe limits, causing performance degradation, accelerated aging, or sudden functional shutdowns during peak load operation [9,12]. Furthermore, repeated thermal cycling induced by engine on/off cycles and environmental variations leads to mechanical fatigue, solder joint cracking, and material deterioration over time [12]. Such failure modes directly reduce the operational lifetime of embedded systems and pose substantial warranty and safety risks for OEMs.

Automotive environmental standards (e.g. ISO 16750-4) require ECU housings to maintain thermal stability under high-temperature soak conditions and severe thermal shocks typical of under-hood or headlamp environments [13,14]. Therefore, thermal conductivity of enclosure materials becomes a key performance metric, ensuring rapid heat spreading away from hotspots and preserving electronic integrity throughout the vehicle lifetime.

In compact automotive electronics, the housing itself increasingly acts as a functional heat-transfer pathway rather than merely a protective shell. Therefore, enclosure materials with enhanced thermal conductivity are becoming essential for maintaining acceptable operating temperatures in space-constrained electronic architectures.

2.2. Limitations of Conventional Metal Housings

Metals such as aluminium and steel have traditionally been the preferred choice for automotive electronic enclosures due to their inherently high electrical conductivity and excellent heat dissipation capability two critical requirements for maintaining electromagnetic compatibility (EMC) and thermal stability [15,16]. However, as vehicles incorporate increasing numbers of compact power modules, radar sensors, and communication devices, the industry's priorities have shifted toward reducing weight, integrating functions, and maximizing packaging efficiency. In this context, the high density of metallic housings introduces a significant disadvantage: even small increases in component mass negatively impact fuel consumption in combustion platforms and reduce driving range in electric vehicles. Extensive studies indicate that reducing the overall vehicle weight by 10% can improve energy efficiency by 6–8%, underscoring lightweighting as an essential engineering target in next-generation mobility [17].

Production of metallic housings also presents manufacturing challenges that conflict with speed, cost-efficiency, and sustainability goals. Multi-stage processes such as machining, die-casting, drilling, and finishing require high-temperature operations and substantial energy input, contributing to notable CO₂ emissions during manufacturing [18,19]. Exposure to moisture, de-icing salts, and thermal cycling increases corrosion risk over a vehicle's lifetime, necessitating additional surface treatments and coatings for durability [19]. Late-stage design modifications further escalate costs, as changes to metal tooling are expensive and slow to iterate. These factors collectively increase per-part cost and lengthen development cycles, reducing industrial adaptability in fast-evolving electronic architectures. Consequently, although metallic housings continue to provide excellent thermal and electromagnetic performance, their compatibility with emerging lightweight, highly integrated, and sustainability-oriented vehicle architectures is progressively being questioned.

The mechanical nature of metals also restricts innovation in enclosure geometry. Their limited formability complicates thin-wall structures, internal channel design, and complex surface styling capabilities increasingly required in LED headlamps, radar housings, and ADAS camera modules [18,20]. For instance, intricate shapes that integrate airflow pathways or sealing features typically demand secondary machining or assembly steps when manufactured from metal. This constraint hinders part consolidation and prevents seamless integration of structural, optical, and electronic functionalities into a single compact unit. As styling trends progress toward low-profile, embedded electronic systems, the physical rigidity of metallic components becomes misaligned with evolving packaging expectations.

Moreover, incorporating multiple fastening points, brackets, and inserts to compensate for design inflexibility often increases total component count and adds extra interfaces that may compromise durability under vibration or dynamic loading. At end-of-life, disassembly of metallic housings containing bonded coatings, seals, and dissimilar materials is difficult, reducing recyclability and contradicting circular-economy strategies that OEMs are now mandated to adopt [18].

Together, these factors indicate that while metals still deliver superior EMI shielding and thermal performance, their drawbacks including weight, production complexity, high tooling cost, design limitations, and sustainability concerns have become increasingly incompatible with the performance and economic priorities of future automotive electronic systems.

These limitations have accelerated interest in multifunctional polymer composites capable of simultaneously addressing lightweighting, manufacturability, thermal management, and EMI shielding requirements. Although extensive research has been conducted on conductive polymer composites for EMI shielding and thermal-management applications, a large portion of the literature remains focused on coupon-level material characterisation under simplified laboratory conditions. Many studies primarily report intrinsic thermal conductivity or shielding effectiveness values without considering the influence of injection-moulding process parameters, gate-induced filler orientation, or full-component validation under realistic automotive operating conditions [21-24].

In addition, thermal-management and EMC requirements are often investigated separately, despite the fact that automotive electronic housings must simultaneously satisfy both functions while remaining manufacturable at industrial scale. Consequently, there remains a limited number of studies integrating material selection, injection-moulding process optimisation, CAE-assisted validation and component-level thermal/EMC testing within a unified industrial framework.

The present thesis addresses this gap by evaluating conductive polymer composites not only at standard-specimen level, but also through full-scale automotive housing validation involving thermal simulation, climatic-chamber testing, infrared thermography and EMC qualification procedures.

Consequently, the following chapter focuses on conductive polymer composites, their functional fillers, and the mechanisms governing electromagnetic and thermal behaviour in polymer-based electronic housings.

Chapter 3

From Neat Polymers to Functional Composites: Limits and Opportunities

Building on the thermal and electromagnetic requirements discussed in Chapter 2, the present chapter examines the potential of polymer-based materials for automotive electronic housings.

Particular attention is given to the advantages and limitations of neat thermoplastics, as well as to the growing role of conductive fillers in enabling multifunctional behaviour.

The chapter therefore establishes the scientific foundation for the conductive composite systems investigated throughout the remainder of this thesis.

3.1. Motivation for Polymer Adoption in Automotive Electronics

The rapid growth of electrified, lightweight, and software-defined vehicles has reshaped the requirements for automotive electronics. As the number of electronic control units (ECUs), sensors, and lighting modules increases, housings must deliver high functional integrity while minimizing weight and manufacturing cost. This shift has positioned polymeric materials as a core enabler of next-generation mobility platforms [15–18]. In particular, replacing metal housings with engineered polymers supports lightweighting strategies, an essential approach for improving energy efficiency and extending driving range, especially in electric vehicles where mass reduction directly translates into increased vehicle autonomy [15,17].

Figure 5 illustrates a well-recognized trend in manufacturing economics: while metal component cost rises sharply with increasing geometric complexity, polymer parts maintain cost efficiency even for advanced integrated designs. This enables part consolidation, reduced fastener requirements, and improved aerodynamic and aesthetic outcomes [16,20].

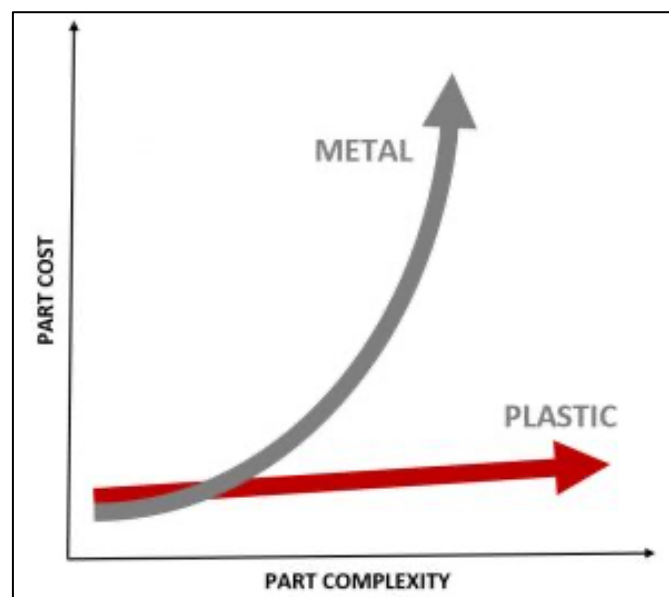


Figure 5. Cost evolution of metal vs. polymer components with increasing part complexity [16,20].

In addition to cost and manufacturability, polymers also provide significant environmental benefits. Their processing routes (e.g. injection moulding) consume substantially less energy than machining or casting operations typical for aluminium and steel housings [16–19]. Moreover, design flexibility enables built-in sealing features, snap-fits and cooling pathways, reducing secondary assembly steps while enabling thinner and lighter structures suitable for smart lighting, ADAS sensors, camera modules, and in-cabin electronics [16,18,20].

The material selection trend is further supported by density-performance mapping, where polymers and composites occupy advantageous low-weight regions compared to metals, as seen in Figure 6. This strength-to-weight benefit is crucial for components located far from the vehicle centre of gravity such as headlamp housings, where even small mass reductions yield notable handling improvements.

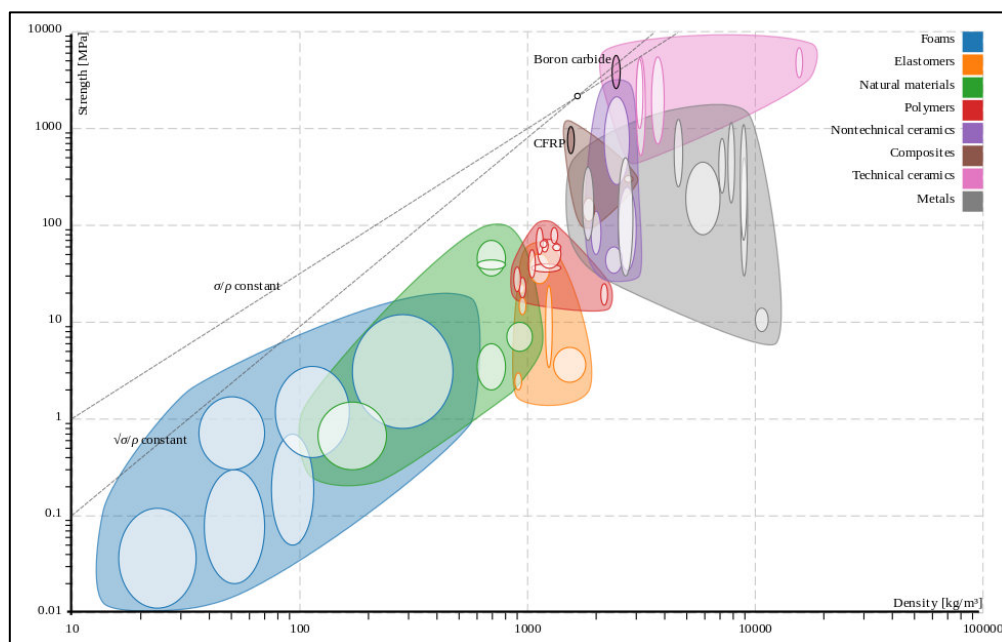


Figure 6. Strength vs. density comparison of engineering materials. Adapted from Ashby maps- polymers located in low-density, good strength to weight region. Adapted from 3DX Research [25].

In summary, polymers are increasingly favored as housing materials because they align directly with the dominant automotive engineering directions:

- Lightweighting for energy efficiency
- Complex geometries and design freedom
- Cost reduction and manufacturing simplicity
- Sustainability and reduced carbon footprint

However, these advantages alone are insufficient for safety-critical electronics, leading to the limitations discussed in the following section.

3.2. Limitations of Neat Polymers in EMI Shielding & Thermal Management

Despite their advantages in lightweighting and manufacturability, neat polymers inherently behave as electrical insulators due to the localized electron structure of covalent polymer chains. Their extremely low charge-carrier mobility (electrical conductivity $\sim 10^{-14}$ – 10^{-17} S/m) prevents the formation of conductive pathways and disables the fundamental mechanisms of electromagnetic shielding; reflection, absorption, and multiple internal wave dissipation (Table 2.) [15,22,26,27]. As a result, enclosure walls made of unmodified PA6, PC or PP allow electromagnetic radiation to propagate freely, increasing coupling between nearby power converters, high-speed data buses, and radar/communication modules. In safety-critical functions such as emergency braking or lane-keeping assistance, even transient disturbance may propagate as a control error [6,7].

Table 2. Thermal and electrical conductivities of neat polymers.

Material	Electrical Conductivity (S/m)	Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Source
PA6	$10^{-14} - 10^{-16}$	0.23	[22,24]
PC	$10^{-14} - 10^{-17}$	0.19 – 0.22	[24]
ABS	$10^{-14} - 10^{-16}$	0.17 – 0.21	[24]
ASA	$10^{-14} - 10^{-16}$	0.18 – 0.22	[24]
PP	$10^{-14} - 10^{-17}$	0.10 – 0.22	[24]

These challenges are magnified by rising ECU integration density inside modern vehicles. A typical passenger car that once required fewer than 30 ECUs now commonly exceeds 100 interconnected modules operating within compact packaging zones, intensifying both radiated and conducted EMI exposure [2–3]. For compliance with automotive EMC regulations (e.g. CISPR 25), housings must maintain 30–60 dB shielding levels depending on placement and depending on placement and frequency band [4–5], a performance level that neat polymers fundamentally fail to achieve. Consequently, neat polymers alone are fundamentally unable to satisfy the combined EMI shielding and thermal-management requirements of compact automotive electronic systems.

Table 3. Comparative assessment of metals, neat polymers and conductive polymer composites for automotive electronic housings.

Property	Metals	Neat Polymers	Conductive Polymer Composites
Density	High	Very Low	Low
EMI Shielding	Excellent	Poor	Moderate–High
Thermal Conductivity	Excellent	Very Poor	Improved
Corrosion Resistance	Moderate	Excellent	Excellent
Design Flexibility	Limited	High	High
Manufacturing	Machining/Casting	Injection Moulding	Injection Moulding
Cost of Complex Geometry	High	Low	Moderate
Recyclability	Good but energy-intensive	Moderate	Depends on filler system

Thermal limitations create a second major problem for polymer housings. Most automotive thermoplastics exhibit thermal conductivity below $0.25 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, impairing heat spreading from semiconductor junctions in LED drivers, DC–DC converters or ADAS processors [9,15,22]. Localized hotspots trigger thermal runaway, accelerate polymer degradation, and induce fatigue failures (e.g. solder cracking, substrate delamination, wire bond fracture) throughout prolonged temperature cycling [28]. Under headlamp operating conditions, where housing wall temperatures frequently exceed 100°C , neat polymers struggle to maintain dimensional stability and thermal reliability.

Several industrial attempts to replace metallic housings with polymer-based alternatives have reported limitations associated with insufficient thermal dissipation, dimensional instability, or inadequate EMI shielding under severe operating conditions [28,29]. These examples demonstrate that lightweight substitution alone is insufficient unless conductive performance and manufacturability are simultaneously addressed.

As electronics continue to scale in power and frequency, EMI and thermal stresses rise non-linearly, particularly in electric vehicles where battery electronics and fast-charging circuits introduce even higher heat flux and switching noise. Therefore, unfilled polymers cannot satisfy the combined performance requirements of next-generation automotive electronics. These growing performance gaps have propelled the automotive industry to actively pursue alternative material solutions. As a result, significant research and industrial innovation have focused on incorporating electrically and thermally conductive fillers into polymer matrices in order to approach the multifunctional performance of conventional metals.

Nevertheless, conductive filler addition alone does not guarantee successful industrial implementation. The final thermal and electromagnetic behaviour of conductive polymer

composites strongly depends on filler dispersion, orientation, network connectivity and process-induced microstructural evolution during injection moulding [22,30].

Consequently, conductive polymer development must be approached as an integrated material-process-performance problem rather than solely as a material formulation challenge. This perspective forms the central scientific framework of the present thesis. In this context, injection-moulding parameters and gate-induced flow behaviour become particularly important because they directly influence filler orientation and conductive network formation within the final component.

Therefore, understanding the role of conductive fillers, transport mechanisms and processing-related microstructural effects becomes essential for the development of reliable multifunctional polymer housings [31].

The following chapter focuses on conductive filler systems and the mechanisms governing EMI shielding and thermal transport in polymer composites.

Chapter 4

Solution Direction: Polymers & Composites

4.1. Functional Enhancement Through Conductive Fillers

The rapid growth of electric, hybrid and highly automated vehicles has transformed the functional requirements of automotive electronic housings. Plastic covers that were once responsible only for mechanical protection are now expected to contribute to electromagnetic compatibility, heat management and long-term reliability in crowded electronic environments [15–18]. Metals can deliver this level of functional protection but conflict with lightweight, cost and sustainability targets, whereas neat polymers lack the electrical and thermal properties needed for EMI shielding and efficient heat spreading [21,22,26–29]. This mismatch has motivated an intensive shift toward advanced conductive polymer composites: polymer matrices such as PA6, PC, PP, ABS or ASA that are modified with functional fillers to provide electrical and/or thermal conduction in addition to the usual benefits of low density, corrosion resistance and geometric freedom [16,21,22,26–30].

These composite systems are increasingly adopted in modules where the housing is part of the functional architecture rather than an inert support. Examples include LED headlamp and rear-lighting bodies, radar and camera enclosures, domain and gateway ECUs, infotainment units mounted in confined dashboards, and control electronics embedded in battery packs or on-board chargers [16,18, 20,26]. In such applications, the enclosure shapes the electromagnetic environment around antennas and high-speed buses, and it defines the main path through which heat leaves power devices. The possibility of tailoring electrical and thermal properties through filler design, while preserving the mechanical and packaging advantages of polymers, is therefore central to metal-replacement strategies in modern automotive electronics.

From a formulation standpoint, conductive fillers used to upgrade neat polymers can be grouped into four main families, schematically illustrated in Figure 7: metal fillers, carbon-based fillers, ceramic fillers and hybrid systems. Metal fillers include stainless-steel, copper or aluminium fibres and powders, which offer high electrical conductivity and, consequently, strong shielding by reflection; they also assist heat conduction but at the cost of higher density [26,31]. Carbon-based fillers such as carbon fibres, graphite flakes, carbon nanotubes (CNTs) and graphene nanoplatelets provide a combination of good electrical and thermal conductivity with comparatively low density and high aspect ratio, making them attractive for lightweight housings [26,28,34–38]. Ceramic fillers (e.g. alumina, aluminium nitride, hexagonal boron nitride) are electrically insulating yet thermally conductive; they are preferred where galvanic isolation must be preserved while still spreading heat away from components [22,27]. Hybrid systems combine two or more filler types for example, metal fibres with CNTs or graphite with ceramic powders to balance shielding, thermal conduction, mechanical integrity and processability in a single compound [[21,22,26,35–37]].

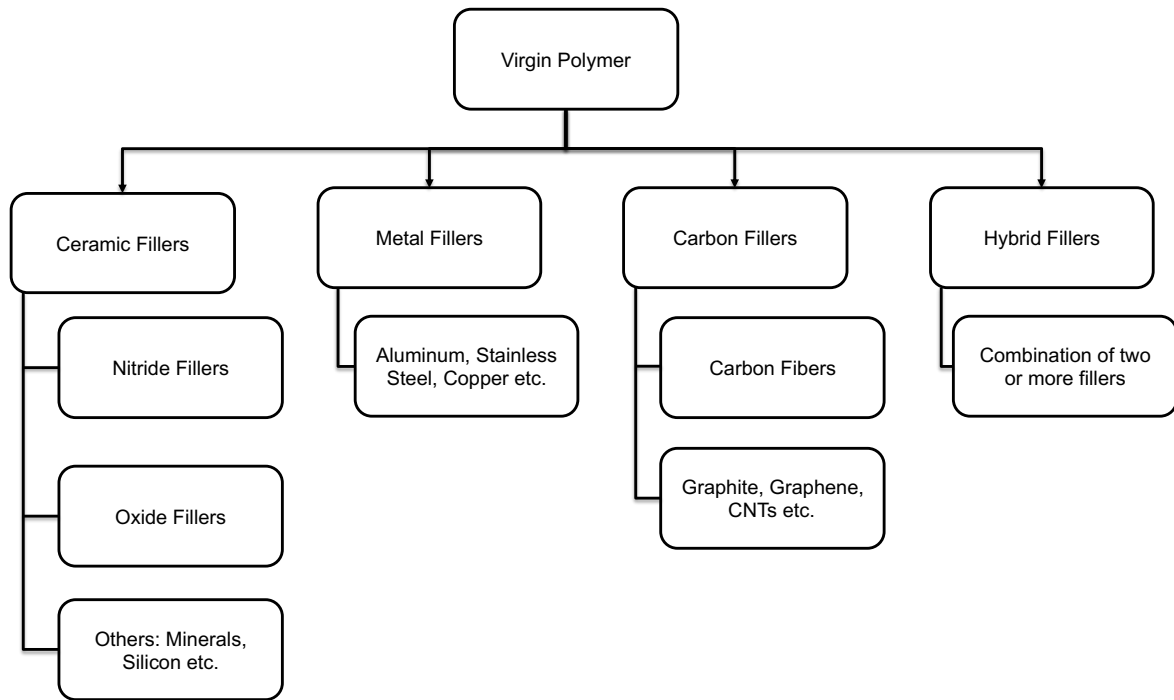


Figure 7. Classification of conductive fillers used in polymer composites [38].

A common feature of these systems is the formation of interconnected filler networks inside the polymer matrix. As discussed in Chapter 2, neat polymers exhibit extremely low electrical conductivity and poor heat transport. When the concentration, geometry and dispersion of conductive fillers are chosen appropriately, a continuous path forms across the material, enabling the composite to conduct charge carriers and phonons much more efficiently than the base resin alone [21,22,26]. For EMI shielding, this network provides multiple interfaces that reflect incident electromagnetic waves and dissipate them by Joule heating as they traverse the lossy composite [21,26,28,31,32,33,34,36]. For thermal management, the same network shortens heat-flow paths and reduces temperature gradients, which is crucial in compact LED drivers and power-electronics enclosures [9,22,34,35]. High-aspect-ratio fillers; fibres, platelets, nanotubes are particularly effective because they can build such networks at lower volume fractions than spherical particles.

The impact of network design on EMI shielding effectiveness (EMI SE) is evident in the literature data summarised in Table 4. Layered CNT-PMMA structures, in which nanotubes are concentrated into specific regions of the polymer, achieve 50–60 dB EMI SE in the X-band [32]. PLA/CNC/CNT hybrids combine bio-based matrices with CNTs and reach 30–50 dB between 8 and 12 GHz [38]. Graphene-nanoplatelet composites, especially those with segregated or foam-like architectures, often show 40–80 dB over broad frequency ranges [36]. Even ABS composites processed by fused-deposition modelling retain 30–45 dB shielding, demonstrating that printed structures can also host effective conductive networks [34]. These ranges fall within, or exceed, the 30–60 dB window typically targeted for automotive modules, indicating that well-designed composites can satisfy EMC requirements without relying exclusively on metal housings [1,5–7,32-34,36].

Table 4. Representative EMI shielding performance of conductive polymer composites.

Composite Polymers	EMI SE (dB)	Frequency Range	Source
CNT–PMMA layered structure	50–60 dB	X-band	Pande et al., 2009 [32]
PLA/CNT/CNC hybrid	30–50 dB	8–12 GHz	Yu et al., 2019 [36]
Graphene-loaded polymer	40–80 dB	Broadband	Li et al., 2023 [34]
ABS + Carbon composite (FDM)	30–45 dB	Various	Schmitz et al., 2018 [33]

It is important, however, to recognise the limitations and trade-offs associated with some filler families. CNTs, for instance, appear in many academic studies because of their outstanding intrinsic conductivity and aspect ratio, yet their practical benefits are not always proportional to their theoretical potential. Bai et al. showed that adding CNTs to PA12 for selective laser sintering only modestly improved thermal behaviour, with gains constrained by dispersion challenges and interfacial resistance [39]. Similar observations are reported in other thermoplastic systems where CNT networks remain incomplete or are disrupted during processing [32,36]. In addition, CNTs are costly and their production raises environmental and health concerns, which complicates large-scale adoption. These types of graphite, graphene, stainless-steel fibres or hybrid networks that can deliver comparable shielding with simpler processing and more favourable sustainability profiles [26,28,31,33,34].

The second key performance requirement for automotive housings is thermal conductivity. Typical thermoplastics exhibit conductivities below about $0.25 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, which is insufficient to dissipate heat from densely packed power devices [9–11,15,22]. Conductive fillers address this by creating preferential pathways for phonon transport. Graphite and graphene, with their high in-plane thermal conductivity, are particularly effective when arranged into continuous or cellular networks; ceramics such as boron nitride offer an electrically insulating alternative; copper and other metals provide highly conductive backbones at the expense of density [24,34–36]. The gains achievable through careful filler architecture are summarised in Table 5.

Table 5. Thermal conductivity improvements via conductive fillers.

Composite Polymers	Thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Improvement vs. neat polymer	Source
Graphene cellular composite	10–20	~50×	Alam et al., 2017 [35]
Graphene nanoplatelet composite	5–15	~20–40×	Li et al., 2023 [34]
CNT-annealed polymer	+200% conductivity	–	Thi et al., 2022 [37]

Overall, the literature demonstrates that advanced conductive polymer composites can, when properly formulated, deliver EMI shielding levels compatible with automotive EMC standards and thermal conductivities far beyond those of neat polymers [19,30–35,39]. The decisive factor is not only which fillers are chosen, but how they are distributed,

oriented and connected at multiple length scales. This microstructural control is strongly influenced by processing conditions compounding, moulding, part geometry and gate design, which govern whether a robust conductive network is established or disrupted. The next section therefore shifts from material formulation to manufacturability, examining how highly filled composites behave during injection moulding and how process parameters can be used to steer filler orientation and network formation toward the EMI and thermal performance targets of this thesis.

4.2. Manufacturability Challenges in Highly Filled Polymer Composites

The same conductive fillers that enable polymers to meet electromagnetic and thermal requirements also make them significantly more difficult to process. When the filler content is raised to the levels needed for EMI shielding or heat-spreading, the melt rheology departs from that of neat PA6, PC, PP or ABS and becomes highly viscous and often shear-sensitive. Hybrid systems containing stainless-steel fibres, copper microfibrils, graphite flakes or CNTs form internal particle–particle networks that increase the apparent viscosity and reduce flowability, especially in thin ribs and long flow paths typical of headlamp housings and ECU cover [23,24,33,34,35]. As a result, highly filled composites are more prone to incomplete filling, jetting, weld lines, voids and local segregation if the process window is not carefully adjusted [41,42,43]. At the same time, excessive shear cannot be used as a simple solution: very high injection speeds and pressures may break fibres, disturb the conductive network and deteriorate both EMI SE and thermal conductivity, so processing cannot rely on “pushing harder” with higher speed and pressure [23,24,44].

Among the various forming routes for thermoplastics (extrusion with secondary forming, thermoforming, compression moulding and additive manufacturing), injection moulding is the technology that best matches automotive requirements for electronic housings. A single injection cycle can reproduce complex three-dimensional geometries with integrated clips, sealing features and thin walls at cycle times compatible with high-volume production and at a cost per part that remains competitive for millions of units [30,42]. Figure 8 schematically illustrates a typical injection-moulding cell and headlamp housing tool, highlighting the link between pellet feeding, screw plasticisation, cavity filling and ejection. For highly filled composites, however, the standard parameter windows used for neat polymers are rarely adequate. Melt and mould temperatures, injection profile, packing pressure and cooling strategy must all be re-tuned so that the viscous, particle-rich melt can reach thin ribs, stand-off pins and remote corners without premature solidification, while still avoiding excessive shear at the gates and sharp turns [40-44]. Process design therefore becomes an integral part of functional material design, not a downstream step.

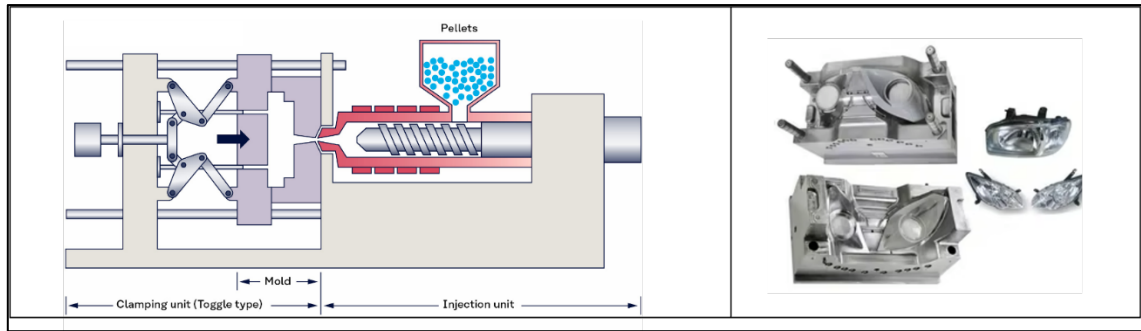


Figure 8. Schematic representation of an injection-moulding cell for an automotive headlamp housing, showing pellet feeding, plasticising screw, closed steel tool and ejected parts [45].

Compared with neat polymers, conductive composites operate within a much narrower and more sensitive injection-moulding window. Experimental and numerical studies on fibre-reinforced and particle-filled thermoplastics show that barrel temperature, injection speed, packing pressure and cooling profile strongly influence defect formation, shrinkage/warping and internal stresses [40,41,46]. Too low a melt temperature or injection rate can cause hesitation and frozen fronts, leading to short shots, exaggerated weld lines and poor surface quality; excessively high settings may induce flash, residual stresses, surface defects and even local degradation of sensitive fillers [41,43,47]. Packing and holding conditions must be sufficient to compensate for increased solidification shrinkage while avoiding over-packing, which can generate internal stresses, sink marks or distortion in optical regions. These trade-offs are particularly severe in composites with 40–80 wt% filler, where pressure drop along the flow path increases rapidly and the available processing window shrinks [22,30,40,41].

Beyond defect avoidance, injection-moulding conditions also control the internal architecture of the composite, particularly fibre or platelet orientation. Classical orientation studies and modern simulations consistently show that the cavity develops a characteristic layered structure: a high-shear skin layer near the wall where elongated fillers align with the flow direction, and a lower-shear core region where orientation is more random or even transverse [23,44]. This morphology produces strong anisotropy: stiffness, electrical conductivity and thermal conductivity are often enhanced in-plane along the main flow direction, whereas through-thickness properties remain comparatively low [22,24,48]. For conductive composites, this means that EMI shielding and heat transport are governed not only by filler content but also by the microstructure generated by the moulding process. Recent reviews on surface quality and dimensional stability further emphasise that flow-induced morphology, pVT behaviour and cooling gradients jointly determine residual stresses, warpage and local defect sensitivity in highly filled systems [30,43,46,47].

