Advanced Materials Science and Technology Vol 8 Issue 1 2026

Review

Open Access

Omniscient Pte.Ltd.

Adaptive Structures and Additive Technologies for Defensive Missiles

Nur Fatin Ashiqin Ahmad Ridzwan, Wan Luqman Hakim Wan A Hamid*

Department of Mechanical and Aerospace Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, 53100 Gombak, Kuala Lumpur, Malaysia

***Correspondence to:** Wan Luqman Hakim Wan A Hamid, Department of Mechanical and Aerospace Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, 53100 Gombak, Kuala Lumpur, Malaysia; Email: wanluqmanhakim@iium.edu.my

Abstract: The rapid evolution of modern missile threats, particularly in the hypersonic regime, has driven the need for highly integrated defensive missile systems capable of operating autonomously and reliably under extreme aerodynamic, thermal, and structural conditions. This review presents a comprehensive examination of adaptive and additive structures technology for defensive missiles, emphasizing the interdependent roles of aerodynamics, structural optimization, guidance and control, materials, and additive manufacturing. Missile classifications based on trajectory, function, and geometry are first reviewed to establish the operational context, followed by an in-depth discussion of aerodynamic and structural optimization strategies, including noncircular forebody designs, folding arc-wing configurations, aeroelastic effects, and nose cone trade-offs in hypersonic flow regimes. The review further analyzes advanced adaptive guidance and control architectures, highlighting the limitations of conventional reactive laws and the growing importance of nonlinear adaptive, vision-based, and AI-assisted guidance systems for intercepting highly maneuverable targets. Material considerations for hypersonic environments are discussed, with particular focus on carbon–carbon composites, ultra-high temperature ceramics, and honeycomb sandwich structures that balance thermal resistance, structural integrity, and weight efficiency. Finally, the strategic role of additive manufacturing is evaluated, demonstrating its impact on rapid prototyping, modular hypersonic testing infrastructure, and the fabrication of mission-critical components with reduced cost and lead time. Overall, this review underscores that future defensive missile development requires a tightly coupled, multidisciplinary systems approach, where aerodynamic efficiency