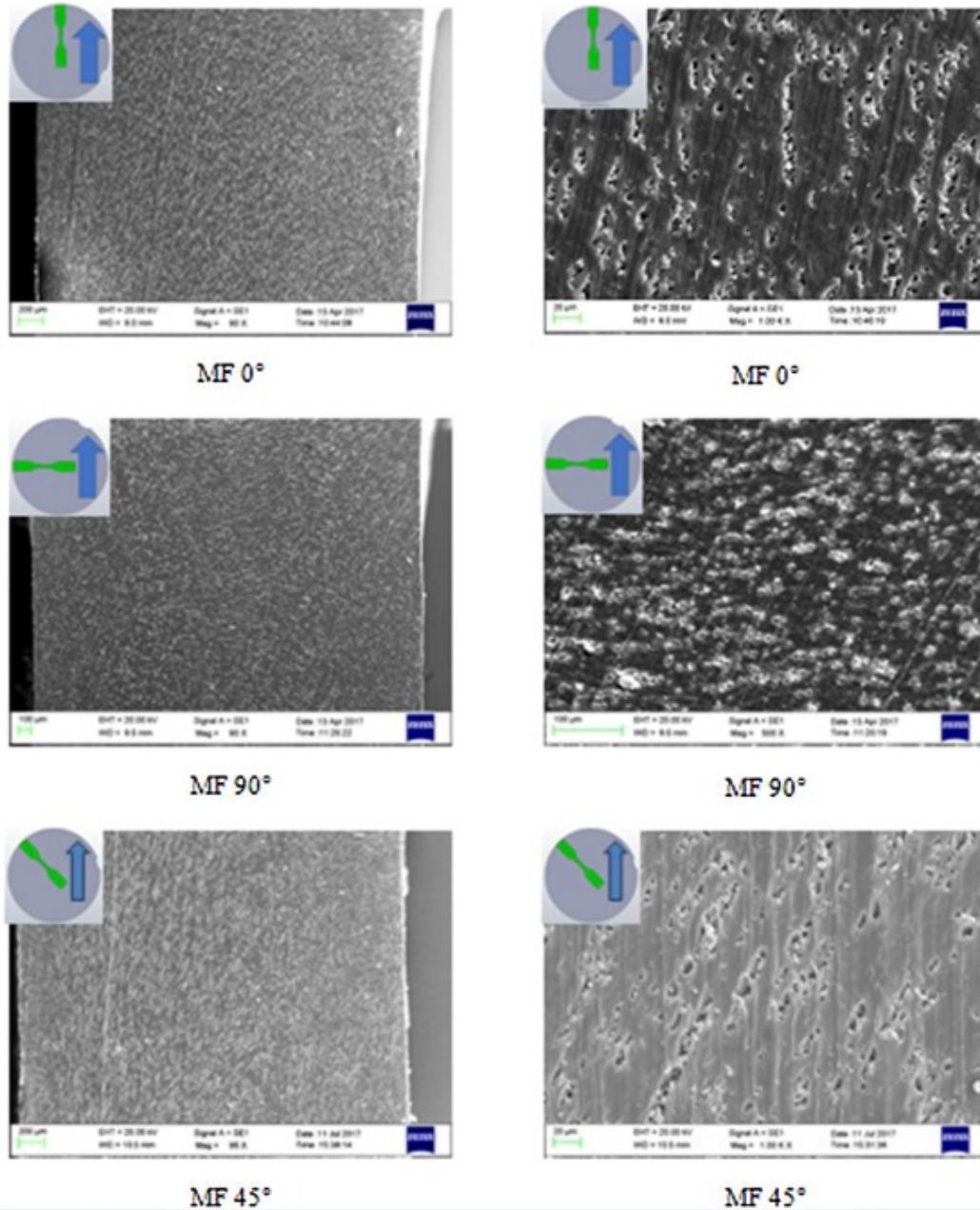


Figure 9. SEM micrographs of magneto-sensitive polymer composites with oriented magnetic fillers at different angles with respect to the applied magnetic field (adapted from Volpe et al. [49]).

Magneto-sensitive polymer composites provide an instructive extreme case of how processing can reshape the internal network. In polypropylene-matrix and thermoplastic elastomer systems containing magnetic particles, the combination of fountain flow and external magnetic fields leads to directional migration and alignment of fillers, producing gradient structures and strongly anisotropic mechanical behaviour [49,50]. Figure 9, adapted from Volpe et al. [49], shows SEM micrographs of magneto-sensitive composites moulded with different orientations relative to the applied magnetic field, where columnar particle chains form along preferred directions. Although the present thesis does not employ magnetic fields, these studies clearly demonstrate that the conductive network in

a composite part is not fixed by formulation alone; it is co-defined by the flow and thermal history imposed during injection moulding.

For electrically and thermally functional composites, gate design is one of the most powerful levers for steering this process-induced microstructure. In this context, gate design should not be regarded merely as a mould-filling parameter, but as a microstructure-engineering tool capable of steering conductive-network formation and anisotropic functional behaviour within the final component. Gate type, size and location determine the dominant flow directions, shear rates and weld-line positions throughout the cavity. Fan and diaphragm gates distribute the melt over a wide front, promoting smoother filling and more homogeneous orientation fields in large plate-like regions, whereas small pin or tunnel gates inject the melt through a narrow entrance, generating high shear and strongly oriented “jet” regions downstream [43-45]. As illustrated schematically in Figure 10 commonly used gate geometries in automotive housings include sprue, pin, edge, fan, tunnel and diaphragm gates, each associated with a characteristic filling pattern. By locating gates close to thermally or electromagnetically critical regions for example beneath LED driver boards or around connector interfaces it becomes possible to align conductive fibres and flakes in directions that favour in-plane heat spreading and continuous shielding paths, while still avoiding weld lines in optically or mechanically sensitive zones [42,43,51,52].

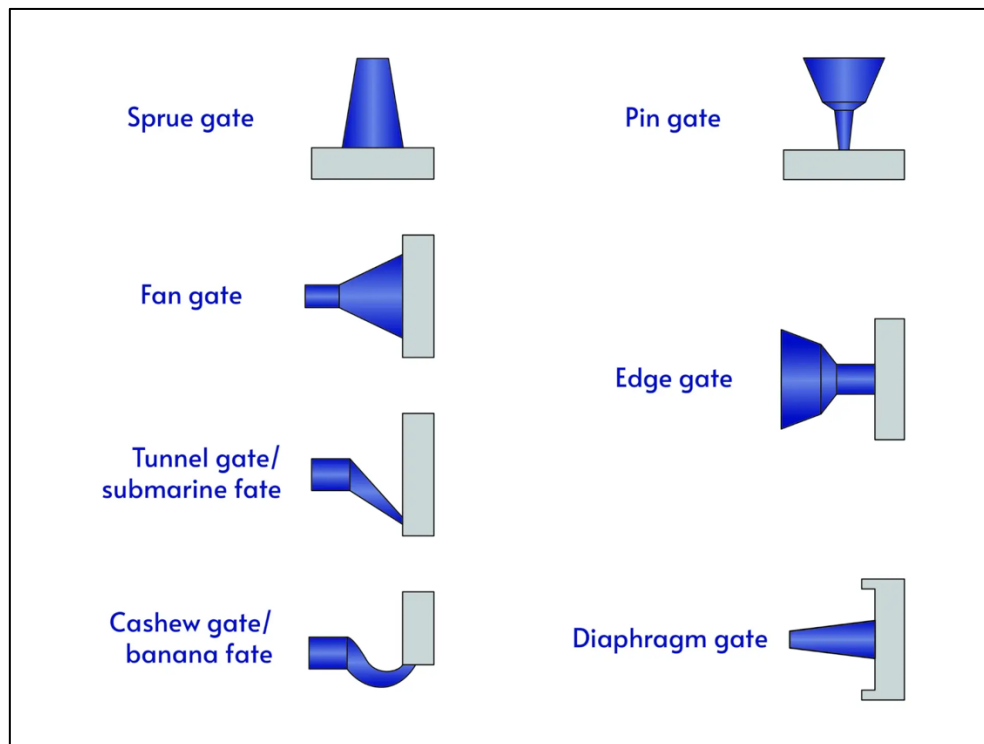


Figure 10. Examples of gate types used in injection moulding of polymer housings (sprue, pin, edge, fan, tunnel and diaphragm gates) and their typical flow-front development. Adapted from SW CPU[52].

In summary, once high filler loadings are introduced to meet EMI and thermal targets, manufacturability becomes a coupled material-and-process challenge. Conductive

polymer composites can only deliver metal-like functional performance if their injection-moulding behaviour is engineered with equal care: viscosity and pressure must remain compatible with industrial cycle times, defects and warpage must be controlled, and gate-driven flow patterns must be exploited to build favourable conductive networks rather than random, anisotropic ones. The next chapter therefore integrates computer-aided engineering (CAE) simulations with experimental moulding trials to identify process windows and gate configurations that simultaneously satisfy shielding effectiveness, thermal management and robust mouldability for the automotive housings studied in this thesis.

4.3. CAE-Based Injection Moulding Simulation for Process and Warpage Optimisation

The transition from neat polymers to highly filled conductive composites makes empirical, trial-and-error process setup increasingly inadequate. In conventional practice, injection-moulding parameters are tuned directly on the machine, relying on operator experience and successive adjustments. For complex housings with thin ribs, integrated clips and highly viscous composite melts, this approach leads to long start-up times, high scrap rates and only a superficial understanding of why certain parameter combinations work while others fail. Computer-aided engineering (CAE) tools for injection moulding have therefore become essential to predict filling, packing, cooling and warpage behaviour before steel is cut and before production trials are launched [30,42,53]. Modern 3D solvers couple non-Newtonian rheology, heat transfer and shrinkage models with fibre-orientation or particle-transport equations, allowing engineers to explore process windows and tooling options virtually for both neat and highly filled materials.

Among the available software, Moldex3D is widely adopted for engineering thermoplastics and has been successfully applied to standard grades as well as highly filled composites [42,44,51,53]. Its flow-front, pressure and temperature predictions help identify the risk of short shots, air traps, weld lines and local overheating, while its shrinkage and warpage modules estimate post-ejection deformation under realistic cooling conditions. For conductive composites, these capabilities are particularly valuable because the same regions that are difficult to fill thin walls, long flow paths and sharp transitions are often the locations where EMI shielding continuity and heat-spreading performance are most critical.

Figure 11 illustrates a typical Moldex3D analysis for an automotive exterior component, where a gate-location advisor proposes candidate gate positions and the corresponding filling simulation displays the melt-front-time distribution. Such results provide a first quantitative indication of whether a proposed gate layout and process window are compatible with the rheological constraints imposed by high filler loadings [42,44,53,54].

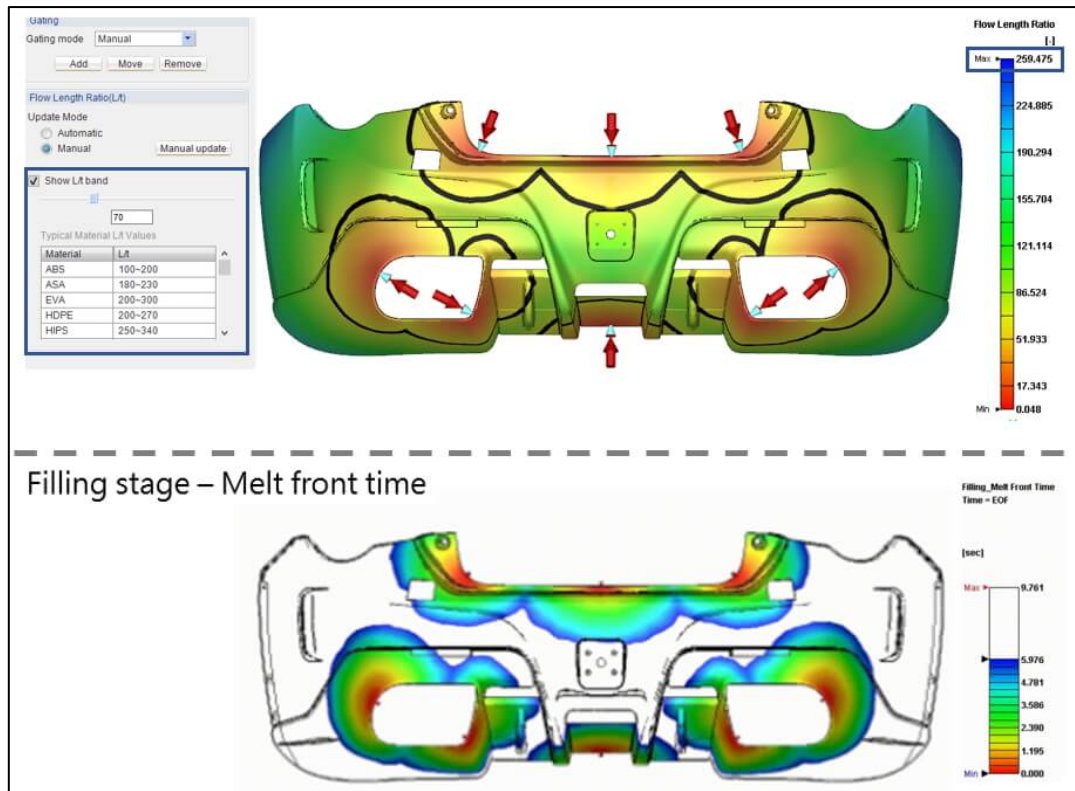


Figure 11. Example of Moldex3D gate-location advisor and filling simulation for an automotive bumper-like component: (top) suggested gate positions based on flow-length ratio, (bottom) melt-front-time distribution at the end of filling (adapted from Moldex3D Technical Blog [53]).

Recent literature confirms the effectiveness of CAE-driven optimisation in reducing defects and development time. Otieno and co-workers combined computer-aided engineering simulations, design-of-experiments techniques and intelligent optimisation algorithms to develop predictive models for shrinkage and warpage in injection-moulded plastic components [55]. Their results demonstrated that process parameters such as melt temperature, mould temperature, packing conditions and cooling strategy can be systematically optimised in a virtual environment, allowing defect prediction and quality improvement before physical production trials are undertaken. The developed models achieved high predictive accuracy for both shrinkage and warpage, highlighting the potential of simulation-assisted optimisation to reduce material waste, shorten development cycles and minimise costly trial-and-error experimentation. Similar workflows have been reported for optical and technical parts, where CAE-guided parameter screening replaces large experimental matrices and shortens process-development cycles from weeks to days [30,42,55]. In the context of advanced conductive composites, such methods avoid costly mould modifications and minimise scrap associated with over-packing, sink marks or deformation in mechanically and functionally sensitive regions

Beyond defect prediction, CAE tools play a central role in understanding how process conditions influence microstructure. Flow-induced fibre or platelet orientation, discussed in Section 3.2, can be quantified via orientation tensors that are solved alongside the filling

kinematics. Studies combining Moldex3D simulations with X-ray microtomography or microscopy have shown strong correlations between predicted orientation fields and measured mechanical properties in glass-fibre-reinforced thermoplastics [24,44,56]. Related approaches are being extended to magneto-sensitive and highly filled particulate systems, where simulations help interpret directional particle migration and network formation under complex flow histories [49,50]. For conductive polymer composites, this means that CAE is not only a tool for checking whether a part fills, but also a means of anticipating where conductive pathways will be strong or weak and how gate design or process tuning can be used to steer the internal architecture toward favourable EMI shielding and thermal performance. Orientation tensors are commonly used to quantify the degree and directionality of filler alignment generated during injection moulding. Such descriptors are increasingly employed in effective-conductivity modelling to correlate local microstructure with anisotropic electrical and thermal transport behaviour in conductive composites [48,56]

In this thesis, injection-moulding simulations are therefore employed as an integral element of the technical strategy rather than as an ancillary verification step. Moldex3D is used to virtually compare gate concepts; to screen combinations of melt and mould temperatures, injection times and packing levels; and to predict filling completeness, pressure requirements, temperature gradients, fibre-orientation patterns and warpage for both neat and filled PA6 and PC housings. By combining CAE results with targeted moulding trials, the work aims to identify process windows and gate configurations that deliver robust manufacturability while preserving the electromagnetic and thermal benefits of conductive polymer composites.

4.4. Implications for the Present Thesis

The literature reviewed in this chapter confirms that conductive polymer composites represent a technically credible route for replacing metallic housings in selected automotive electronic applications. Functional fillers can substantially increase EMI shielding effectiveness and thermal conductivity [21,22,26,28,31–37,39], while injection-moulding simulation provides valuable support for predicting flow behaviour, pressure requirements, defect formation and warpage [30,42–44,53].

Nevertheless, the transition from material potential to industrial implementation remains only partially resolved. Much of the available literature focuses on material formulation and coupon-level characterisation, whereas fewer studies address how conductive composites behave in realistic housing geometries under industrial processing constraints. In particular, the role of gate design is often discussed mainly in terms of filling quality, weld-line formation or dimensional stability, rather than as a possible lever for controlling filler orientation, conductive-network continuity and anisotropic EMI/thermal performance.

This gap is directly relevant to the present thesis. The work does not treat filler selection, injection-moulding parameters, gate configuration and CAE simulation as independent topics. Instead, they are considered as coupled variables within a material–process–performance framework. Within this framework, gate-induced flow fields are investigated

as a means of influencing filler orientation and therefore the functional behaviour of the final housing[56,57,58].

Accordingly, the following chapters focus on the experimental and numerical evaluation of PA6- and PC-based conductive composites under representative industrial conditions. The objective is to determine whether optimized material selection and process design can provide not only acceptable mouldability, but also reliable EMI shielding and thermal-management performance at component level.

Chapter 5

Research gap and Thesis Motivation

Over the past decade, significant research efforts have focused on conductive polymer composites for automotive applications, particularly for electromagnetic shielding and thermal-management purposes. However, most published studies remain limited to coupon-level material characterisation, primarily reporting intrinsic thermal conductivity or EMI shielding effectiveness under simplified laboratory conditions. In many cases, material formulation, injection-moulding process design, and component-level functional validation are investigated separately rather than as an integrated engineering problem.

For real automotive electronic housings, however, thermal management, EMC performance, manufacturability, dimensional stability, and surface quality must be achieved simultaneously under industrial production conditions. The final functional behaviour of conductive polymer composites is not governed solely by filler type or loading, but also by process-induced microstructural features such as filler orientation, dispersion quality, and conductive-network continuity, all of which strongly depend on injection-moulding parameters and gate design. Despite this, relatively few studies have addressed the combined relationship between material formulation, processing conditions, and final component-level performance.

In addition, many conductive-polymer studies remain positioned at relatively low Technology Readiness Levels (TRLs), where validation is limited to laboratory specimens or simplified demonstrators. The transition toward industrially relevant validation including full-scale injection-moulded components, climatic-chamber testing, thermal imaging, EMC qualification, and manufacturability assessment remains comparatively limited in the literature.

The present thesis addresses this gap through an integrated process–structure–function framework specifically developed for automotive electronic housings. Rather than proposing entirely new filler chemistries, the work focuses on the industrial implementation and validation of commercially available conductive polymer systems under realistic manufacturing and operating conditions. The thesis combines:

- conductive material selection,
- Moldex3D-assisted injection-moulding optimisation,
- gate-design analysis,
- standard-specimen characterisation,
- statistical evaluation,
- and full component-level thermal and EMC validation.

A dual-path strategy was adopted throughout the study:

- a thermal-driven route for lighting-housing applications requiring enhanced heat dissipation,
- and an EMI-driven route for electronic screening enclosures requiring high electromagnetic shielding effectiveness.

Through this approach, the thesis bridges the gap between laboratory-scale material characterisation and industrially relevant automotive validation, demonstrating the

feasibility and limitations of conductive polymer composites as alternatives to conventional metal or ASA-based housings in next-generation vehicle electronics.

Chapter 6

Materials and Methods

The overall methodology of this work was divided into two main stages, as summarized in Figure 12. The first stage, named Preliminary Campaign (PC), was dedicated to the identification of the most suitable composite materials for thermal and electromagnetic applications. The second stage, referred to as Industrial Production (IP), focused on the validation of the selected materials through the manufacturing and testing of real automotive components.

In the Preliminary Campaign (PC) phase, various polymer-based composites were selected based on their filler type and concentration (PC1). Standard demonstrator geometries were then designed according to EMI and thermal conductivity testing standards (PC2), and Finite Element Method (FEM) simulations were performed using Moldex3D to identify the optimal moulding parameters [42,53,54].

After production of standard specimens, thermal conductivity and EMI shielding effectiveness (EMI SE) were measured following the respective testing standards. The obtained results were analysed to identify the best-performing materials for each functional requirement, namely thermal management or EMI shielding, which were subsequently used for the design of the industrial parts.

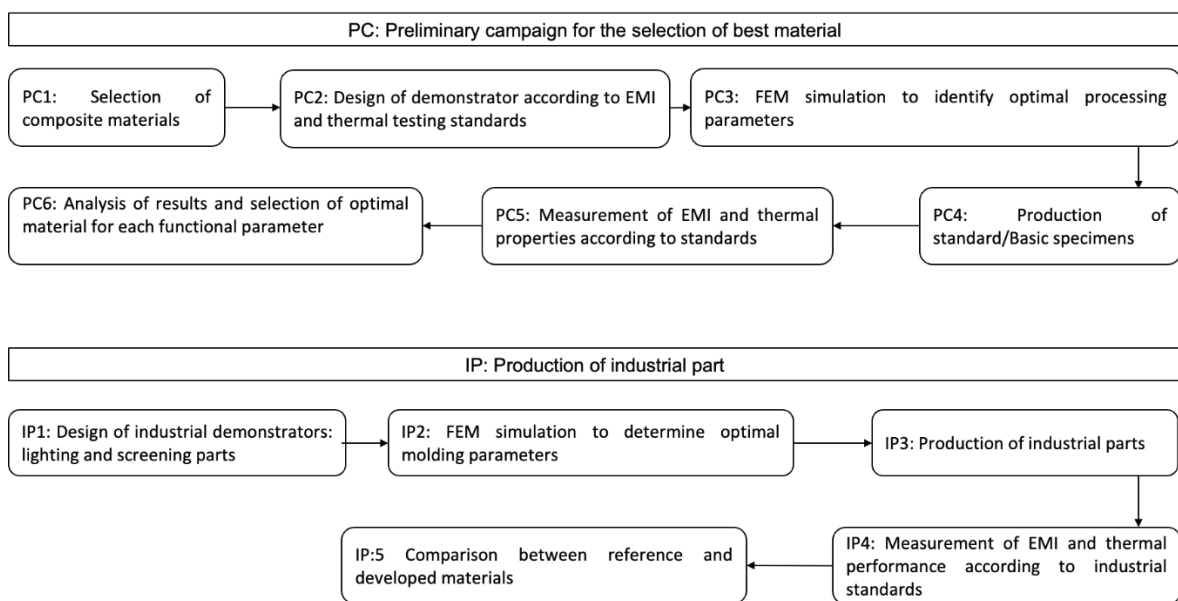


Figure 12. Overall workflow of the study: from preliminary material screening to industrial validation of automotive housings.

The second phase, Industrial Production (IP), aimed to validate the selected materials at the component level. Two different parts were considered: a lighting housing for thermal optimisation and a dashboard screening component for EMI protection (IP1). Each part was simulated through FEM analysis to define the optimal process conditions prior to moulding. The selected materials were then processed via injection moulding, and the manufactured components were tested according to relevant automotive industrial standards [59-61].

Table 6. Summary of the methodological workflow from preliminary screening to industrial validation.

Stage	Step	Objective	Main output
PC	PC1 Material selection	Select filled polymers for thermal and EMI screening	Candidate material matrix
PC	PC2 Demonstrator design	Define standard specimen geometry compatible with testing methods	Rectangular plate geometry
PC	PC3 Moldex3D simulation	Identify process windows and compare gate configurations	Optimized moulding parameters
PC	PC4 Injection moulding	Produce standard specimens	Moulded plates for testing
PC	PC5 Characterisation	Measure thermal conductivity and EMI SE	Material-level performance data
PC	PC6 Material selection	Rank materials using functional and manufacturability criteria	Selected candidates for IP
IP	IP1 Industrial demonstrator design	Define real automotive parts	Lighting housing and dashboard enclosure
IP	IP2 CAE simulation	Optimize industrial moulding conditions	Process windows and warpage predictions
IP	IP3 Industrial moulding	Produce full-scale components	Moulded industrial parts
IP	IP4 Functional validation	Test thermal and EMC performance under industrial standards	Component-level validation results
IP	IP5 Comparison	Compare polymer solutions with reference materials	Feasibility assessment

Finally, the performance of the newly developed polymer composites was compared with that of conventional materials to assess improvements in both thermal management and electromagnetic shielding capabilities.

6.1. Selection of Composite Materials and Formulations (PC1)

In this work, several commercially available filled polymer composites were selected to investigate their suitability for thermal management and electromagnetic interference (EMI) shielding applications in automotive electronic housings. The materials were supplied by SABIC, Radici Group, and LATI, representing three industrial manufacturers with established expertise in high-performance polymer formulations (Table 7) [59-61].

The selection of materials was guided by three main criteria:

1. Base polymer type (PA6, PC, or PPc) to evaluate the influence of the polymer matrix on processability, thermal behaviour, and electrical properties.

2. Filler composition and concentration including graphite, carbon fibre (CF), stainless steel, glass fibre, ceramic, and hybrid systems (e.g. CF + steel fibre), to study how filler type and content affect conductivity and flow behaviour during injection moulding.
3. Target functional property distinguishing between materials optimized for thermal conductivity, EMI shielding effectiveness (EMI SE), or both.

A summary of the selected materials, their compositions, and main datasheet properties is reported in Table 7.

Table 7. Summary of selected materials, their compositions and key datasheet properties for EMI and thermal performance screening (data adapted from supplier technical documentation [59-61])

Supplier	Material Code	Base Polymer	Filler Type & Content (wt%)	Target Property	Elongation at Break (%)	Tensile Strength (MPa)	Elastic Modulus (MPa)	HDT (1.8 MPa, °C)
SABIC	PX10323	PA6	Graphene, Glass fibre, and hybrid fillers	EMI SE + Thermal	2.0	65	7000	180
	DS0036I	PC	Stainless steel fibre (15%)	EMI SE + Thermal	2.1	54	3300	125
	DTK22	PC	Mineral fillers	EMI SE + Thermal	2.5	55	5500	135
Radici Group	LX24059	PA6	15% CF	EMI SE + Thermal	2.5	200	20500	205
	LX24060	PA6	15% CF + Steel fibre	EMI SE + Thermal	2.1	190	19000	205
	LX24061	PA6	20% CF	EMI SE + Thermal	2.3	225	26000	205
LATI	66 H2 K/40 NT	PA6	20% CF + 5% Steel fibre	EMI SE	1.5	245	27000	252
	62GR50	PA6	50% Graphite	Thermal conductivity	1.2	50	13000	180
	62GR70	PA6	70% Graphite	Thermal conductivity	0.8	40	12000	190
	87/24-08A	PC	8% SS fibre	EMI SE	2.0	45	3000	132
	87/28-10A	PC	10% SS fibre	EMI SE	1.5	65	2500	125
	47/30 CP1/800	PPc	Ceramic filler (30%)	Thermal conductivity	2.5	12	1500	49

The selected materials cover a wide range of formulations and performance levels.

- SABIC materials (e.g. Konduit-PX10323 and DTK22) are hybrid-filled compounds containing graphene, minerals, and stainless steel, specifically engineered to balance thermal conductivity and EMI shielding.

- Radici Group materials (e.g. LX24059–LX24061) are PA6-based composites reinforced with carbon and steel fibres, suitable for dual-function applications where both thermal and electromagnetic performance are required.
- LATI materials (e.g. 62GR70, 87/24-08A, and 66H2K40NT) include graphite- and steel-filled compounds optimized for either thermal dissipation or EMI shielding, allowing a comparative evaluation between single-function and multi-function formulations.

6.2. Design of Standard Demonstrator and FEM Simulation (PC2–PC3)

To evaluate the selected materials under realistic moulding and testing conditions, a standard demonstrator part was designed according to thermal and EMI testing standards. The geometry was defined to ensure compatibility with both ASTM D4935 (for EMI shielding effectiveness) [62] and ISO 22007-2 (for thermal conductivity) [63] sample requirements, allowing a unified design to be used for both functional evaluations. This approach ensured consistency across different materials and simplified comparative analysis.

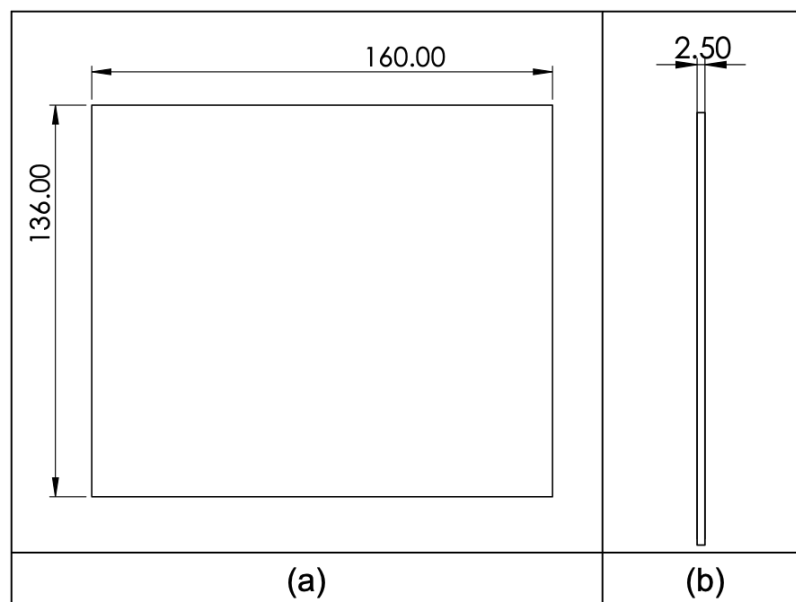


Figure 13. Geometry of the rectangular plate specimen: (a) front view, (b) side view.

The demonstrator was designed, according to the standards as a rectangular plate geometry (dimensions: 160 mm × 136 mm × 2.5 mm) by SolidWorks (Figure 13). This configuration allowed the assessment of material flowability, warpage tendency, and surface quality while maintaining sufficient surface area for EMI and thermal measurements.

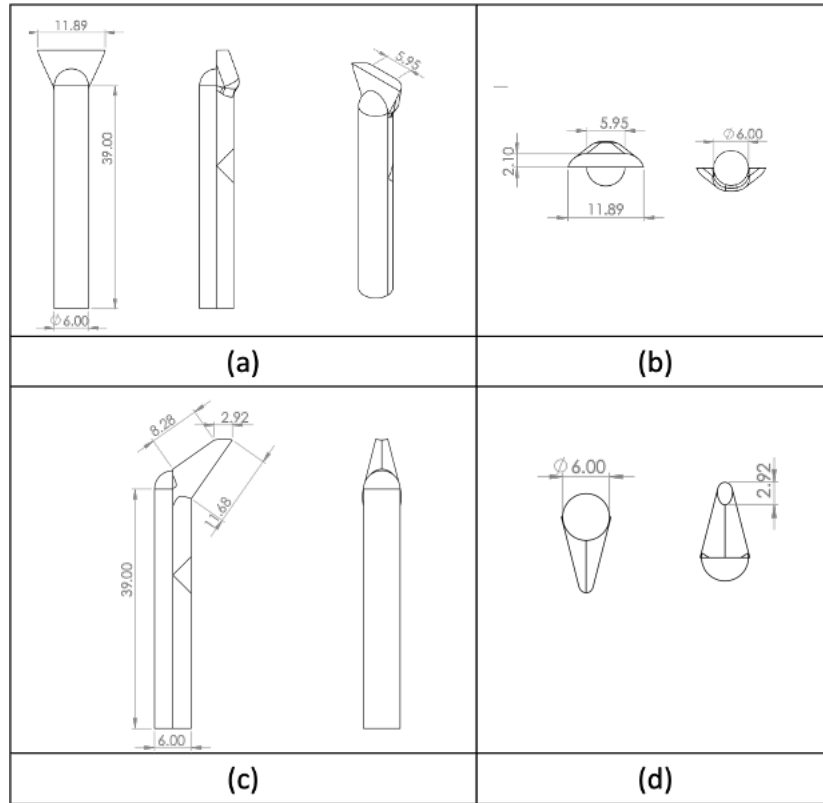


Figure 14. CAD views of standoff pin geometries: (a,b) direct-gate configuration, (c,d) tunnel-gate configuration.

To investigate the influence of gate design on filling behaviour and dimensional accuracy, two alternative gate configurations were developed and simulated in Moldex3D:

- Direct gate (Figure 14(a,b)) positioned on one corner of the plate, designed to achieve a short flow path and uniform front advancement,
- Tunnel gate (Figure 14(c,d)) located beneath the plate and connected through a conical runner, intended to promote symmetric filling and improved packing.

Both gate types were analysed for each material formulation to evaluate differences in pressure distribution, flow uniformity, fibre orientation, and warpage. Comparative analysis of the two gating systems provided useful insights for selecting the most suitable configuration for the subsequent injection moulding trials.

Prior to injection moulding, Finite Element Method (FEM) simulations were performed using Moldex3D to identify the optimal processing parameters for each material [51,53,54]. The simulation workflow included:

- Filling and packing analysis, to evaluate viscosity and flow pattern variations as a function of filler content and temperature;
- Fibre orientation prediction, to assess potential anisotropy introduced by fibre-reinforced systems;
- Warpage and shrinkage estimation, to minimize dimensional deformation during cooling.

6.3. Production of Standard Specimens and Experimental Characterisation (PC4–PC5)

Based on the Moldex3D simulation results, all selected polymer formulations were subsequently processed by injection moulding to evaluate their manufacturability and functional performance. The trials were carried out using a Zhafir VEII 1500/430 injection-moulding machine equipped with a temperature-controlled steel mould and a cold-runner system. Processing parameters including melt temperature, mould temperature, injection speed and packing pressure were selected according to the optimized simulation outputs in order to ensure stable cavity filling, limited warpage and consistent surface quality.

For each material formulation, at least ten specimens were produced. This number was considered sufficient for visual inspection, dimensional verification, sample preparation and repeated thermal or EMI-related measurements. Since the objective of this stage was preliminary material screening, the focus was placed on identifying comparative performance trends between commercially available conductive polymer systems rather than establishing full industrial qualification limits.

Table 8. Processing parameters used in Moldex3D simulations and corresponding injection-moulding trials.

Parameters	Moldex3D	Injection Moulding
Melt temperature (°C)	270-300	270-300
Filling Time (s)	0.32-0.78	0.32-0.78
Packing Time (s)	7-12	7-12
Packing Pressure (MPa)	50-70	50-70
Cooling Time (s)	10-20	10-20

The injection cycle consisted of the filling, packing, cooling, and ejection stages, each closely monitored to guarantee reproducibility across different formulations. After moulding, the samples were visually inspected for surface defects (e.g. weld lines, short shots, sink marks, flash), and dimensional stability was verified through warpage and flatness measurements, later compared against Moldex3D predictions to validate simulation accuracy.

6.3.1. Thermal characterisation

Thermal conductivity was measured using two complementary methods, Transient Plane Source (TPS) and Heat Flow Meter (HFM), to ensure cross-validation of results. The tests were conducted in accordance with ISO 22007-2, ASTM C518, and ISO 8301, using the Hot Disk TPS 2500S and FOX 50 Heat Flow Meter (HFM) instruments (Figure 15, Figure 16) [63-65].

Each sample was tested in 3 replicates to ensure reproducibility, and the mean thermal conductivity value (λ , W/mK) was calculated.

(a) Hot Disk – Transient Plane Source (TPS) Method

The Hot Disk TPS 2500S determines thermal conductivity and diffusivity by applying the Transient Plane Source (TPS) principle [63,66].

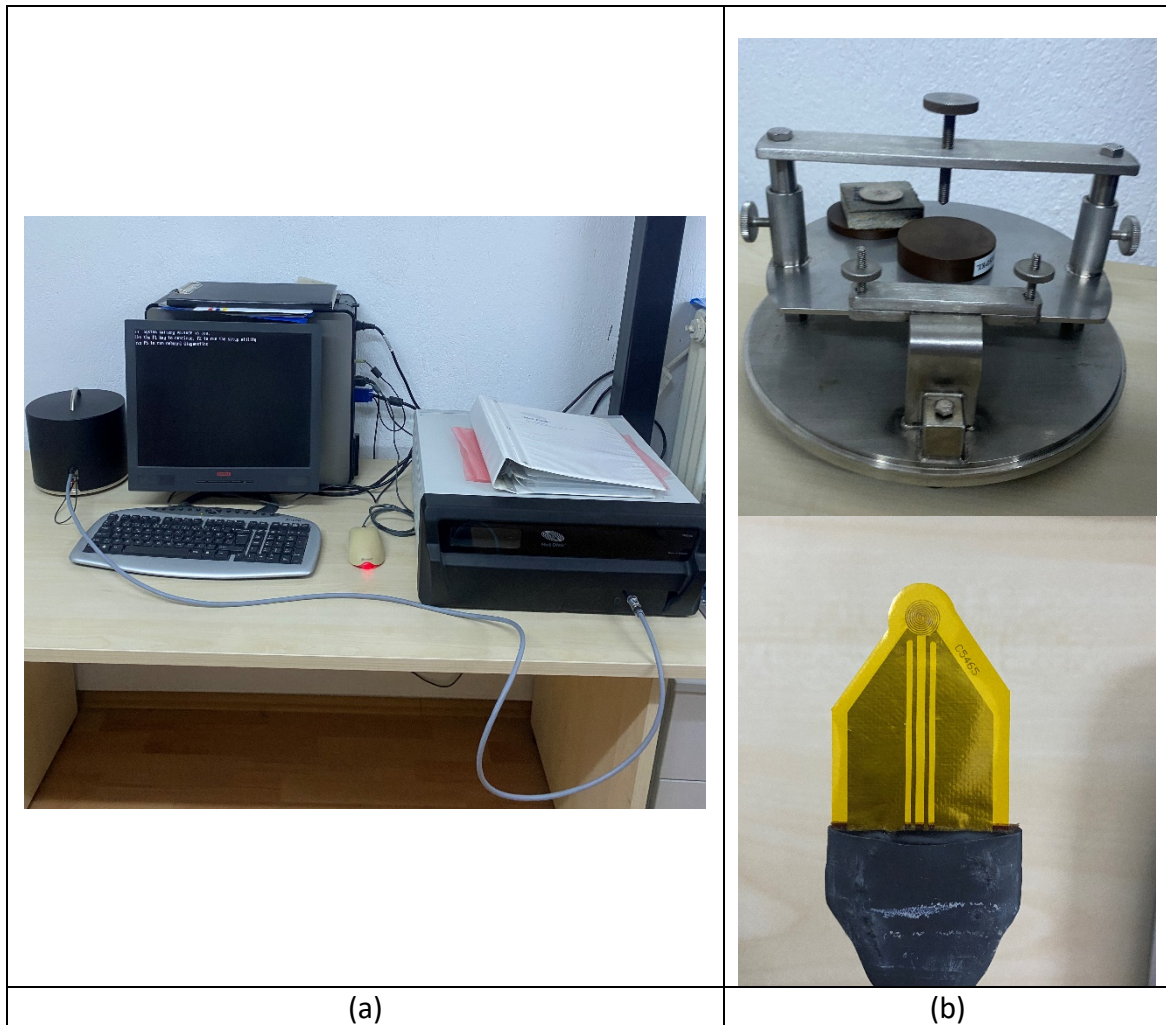


Figure 15. Hot Disk thermal conductivity measurement setup based on the Transient Plane Source (TPS) method (a), and detailed views of the sensor and sample positioning during testing (b).

A double-spiral nickel sensor embedded between two halves of the sample acts simultaneously as a heat source and temperature detector (Figure 15 (b)).

When a controlled electrical pulse is applied to the sensor, heat propagates radially through the specimen. The temperature rise over time (ΔT) is recorded, and the thermal conductivity (λ) is obtained from the analytical solution of transient heat conduction [63,66]:

$$\lambda = P / (\pi^{3/2} \cdot r_s \cdot (\Delta T / \sqrt{t}))$$

(Eq.1)

where P is the applied power, r_s is the sensor radius, and t is time.

This non-destructive technique allows localized mapping of heat transfer paths, making it ideal for heterogeneous composite systems with anisotropic filler distributions.

(b) Heat Flow Meter (HFM) – Steady-State Method

Complementary measurements were performed using a FOX 50 Heat Flow Meter based on the steady-state heat transfer principle (Figure 16) [64,65].

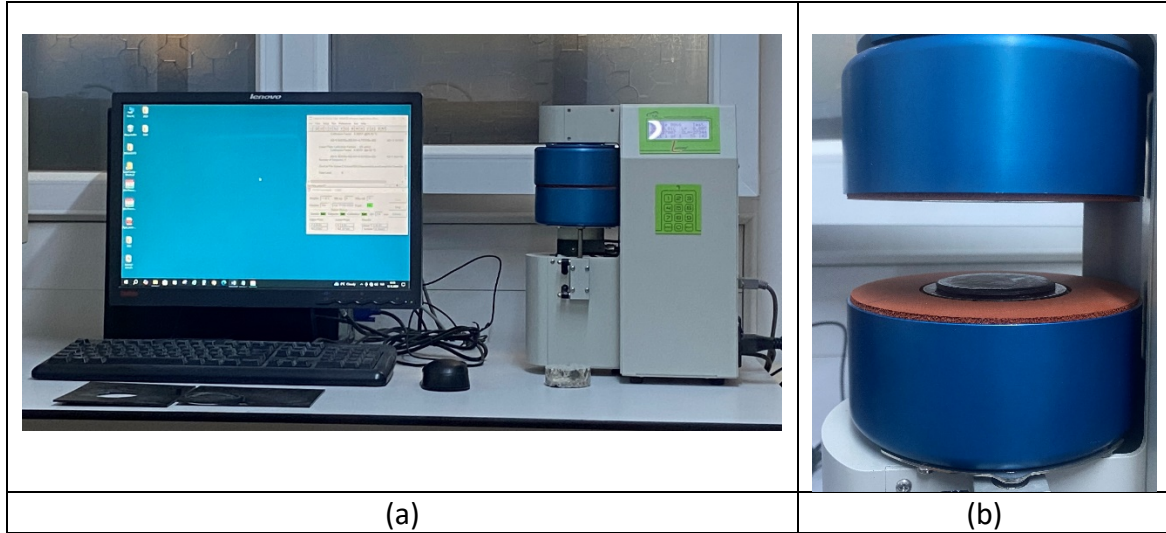


Figure 16. PC-controlled HFM test setup for evaluating the heat transfer performance of polymer composite specimens (a). Close-up image showing the specimen clamped between dual temperature-regulated plates for heat flow measurement (b).

In this method, the specimen is placed between two parallel plates maintained at different temperatures by Peltier elements. Once thermal equilibrium is achieved, the heat flux (q) passing through the sample and the temperature gradient (ΔT) across its thickness (d) are recorded.

Thermal conductivity is governed by Fourier's law of heat conduction [67]:

$$q = -kA(dT/dx)$$

(Eq. 2)

where:

- q is the heat-transfer rate (W),
- k is the thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$),
- A is the cross-sectional area normal to heat flow (m^2),
- and dT/dx is the temperature gradient through the material thickness.

Under steady-state one-dimensional heat flow conditions, the equation can be simplified as [64,65,67]:

$$\lambda = (Q \times d)/\Delta T$$

(Eq. 3)

where:

- λ is the thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$),
- Q is the heat flux through the specimen ($\text{W}\cdot\text{m}^{-2}$),
- d is the specimen thickness (m),
- and ΔT is the temperature difference across the specimen thickness (K).

The HFM test provides bulk through-plane thermal conductivity data under steady-state conditions and complements the transient, localized information obtained from the TPS method. The combination of these two approaches ensures a more comprehensive understanding of both steady-state and transient heat-transport behaviour in the filled polymer systems [63-67].

6.3.2. EMI Shielding measurements

The electromagnetic shielding effectiveness (EMI SE) of the moulded plates was measured according to ASTM D4935, using a coaxial transmission line test fixture connected to a Vector Network Analyzer (VNA) (Figure 17.) [62].

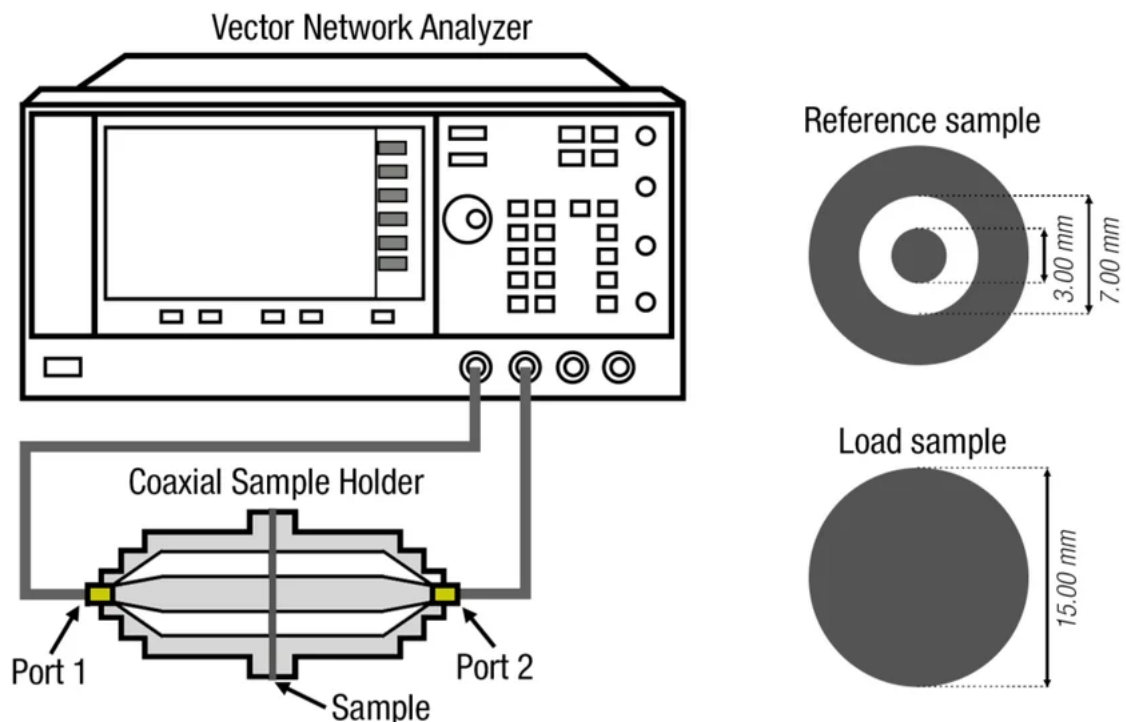


Figure 17. Schematic of the coaxial transmission-line setup for EMI shielding measurements (ASTM D4935) [62].

Measurements were performed over the frequency range used in the experimental campaign, covering the frequency interval relevant to the investigated automotive electronic applications.

Three specimens per formulation were tested to ensure statistical repeatability, and the mean shielding effectiveness (SE) value was reported in decibels (dB).

Materials containing conductive fillers such as stainless steel, graphite, or carbon fibre exhibited the highest SE values, indicating improved electromagnetic attenuation.

The ASTM D4935 coaxial transmission method evaluates how much electromagnetic energy is reflected and absorbed by a material when exposed to a plane wave in a coaxial setup.

The circular disk specimen (outer diameter = 15 mm, inner hole = 7 mm) is mounted between the inner and outer conductors of the coaxial line (Figure 17).

The Vector Network Analyser (VNA) measures the scattering parameters (S_{11} and S_{21}) [62]:

- S_{11} represents the reflected signal (reflection loss),
- S_{21} represents the transmitted signal (transmission loss).

The total shielding effectiveness (SE) is then derived as [62,68]:

$$SE_{total} = 10 \log_{10}(P_i / P_t) = SE_R + SE_A + SE_M$$

(Eq. 4)

where P_i is the incident power, P_t is the transmitted power, SE_R is reflection loss, SE_A is absorption loss, and SE_M is multiple-reflection correction. This method provides frequency-dependent SE data, allowing the evaluation of both conductive and dielectric shielding mechanisms in polymer composites.

6.4. Analysis of Results and Material Selection (PC6)

Measurement uncertainty was considered during the analysis of thermal and EMI results. For thermal conductivity, uncertainty may arise from sensor calibration, sample thickness measurement, contact resistance, surface flatness, temperature stability, and material heterogeneity. For EMI shielding measurements, the main uncertainty sources include VNA calibration, specimen positioning inside the coaxial fixture, sample thickness tolerance, edge contact quality, and frequency-dependent instrumental noise. To reduce the influence of these factors, measurements were repeated on three specimens per formulation, mean values and standard deviations were calculated, and the same fixture, calibration procedure and testing protocol were maintained across all materials [62,66].

Error propagation was treated qualitatively by identifying the dominant uncertainty sources and quantitatively through the use of replicate measurements. Since the main

objective of the preliminary campaign was comparative material ranking [69], the interpretation focused on differences larger than the observed experimental scatter rather than on single-point values.

The experimental data collected from mechanical, thermal, electromagnetic, and mouldability evaluations were integrated into a systematic assessment framework. Prior to analysis, all datasets underwent reliability screening including repeatability verification and statistical consistency checks. Mean values and variance descriptors were extracted to construct a robust basis for comparison among material formulations.

Subsequently, statistical inference was performed via analysis of variance (ANOVA) to quantify the influence of material-design parameters namely polymer matrix, filler morphology and filler loading on the key performance indicators [69]. Complementary main-effects plots were used to visualise parameter sensitivities and to interpret how these factors govern mechanical, thermal and EMI-shielding properties. In parallel, manufacturability was assessed through injection-moulding trials, in which flow behaviour, surface integrity and dimensional stability were evaluated as processing-critical metrics.

The integration of statistical evaluation with process-level evidence enabled a rational material down-selection strategy driven by both functional performance and industrial feasibility. Based on this multi-criteria decision framework, the most promising material formulations were selected for advancement into the industrial validation stage (IP phase).

6.5. Design of Industrial Demonstrators: Lighting and Screening Parts (IP1)

The final stage of this study focused on the validation of the selected filled polymer formulations through the design, production, and testing of industrial demonstrator parts representative of real automotive applications. Two distinct components were developed in collaboration with COBO S.p.A.:

(a) a lighting housing, designed to assess thermal conductivity and heat dissipation;

The lighting component reproduces the rear body of an automotive headlamp. The CAD incorporates LED board seating, rear cooling fins, sealing grooves, screw bosses and connector interfaces, matching the functional envelope used at COBO. Wall thickness transitions and rib networks were kept consistent with industrial practice to promote heat spreading while avoiding sink marks. Figure 18. shows the final drawing used for tool manufacture.

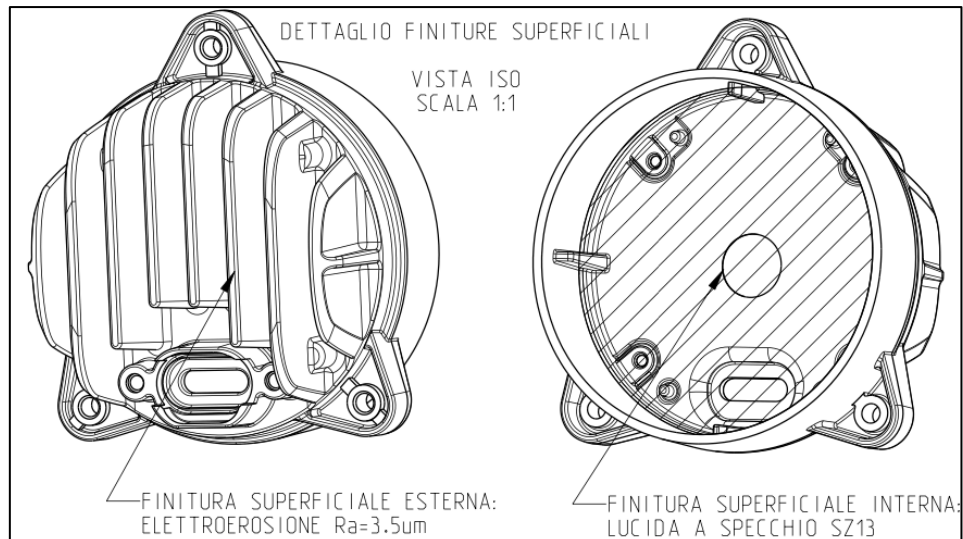


Figure 18. Technical drawing of the LED module housing showing the specified external and internal surface

(b) a dashboard screening enclosure, dedicated to electromagnetic shielding effectiveness (EMI SE).

Two enclosure variants representative of in-vehicle HMIs were developed: indash and outdash (Figure 19.). Both include connector frames, metallic inserts, ventilation slots and front bezel features. The geometry follows the real assembly constraints so that EMC can be verified on a functional module. The overall dimensions of the lighting housing are shown in Figure 18.

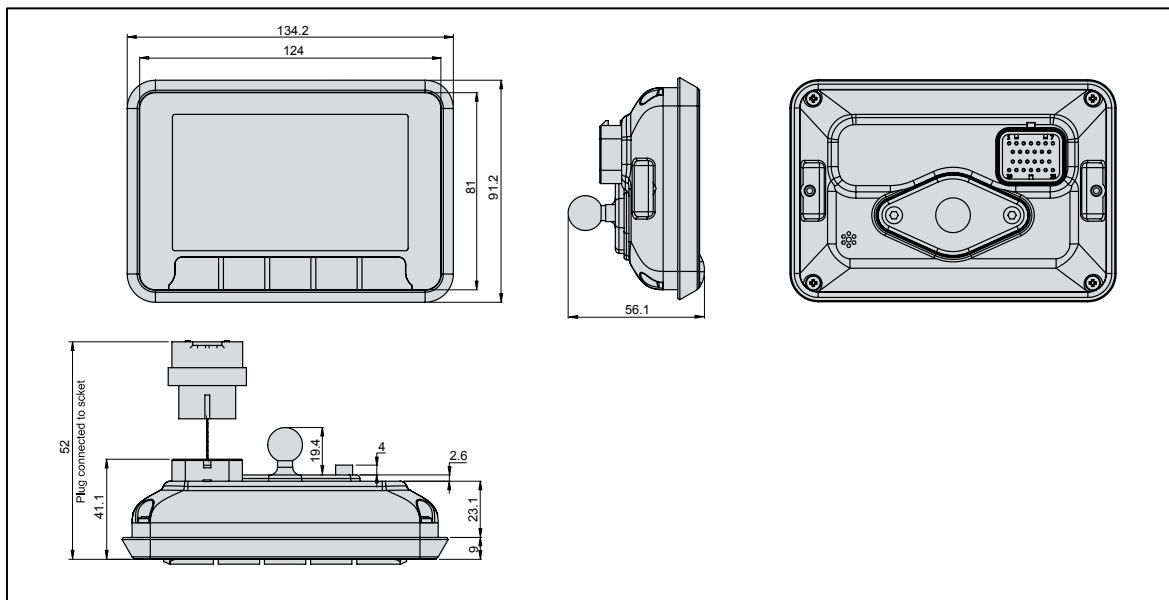


Figure 19. Technical geometry and overall dimensions of the TERA7 outdash housing used for EMC validation experiments (adapted from COBO technical documentation).

Both components were designed, simulated, moulded, and validated under industrial conditions to evaluate the feasibility of replacing metallic housings with polymer-based alternatives [34,68].

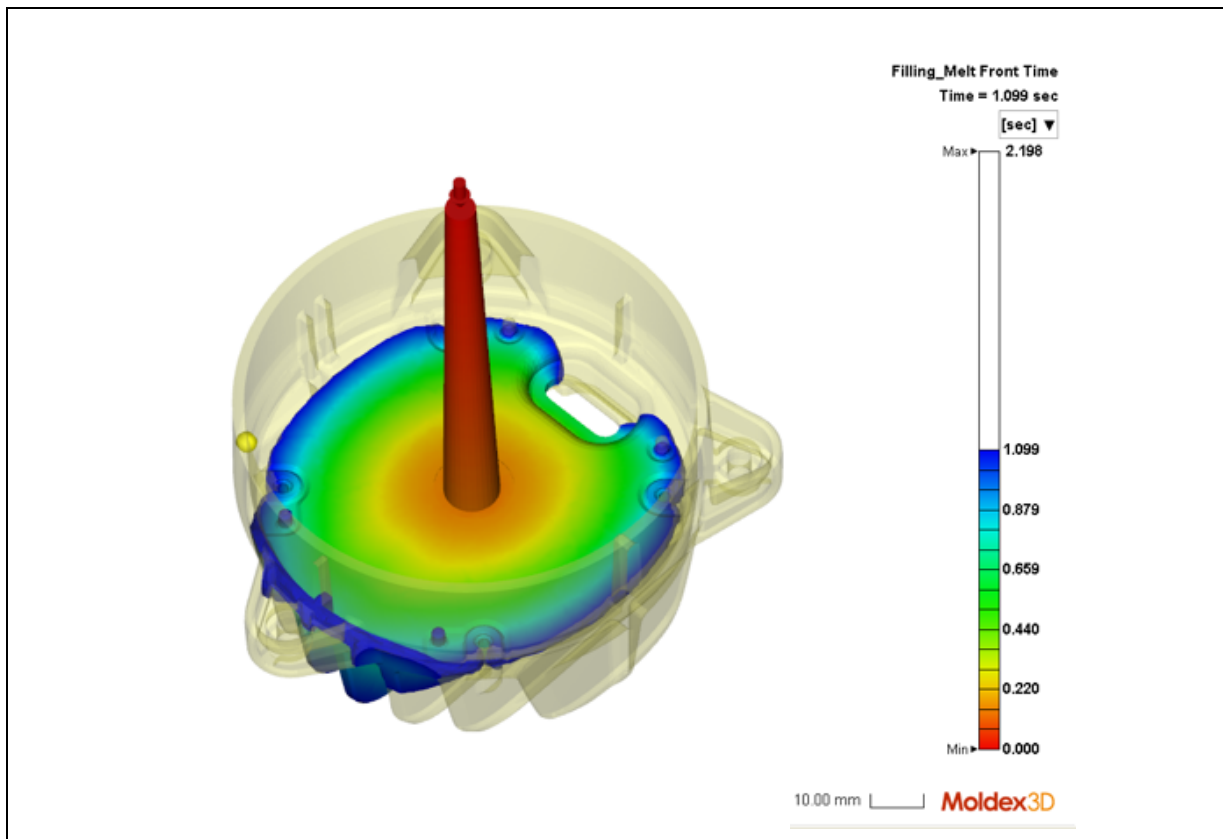
6.6. FEM Simulation to Determine Optimal Moulding Parameters (IP2)

To ensure accurate replication of industrial moulding conditions and to minimize dimensional deformation, a complete filling–packing–cooling–warping simulation was performed in Moldex3D for both selected thermal-oriented and EMI-oriented compounds polymer systems:

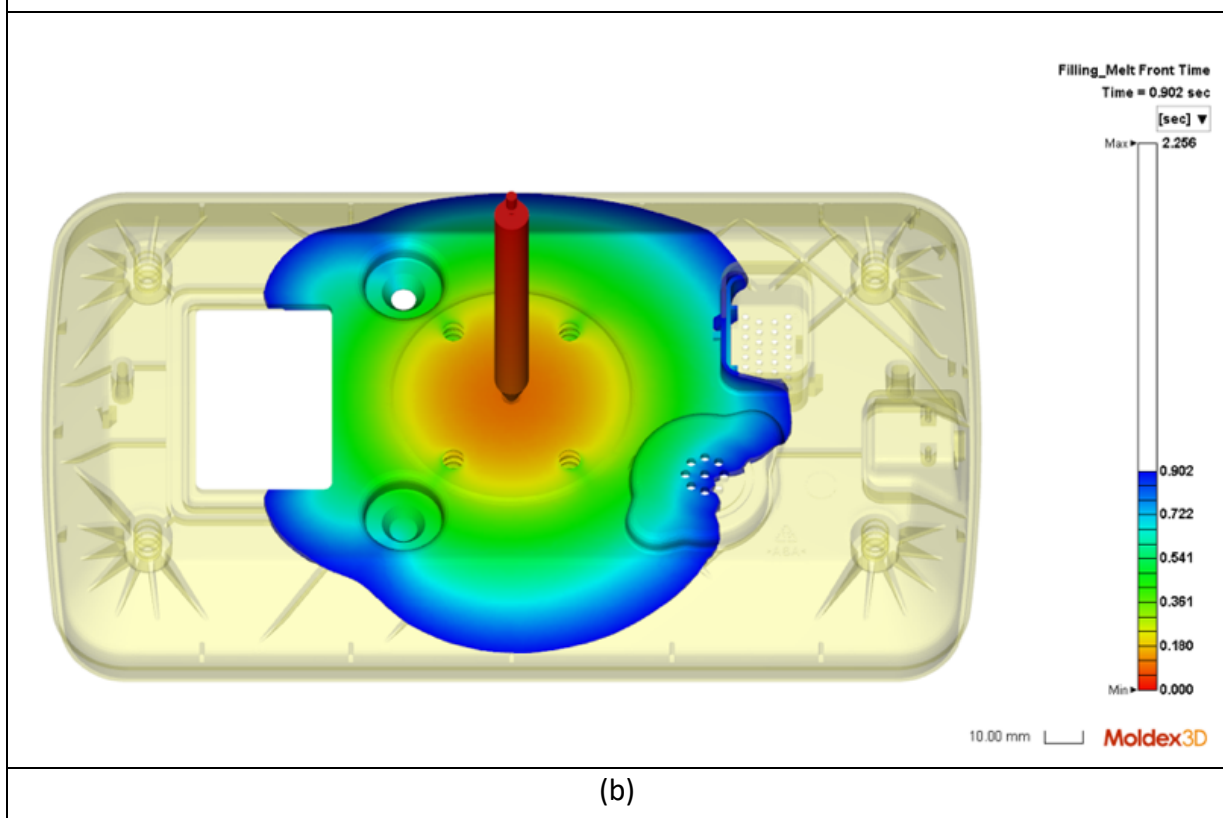
Different gate configurations had been preliminarily examined during the standard demonstrator campaign; based on those results, a single optimized gate design was adopted for both industrial parts to minimize flow hesitation and residual stress while maintaining balanced cavity filling.

This configuration was maintained throughout all injection moulding trials to ensure consistency across the two components.

Figure 20. shows the simulated filling pattern for the lighting housing, illustrating uniform flow distribution from the central gate and well-oriented fibres around the finned areas, which are critical for thermal dissipation.



(a)



(b)

Figure 20. Moldex3D filling simulation example showing melt-front time distribution for the selected conductive composite: (a) round LED headlamp housing, (b) dashboard display housing (central gate configuration).

Similarly, the screening (dashboard-type) component was analysed to assess potential weld line formation, pressure drop, and volumetric shrinkage in the EMI-sensitive regions, particularly around the connector and display zones.

The simulations provided quantitative predictions for:

- Melt front advancement and filling pressure,
- Shear rate and viscosity distribution,
- Fibre orientation and anisotropy index,
- Cooling rate and temperature uniformity,
- Volumetric shrinkage and warpage deformation.

The simulation outputs were used to select the most suitable injection parameters, including melt and mould temperatures, injection speed, and packing pressure, for each material, with the aim of ensuring complete filling and minimal deformation.

These parameters were subsequently implemented during the experimental moulding trials on the Zhafir VEII 1500/430 (Figure 21) injection moulding machine.

This simulation-based optimisation ensured that the selected materials could be processed under realistic industrial conditions while maintaining high dimensional accuracy, good surface finish, and stable filler orientation essential for both thermal conductivity and EMI shielding performance in the final assemblies.

6.7. Injection Moulding and Production of Industrial Parts (IP3)

The selected polymer formulations identified through the preliminary testing phase were moulded using the Zhafir VEII 1500/430 injection moulding machine (Figure 21)

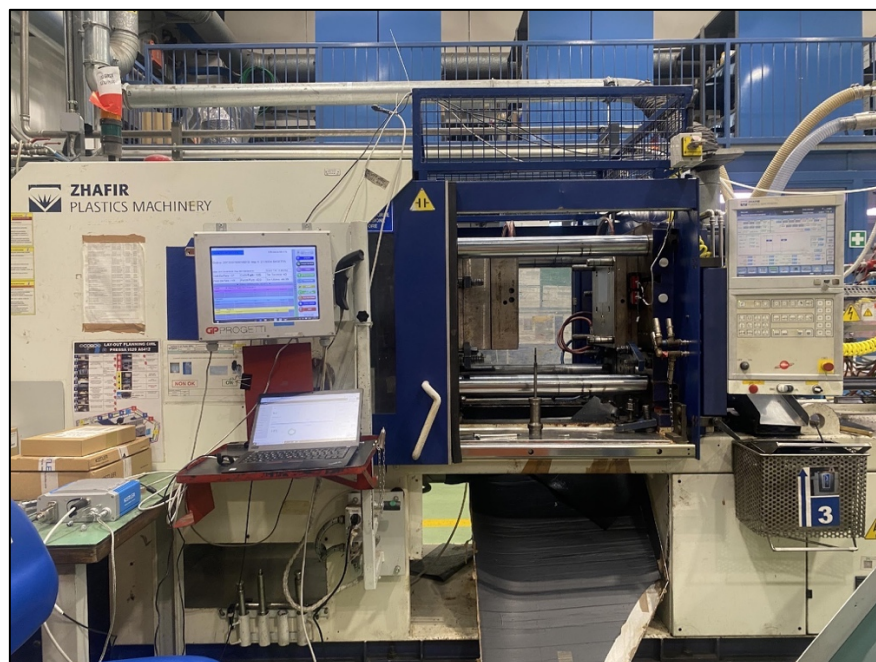


Figure 21. Industrial moulding work station used for experimental production trial.

As described in the previous section, the process parameters optimized through Moldex3D simulations including melt temperature, mould temperature, injection speed, and packing pressure were directly implemented to replicate industrial conditions.

This ensured stable flow behaviour, minimal warpage, and consistent fibre orientation, enabling accurate validation of the materials under real manufacturing environments.

All moulded components were then visually inspected to verify complete cavity filling, absence of surface defects, and overall dimensional integrity before proceeding with the subsequent thermal and EMI testing stages.

6.8. Functional Validation: Thermal and EMI Testing according to Industrial Standards (IP4)

This phase focused on the functional validation of the injection-moulded industrial components, evaluating their performance under realistic automotive operating conditions.

Two complementary validation routes were followed:

1. Thermal validation, conducted on the lighting housing, to assess heat dissipation and thermal stability.
2. EMI validation, performed on the dashboard screening enclosure, to evaluate electromagnetic compatibility (EMC) and shielding performance.

All tests were designed in accordance with international automotive standards, ensuring direct comparability with industrial qualification procedures.

6.8.1. Thermal validation of the lighting housing

• Thermal Simulation of Housing Materials (Siemens Simcentre)

Before conducting the experimental thermal validation tests, a preliminary computational study was performed using Siemens Simcentre FloEFD to predict the heat dissipation behaviour of the candidate housing materials under controlled and identical boundary conditions [67,70]. This virtual evaluation provides a first indication of the thermal pathways and temperature distribution within the lighting module during LED operation, enabling a fair comparison of the intrinsic thermal capabilities of the selected materials.

Heat transfer within the housing predominantly follows conduction through the solid polymer or metal structure, combined with natural convection and radiative heat loss from the outer surfaces to the surrounding air. The simulation is governed by the three-dimensional energy conservation equation [67,70]:

$$\rho \cdot c_p \cdot \partial T / \partial t = \nabla \cdot (k \cdot \nabla T) + Q$$

(Eq.5)

where k is the thermal conductivity of the housing material and $\dot{q}$ represents the thermal power transferred from the LED into the structure. All geometric features of the final design were included, including the heatsink body, internal ribs, mounting surfaces, lens-contact interfaces, and LED PCB interface regions. Thermal loads were applied directly to the LED contact area in accordance with manufacturer specifications.

To ensure that performance differences arise solely from the material properties, all parameters except the housing material were kept constant. The boundary conditions and simulation environment are listed in Table 9. Boundary conditions applied in the Siemens Simcentre FloEFD thermal simulation

Table 9. Boundary conditions applied in the Siemens Simcentre FloEFD thermal simulation

Boundary Condition	Value
Ambient temperature	25 °C
Cooling condition	Natural convection + radiation
Heat input	Manufacturer-specified LED thermal load
External surface	Convective and radiative heat exchange
PCB–housing interface	Thermal contact resistance applied

Three materials were evaluated using the same headlamp housing geometry: reference aluminium, a PA6-based conductive compound (LATI 62GR70) and a PC-based compound (SABIC PX10323). Aluminium was included as a benchmark with high heat-spreading capability, enabling a relative assessment of the improved conductive polymers targeted in this thesis. This simulation stage therefore serves as an analytical precursor to the experimental thermal validation tests, where the predicted trends were later confirmed through infrared thermography and step-temperature derating evaluations.

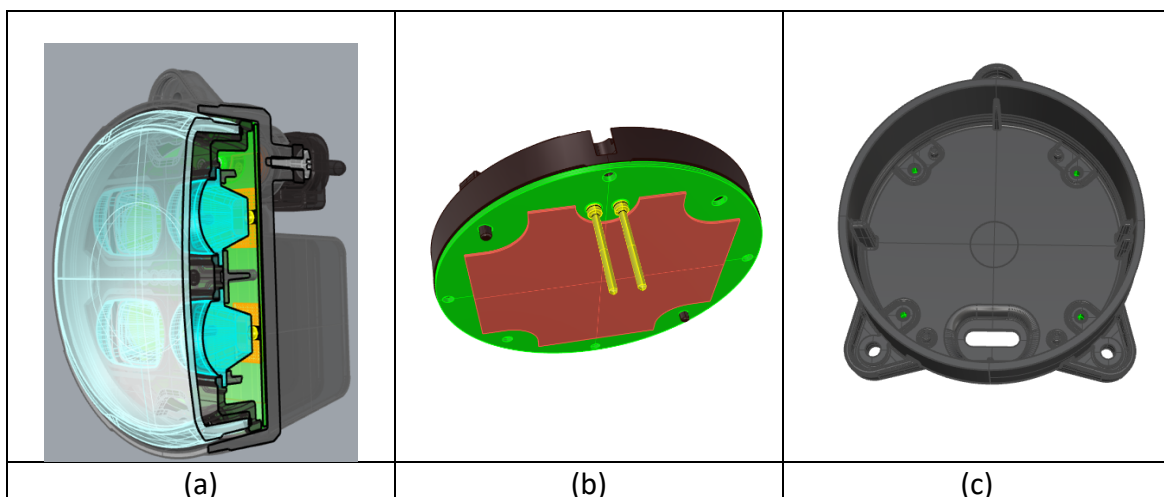


Figure 22. CAD geometry used for the Siemens Simcentre thermal simulation: (a) optical and mechanical cross-section of the D80 module, (b) heat-transfer interface between PCB and housing, and (c) rear-housing internal features.

The aim of this numerical study is not to replace experimental testing but to guide material selection and establish safe and effective thermal performance expectations before physical production.

• **Thermal Characterisation Test (Temperature-Step Method)**

Standard references: ISO 16750-4 (Road vehicles - Environmental testing - Part 4: Climatic loads) and IEC 60068-2-14 (Change of temperature) [13,71].

The temperature-step test was designed to evaluate the temperature rise and heat dissipation behaviour of the headlamp housings during prolonged operation. Fully assembled lighting modules were placed inside a climatic chamber, starting from +20 °C up to +60 °C, with +5 °C increments per hour (total duration: 9 h). During testing, both current absorption and rear body temperature were continuously recorded to assess the material's thermal stability and dissipation capability under realistic load conditions.

The temperature sensor (thermocouple) was positioned at the centre of the rear housing, as illustrated in Figure 23. , to capture the representative temperature of the heat-dissipating area.



Figure 23. Position of the thermocouple on the rear housing used for temperature-step (derating) test.

This step-based protocol reproduces the thermal fatigue conditions typically experienced by automotive lighting systems, allowing direct comparison of polymer vs. aluminium housings in terms of operational thermal management.

- Infrared Thermal Imaging (FLIR E95)

Standard references: ISO 18434-1 (Condition monitoring and diagnostics of machines – Thermography general procedures) [72], ISO 16750-4 (Climatic loads)[13].

Complementary infrared thermal imaging was performed using a FLIR E95 thermal camera to visualize and quantify the surface-temperature distribution on the lamp assembly. The lighting modules were operated inside the climatic chamber under steady-state conditions, and infrared images were recorded after 30 minutes and 1 hour of operation. An emissivity value of 0.96 was applied for the polymer surfaces to ensure accurate temperature conversion according to the Stefan–Boltzmann radiation law [67,70].

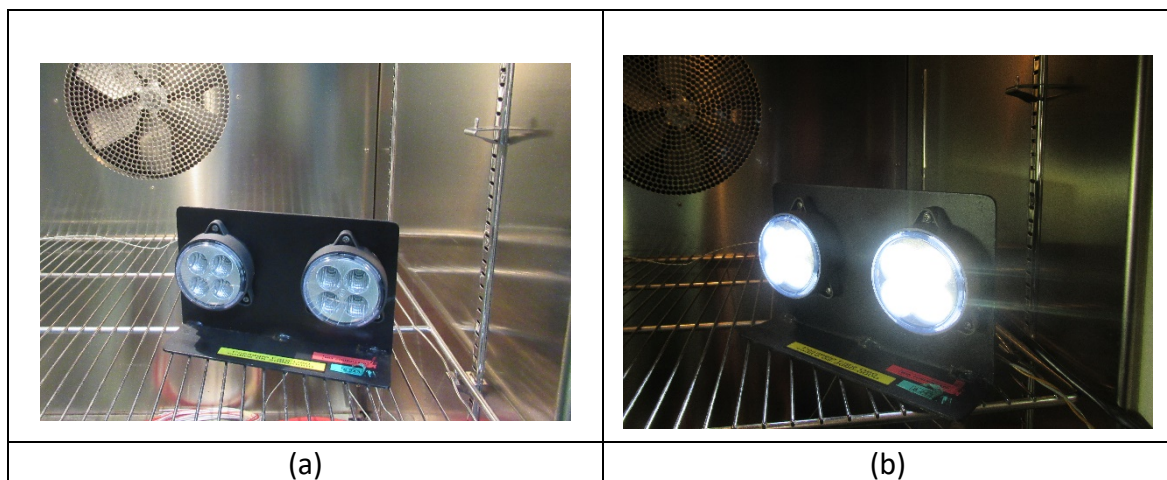


Figure 24. IR thermal imaging test setup of the LED headlamp housing inside the climatic chamber, before (a) and during illumination (b), using a FLIR E95 infrared camera.

The IR images were used to identify localized hot spots, evaluate finned heat-sink performance, and compare the temperature distribution between the rear housing and LED regions.

This non-contact technique provided a direct visual confirmation of the heat transfer efficiency previously inferred from thermal conductivity measurements, thus linking material properties to functional component performance.

6.8.2. EMI validation of the screening enclosure

- **Radiated Emission Test**

Standard references: CISPR 25 (Vehicles, boats and internal combustion engines - Radio disturbance characteristics), UNECE Regulation No. 10 (Uniform provisions concerning the approval of vehicles with regard to electromagnetic compatibility) [73].

The Radiated Emission (RE) test was conducted to verify that the electromagnetic radiation emitted by the operational electronic module remained below the regulatory limits.

Measurements were performed inside an anechoic chamber, which is designed to suppress signal reflections and simulate free-space conditions.

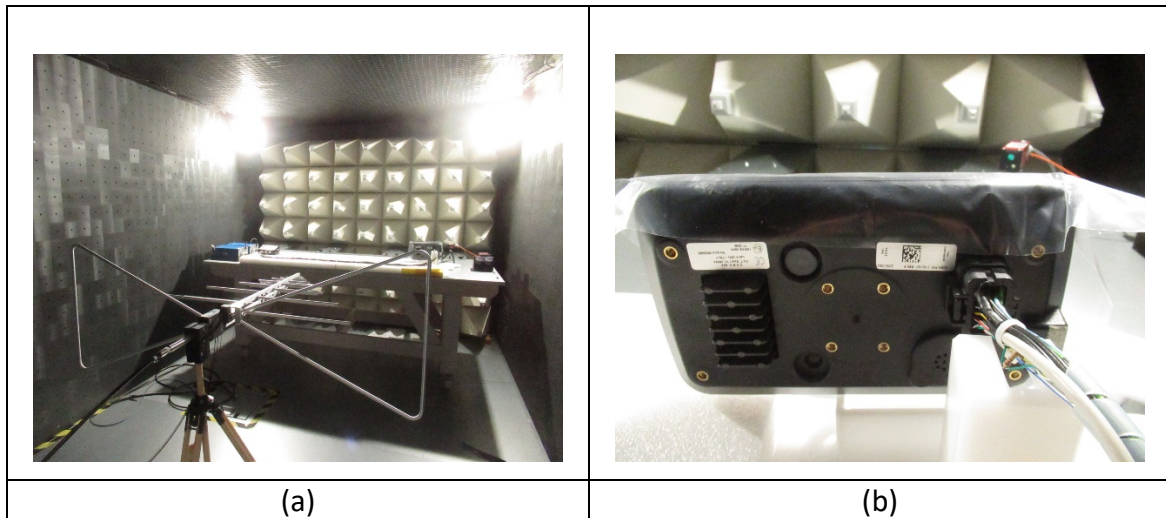


Figure 25. CISPR 25 radiated-emission test setup: (a) anechoic chamber with broadband antenna, (b) automotive dashboard unit mounted on the test fixture

A VULB9163 broadband antenna, connected to a calibrated EMI receiver, was positioned at a standard distance from the unit under test (UUT).

The system continuously scanned the frequency range of 20 MHz to 1 GHz, while the module operated in normal functional mode.

The receiver recorded the electric field strength in dB μ V/m, which represents the magnitude of radiated emissions at each frequency (Figure 25.).

The measured emission spectrum was compared against the regulatory thresholds defined by CISPR 25 Class 3 limits.

• **Radiated Immunity Test**

The Radiated Immunity Test was performed to assess the resistance of the dashboard module to external electromagnetic fields [68,74].

The test was conducted according to ISO 11452-3 and IEC 61000-4-20 inside a GTEM 500 cell (EMC Test Technologies, Italy), where a uniform Transverse Electromagnetic (TEM) field was generated by a signal generator, RF amplifier, and field probe for calibration (Figure 26.).



Figure 26. GTEM cell setup for EMC testing: (a) external view of the GTEM chamber, (b) dashboard unit positioned inside the test section with RF instrumentation.

The module was exposed to a continuous electromagnetic field within the frequency range of 20 MHz to 2 GHz, while operating conditions were monitored to detect any possible functional disturbance (e.g. display color change, touch-screen sensitivity variation, or stand-by state activation) [74].

The field strength was gradually increased according to the standard-defined test levels until the full sweep was completed.

• **Electrostatic Discharge,**

The Electrostatic Discharge Test evaluated the immunity of the dashboard housing to electrostatic events that may occur during human handling or normal operation. The procedure followed IEC 61000-4-2 (Electromagnetic compatibility -Testing and measurement techniques- Electrostatic discharge immunity test) [75]. Electrostatic discharges were applied using an ESD NX30 generator (EM TEST, AMETEK CTS, Reinach, Switzerland) equipped with a 150 pF capacitor and a 330 Ω discharge resistor was used to apply discharges in both contact and air modes.

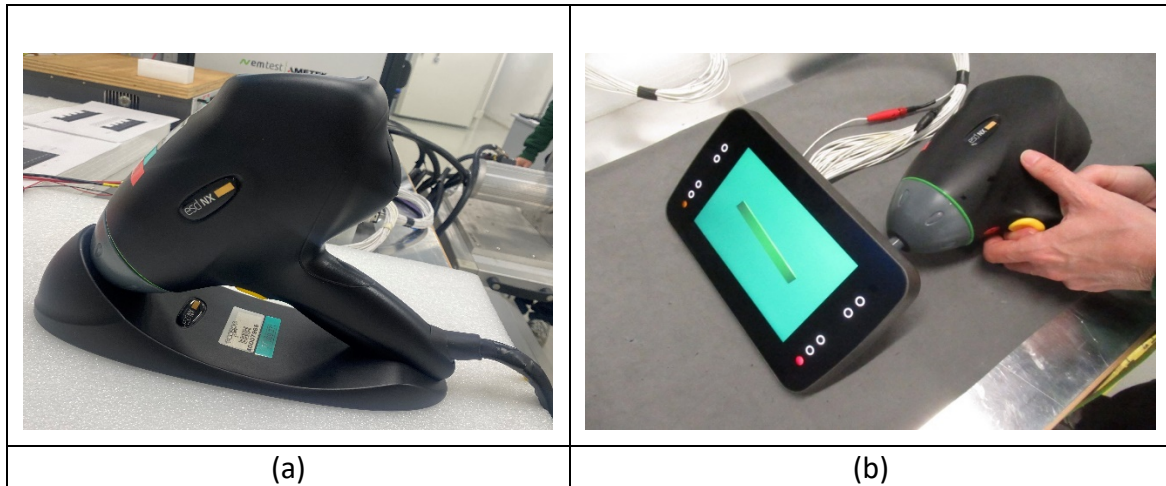


Figure 27. Electrostatic discharge (ESD) test equipment used for IEC 61000-4-2 validation: (a) ESD NX30 generator in docking station, (b) handheld application of electrostatic discharge to the dashboard module surface.

The test was carried out at ± 6 kV and ± 8 kV, focusing on the rear heatsink region, which represents the most conductive and exposed part of the module.

The device operation was continuously monitored during and after each discharge to identify any potential temporary or permanent functional effects.

6.9. Comparison between Reference and Developed Materials (IP5)

To assess the overall effectiveness of the developed polymer formulations, a comparative evaluation was established between the reference commercial materials and the optimized filled polymer systems produced during this study.

This comparison aimed to determine whether the developed formulations can meet or exceed the performance of conventional materials used in automotive electronic housings.

The comparison framework included both PC and IP steps, as summarized below:

- Material-level tests: mechanical (tensile strength, elongation, modulus, HDT), thermal conductivity (λ), and EMI shielding effectiveness (EMI SE).
- Component-level validations: thermal performance of the lighting housing and EMI robustness of the screening enclosure under industrial testing standards.

The reference materials correspond to the baseline compounds currently adopted by the industrial partner (COBO S.p.A.) for headlamp housings and dashboard enclosures, while the developed materials refer to the new filled polymer formulations optimized within this thesis (e.g. LATI 62GR70, SABIC PX10323, LATI 87/24-8A, LATI 87/24-10A, DS0036I).

All experimental data were collected and statistically processed using Minitab and Microsoft Excel, ensuring consistency and traceability across measurement campaigns [69].

The comparative analysis integrates quantitative indicators such as conductivity (W/mK), EMI SE (dB), tensile strength (MPa), and warpage deviation (mm), to provide a clear understanding of how mechanical strength, heat transfer, and electromagnetic protection balance in each material.

This step establishes the foundation for the following Results and Discussion chapter, where the detailed performance outcomes of each material and their industrial implications are analysed.

Chapter 7

Results & Discussion

7.1. Mouldability & FEM-Based Processability Assessment

The twelve polymer composite formulations initially selected for this study exhibit a broad range of mechanical and thermal performance, directly influencing their mouldability. Table 8 summarizes these properties, classified into qualitative mouldability categories based on manufacturer datasheets and ISO testing standards (ISO 527-1, ISO 75-2). Materials with low elongation at break and limited thermal resistance are expected to be prone to premature solidification, cracking during ejection, and narrow processing windows well-known constraints in injection moulding of highly-filled systems [40-43, 46,51,76].

Table 10. Mechanical and thermal baseline properties of candidate polymer composite formulations (categorical rating scale) [59-61].

Materials	Producer	Compound	Filler	Elongation at Break (%)	Tensile Strength (Mpa)	Youngs Modulus (Mpa)	HDT at 1,8MPa (°C)
LX24059	Radici	PA6	15% CF	brittle	strong	stiff	high
LX24060	Radici	PA6	15% CF + Steel fibre	brittle	strong	stiff	high
LX24061	Radici	PA6	20% CF	brittle	strong	stiff	high
PX10323	Sabic	PA6	multi material	brittle	balanced	stiff	high
66 H2 K/40 NT	LATI	PA6	20% CF + 5% Steel fibre	brittle	strong	stiff	high
62GR50	LATI	PA6	50% Graphite	brittle	balanced	stiff	high
62GR70	LATI	PA6	70% Graphite	brittle	Soft	stiff	high
DS0036I	Sabic	PC	15% SS fibre	acceptable	balanced	balanced	medium
87/24-08A	LATI	PC	8% SS fibre	excellent	Soft	balanced	medium
87/28-10A	LATI	PC	10% SS fibre	acceptable	balanced	balanced	medium
DTK22	Sabic	PC	minerals	acceptable	Soft	flexible	medium
47/30 cp1/800	LATI	PPC	ceramic filler	acceptable	Soft	flexible	low

The qualitative levels shown in Table 10 (e.g. brittle, balanced, strong, soft, stiff, flexible) were derived from datasheet values following ISO 527–1, ISO 75–2, and manufacturer reference ranges [77,78]

The classification ranges were defined as follows:

- Elongation at break < 3 % → Brittle, 3–8 % → Acceptable, 8–15 % → Excellent;
- Tensile strength < 30 MPa → Soft, 30–70 MPa → Balanced, > 70 MPa → Strong;

- Young's modulus < 2000 MPa → Flexible, 2000–6000 MPa → Balanced, > 6000 MPa → Stiff;
- HDT (1.8 MPa) < 80 °C → Low, 80–140 °C → Medium, > 140 °C → High.

Based on these considerations, an initial screening was carried out purely from a mouldability point of view. LATI 47/30 CP1/800 was classified as the most critical material, due to its combination of low elongation at break and low HDT, and was therefore excluded from the subsequent stages of the work. In contrast, the PA6-based compounds (such as 62GR50, 62GR70 and 66 H2 K/40 NT) and the PC-based shielding grades (DS0036I and 87/24-10A) showed more favourable property profiles, providing a wider and more robust processing window as expected for filled engineering polymers used in injection moulding [72,74,76] However, this datasheet-based classification only suggests potential mouldability; it does not guarantee defect-free processing. Highly-filled polymer systems drastically change melt behaviour and cooling kinetics, and their true processability must therefore be validated through mould filling simulations.

7.2. Simulation-based Optimisation of Processing

Following the datasheet-based screening, a second step was carried out to verify whether the standard processing conditions of a well-known base polymer (neat PA6) could be directly transferred to a highly filled conductive grade (PA6 + 70 wt% graphite, LATI 62GR70). Loaded polymer composites are known to exhibit markedly different rheological and thermal behaviour compared with their neat matrices, including increased viscosity, higher density and enhanced thermal conductivity, all of which tend to narrow the processing window and promote defects such as short-shots and excessive pressure build-up. For this reason, Moldex3D simulations were employed as a virtual trial-and-error tool to (i) test the feasibility of using baseline PA6 parameters for 62GR70 and (ii) derive an optimised set of injection-moulding conditions before starting physical trials. In this section, 62GR70 was selected as a representative case to illustrate the simulation-based optimisation workflow; the same methodology was applied to the remaining PA6-based compounds in this study prior to production stage.

7.2.1. Baseline simulation with pure PA6 (Run 1)

A reference process window was initially defined for neat PA6, a well-established material in injection-moulding literature and industrial practice. Conditions within typical processing recommendations were validated through Moldex3D simulations:

- Run 1 - Pure PA6:

$T_{\text{melt}} = 250\text{ °C}$, $T_{\text{mould}} = 70\text{ °C}$, filling time = 1.0 s.

Under these settings, complete cavity filling (100%) was achieved with an injection pressure of approximately 81 MPa and acceptable clamping-force requirements. Melt-front progression was (Figure 28.), with no hesitation marks or early freezing risk. Therefore, Run 1 was adopted as the benchmark against which the highly filled composite would be evaluated.

7.2.2. Direct transfer to PA6/70% graphite and short-shot formation (Run 2)

To isolate the influence of filler content on mouldability, the same processing parameters were directly applied to the conductive composite:

- Run 2- 62GR70 using PA6 baseline parameters

This approach reflects common industrial practice when substituting materials without redesigning the process window at the early stage.

However, a short-shot defect occurred (Figure 28.)

The melt front stagnated before reaching thin distal regions, resulting in incomplete filling of the part. Simultaneously, the maximum injection pressure nearly doubled relative to Run 1 ($\approx 81 \text{ MPa} \rightarrow \approx 160 \text{ MPa}$), approaching the machine pressure limitations (Figure 29.). This behaviour arises from:

- significantly higher viscosity of the 70 wt% graphite melt
- faster heat extraction to the mould due to enhanced thermal conductivity
- earlier frozen-layer formation, limiting flow length and delaying packing

Thus, Run 2 confirms the need for specifically optimised injection-moulding parameters for highly filled thermally conductive composites in order to avoid severe mouldability drawbacks.

7.2.3. Process optimisation for 62GR70 (Run 3)

To obtain full cavity penetration, three parameters were refined based on Run 2 outputs and manufacturer guidelines:

Table 11. Process-parameter adjustments applied to 62GR70 (Run 3) based on Moldex3D results for Run 2.

Adjustment	Optimised Parameter	Target
T_melt	250 $\rightarrow$ 290 °C	lower melt viscosity
T_mould	70 $\rightarrow$ 85 °C	delay solidification at walls
Filling time	1.0 $\rightarrow$ 1.8 s	maintain flow front mobility

- Run 3 - Optimised 62GR70:

T_melt = 290 °C, T_mould = 85 °C, filling time = 1.8 s.

The cavity was successfully filled again (100%), while injection pressure returned to acceptable levels (Table 10). Melt-front visualization (Figure 28.) confirmed uniform progression to the farthest regions. This study validated Run 3 as a stable and industrially feasible process window for PA6 + 70 wt% graphite.

Comparison of simulation outcomes for Run 1–Run 3

The main processing parameters and Moldex3D outputs for the three cases are summarised in *Table 12*.

Table 12. Moldex3D results for reference PA6 and 62GR70 before and after process optimisation (Runs 1–3).

Run	Material Name	Base Polymer + Filler	Mould Temperature [°C]	Melt Temperature [°C]	Filling Time [s]	Filled Part [%]	Max. Injection Pressure [MPa]	Clamping Force [kN]	Max. Total Displacement Warpage [mm]	Max. Volumetric Shrinkage-Packing [%]
1	Pure PA6	PA6	70	250	1.0	100	81	1148	0.84	4.0
2	62GR70	PA6+ 70% Graphite	70	250	1.0	<100	160	736	0.27	2.2
3	62GR70	PA6+ 70% Graphite	85	290	1.8	100	110	942	0.26	1.3

In addition, selected field plots and process curves are compared in Figures 29-31:

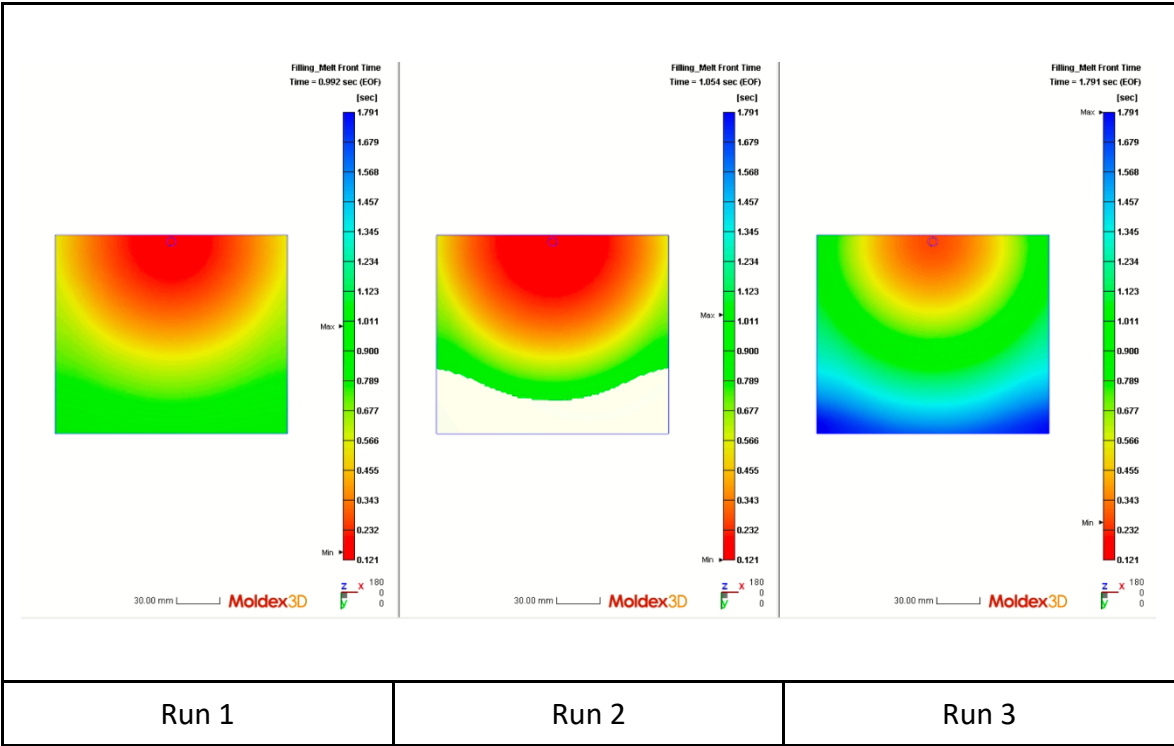


Figure 28. Filling melt-front time (EOF) for Run 1 (pure PA6), Run 2 (62GR70 with PA6 parameters) and Run 3 (62GR70 optimised).

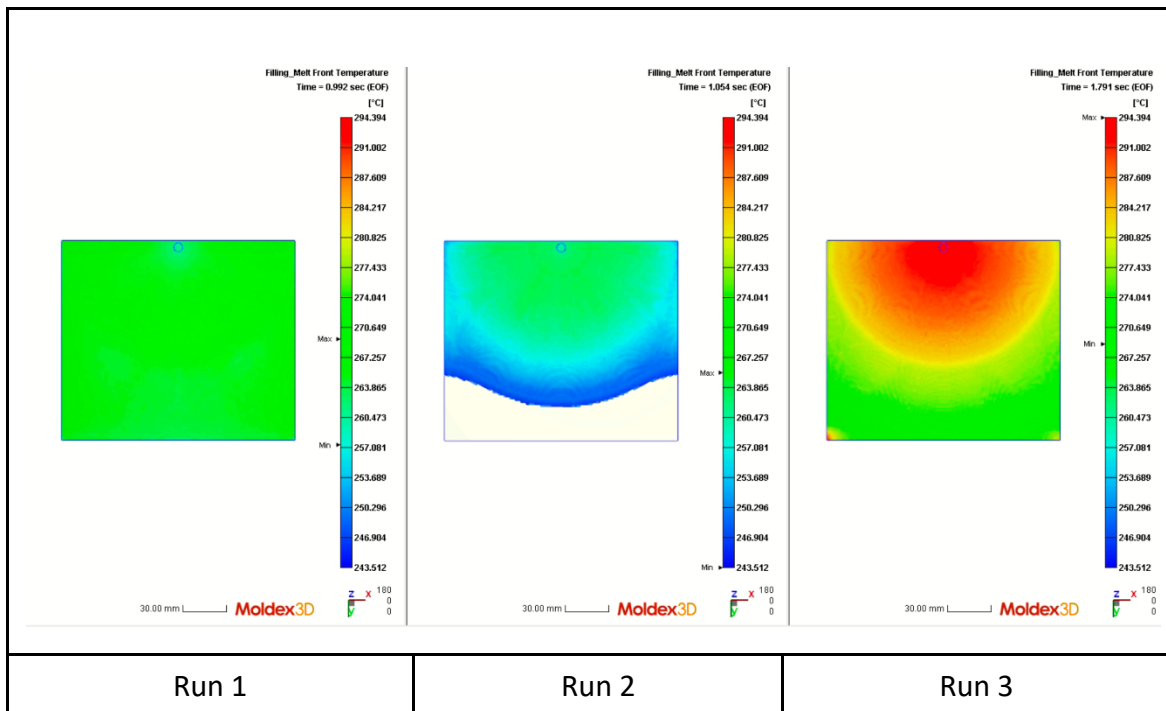


Figure 29. Filling pressure distribution at EOF for the three runs.

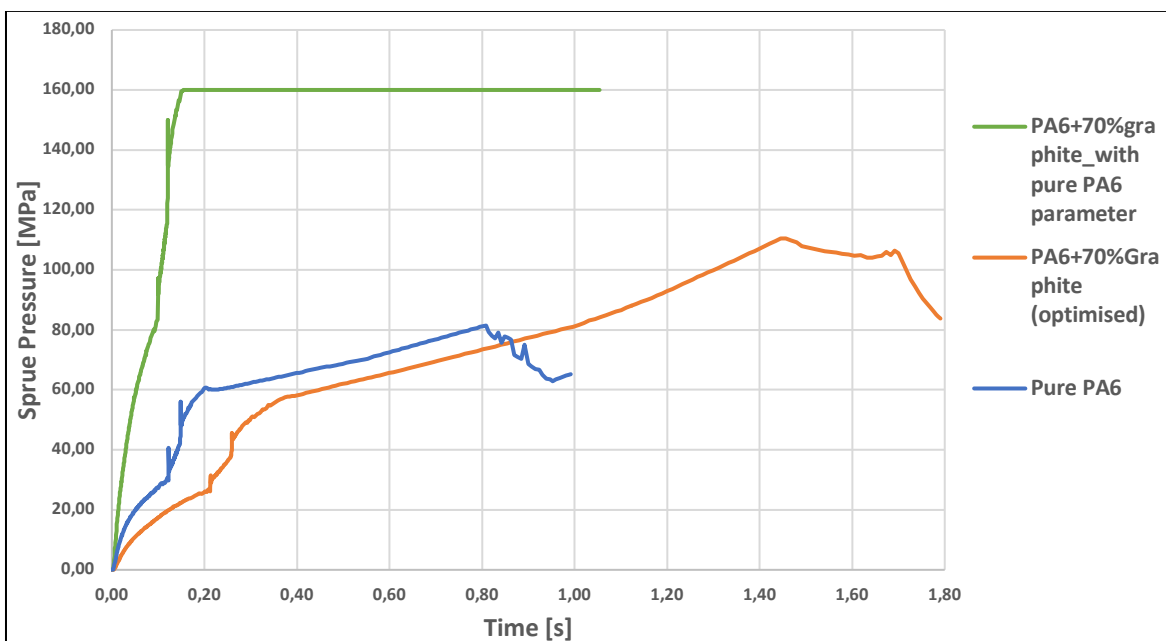


Figure 30. Sprue pressure as a function of time for Run 1-3.

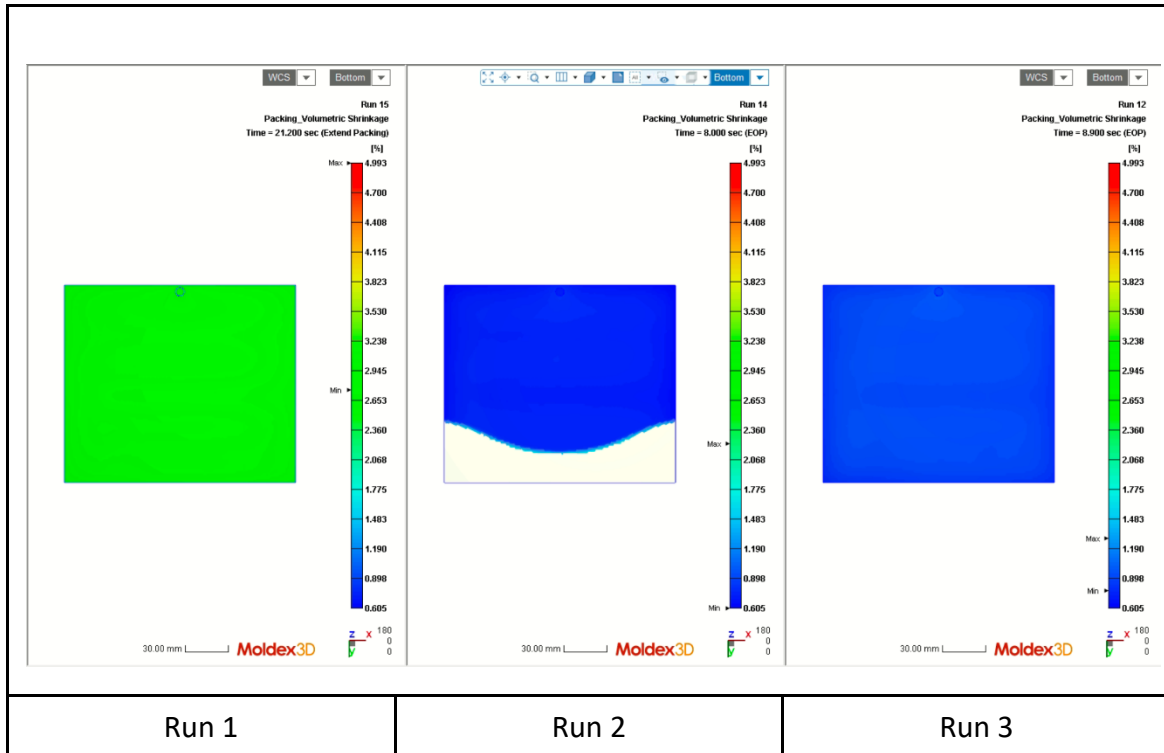


Figure 31. Volumetric shrinkage after end of packing for Run 1-3.

Overall, this three-step simulation campaign demonstrates how the introduction of a highly filled conductive compound requires a dedicated adjustment of processing parameters, rather than a direct transfer of neat-polymer conditions. By systematically comparing Run 1 (pure PA6), Run 2 (62GR70 with PA6 settings) and Run 3 (62GR70 with optimised settings), Moldex3D was used to; reveal the short-shot and excessive pressure issues arising from the use of non-adapted parameters, guide the selection of a new combination of melt temperature, mould temperature and filling time; and verify that the optimised process window yields complete filling with acceptable pressure, shrinkage and warpage levels.

The identified parameters were subsequently adopted as the starting point for the experimental injection-moulding trials presented in Section 6.3, where the actual production behaviour of the advanced polymers are discussed.

7.2.4. Transition to gate-oriented processing optimisation

The primary objective of this thesis is to improve the EMI shielding effectiveness and thermal conductivity of polymer-based automotive electronic housings by optimizing both the material formulation and the injection moulding process. While the use of highly conductive fillers (e.g. graphite at 70 wt%) significantly enhances bulk transport properties, the final performance of the moulded part is strongly governed by the microstructure developed during processing, particularly the spatial distribution and alignment of fibres or platelet-like fillers within the flow field [44,56-58].

Because filler orientation is highly dependent on melt flow direction and shear gradients inside the cavity, gating strategy becomes a key lever to tailor anisotropic thermal–electrical pathways and to achieve more uniform dimensional stability [44,47]. In our study, we specifically focus on analysing how the gate-induced flow kinematics affect mouldability and microstructure formation.

To this end, two different gate configurations were investigated using the same industrial-grade conductive composite (PA6 + 70 wt% graphite - 62GR70):

(1) a tunnel gate, which served as the baseline configuration in previous simulations including Run 3, and

(2) a direct gate, expected to shorten flow paths, increase shear uniformity, and generate a different fibre orientation distribution (Run 4)

Table 13. Simulation-based mouldability comparison under equal processing conditions

Run	Gate Type	Material Name	Base Polymer + Filler	Mould Temperature [°C]	Melt Temperature [°C]	Filling Time [s]	Filled Part [%]	Max. Injection Pressure [MPa]	Clamping Fore [kN]	Max. Total Displacement Warpage [mm]	Max. Volumetric Shrinkage-Packing [%]
3	Tunnel	62GR70	PA6+ 70% Graphite	85	290	1.8	100	110	942	0.28	1.3
4	Direct	62GR70	PA6+ 70% Graphite	85	290	1.8	100	111	883	0.28	1.2

To isolate the effect of gate design on mouldability, the same composite grade (62GR70) and the same optimised process conditions from Run 3 were applied to the direct-gate configuration, hereafter referred to as Run 4 (Table 13) Thus, Runs 3 and 4 differ solely in gate design, enabling a direct comparison of how flow-controlled microstructure affects filling behaviour and dimensional stability.

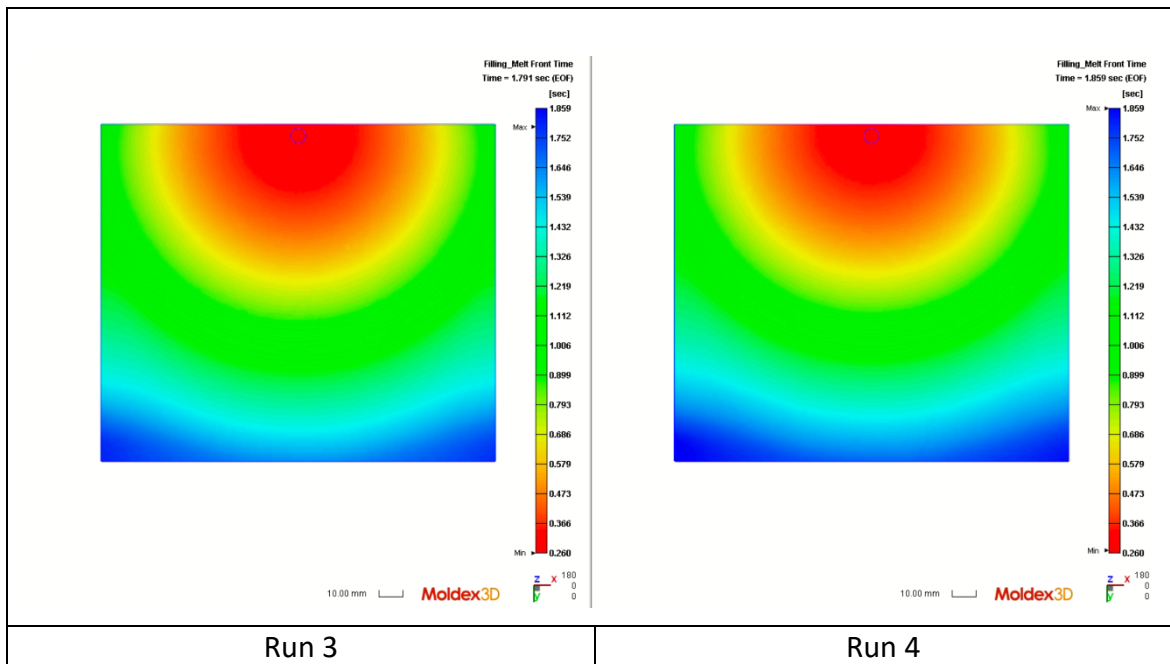


Figure 32. Melt-front advancement distribution at at end-of-filling (EOF) for both gate configurations.

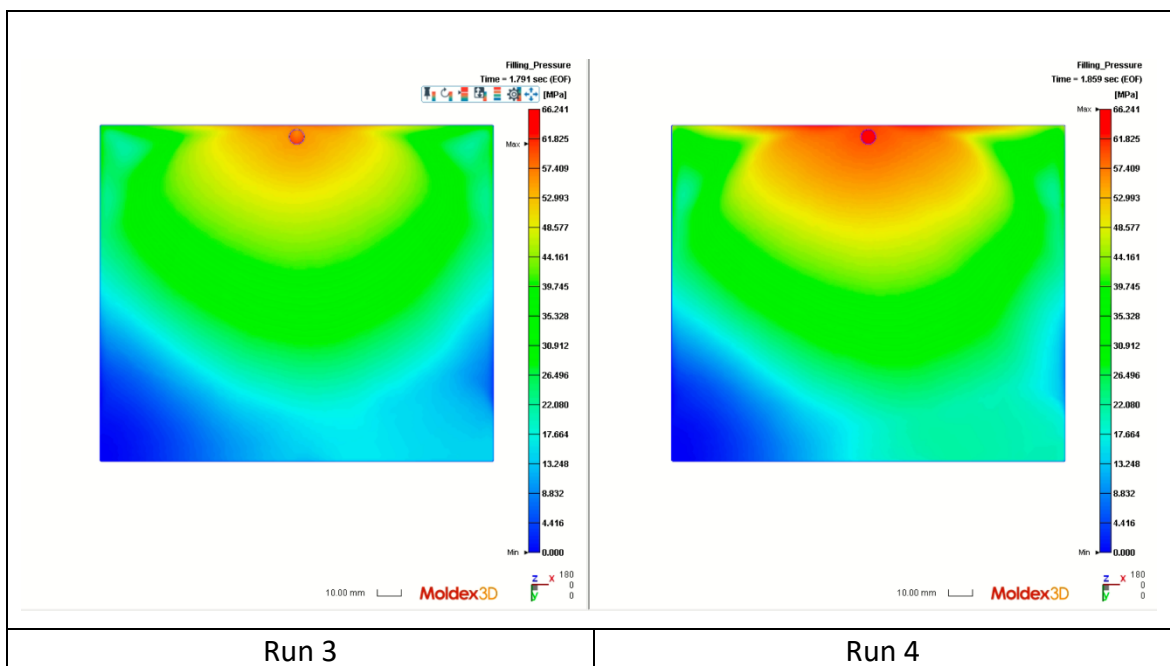


Figure 33. Comparison of filling pressure fields at EOF for tunnel (Run 3) and direct (Run 4) gates.

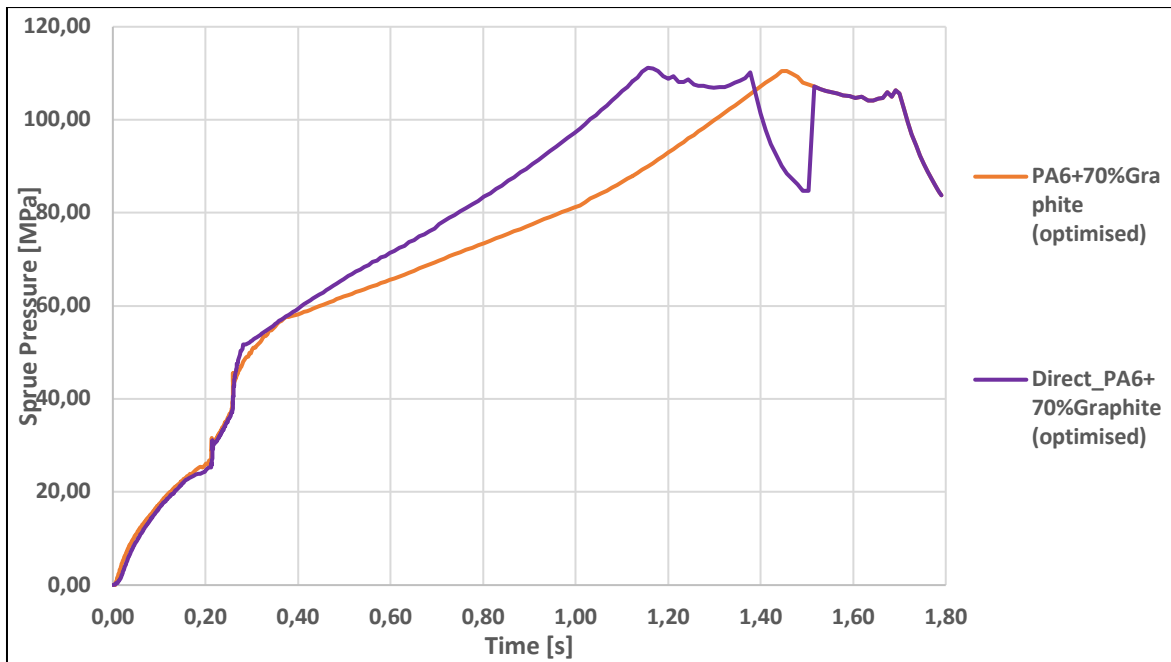


Figure 34. Sprue pressure evolution over filling time for tunnel (Run 3) and direct (Run 4) gate configurations under identical processing conditions.

The comparison between the tunnel-gate (Run 3) and direct-gate (Run 4) configurations under identical optimized moulding parameters shows that both designs achieve complete cavity filling with a very similar melt-front progression and filling-pressure distribution at the EOF. In addition, the sprue-pressure evolution indicates that the direct gate reaches the required packing pressure with a slightly smoother profile, suggesting a reduced resistance to flow during cavity filling (Figure 34). No hesitation zones or filling delays were observed for the direct gate, confirming that the change in gating does not impair mouldability or increase dimensional instability. These findings are consistent with the nearly identical total warpage values obtained in both cases (~ 0.28 mm) (Table 13), demonstrating that the overall deformation behaviour remains unaffected by the gate modification.

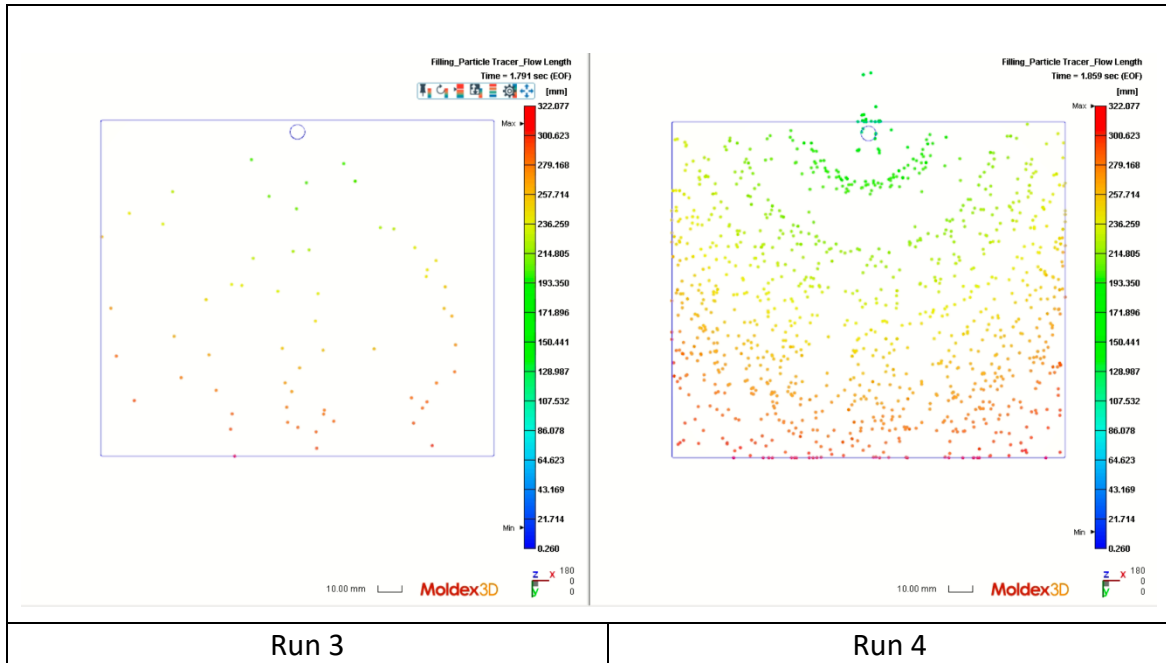


Figure 35. Melt-flow particle tracer visualization showing flow-length distribution at the EOF for tunnel (Run 3) and direct (Run 4) gate configurations.

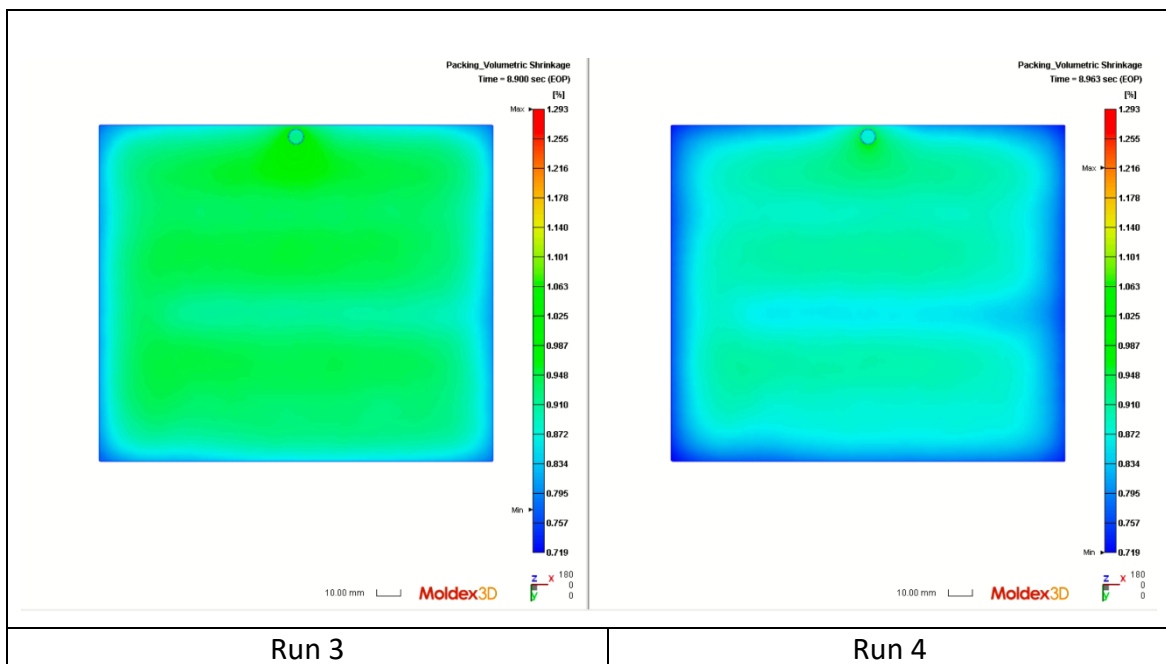


Figure 36. Packing-induced volumetric shrinkage distribution for tunnel and direct gates.

Despite these similarities in macroscopic indicators, the flow-induced filler distribution exhibits a clear difference between the two designs (Figure 35). The direct gate produces a more homogeneous convective transport of graphite particles throughout the cavity, which is attributed to shorter flow paths and a more uniform shear field at the inlet region [47,56-58,76]. This also correlates with the enhanced uniformity in volumetric shrinkage and the slightly reduced pressure gradients detected across the part surface (Figure 36, Table 13), pointing to improved internal density distribution and lower local stress

accumulation. Overall, these results confirm that gate design can act as a microstructure-tuning parameter while maintaining mouldability. Therefore, the direct-gate configuration is selected for industrial validation and subsequent evaluation of thermal conductivity and EMI shielding performance.

7.3. Observed Defects and Morphologies

Injection moulding trials were conducted to validate the accuracy of the optimised processing parameters obtained from the Moldex3D simulations and to evaluate the real manufacturing behaviour of the selected materials. Although the simulations predicted complete filling and acceptable deformation levels for most PA6- and PC-based grades, the experimental findings revealed that the occurrence of defects strongly depended on material formulation and gate configuration. These discrepancies indicate that filler–matrix interactions, brittleness, and flow-induced microstructural features play a significant role in moulding performance and cannot be fully anticipated by flow simulation alone [54,79].

The most critical behaviour was observed for LATI 47/30 CP1/800, which could not be successfully moulded under any condition. The part consistently fractured during ejection, particularly near the cold runner–gate transition, where the melt front solidified prematurely. In addition, visible flash formation around the gate area was detected, indicating excessive local packing and insufficient melt sealing due to the extremely brittle nature and low thermal resistance of the compound [59,79-81] who linked such failures to insufficient melt elasticity and reduced relaxation capability under high packing pressure.

In contrast, all PA6-based Radici compounds (PA6 + CF and PA6 + CF + SSF) filled the mould completely but exhibited surface delamination defects along the flow direction. These defects appeared as fibrous, peel-like layers near the outer edges, suggesting partial separation between fibre-rich and matrix-rich regions during flow. This phenomenon is consistent with previous findings where fibre orientation gradients and uneven shear distribution in highly filled systems were identified as the main causes of delamination [44,57,76]

Moreover, in all high-SSF formulations, distinct flow marks were observed across the moulded surfaces. These wavy or streak-like patterns followed the direction of flow and were more pronounced near thick-to-thin transitions, consistent with localized cooling rate differences and viscosity fluctuations. Similar flow mark phenomena in fibre- and metal-filled polymers have been discussed, who reported that local shear rate oscillations during fountain flow produce characteristic streaks and color variations [76,80,82].

Representative examples of these observations are shown in Figure 37. , including:

- (a) the fractured LATI 47/30 CP1/800 near the cold runner,
- (b) delamination and fibre-rich surface defects in Radici compounds, and
- (c) characteristic flow marks in SSF-filled materials

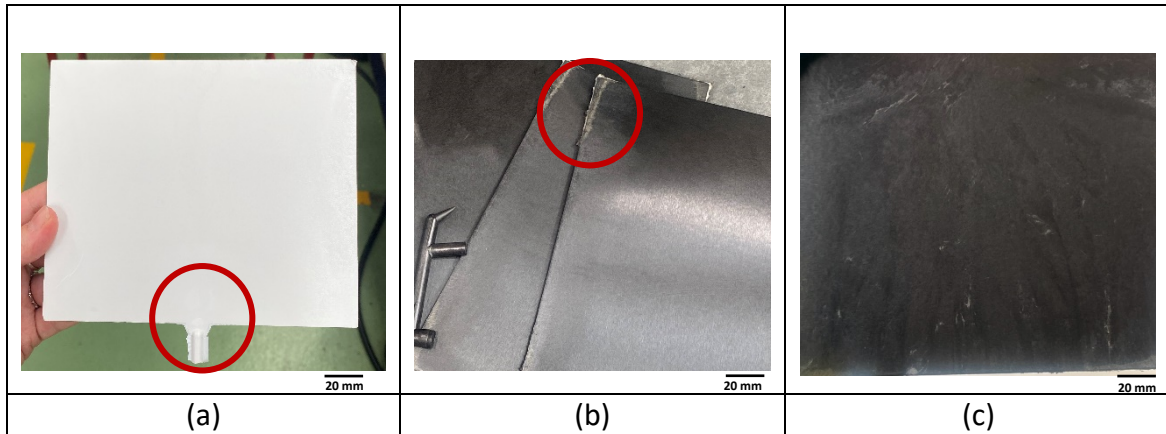


Figure 37. Typical injection-moulding defects observed on test plaques: (a) gate fracture, (b) crack at runner–gate region, (c) surface delamination/flow marks. Scale bars: 20mm.

For the LX24061 (PA6 + CF + SSF) specimens, parts moulded through a tunnel gate exhibited visible bending and warpage, while those moulded through a direct gate retained a much straighter geometry.

This behaviour is attributed to the anisotropic shrinkage and residual stress gradients induced by fibre orientation along the flow path effects that intensify when the flow length increases, as commonly reported in the literature [43,44,55,58].

In contrast, the LATI 87/28-10A (PC + 10 % SSF) parts, which were moulded through a tunnel gate, displayed excellent dimensional stability and minimal bending, confirming the high mouldability of PC-based systems already highlighted in Section 6.1.

This result demonstrates that material ductility and thermal stability can compensate for geometric or gate-related constraints: The amorphous PC matrix exhibits lower shrinkage anisotropy and better stress relaxation during cooling, leading to improved dimensional accuracy even under less favorable gate configurations. Similar trends have been reported in studies on warpage and shrinkage control in injection-moulded parts, where deformation severity decreases in tougher, less crystalline polymers and where gate-induced stress gradients are mitigated by improved melt relaxation behaviour [43,76,80].

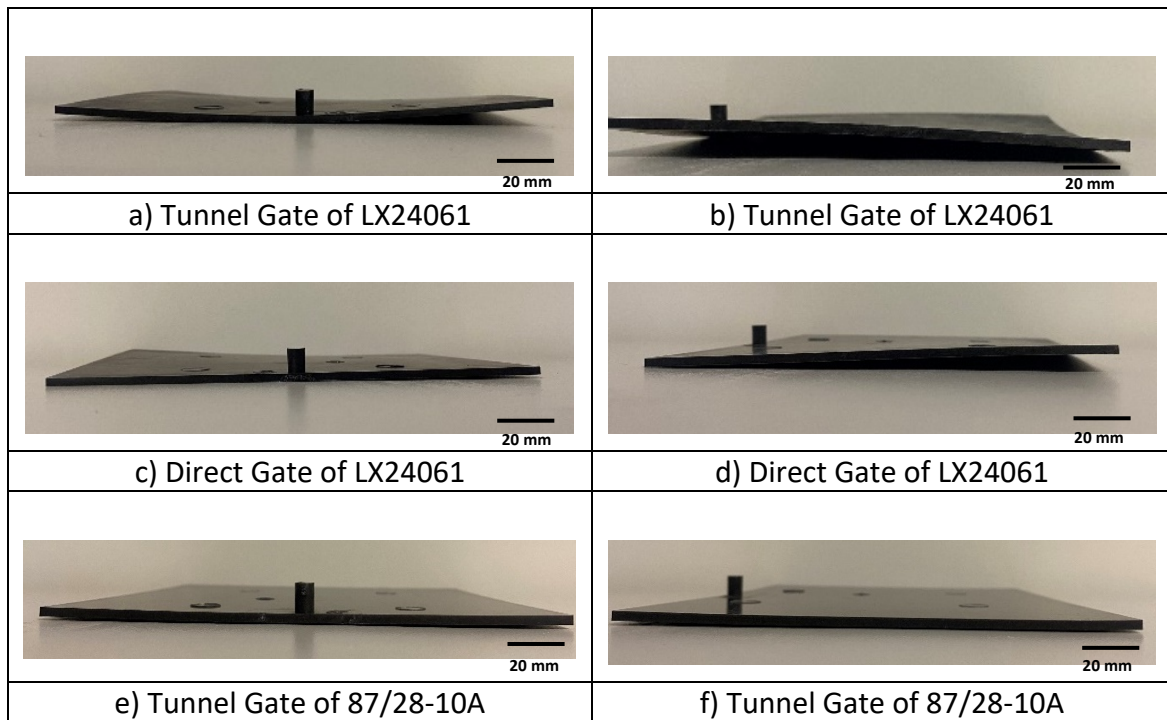


Figure 38. Side views of injection-moulded plaques showing warpage for LX24061 and 87/28-10A with tunnel and direct gates. Scale bars=20 mm.

7.4. Thermal-driven path: Standard Specimen tests and Material down-selection

7.4.1. Standard specimen thermal conductivity (TPS & HFM)

The thermal conductivity of twelve filled formulations, along with the neat PA6 and PC base polymers, was measured using the Hot Disk (TPS) technique (Table 14).

Table 14. Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) of neat PA6, PC and filled formulations for tunnel and direct gate specimens measured by the Hot Disk TPS method.

Materials	Gate Type	Thermal Conductivity (W/mK)		
		Sample 1	Sample 2	Sample 3
PA6	Tunnel	0,33	0,32	0,32
	Direct	0,34	0,32	0,30
LX24059	Tunnel	0,76	0,76	0,73
	Direct	0,67	0,74	0,74
LX24060	Tunnel	0,70	0,70	0,70
	Direct	0,70	0,71	0,70
LX24061	Tunnel	0,77	0,81	0,80
	Direct	0,86	0,83	0,83
PX10323	Tunnel	7,24	7,30	7,34
	Direct	7,37	7,45	7,28
66 H2 K/40 NT	Tunnel	1,16	1,12	1,15
	Direct	1,18	1,16	1,19
62GR50	Tunnel	4,76	4,73	4,79
	Direct	4,24	4,16	4,30
62GR70	Tunnel	13,86	13,90	13,89
	Direct	12,09	12,19	12,17
PC	Tunnel	0,28	0,27	0,26
	Direct	0,28	0,27	0,26
DS0031	Tunnel	0,29	0,30	0,30
	Direct	0,31	0,32	0,31
87/24-08A	Tunnel	0,30	0,30	0,29
	Direct	0,31	0,30	0,30
87/28-10A	Tunnel	0,34	0,32	0,3
	Direct	0,35	0,32	0,32
DTK22	Tunnel	0,58	0,57	0,56
	Direct	0,57	0,58	0,57
47/30 cp1/800	Tunnel	3,98	3,95	3,95
	Direct	3,83	3,82	3,88

Following this preliminary screening, the four top-performing materials namely PX10323, 62GR50, 62GR70, and 47/30 CP1/800 were selected for comparative analysis, and their mean values from both TPS and HFM measurements are summarized in Table 15.

As shown, the incorporation of thermally conductive fillers led to substantial improvements compared with the neat polymer matrices.

For instance, the PA6 baseline exhibited an average thermal conductivity of only $\approx 0.32 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, whereas the filled compounds reached up to 40-fold enhancement ($\approx 13\text{--}14 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for 62GR70).

Similarly, the PC base resin ($\approx 0.27 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) improved modestly when reinforced with stainless-steel and mineral fillers ($\approx 0.6 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), while the PP-copolymer with ceramic filler (47/30 CP1/800) achieved $\approx 3.9\text{--}4.0 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ about ten times higher than neat polypropylene.

These results confirm that once the percolation threshold of the conductive network is reached, heat transfer is primarily governed by the interconnected filler pathways rather than the polymer matrix, consistent with literature reports [22,35,39].

Table 15. Average thermal conductivity (W/mK) of moulded specimens measured by Hot Disk (TPS) and FOX Analyser (HFM).

Material	Gate Type	TPS-Thermal Conductivity (W/mK)	HFM-Thermal Conductivity (W/mK)
PA6	Tunnel	0.32 ± 0.01	0.42 ± 0.03
	Direct	0.32 ± 0.02	0.22 ± 0.02
PX10323	Tunnel	7.29 ± 0.05	1.36 ± 0.00
	Direct	7.37 ± 0.09	1.18 ± 0.00
62GR50	Tunnel	4.76 ± 0.03	0.87 ± 0.00
	Direct	4.23 ± 0.07	0.91 ± 0.00
62GR70	Tunnel	13.88 ± 0.02	1.33 ± 0.00
	Direct	12.15 ± 0.05	1.49 ± 0.00
PC	Tunnel	0.27 ± 0.01	0.20 ± 0.01
	Direct	0.27 ± 0.01	0.20 ± 0.01
47/30 cp1/800	Tunnel	3.96 ± 0.02	1.55 ± 0.18
	Direct	3.84 ± 0.03	1.53 ± 0.14

A two-way ANOVA was performed using Filler type (ceramic, graphite 50 %, graphite 70 %, multi-filler) and Gate configuration (direct vs tunnel) as fixed factors ($\alpha = 0.05$), followed by Tukey.

- Hot Disk (TPS) results

Filler type had a highly significant influence on λ ($p < 0.001$), while Gate also showed a smaller but statistically relevant effect ($p = 0.002$).

According to Tukey grouping, graphite 70 % (62GR70) achieved the highest mean conductivity ($\approx 13 - 14 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), followed by multi-filler (PX10323) with $\approx 7 - 7.5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, graphite 50 % (62GR50) with $\approx 4 - 4.5$, and ceramic (47/30 CP1/800) with $\approx 3.8 - 4.0$.

The tunnel gate condition yielded slightly higher values than the direct gate ($\approx 5\text{--}7\%$ difference), consistent with enhanced in-plane filler alignment during filling [57,58,76].

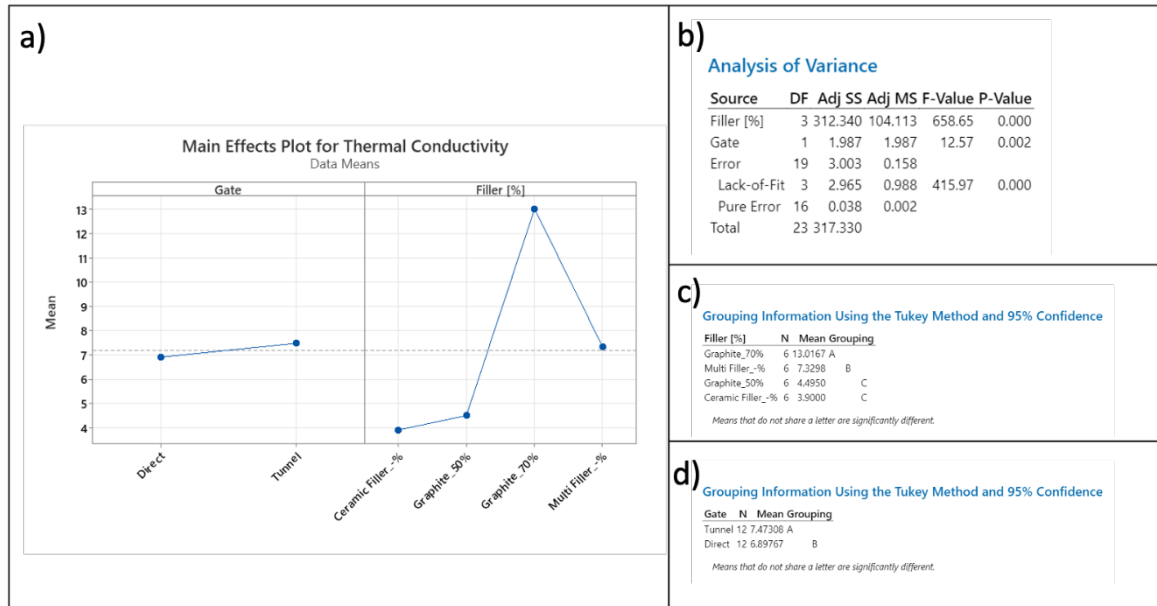


Figure 39. Main effects plot and ANOVA summary for Hot Disk conductivity.

- Fox Analyser (HFM) results

Through-thickness conductivity was governed primarily by filler ($p < 0.001$), while gate type had no measurable influence ($p = 0.788$).

Tukey grouping ranked ceramic, graphite 70 %, and multi-filler in the top, statistically indistinguishable tier ($\approx 1.3 - 1.5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), whereas graphite 50 % remained significantly lower ($\approx 0.85 - 0.95$).

The absence of a gate effect confirms that steady-state measurements average out local anisotropy, reflecting bulk thermal pathways rather than surface orientation effects [23, 24, 76].

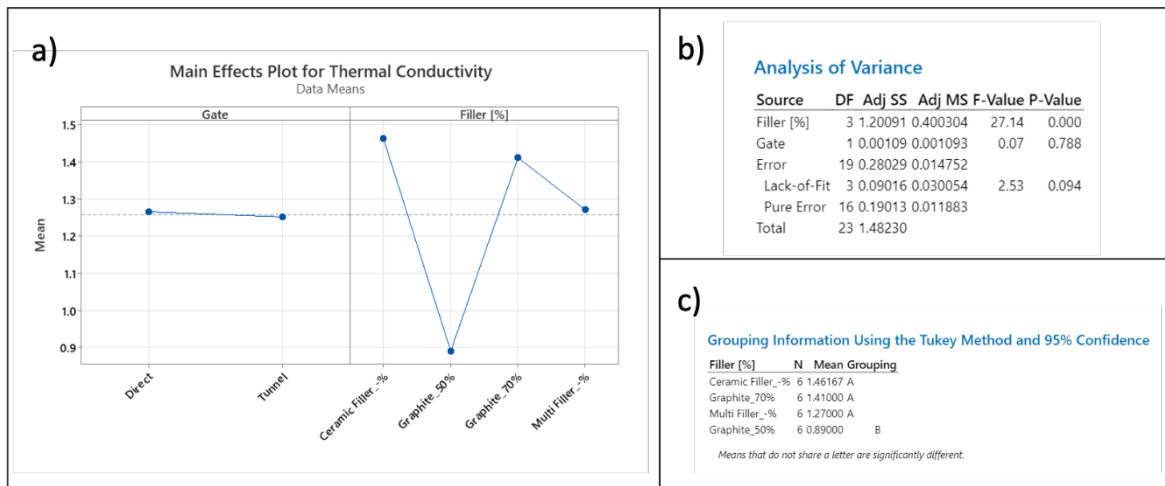


Figure 40. Main effects plot and ANOVA summary for HFM conductivity.

The difference between TPS and HFM measurements also highlights the anisotropic nature of highly filled conductive polymer composites. TPS measurements are more sensitive to in-plane heat propagation, which is strongly influenced by filler alignment along the melt-flow direction during injection moulding. In contrast, HFM measurements mainly capture through-thickness heat transfer, where conductive pathways are less affected by gate-induced orientation. This explains why gate configuration significantly influenced TPS conductivity values but had little effect on HFM results. Similar anisotropic thermal behaviour has been widely reported in graphite- and fibre- filled polymer systems [22,23].

7.4.2. Down-selection criteria and outcome

Based on the combined results from thermal conductivity, mouldability, and surface quality assessments, two materials were selected for the lighting housing application.

The housing requires high heat dissipation, robust injection processability, and acceptable surface appearance [9,18,30]

By combining:

1. TPS results (sensitive to in-plane spreading),
2. HFM results (through-plane, steady-state), and
3. Empirical mouldability observations (Section 7.3),

the following PA6-based compounds were retained as optimal:

- LATI 62GR70 – PA6 + 70 % graphite: exhibited the highest λ (13–14 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and stable processing after minor parameter optimisation, despite surface roughness.
- SABIC PX10323 – PA6 multi-filler system: offered balanced thermal conduction ($\approx 7 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), excellent surface finish, and high moulding.

7.4.3. Key findings of the thermal-driven path

Overall, the thermal-driven screening pathway demonstrated that graphite-rich PA6 systems provided the highest thermal conductivity, particularly in the in-plane direction measured by TPS analysis. The comparison between TPS and HFM measurements further highlighted the anisotropic nature of conductive polymer composites and the influence of filler orientation generated during injection moulding. While 62GR70 exhibited the highest thermal conductivity values, PX10323 showed a more balanced combination of thermal performance, mouldability, and surface quality. Consequently, both formulations were selected for subsequent industrial-level validation of the lighting-housing application.

7.5. Thermal-Driven Industrial Validation: Lighting Housing

7.5.1. Injection moulding window and final settings

The injection moulding process parameters for the two down-selected compounds 62GR70 and PX10323 were optimized based on the Moldex3D CAE simulations and verified experimentally on the Zhafir VEII 1500/430 machine. The simulation results defined a process window, i.e. the safe operational range of melt and mould temperatures, packing pressures, and cooling times that ensured complete filling with minimal warpage or air traps.

The final machine settings were then adjusted within this window to achieve stable production and high surface quality.

Both materials exhibited good agreement between simulated and actual settings.

The only notable difference was in the packing stage of the 62GR70, where the simulation used a two-step packing pressure profile (500–700 bar), while the actual injection cycle was simplified to a single-stage packing at 700 bar without affecting part quality or dimensional stability.

Table 16. Comparison between CAE-predicted and experimentally applied injection-moulding parameters for 62GR70 and PX10323. Source: developed from Moldex3D simulations and injection-moulding trials performed in the present study.

Parameter	CAE Results		Injection Moulding	
	62GR70	PX10323	62GR70	PX10323
Filling Time (s)	3.0	2.5	3.17	2.73
Packing Profile (s)	4 + 5 *	4 + 5 *	9.0	4 + 5 *
Packing Pressure (bar)	500-700	350-550	700	350-550
Cooling Time (s)	20	20	20	20
Velocity (mm/s)	58	42	60	40
Melt Temperature (°C)	285	290	285	290
Mould Temperature (°C)	90	90	80	80

*Packing profile consisted of 4 s high-pressure packing followed by 5 s secondary packing.

Both materials demonstrated complete cavity filling and consistent cycle performance. The PX10323 parts showed excellent surface uniformity and dimensional stability, confirming that the multi-filler system provided a balanced combination of flowability and mechanical robustness.

In contrast, the 62GR70 compound, although successfully moulded, displayed a localized defect near the thin standoff pin area of the lighting housing (Figure 41. (d,e)).

The overall surface finish and dimensional accuracy were satisfactory; however, the slender pin located close to the connector consistently fractured during ejection or handling. This issue was identified as a local brittle failure of the standoff pin, rather than a filling or warpage defect.

It is attributed to the high graphite loading (70 %), which significantly increases stiffness but reduces ductility, combined with the sharp geometry and high local stress concentration induced during the packing stage. Such behaviour is typical of heavily filled, high-modulus polymer composites, where residual stresses accumulate in thin or constrained zones during cooling and ejection [51,55,79]

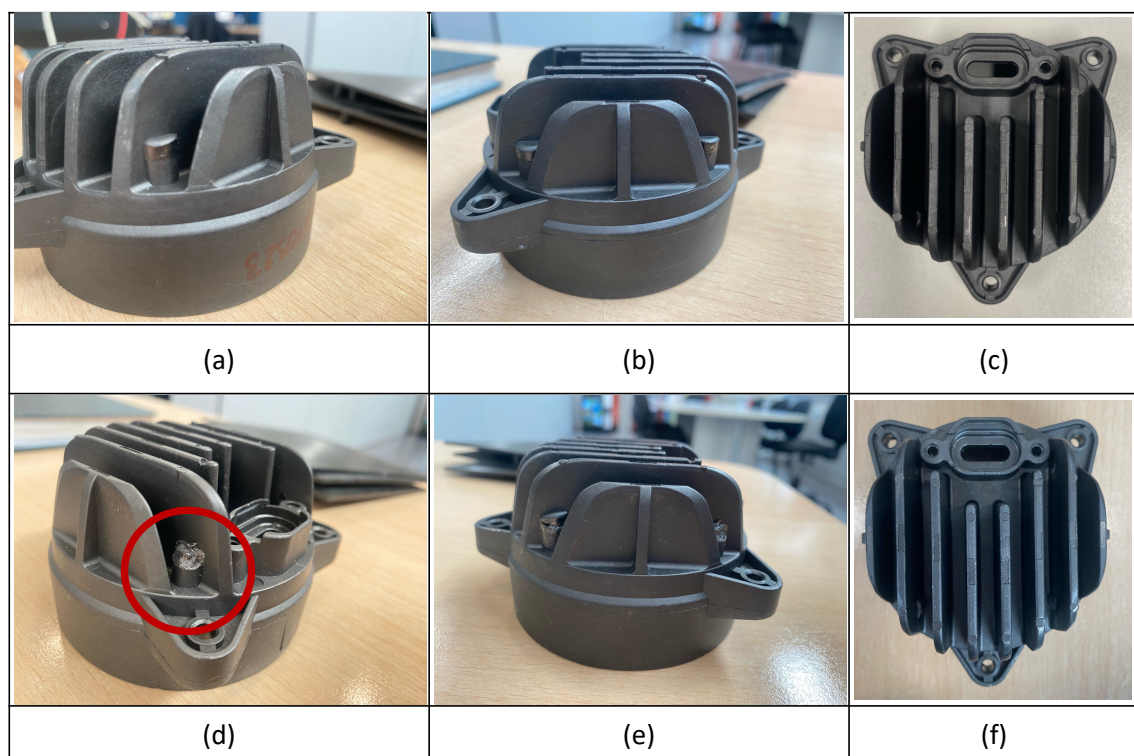


Figure 41. Comparison of moulded lighting housings: (top) PX10323, (bottom) 62GR70 showing local brittle fracture at the standoff pin region (circled).

7.5.2. Thermal simulation of housing materials (siemens simcentre)

Before performing the experimental thermal-validation tests preliminary numerical thermal simulation was carried out using Siemens Simcentre/Nastran. The objective was to estimate the heat-dissipation behaviour associated with three different housing

materials and to verify whether the expected thermal trends derived from thermal-conductivity data would be reflected in the real components. The full 3D geometry of the lighting module with thick lenses (1500 lm) was used, including the heatsink body, LED support structures, optical system, PCB, and mechanical mounting features (Figure 42.). To isolate the influence of the housing material, the same geometry was simulated using three alternatives:

- Aluminium (reference)
- LATI 62GR70; PA6 reinforced with a high graphite content
- SABIC PX10323; PA6 containing a multi-filler conductive network

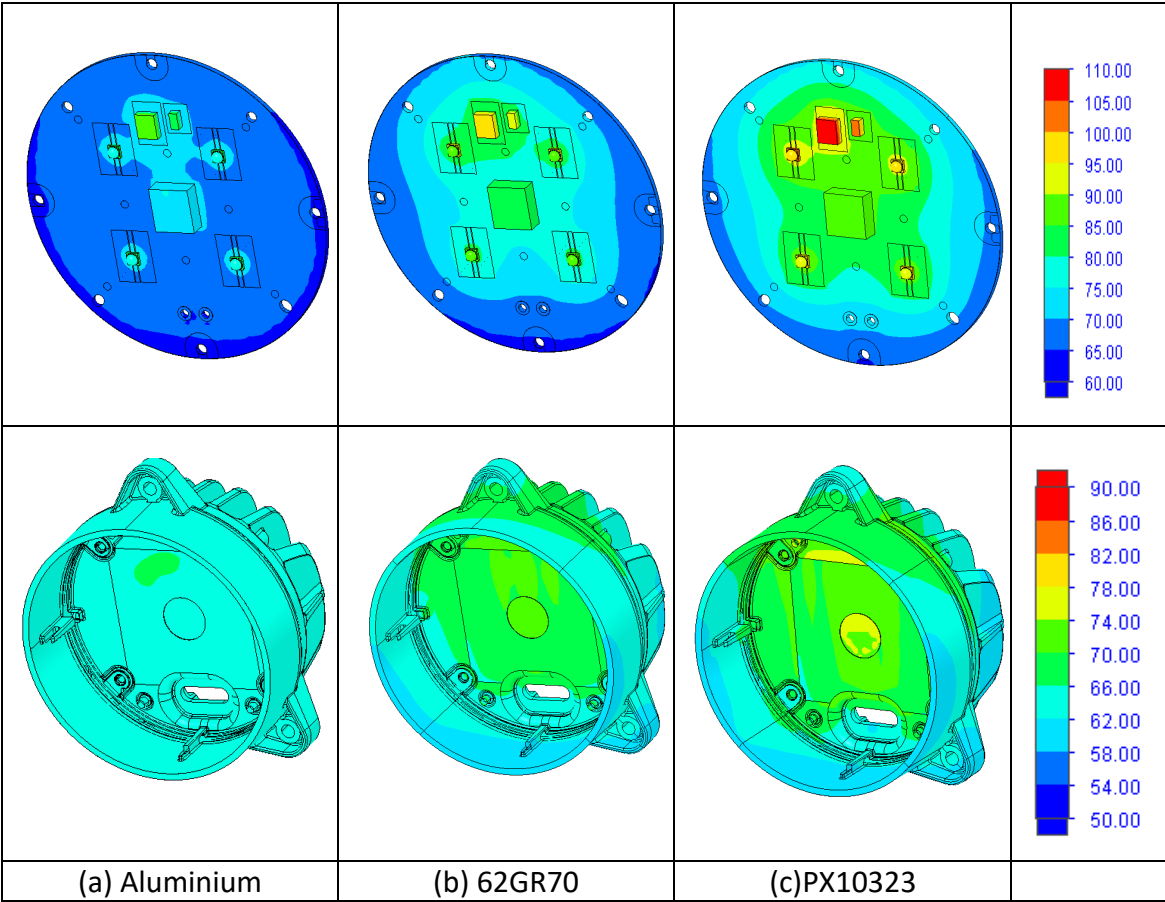


Figure 42. Simulated temperature distribution on the electronic assembly (top) and rear housing (bottom) for the three materials: Aluminium, LATI 62GR70, and SABIC PX10323 at 25 °C ambient.

Material properties thermal conductivity, density and specific heat were assigned using experimentally measured values and literature sources on conductive polymer composites [22,30,39]. Aluminium values were taken from standard thermal-design references used in automotive applications. LEDs were modelled as volumetric heat sources according to manufacturer power-dissipation data. All simulations were performed at 25 °C with natural-convection boundary conditions, and identical loads and constraints were applied to each model to enable a direct comparison.

Table 17. Simcenter thermal-simulation results showing average component temperatures [°C] for aluminium, 62GR70 and PX10323 housings.

Component	Aluminium	62GR70	PX10323
Housing Body	64,9	65,6	65,9
Cover	66,3	67,4	69,4
Lens	69,8	72,3	75,0
Support	71,4	74,2	77,3
PCB	66,3	70,9	75,7
MOSFET	83,9	94,4	102,7
Diode	80,0	89,8	97,5
Inductor	74,5	82,0	97,5
LED	80,9	91,6	100,2

Table 17 reports the average temperatures reached by the main electronic and optical components for the three materials, while Figure 42. illustrate the temperature distribution across both the electronic assembly and the rear housing.

The colour maps reveal how material choice influences both component temperatures and the overall heat-spreading pattern. Aluminium exhibits the lowest and most uniform temperature fields, with wide blue-light-blue regions indicating efficient heat dissipation without localised accumulation consistent with its high thermal conductivity [9,22].

In contrast, 62GR70 and PX10323 display higher temperature gradients and material-dependent spreading behaviour. Thanks to its high graphite loading, 62GR70 distributes heat laterally across a wider area, reducing hotspot severity relative to conventional PA6 materials. PX10323, despite its multi-filler system, shows more pronounced hotspots near the LED and MOSFET regions and a more restricted heat-spreading pattern, reflecting the limited continuity of its conductive pathways compared with graphite-rich networks.

Although aluminium clearly provides the best thermal performance, both conductive PA6-based housings remain within acceptable temperature limits for automotive lighting electronics [12-14,27]. The overall ranking derived from Table 17 is therefore: aluminium < 62GR70 < PX10323. Moreover, the thermal trends observed in this simulation were consistent with the subsequent climatic-chamber derating tests and infrared thermography, confirming a strong agreement between predictive modelling and the actual thermal response of the components.

7.5.3. Climatic-chamber current/temperature test (derating behaviour)

According to ISO 16750-4, a 9-hour temperature-step test (20→60 °C, +5 °C/h per step) was performed to evaluate the derating tendencies of modules assembled with an aluminium reference housing and the PX10323 and 62GR70 polymer housings. During the test, the ambient temperature (T_{room}), rear-body temperature (T_{body}), and absorbed current (I_{abs}) were continuously monitored. The rear-body temperature was measured

using an NTC thermal probe positioned at the critical hotspot on the heatsink surface, as shown in Figure 23. , ensuring that the thermal response of each housing was captured at its most sensitive location. The temperature and current evolution for aluminium, PX10323 and 62GR70 are presented in Figure 43 b,c, respectively.

The results show that the aluminium housing rapidly reached a new thermal equilibrium after each temperature step, with T_{body} stabilising within a short time. This behaviour is consistent with the fast heat-spreading capability of high-conductivity metallic materials. In contrast, both PX10323 and 62GR70 polymer housings did not display a well-defined plateau at any temperature step; instead, T_{body} continued to rise progressively throughout the test. This monotonic temperature increase indicates thermal accumulation behaviour characteristic of graphite and metal filled polymer composites, where the effective thermal conductivity although significantly improved compared to unfilled polymers remains distinctly lower than aluminium, resulting in slower heat dissipation and higher steady-state body temperatures (34,35).

The absorbed-current behaviour shown in Figure 43 further illustrates the impact of these thermal differences on derating. Up to approximately 25–28 °C, all modules drew similar current levels ($\approx 2.0\text{--}2.1\text{ A}$), indicating comparable performance in low-temperature conditions. Beyond $\sim 30\text{ }^{\circ}\text{C}$, all housings exhibited a downward trend in I_{abs} due to increased thermal load; however, the rate and severity of derating diverged between materials. In aluminium, the current reduction was mild and gradual, consistent with the stable T_{body} profile. In the polymer housings, the faster rise in T_{body} caused the LED driver's internal thermal-protection mechanism to activate earlier, resulting in a more pronounced decrease in I_{abs} . By the time the chamber reached 60 °C, both polymer-based modules exhibited substantially lower current levels than aluminium, confirming the earlier onset of thermally induced derating that has also been reported in conductive PA6 composites subjected to elevated temperatures (9,34,35,39)

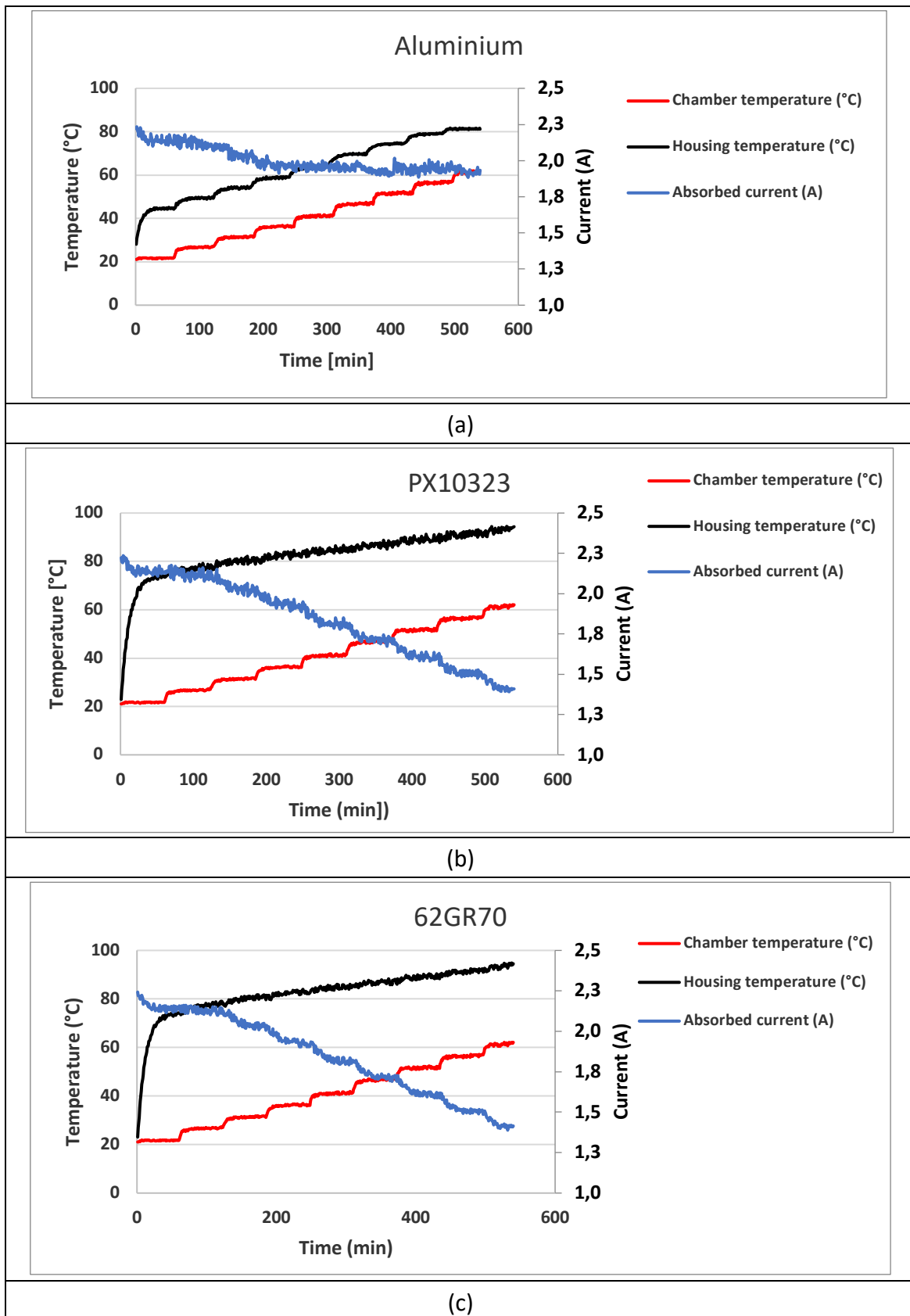
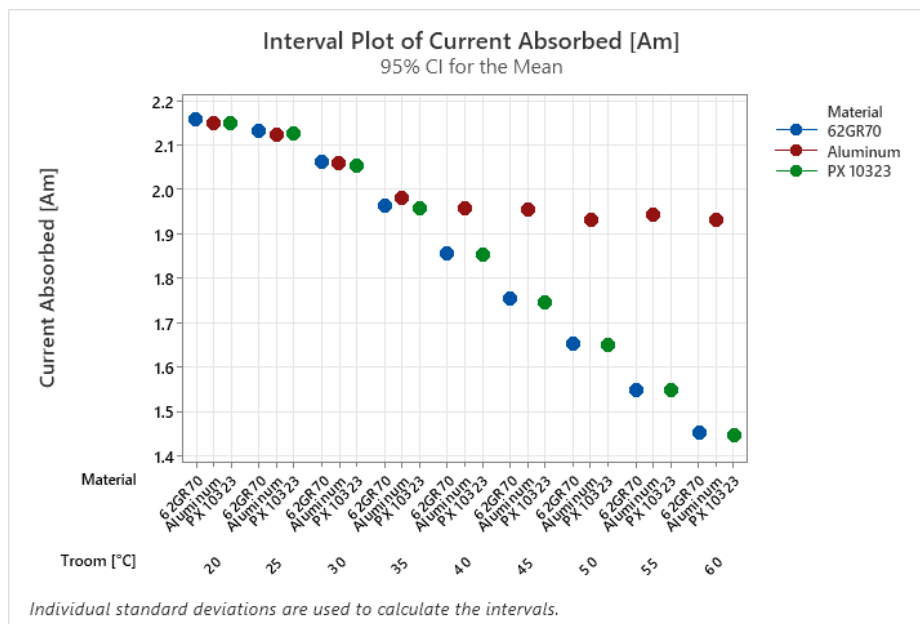


Figure 43. Climatic-chamber derating test results for aluminium, PX10323 and 62GR70 lighting housings: chamber temperature, housing body temperature and absorbed current as a function of time.

Statistical evaluation of the absorbed-current data is presented in Figure 44. . The 95% confidence-interval plot (Figure 44. (a)) and ANOVA results (Figure 44. (b)) reveal that both temperature and material type have a significant influence on I_{abs} , while the Tukey grouping (Figure 44. (c)) confirms that differences between materials become statistically significant above approximately 35–40 °C. These results validate that derating is strongly governed by the ability of each housing to manage rear-body temperature as the ambient conditions increase.



(a)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Troom [°C]	8	55.158	6.89478	5652.66	0.000
Material	2	9.684	4.84187	3969.58	0.000
Troom [°C]*Material	16	11.066	0.69160	567.00	0.000
Error	1593	1.943	0.00122		
Total	1619	77.851			

Grouping Information Using the Tukey Method and 95% Confidence

Troom [°C]*Material	N	Mean	Grouping
20 62GR70	60	2.15657	A
20 PX 10323	60	2.15059	A B
20 Aluminum	60	2.15044	A B
25 62GR70	60	2.13094	B C
25 PX 10323	60	2.12468	C
25 Aluminum	60	2.12238	C
30 62GR70	60	2.06124	D
30 Aluminum	60	2.05864	D
30 PX 10323	60	2.05491	D
35 Aluminum	60	1.98062	E
35 62GR70	60	1.96257	E F
40 Aluminum	60	1.95833	E F
35 PX 10323	60	1.95787	E F
45 Aluminum	60	1.95442	F G
55 Aluminum	60	1.94336	F G
60 Aluminum	60	1.93270	G
50 Aluminum	60	1.93092	G
40 62GR70	60	1.85592	H
40 PX 10323	60	1.85258	H
45 62GR70	60	1.75442	I
45 PX 10323	60	1.74746	I
50 62GR70	60	1.65318	J
50 PX 10323	60	1.65035	J
55 62GR70	60	1.54970	K
55 PX 10323	60	1.54784	K
60 62GR70	60	1.45308	L
60 PX 10323	60	1.44850	L

Means that do not share a letter are significantly different.

(b)

(c)

Figure 44. Statistical evaluation of the absorbed-current data of Aluminium, PX10323 and 62GR70.

Despite the differences at high temperature, both PX10323 and 62GR70 performed comparably to aluminium up to ~30 °C, demonstrating that their thermal behaviour remains within acceptable limits for moderate operating loads. The high graphite content of 62GR70 and the multi-filler conductive network of PX10323 contribute to enhanced heat spreading relative to conventional polymer housings, resulting in a more balanced derating profile than typical reinforced polymers (34,35,58). Overall, while aluminium unsurprisingly remains superior in sustaining performance under high ambient temperatures, the selected PA6-based conductive composites provide adequate thermal management in the mid-temperature range.

In the context of automotive lighting systems, the ambient temperature inside the front compartment of a vehicle generally falls between 20 and 45 °C under normal operating conditions, with temperatures above 50–55 °C occurring only under extreme environmental or stationary idle conditions (9,13,14). Considering this operational window, both PX10323 and 62GR70 remain within acceptable derating behaviour throughout the majority of real-world conditions. Their performance matches aluminium up to ~30 °C and remains functionally stable at mid-range temperatures, with derating becoming significantly relevant only above ~40–45 °C. Therefore, although aluminium provides a wider thermal-safety margin, the polymer housings can still be reliably integrated into automotive lighting modules.

7.5.4. Infrared Thermal Imaging on Assembled Modules

An infrared thermal-imaging test was performed to compare the front-side thermal behaviour of assembled lighting modules manufactured from aluminium (benchmark material), LATI 62GR70 (PA6 + 70 wt% graphite), and SABIC PX10323 (PA6 multi-filler system) [72].

Each module contained four LEDs operating at nominal current, with thermal probes (Sp1–Sp4) positioned directly above each LED (Figure 45). Measurements were recorded at the initial condition, after 30 min, and after 60 min under steady-state operation.

As summarised in Table 18 and illustrated in Figure 45, all materials exhibited progressive temperature increases during continuous operation. After 60 min, the mean surface temperatures reached approximately 45.6 °C for aluminium, 40.5 °C for 62GR70, and 40.6 °C for PX10323.

Table 18. Front-side infrared temperature measurements obtained during continuous LED operation.

Material	Condition	Sp1 (°C)	Sp2 (°C)	Sp3 (°C)	Sp4 (°C)	Mean (°C)
Aluminium	Initial condition	25.7	25.7	25.5	25.5	25.6
Aluminium	After 30 min	43.1	41.0	41.4	41.1	41.7
Aluminium	After 60 min	46.3	44.6	45.0	46.4	45.6
62GR70	Initial condition	22.3	22.6	22.3	22.0	22.3
62GR70	After 30 min	38.3	37.0	38.0	40.0	38.3
62GR70	After 60 min	40.7	38.9	39.0	43.0	40.4
PX10323	Initial condition	22.6	22.3	22.0	22.1	22.3
PX10323	After 30 min	40.0	37.6	40.0	38.0	38.9
PX10323	After 60 min	41.6	38.8	41.7	38.3	40.1

Despite the higher intrinsic thermal conductivity of aluminium, both conductive polymer housings exhibited only an approximately 5 °C difference in mean surface temperature, indicating effective lateral heat spreading within the housing structure.

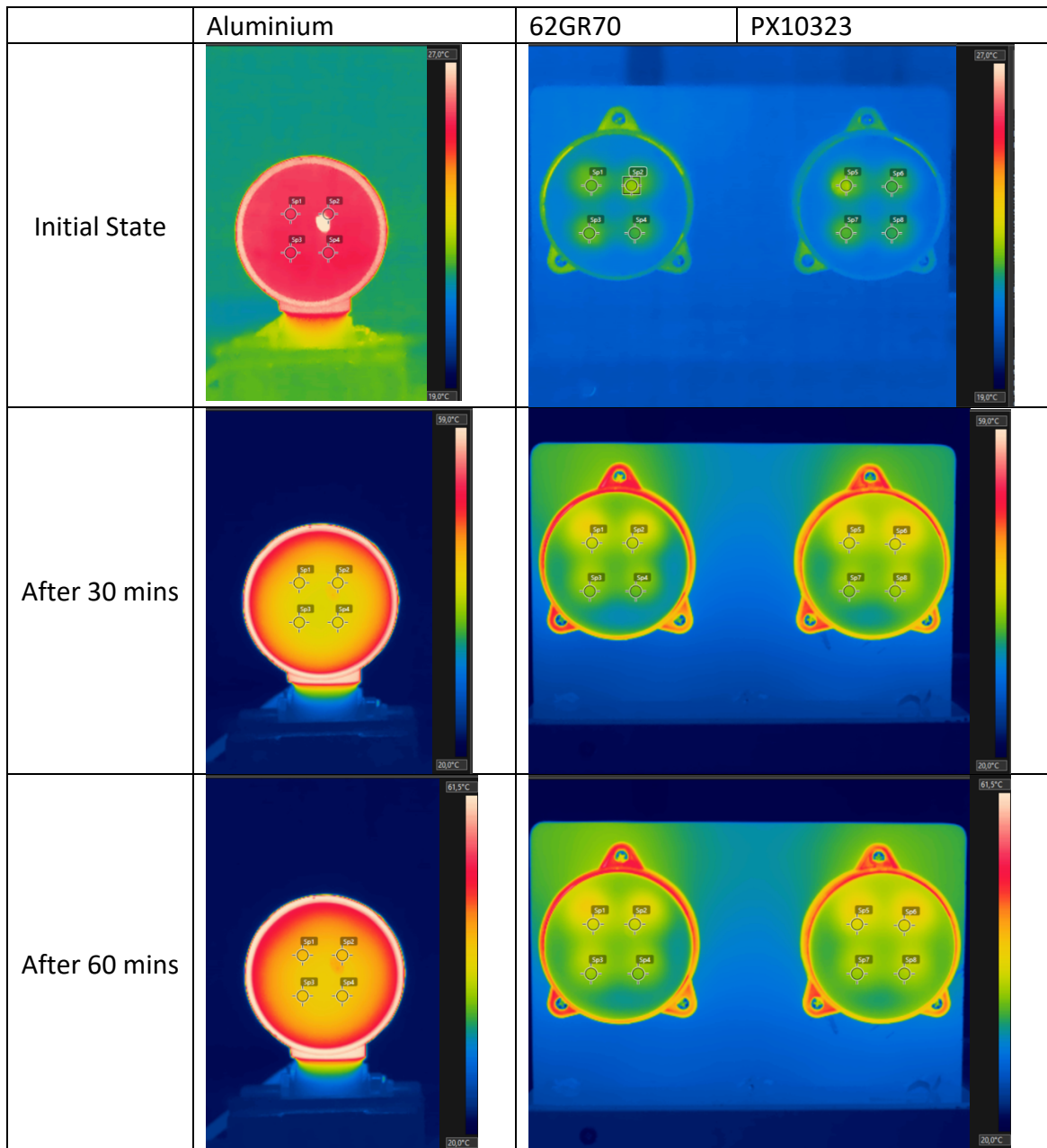


Figure 45. Infrared thermograms at 0, 30 and 60 min for Aluminium, 62GR70, and PX10323 housings.

Infrared thermography (Figure 45) further confirmed distinct thermal-distribution behaviours for the investigated materials. Aluminium exhibited the most uniform temperature field due to its intrinsically high thermal conductivity and rapid heat-spreading capability [67,70]. Nevertheless, both conductive PA6 systems demonstrated effective in-plane heat propagation with limited localised hotspot formation.

Among the conductive polymer systems, 62GR70 exhibited relatively homogeneous lateral heat conduction, which may be associated with the graphite-rich conductive network generated during injection moulding. PX10323 showed slightly lower thermal uniformity; however, the measured peak temperatures remained comparable to those of 62GR70.

Overall, no critical difference in surface temperature was observed between aluminium and the conductive polymer housings, demonstrating that graphite-reinforced PA6 systems can provide effective thermal management for lighting-housing applications operating under moderate thermal loads.

Infrared thermal imaging was also performed on the rear side of the assembled housings to evaluate heat transfer through the fin structure. Two thermal monitoring points were positioned at the rear-body centre and fin-tip regions (Figure 46).

Table 19. Rear-side infrared temperature measurements obtained during continuous LED operation.

Material	Condition	Rear-body centre (°C)	Fin-tip region (°C)	Mean (°C)
62GR70	Initial condition	27.4	24.1	25.8
62GR70	After 30 min	58.2	58.3	58.3
62GR70	After 60 min	61.3	61.7	61.5
PX10323	Initial condition	24.1	24.1	24.1
PX10323	After 30 min	57.7	57.7	57.7
PX10323	After 60 min	61.4	60.6	61.0

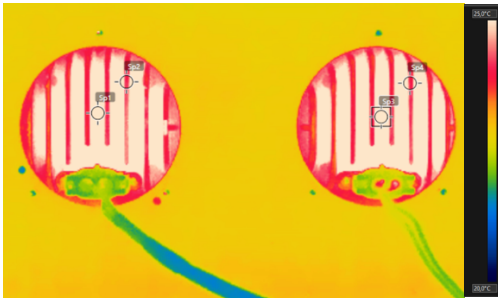
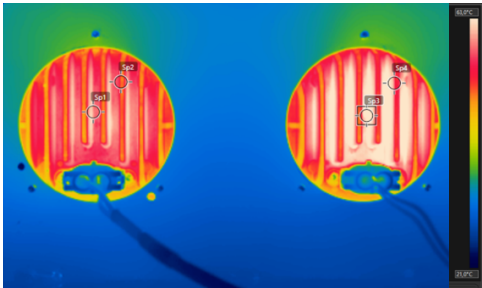
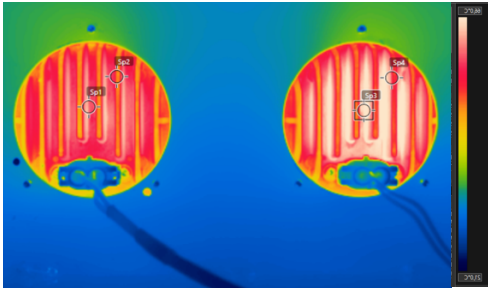
	62GR70	PX10323
Initial State		
After 30 mins		
After 60 mins		

Figure 46. Rear-side thermographic images of 62GR70 and PX10323 modules at 0, 30, and 60 min.

Infrared thermal imaging was also performed on the rear side of the assembled housings to evaluate heat transfer through the fin structure. Two thermal monitoring points were positioned on each module at the rear-body centre and fin-tip regions (Figure 46). For the conductive polymer housings, Sp1–Sp2 corresponded to the 62GR70 module, whereas Sp3–Sp4 corresponded to the PX10323 module.

As summarised in Table 19 and illustrated in Figure 46, both conductive polymer systems exhibited progressive temperature increases during continuous operation. After 60 min, the average rear-side temperatures reached approximately 61.5 °C for 62GR70 and 61.0 °C for PX10323.

The relatively small temperature differences between the rear-body centre and fin-tip regions indicate efficient heat transfer through the conductive polymer structure and suggest limited thermal resistance across the fin geometry. Infrared thermography further

confirmed relatively homogeneous thermal gradients for both materials, with no evidence of severe localised overheating.

Although aluminium remained the benchmark material throughout the thermal investigations due to its intrinsically superior thermal conductivity, both conductive PA6 systems demonstrated stable and reproducible thermal behaviour under representative lighting-operating conditions.

Among the investigated materials, 62GR70 exhibited slightly enhanced lateral heat propagation associated with its graphite-rich conductive network, whereas PX10323 provided a more balanced combination of thermal performance, processability and mechanical robustness. These findings indicate that conductive polymer composites can serve as technically viable lightweight alternatives to aluminium for automotive lighting housings operating under moderate thermal loads [18,22,34].

7.6. EMI-Driven Path: Standard Specimen and Down-Selection

7.6.1. EMI SE test on standard specimen (ASTM D4935, Coaxial Line)

Measurements were performed according to the automotive EMC standards CISPR 25 and ISO 11452-2, covering the full 150 kHz–3 GHz frequency range relevant for dashboard electronics, lighting controllers and in-vehicle communication systems [62,73]. All polymer formulations were moulded into standard test plaques using both direct and tunnel gate configurations to capture gate-induced orientation effects. For each material-gate combination, three independent specimens were tested, and the maximum shielding effectiveness (SE_{max}) across the entire frequency span was extracted as a representative metric for material comparison. The resulting average SE_{max} values are reported in Table 21. , enabling a direct comparison across base resins, filler types and fibre loadings.

Table 20. Electromagnetic frequency bands and corresponding automotive systems considered in EMI tests. Adapted from [1,73].

Frequency Range	Affected Systems
150 kHz – 3 MHz	AM broadcast receivers
3 MHz – 30 MHz	Shortwave/CB radios
30 MHz – 300 MHz	FM radio, VHF systems
300 MHz – 3 GHz	Cellular, GPS, WiFi

Table 21. Maximum EMI shielding effectiveness (SE_{max}) of polymer formulations as a function of material and gate type

Materials	Gate Type	Max. EMI SE (dB)		
		Sample 1	Sample 2	Sample 3
PA6	Tunnel	2,59	2,35	3,00
	Direct	2,14	2,72	3,00
LX24059	Tunnel	31,42	33,36	31,46
	Direct	32,60	33,17	33,18
LX24060	Tunnel	48,42	47,84	47,69
	Direct	47,74	47,13	51,09
LX24061	Tunnel	48,75	48,45	48,02
	Direct	56,22	55,78	57,83
PX10323	Tunnel	19,94	19,62	20,29
	Direct	20,21	20,06	20,17
66 H2 K/40 NT	Tunnel	43,41	44,00	44,85
	Direct	47,61	48,10	47,55
62GR50	Tunnel	19,01	18,78	18,92
	Direct	19,00	18,88	18,76
62GR70	Tunnel	32,85	32,27	31,95
	Direct	31,66	31,27	31,95
PC	Tunnel	4,58	4,60	5,14
	Direct	5,33	5,82	4,80
DS0031	Tunnel	61,27	68,24	75,21
	Direct	93,38	87,64	90,86
87/24-08A	Tunnel	54,83	79,05	60,97
	Direct	91,79	98,26	93,06
87/28-10A	Tunnel	88,01	98,87	87,47
	Direct	109,99	103,58	110,55
DTK22	Tunnel	4,87	4,04	4,19
	Direct	3,61	4,13	3,96
47/30 cp1/800	Tunnel	3,06	2,82	3,07
	Direct	2,65	2,64	3,01

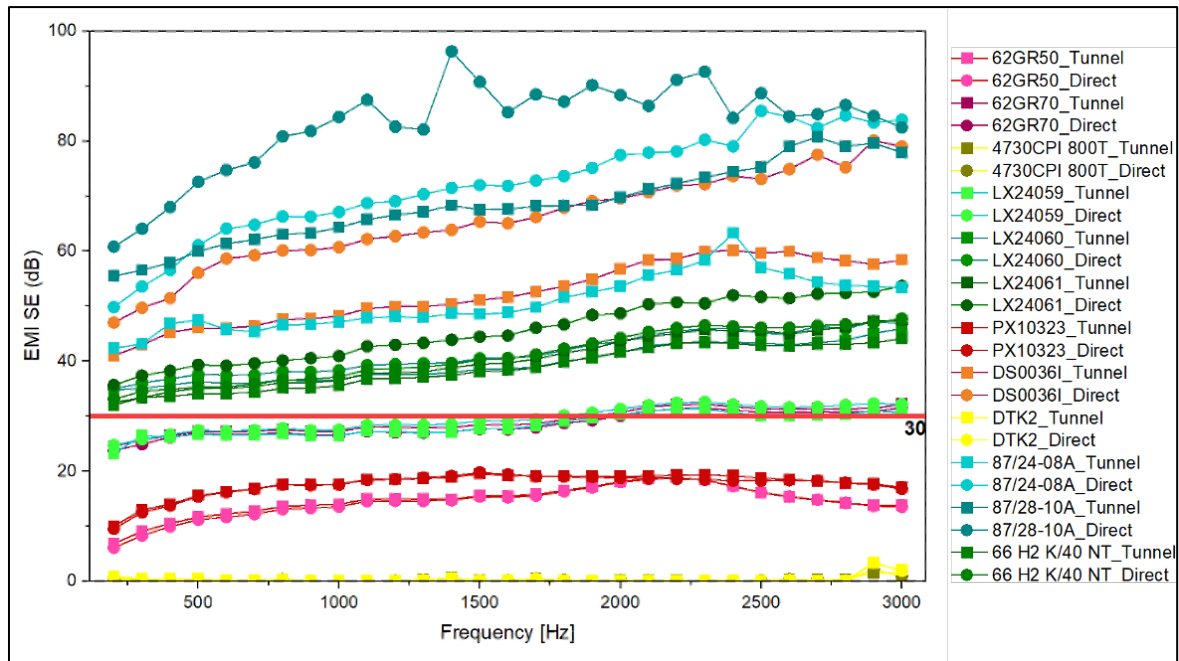


Figure 47. Frequency-dependent EMI shielding effectiveness of all investigated polymer formulations for tunnel and direct gate plaques; the horizontal line indicates the 30 dB target level.

A global view of the frequency-dependent behaviour is shown in Figure 47. (all material), where all curves are plotted together and a 30 dB line is superimposed as the minimum acceptable limit for automotive shielding enclosures. Materials whose curves remain below 30 dB in one or more bands (e.g. neat PA6, neat PC, PX10323, 62GR50, 62GR70, DTK22, 47/30 CP1/800, 66H2K/40 NT) were discarded at this stage. The remaining high-performing compounds are highlighted in Figure 48. (above 30 dB) which shows only the curves consistently above the 30 dB threshold:

- LX24060 (PA6 + CF + SSF)
- LX24061 (PA6 + 20 % CF)
- DS0031 (PC + 15 % SSF)
- 87/24-08A (PC + 8 % SSF)
- 87/28-10A (PC + 10 % SSF)

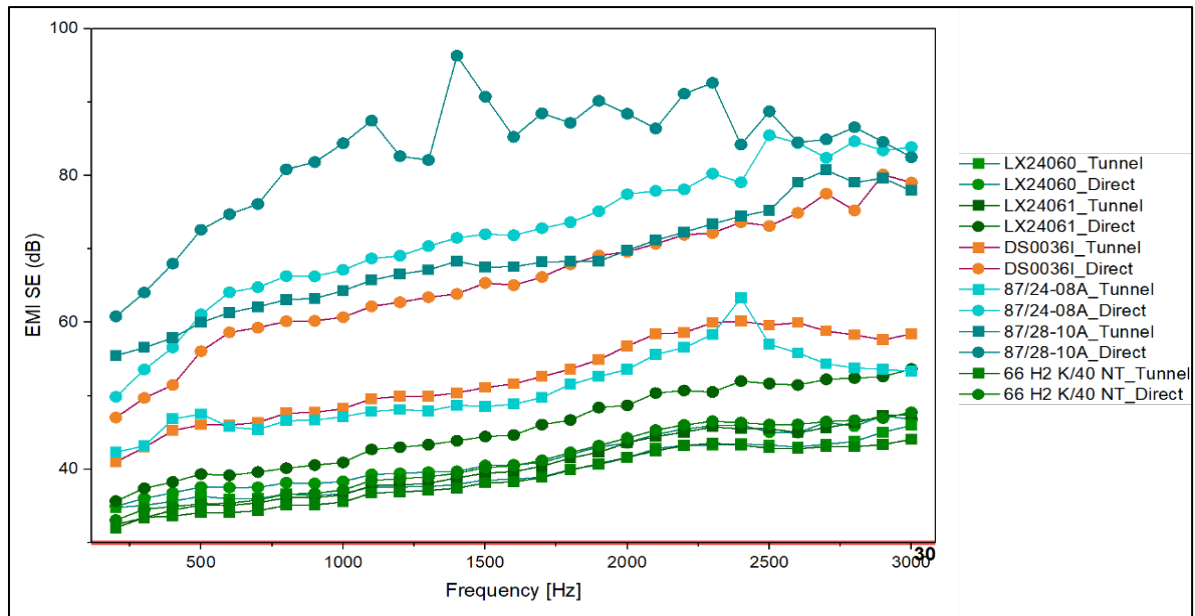


Figure 48. Frequency-dependent EMI shielding effectiveness of investigated polymer formulations above 30 dB for tunnel and direct gate plaques; the horizontal line indicates the 30 dB target level.

Compared with the neat matrices, the improvement is substantial. Neat PA6 shows a maximum EMI SE of only $\approx 2\text{--}3$ dB, and neat PC around ≈ 5 dB, which is effectively negligible shielding. In contrast:

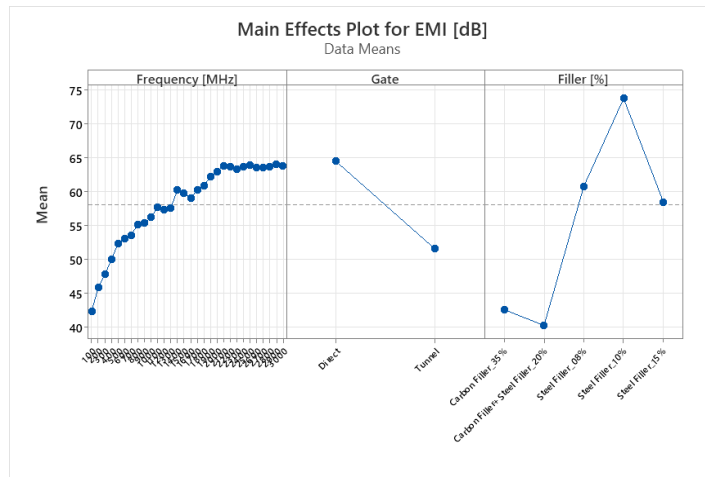
- PA6-based CF/SSF grades (LX24060, LX24061) reach $\approx 50\text{--}60$ dB, corresponding to an enhancement of about $+45\text{--}55$ dB over neat PA6.
- PC-based SSF grades (DS0031, 87/24-08A, 87/28-10A) achieve $\approx 90\text{--}110$ dB, i.e. $+85\text{--}105$ dB over neat PC.

Since EMI SE is expressed on a logarithmic scale, an increase of $40\text{--}60$ dB means that the transmitted power is reduced by four to six orders of magnitude [68,74]. The data therefore confirm that the shielding behaviour is dominated by the conductive network created by the fillers rather than by the base polymer itself [68,74,83].

Effect of filler type and base polymer;

The influence of frequency, gate type and filler system was quantified by a three-factor ANOVA, using:

- Frequency (30 frequencies from 100 to 3000 MHz)
- Gate (direct, tunnel)
- Filler system:
 - Stainless-steel fibre 8 % (PC 87/24-08A)
 - Stainless-steel fibre 10 % (PC 87/28-10A)
 - Stainless-steel fibre 15 % (PC DS0031)
 - Carbon fibre 35 % (PA6 LX24061)
 - Carbon + steel fibre 20 % (PA6 LX24060)



(a)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Frequency [MHz]	29	52738	1818.5	54.54	0.000
Filler [%]	4	189853	47463.3	1423.35	0.000
Gate	1	51141	51140.6	1533.63	0.000
Error	1175	39182	33.3		
Lack-of-Fit	265	27308	103.0	7.90	0.000
Pure Error	910	11874	13.0		
Total	1209	322004			

Grouping Information Using the Tukey Method and 95% Confidence

Frequency [MHz]	N	Mean	Grouping
2900	36	63.1231	A
2500	36	63.0500	A
3000	36	62.9500	A
2800	36	62.8080	A
2400	36	62.7906	A
2600	36	62.7224	A
2700	36	62.7066	A
2300	36	62.5092	A
2200	40	61.2849	A B
2100	42	60.2824	A B C
2000	42	59.4635	A B C D
1900	42	58.6433	A B C D E
1800	42	57.3785	B C D E F
1400	42	56.7512	B C D E F
1700	42	56.7058	B C D E F
1500	42	56.2328	C D E F G
1600	42	55.5336	D E F G
1100	42	54.2064	E F G H
1300	42	54.0899	E F G H
1200	42	53.8230	F G H
1000	42	52.6797	F G H I
900	42	51.8088	G H I
800	42	51.6177	G H I
700	42	50.0892	H I J
600	42	49.5947	H I J
500	42	48.7851	I J K
400	42	46.4732	J K L
300	42	44.2442	K L
200	42	42.3574	L M
100	42	38.8491	M

Means that do not share a letter are significantly different.

(b)

Grouping Information Using the Tukey Method and 95% Confidence

Gate	N	Mean	Grouping
Direct	604	61.9533	A
Tunnel	606	48.9504	B

Means that do not share a letter are significantly different.

(c)

Grouping Information Using the Tukey Method and 95% Confidence

Filler [%]	N	Mean	Grouping
Steel Filler_10%	310	75.0036	A
Steel Filler_08%	360	60.8347	B
Steel Filler_15%	180	58.5031	C
Carbon Filler_35%	180	42.6145	D
Carbon Filler+Steel Filler_20%	180	40.3031	E

Means that do not share a letter are significantly different.

(d)

(e)

Figure 49. ANOVA and Tukey post-hoc analysis of EMI shielding effectiveness: (a) main effects plots for frequency, gate and filler, (b) ANOVA table (c–e) Tukey groupings for gate type, frequency and filler content.

- Frequency: mean EMI SE increases from ≈ 39 dB at 100 MHz to ≈ 63 dB near 2.5–3 GHz, in line with classical skin-depth arguments and the logarithmic increase of shielding with frequency [68,74,83].

Gate: plaques moulded with a direct gate display a significantly higher average EMI SE (≈ 62 dB) than those moulded with a tunnel gate (≈ 49 dB). This can be attributed to a more favourable fibre alignment and fewer weld lines in the central measuring region when the melt enters from a central direct gate [23,24,44,56–58].

- Filler system: Tukey grouping ranks the materials as
 - Steel 10 % > Steel 8 % > Steel 15 % > Carbon 35 % > Carbon + Steel 20 %.

7.6.2. Down-selection for EMI-oriented component

For the subsequent EMI-oriented industrial part, the material choice was guided by:

1. Shielding level: EMI SE ≥ 30 dB across the entire 150 kHz–2.5 GHz band (CISPR 25 window);
2. Average performance from ANOVA (frequency-averaged SE, main-effects and Tukey groups);
3. Mouldability and defect level of the standard plaques (Section 7.3);
4. Material portfolio balance between PA6 and PC families.

Applying these criteria led to the following final selection:

The superior performance of PC + steel fibre (8–10 %) confirms that high-conductivity metallic networks are very effective in attenuating both electric and magnetic components of the incident field [83,84]. Interestingly, the 15 % SSF grade (DS0031) does not outperform the 10 % grade: above a certain content, fibre crowding and contact resistance can reduce the effective network efficiency, which has also been noted in other metal-filled systems [68,74].

Carbon-fibre only PA6 (LX24061) yields lower mean SE than the SSF-PC grades, but still well above 50 dB, providing a lighter alternative with acceptable EMI protection. The hybrid CF + SSF PA6 (LX24060) shows the lowest mean SE among the selected group, suggesting that mixing two filler families may disrupt the percolated network rather than strengthening it, in agreement with previous observations on mixed filler systems [83–85].

Based on the standard coupon results (Section 6.6.1), the down-selection for the EMI-oriented enclosure focused on materials that:

- (i) maintained EMI SE ≥ 30 dB over the full CISPR 25 band,
- (ii) offered the highest shielding margin with respect to the 30 dB threshold, and

(iii) showed acceptable mouldability and surface integrity.

After applying these criteria, three PC-based formulations were retained:

- LATI 87/24-08A (PC + 8 % SSF) – provides high shielding effectiveness (≈ 70 – 85 dB depending on frequency) with good processability and moderate surface waviness.
- LATI 87/24-10A (PC + 10 % SSF) – exhibits the highest EMI SE levels among all tested compounds, reaching up to ≈ 95 – 100 dB in the upper frequency range, thus offering the largest safety margin above the 30 dB requirement (Table 20).
- SABIC DS0036I (PC + 15 % SSF) – despite its higher filler content, this pre-compounded grade combines very good shielding (≈ 80 – 90 dB) with the best surface quality among the steel-fibre materials, thanks to its more homogeneous fibre dispersion [76,86].

These three PC/SSF systems were therefore selected for the second step of the EMI path, involving CAE analysis and injection moulding of the screening housing geometry, as described in Section 6.1-6.2.

7.6.3. Injection moulding window and validation for the EMI screening part

After the material down-selection, the three PC-based EMI grades (87/24-08A, 87/24-10A and DS0031) were first analysed in Moldex3D to define a feasible processing window for the screening component. For each formulation, the filling, packing and cooling profiles were iteratively tuned in CAE to obtain complete cavity filling, limited pressure peaks at the gate and acceptable warpage. The final Moldex3D settings and the parameters adopted on the injection moulding machine are compared in Table 22.

Table 22. Moldex3D settings parameters vs the parameters adopted on the injection moulding machine.

Parameter	CAE Results			Injection moulding		
	87/24-8A	87/24-10A	DS0036I	87/24-8A	87/24-10A	DS0036I
Filling Time (s)	2.93	2,93	2,48	3	3	2,5
Packing Time (s)	4 + 5 = 9	4 + 5 = 9	4 + 5 = 9	4 + 5 = 9	4 + 5 = 9	4 + 5 = 9
Packing Pressure (Bar)	350-550	350-550	350-550	500-700	500-700	500-700
Cooling Time (s)	22	22	22	22	22	22
Velocity (mm/s)	40	40	40	-	-	-
Melt Temperature (°C)	290	290	290	290	290	290
Mould Temperature (°C)	85	85	85	90	90	90

The simulated and experimental parameters are in very good agreement.

- Filling time remained in the 2.5–3.0 s range for all three materials, confirming that the selected injection speed ensures a stable flow front without jetting or hesitation.
- Packing time was fixed to a 4 + 5 s two-stage profile (high-then-medium pressure), exactly as suggested by Moldex3D, in order to compensate volumetric shrinkage while avoiding over-packing of the ribs.

- Packing pressure was slightly increased on the machine (from 350–550 bar up to 500–700 bar) compared to the CAE window, providing a small safety margin against sink marks and ensuring full replication of the screening features.
- Cooling time was kept at 22 s, which matched the simulated time to reach ejection temperature and produced dimensionally stable parts.
- Melt temperature was set to 290 °C for all grades, in line with supplier recommendations and the CAE material cards, while the mould temperature was raised from 85 °C (simulation) to 90 °C in production to improve surface quality and reduce residual stresses.

After the EMI-oriented down-selection, full-scale injection-moulded housings were produced using three stainless-steel-fibre (SSF) reinforced PC compounds: 87/24-08A, 87/24-10A, and DS0036I. Visual inspection of the moulded parts (Figure 50.) revealed clear differences in surface appearance that can be directly linked to filler dispersion quality and compounding route.

Figure 50. Surface inspection of moulded parts 87/24-10A vs DS0036I.

Conversely, DS0036I, despite the highest SSF content (15%), exhibited a much smoother and more homogeneous surface, with only minor streaking. This improvement is consistent with literature showing that industrial melt-compounding via twin-screw extrusion produces more uniform filler networks and significantly reduces waviness and flow-mark intensity compared with simple dry-blending of fibres at the press [51,76,86].

Overall, these results demonstrate that dispersion quality is more decisive than nominal filler content: pre-compounded DS0036I achieves the best moulded appearance and is therefore the most suitable PC/SSF option for EMI-shielding housings.

7.6.5. Key findings of EMI-driven path

The EMI oriented screening pathway confirmed that stainless-steel-fibre-reinforced PC systems provide significantly higher shielding effectiveness than graphite- or carbon-based PA6 compounds. The results also demonstrated that gate configuration influences EMI performance through filler orientation effects, with direct-gate specimens generally exhibiting superior shielding levels. Among the investigated materials, DS0036I and 87/24-10A provided the best balance between shielding effectiveness, mouldability and surface quality, highlighting the importance of homogeneous conductive-network formation. These materials were therefore selected for industrial EMC validation of the screening housing.

7.7. Industrial Validation of EMI-Shielding Candidates Using the Screening Housing

To validate the real-world EMI shielding performance beyond standard specimen testing, the three selected PC/SSF compounds LATI 87/24-8A, LATI 87/24-10A, and SABIC DS0036I were injection-moulded into a full screening-housing geometry and assembled with the electronic module.

These results were compared both internally across the candidate materials and externally against COBO's standard ASA-based housing containing aluminium strings, currently used as the commercial reference.

Industrial validation consisted of three mandatory automotive EMC tests:

1. Radiated Emission Test (CISPR 25, R10)
2. Radiated Immunity Test (GTEM 500, ISO 11452-2)
3. Electrostatic Discharge Test (IEC 61000-4-2)

Each test probes a different EMC failure mechanism, ensuring that the polymer replacement does not compromise the system's electromagnetic robustness.

7.7.1. Radiated emission test (CISPR 25 / R10)

Radiated emission tests were carried out on the complete screening-housing assemblies (display, PCB, wiring, and rear housing) following CISPR 25:2021 Class 3–4 limits using the

ALSE configuration [73]. The radiated spectrum was evaluated across the three receiver-defined service bands;

- C25 Analog broadcast: 150 kHz–944 MHz
- C25 Digital broadcast: 171–770 MHz
- C25 Mobile services: 30–960 MHz

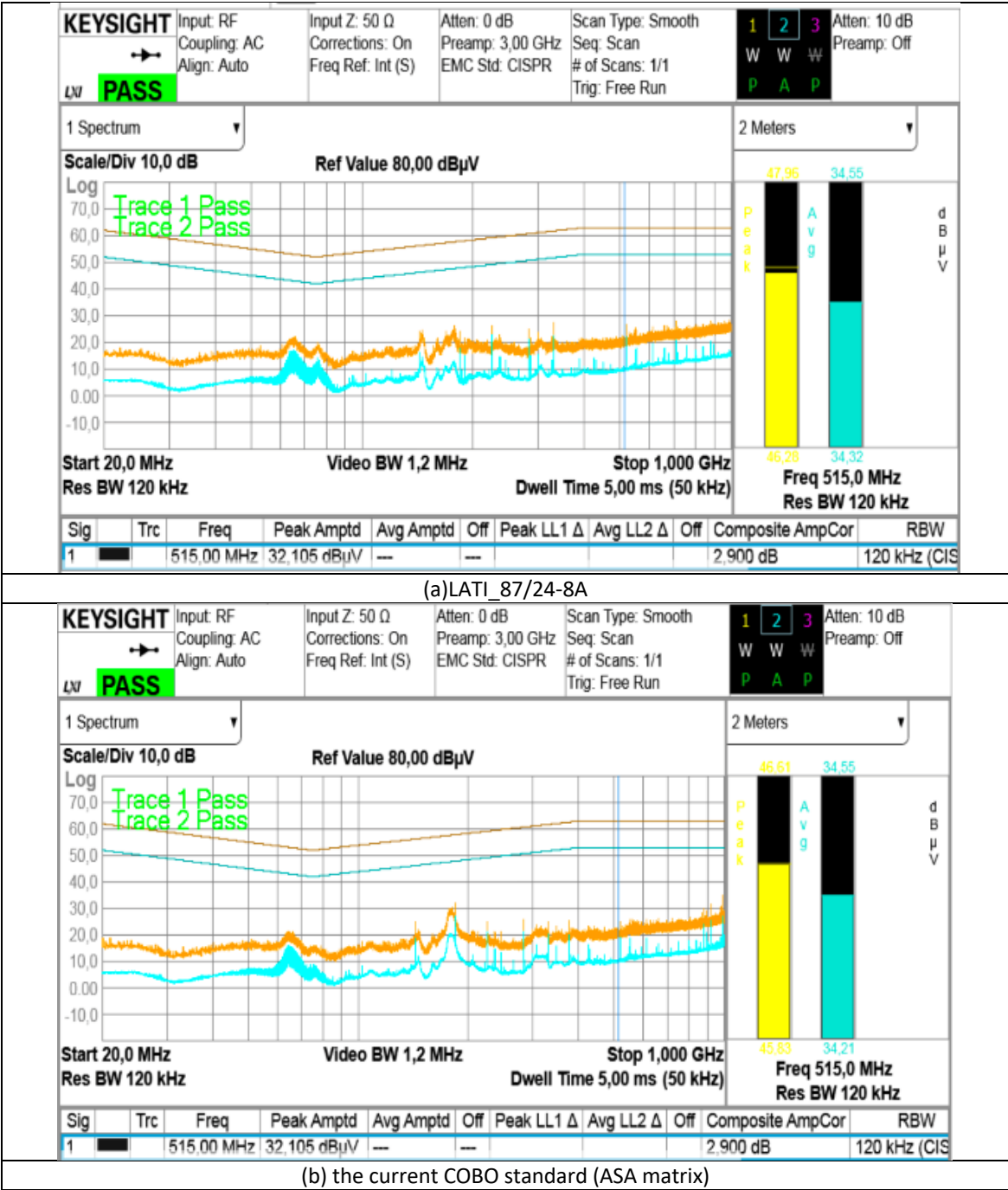


Figure 51. Compares the quasi-peak and average traces for the four housings.

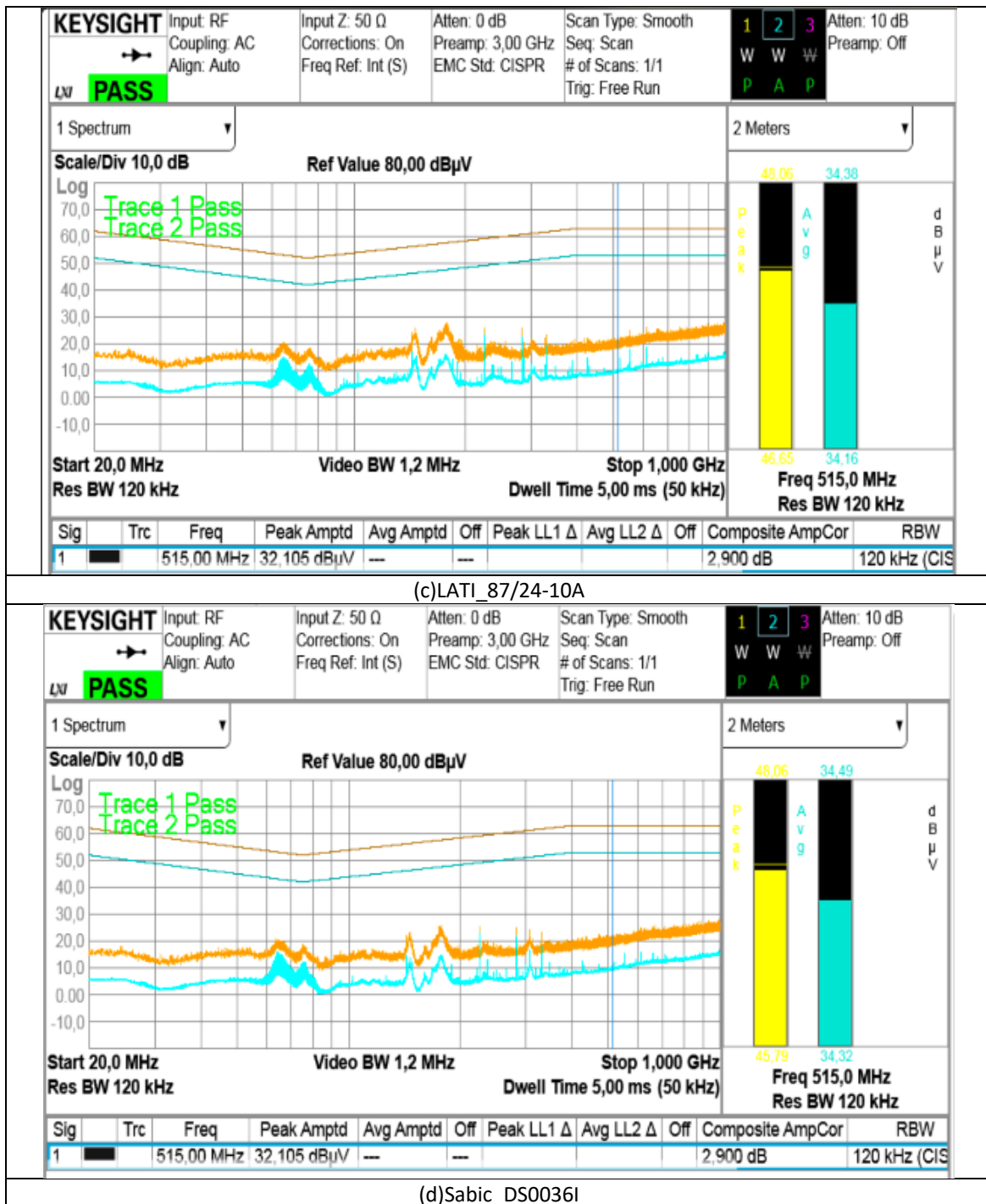


Figure 51 (cont'd). Compares the quasi-peak and average traces for the four housings.

All materials remain fully below the CISPR 25 limits in all frequency ranges, confirming compliance with automotive EMC regulations. Figure 51 (cont'd). compares the quasi-peak and average spectra for the ASA reference housing and the three PC/SSF candidates (87/24-8A, 87/24-10A and DS0036I) across the C25 analog, digital and mobile service bands. All four configurations remain comfortably below the regulatory limits in the entire 150 kHz–944 MHz range, confirming that every housing solution is EMC-compliant at system level.

However, the comparison also shows that the differences between housings are modest. In large parts of the spectrum the emission traces of ASA and PC/SSF housings are almost coincident, and only in selected portions of the analog broadcast band ($\approx 40\text{--}60\text{ MHz}$ and parts of the FM range) do the PC/SSF materials show a slightly larger margin to the limit line. This behaviour is emphasised in Figure 52, where all quasi-peak curves in the C25 analog band are superimposed: the four traces nearly overlap, indicating that the material change alone produces only a small reduction in radiated emissions.

This outcome may appear counter-intuitive given the very high material-level shielding effectiveness measured on plaques, where PC/SSF grades such as 87/24-10A and DS0036I reach up to $\sim 100\text{ dB SE}$ (Section 6.4). The emission results nevertheless confirm a well-established principle in automotive EMC literature: radiated emissions in practical electronic modules are primarily governed by common-mode currents propagating through cables, PCB traces and connector interfaces, whereas the housing typically acts only as a secondary mitigation element unless it forms part of a continuous and properly grounded shielding architecture [4,6,7]. Apertures for the display window, mounting holes, split lines between front and rear shells and the absence of 360° conductive gaskets or bonding to the PCB ground all provide leakage paths that limit how much the intrinsic shielding capability of the polymer can be exploited. As a consequence, moving from an ASA housing to highly conductive PC/SSF compounds yields only incremental improvements in the measured field strength, even though the latter exhibit much higher intrinsic EMI SE.

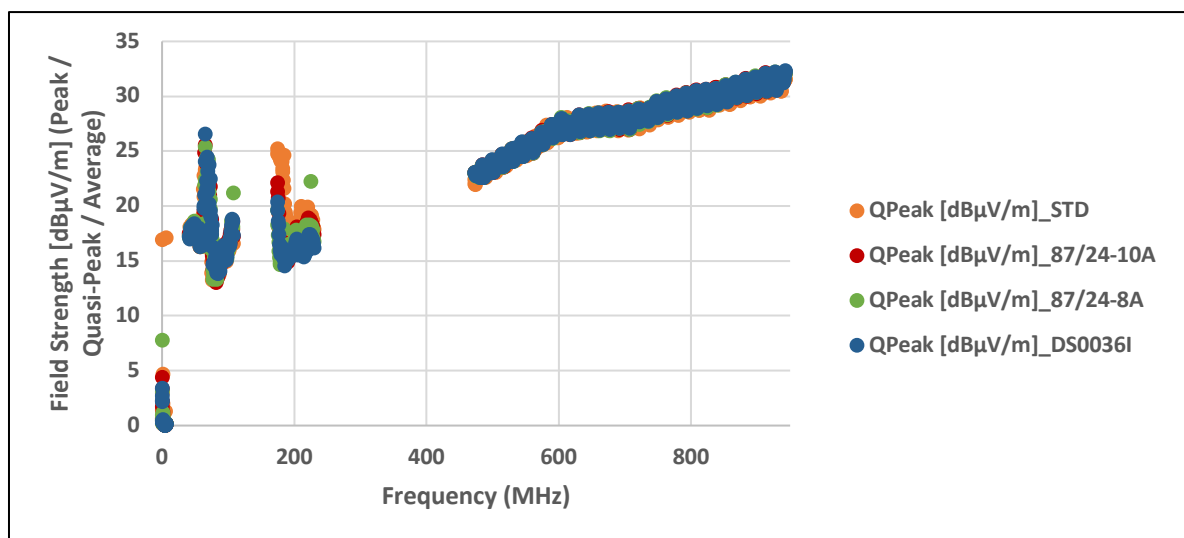


Figure 52. Overlay of quasi-peak radiated emission spectra in the C25 analog broadcast band (150 kHz–944 MHz) for the ASA housing and the three PC/SSF housings, illustrating the very small differences between materials.

Overall, the radiated emission campaign shows that all four housings satisfy CISPR 25 requirements, with a consistent but relatively small performance ranking of $\text{DS0036I} \approx 87/24-10\text{A} > 87/24-8\text{A} > \text{ASA}$. The results are in line with previous reports that conductive polymer composites typically deliver modest system-level emission reductions unless combined with optimised grounding, cable routing or additional shielding measures such as conductive coatings and gasketing [68,74,83].

7.7.2. Radiated immunity test (GTEM 500)

Radiated immunity testing revealed clear performance differences between the standard ASA housing and the three PC/SSF candidate materials. The reference housing exhibited the weakest immunity: the display flickered across a broad band (22–115 MHz) and entered standby mode at frequencies above 800 MHz, indicating strong field penetration into the electronics compartment.

Table 23. Functional immunity performance under radiated fields (GTEM-500 Test).

Sample	Polymer Matrix / Filler	Functional Immunity Observation
STD	PA + Glass beads/fibres	Display flicker at 22–115 MHz; standby > 800 MHz
LATI 87/24-8A	PC + Stainless-steel fibres	Flicker 24–115 MHz; standby/off $\approx$ 946 MHz
SABIC DS0036I	PC + Stainless-steel (metal compound)	Stable above 800 MHz; minor flicker 35–110 MHz
LATI 87/24-10A	PC + Stainless-steel fibres	Minor flicker 45–110 MHz; stable > 800 MHz

The LATI 87/24-8A housing showed a similar disturbance pattern to the reference, with flicker occurring across 24–115 MHz and a complete shutdown at approximately 946 MHz. Although the behaviour is slightly improved compared with ASA, instability at high frequencies highlights insufficient shielding continuity due to lower fibre loading

In contrast, LATI 87/24-10A demonstrated markedly better functional stability. Only minor flicker was observed between 45–110 MHz, and the module remained fully stable above 800 MHz, a performance region where the reference and 87/24-8A failed.

The best immunity response was obtained with SABIC DS0036I. Disturbances were limited to a few narrow bands (35–40 MHz and 96–110 MHz), and the system remained completely stable between 800 MHz and 2 GHz. The superior behaviour aligns with shielding theory: continuous, well-dispersed conductive networks suppress internal field coupling far more effectively than discontinuous or cluster-dominated structures [68,74,83,84,88]. DS0036I's industrial pre-mixing ensures the most homogeneous stainless-steel network, which minimizes electromagnetic penetration into the PCB region.

7.7.3. Electrostatic discharge test (IEC 61000-4-2)

Electrostatic discharge testing (± 6 –8 kV air discharge) was performed on the heatsink region of each assembled module. The reference ASA housing exhibited immediate vulnerability: visible green stripes appeared at ± 6 kV, and display instability occurred repeatedly. This behaviour reflects limited charge redistribution capability and localized field concentration, typical of composites with sparse or discontinuous conductive inclusions [68,74].

Table 24. Effect of conductive fillers on ESD immunity performance.

Voltage (kV)	STD	87/24-8A	DS0036I	87/24-10A
+6	OK	Minor stripes	OK	OK
-6	Screen stripes	OK	OK	OK
+8	—	Minor stripes	Minor stripes	OK
-8	—	Minor stripes	Minor stripes	OK
Result	Problems at ± 6 kV	Partial success	Better	Best

The LATI 87/24-8A housing showed partial improvement. Minor stripes appeared at higher voltages, but overall performance remained borderline, indicating that the 8 % SS fibre content does not provide sufficiently continuous conductive pathways for fast discharge spreading.

LATI 87/24-10A demonstrated substantially better resistance. The system maintained functionality up to ± 8 kV, with only transient distortions that self-recovered immediately

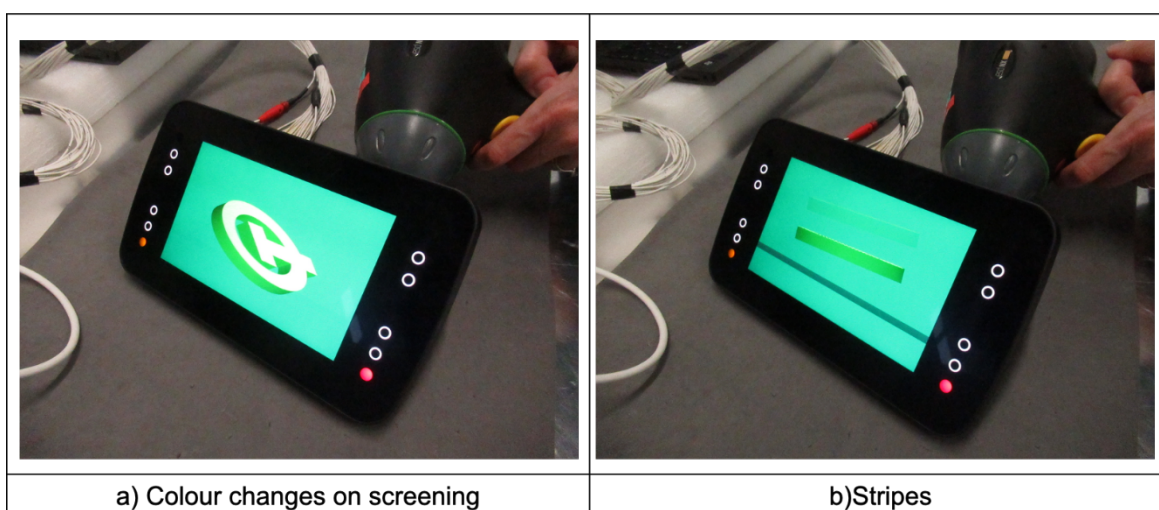


Figure 53. Visual effects observed under ESD stress for the PC/SSF and STD housing.

Once again, DS0036I delivered the strongest performance. Only minimal flicker was observed even at ± 8 kV, and no permanent or repeated functional failures occurred. This confirms the beneficial effect of industrial compounding: homogeneous percolation networks produce lower fibre - fibre contact resistance and enable rapid lateral charge dissipation, preventing the charge localization responsible for stripes and temporary colour-shift events (shown in Figure 53.) [21,31,74,83]

Across all EMC evaluations; radiated emissions, radiated immunity and ESD, the highest-performing materials were SABIC DS0036I and LATI 87/24-10A. Both compounds consistently exceeded the performance of the ASA reference housing, particularly in the high-frequency immunity range (>800 MHz) and under ESD stress, where the ASA material approached functional thresholds.

LATI 87/24-8A also met the required EMC specifications and outperformed ASA, though with reduced stability and higher variability, reflecting its lower fibre loading and less continuous conductive network.

The combined results indicate that:

- PC/SSF composites can replace ASA-based housings for EMC-sensitive modules, provided that fibre dispersion is adequately controlled.
- Melt-compounded formulations (e.g. DS0036I) show superior shielding and immunity compared with dry-mixed blends, due to their more homogeneous conductive pathways.
- High-frequency immunity is strongly governed by conductive-network continuity, with DS0036I exhibiting the most uniform response across all bands.

Overall, DS0036I offers the most balanced EMC behaviour, followed closely by 87/24-10A, while 87/24-8A remains acceptable but less robust. These findings confirm that well-engineered PC/SSF composites provide a technically reliable alternative to ASA for next-generation automotive display and lighting housings.

Chapter 8

Conclusion

In this thesis, the feasibility of replacing traditional metal and ASA-based housings commonly used in automotive lighting systems and EMI-critical electronic modules with thermally conductive and EMI-shielding polymer composites has been investigated. The study has been carried out using a multi-layered assessment approach, including material screening, standard-specimen thermal and EMI testing, mouldability evaluation, CAE simulations, and full-scale industrial validation on a representative lighting housing and an EMI screening-housing geometry.

This comprehensive validation chain demonstrates that the selected composite materials progressed from an initial material-centric TRL level of 3–4 to TRL 6–7 through prototype-part manufacturing, functional tests and system-level thermal and EMC performance assessments. Thus, beyond confirming experimental material suitability, the study systematically establishes the scalability and integration potential of the proposed polymer solutions for industrial applications.

The results of the thermal-driven path show that PA6 composites containing conductive fillers can achieve thermal conductivities in the range of $4\text{--}14\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ up to $\sim 40\times$ higher than neat PA6 when a continuous graphite or multi-filler network is formed, surpassing the performance of other screened polymer candidates. Among these materials, LATI 62GR70 (PA6 + 70 % graphite) and SABIC PX10323 (PA6, multi-filler system) were identified as the most suitable candidates for the lighting-housing application due to their balanced combination of thermal conductivity, processability and surface quality. Moldex3D-supported injection-moulding trials confirmed that both compounds can be produced within a stable processing window; however, 62GR70 exhibited local brittle fracture in the thin standoff-pin region due to its high filler-induced stiffness.

When considered together, the thermal simulation, climatic-chamber derating test and infrared thermography results yielded a consistent thermal ranking: aluminium < 62GR70 < PX10323. As expected, aluminium remains the reference material, providing the lowest absolute temperatures and the most uniform heat-spreading. Nevertheless, both conductive PA6 housings maintained safe operating temperatures for LEDs and power-electronic components under realistic ambient conditions. Their derating behaviour closely matched aluminium up to $\sim 30\text{ }^{\circ}\text{C}$, and functional stability was preserved even within the $40\text{--}45\text{ }^{\circ}\text{C}$ range. Derating became critical only near the $60\text{ }^{\circ}\text{C}$ extreme of the ISO 16750-4 profile. These findings indicate that, in lighting applications where extreme thermal loads are not the dominant design constraint, graphite- and multi-filler PA6 housings provide thermally adequate and industrially viable alternatives to aluminium while offering additional benefits such as weight reduction and geometrical design freedom.

It must be noted that the thermal derating test performed in this work was limited to a 1-hour exposure at each temperature condition. Although this approach is commonly adopted in rapid validation workflows, reaching true steady-state thermal operating conditions may require longer durations, particularly for polymer housings whose thermal diffusivity is significantly lower than metals. Therefore, the present results reliably capture short to mid-term transient behaviour, but they may underestimate the accumulation of thermal stresses and potential material relaxation phenomena that could arise over

extended operation. Future work should incorporate multi-hour or stabilized thermal plateaus and long-term aging conditions to fully characterise thermal safety margins under worst-case scenarios.

Within the EMI-driven path, ASTM D4935 coaxial-line measurements on moulded plaques demonstrated that neat polymers ($\approx 2\text{--}5$ dB SE) are effectively “non-shielding” in the absence of a conductive network, whereas appropriate filler design enables very high shielding levels. PA6 + CF/SSF grades achieved $\approx 50\text{--}60$ dB EMI SE, and PC + SSF compositions reached $\approx 90\text{--}110$ dB across the CISPR 25 band reducing transmitted power by several orders of magnitude. ANOVA analysis on frequency, gate type and filler class confirmed that filler architecture and processing conditions (especially gate-induced fibre orientation) strongly affect shielding; plaques moulded through direct gates generally exhibited higher EMI SE than those moulded through tunnel gates.

Considering shielding performance, mouldability and surface integrity together, three PC/SSF grades LATI 87/24-8A, LATI 87/24-10A and SABIC DS0036I (PC + 15 % SSF, pre-compounded) were selected for the EMI screening-housing application. Full automotive EMC testing (radiated emissions, radiated immunity and ESD) on fully assembled modules (display, PCB, wiring and rear housing) confirmed that all polymer housings satisfied automotive EMC requirements, and that the PC/SSF candidates systematically outperformed the current ASA-based reference housing. Improvements in radiated emissions were generally modest and spectrally overlapped, indicating that the housing material plays a secondary role relative to the electronic architecture. In contrast, clear differences emerged in radiated immunity and ESD performance: 87/24-10A and DS0036I demonstrated substantially greater functional stability than the ASA housing at high frequencies and at ± 8 kV ESD levels.

These findings lead to several design-oriented conclusions:

- Thermal management: Conductive PA6 composites such as 62GR70 and PX10323 can replace aluminium housings in lighting applications where ambient temperatures typically remain within $20\text{--}45$ °C. While they offer acceptable derating behaviour and surface temperatures, their thermal safety margin is narrower at extreme conditions, and highly filled brittle regions (e.g. thin standoff pins) may require geometric optimisation.
- EMC performance: PC/SSF systems with well-designed composite architectures and homogeneous fibre dispersion can successfully replace metal-containing ASA housings. The continuity of the stainless-steel fibre network is more critical than nominal filler loading; industrially pre-compounded DS0036I achieves the best combination of shielding, immunity, ESD robustness and surface quality, while dry-blended systems show greater variability and surface artefacts.
- Integrated perspective: Both thermal and EMI evaluations confirm that composite design, dispersion quality, gate choice and part geometry must be considered together. Although high filler loadings can dramatically enhance thermal conductivity or shielding, inadequate compounding or design support may introduce brittleness, surface waviness or process sensitivity.

8.1. Doctoral Contributions of the Thesis

The main doctoral contributions of this thesis can be summarised in three complementary dimensions. From a scientific perspective, the work clarifies the relationship between filler type, conductive-network formation, gate-induced orientation and the resulting thermal or EMI performance of polymer composite housings. The results show that functional performance is not governed by filler content alone, but by the combined effects of material formulation, microstructural continuity and processing-induced anisotropy.

From a methodological perspective, the thesis establishes an integrated material–process–function validation framework combining datasheet-based screening, standard specimen testing, CAE-assisted injection-moulding optimisation, statistical analysis and component-level thermal/EMC validation. This approach bridges the gap between coupon-level material characterisation and industrial demonstrator testing.

From an industrial perspective, the thesis demonstrates the feasibility and limitations of replacing aluminium or ASA-based housings with conductive polymer composites in two representative automotive applications: thermal-management-driven lighting housings and EMI-driven electronic screening enclosures. The work identifies material-specific design windows and practical constraints, including reduced thermal safety margins, filler-induced brittleness, surface-quality limitations and the importance of conductive-network continuity.

Finally, this thesis demonstrates that well-engineered conductive polymer composites can serve as technically reliable alternatives to metal housings for next-generation automotive lighting modules and EMI-critical electronic enclosures. Depending on design priorities thermal safety margin, EMC robustness, weight reduction, manufacturability or cost, the leading materials identified in this study (62GR70, PX10323, 87/24-10A and DS0036I) offer complementary solutions for different scenarios. Moreover, the methodology developed here combining standard specimen testing, CAE-assisted design and full-scale industrial validation provides a transferable framework for future metal-to-polymer substitution efforts in automotive electronics

8.2. Limitations and Future Work

Although the present work demonstrates promising thermal and EMC performance under industrial validation conditions, several limitations and future research directions should be acknowledged. First, the thermal and EMC evaluations were primarily focused on short-to mid-term functional validation under controlled laboratory conditions. Long-term durability aspects such as thermal cycling, humidity ageing, vibration loading, and conductive-network stability were not investigated within the scope of this thesis. These factors may significantly influence the long-service reliability of conductive polymer composites in automotive environments.

In addition, the results highlighted the anisotropic behaviour of highly filled polymer systems, particularly the differences between in-plane and through-thickness thermal conduction induced by gate-dependent filler orientation. Future studies should therefore

investigate the relationship between microstructural anisotropy, fibre alignment, and component-level thermal or EMC performance using advanced characterisation techniques such as micro-CT or orientation tensor analysis. From a processing perspective, future work may also explore alternative gate strategies, hybrid filler architectures, and improved compounding routes to further optimize the balance between thermal conductivity, EMI shielding effectiveness, mouldability, and surface quality.

Lastly, the methodology proposed in this thesis may be extended toward additional automotive electronic applications, including battery-management systems, power-electronic housings, and sensor enclosures, where lightweight conductive polymers could provide functional and sustainability-related advantages over conventional metallic solutions.

Acknowledgement

This PhD journey has been much more than an academic experience for me. It was also my first long-term experience living abroad, far from my family, my culture, and everything familiar. Throughout these years, I faced many challenges, both professionally and personally, including emotional, financial, and social difficulties. Therefore, this thesis would not have been possible without the support, guidance, and kindness of many people whom I would like to sincerely thank.

First and foremost, I would like to express my deepest gratitude to my supervisor, Professor Luca Giorleo, for giving me the opportunity to pursue this PhD and for his continuous support throughout this journey. His guidance, encouragement, and willingness to help whenever needed have been invaluable.

I would also like to sincerely thank my industrial supervisor at COBO Group, Roberto Pasino. I am deeply grateful for his constant support, for always taking the time to listen to my ideas and concerns, for answering my endless questions, and for genuinely caring about the success of this research. His trust and encouragement have played a fundamental role in the completion of this work.

My sincere thanks also go to my colleagues at COBO Group, especially Alessandro Pluda and Federico Masiero. When I first started working with Moldex3D, I had no previous experience in the field. Their patience, generosity, and willingness to share their knowledge helped me learn and grow professionally. No matter how many questions I asked, they always answered with kindness and understanding.

I would like to extend a special thank you to my fellow PhD colleague, Giulia Gaudenzi. As an international student living far from home, there were many moments when I felt overwhelmed by the challenges of adapting to a different country and culture. Knowing that I could always count on Giulia's support, friendship, and advice gave me strength and confidence during difficult times.

I would also like to thank the people who became my family away from home during my years in Italy. In particular, I am deeply grateful to Kevser Atmalıoğlu and her family, Giulia Curci and her family, and the Ökkeş ve Emine Madenkuyu family. Their kindness, friendship, generosity, and unwavering support, both emotionally and practically, made my life in Italy much easier and happier. They were always there for me during both good and difficult times, and I will always be grateful for their presence in my life.

Finally, and most importantly, I would like to dedicate my deepest gratitude to my family.

To my mother and father, thank you for every sacrifice both you made so that I could have opportunities that were never available to you. Neither of you had the chance to receive the education that you deserved, yet you never allowed your own limitations to become mine. Every opportunity I have had in life has been possible because of your love, hard work, and unconditional support.

I am especially proud to be the first woman in my family to earn a university degree and to complete a PhD. This achievement is not mine alone; it belongs to you as much as it belongs to me. You believed in my education, my dreams, and my future when many others might not have. Without your support, encouragement, and sacrifices, I would never have reached this point

I hope that this achievement makes you as proud as I am proud to be your daughter.

Lastly, I would like to thank my beloved sister, Rümeyza Deniz, whose support, friendship, and love have always been a source of strength for me. I would also like to thank my brothers, Lütfullah Deniz and Talha Deniz, for their support and for always being part of my journey. A special thank you also goes to my beloved nephew, Barış Alper, whose laughter, joy, and bright spirit have brought happiness to even the most challenging days throughout this journey.

To all of you, thank you for believing in me.

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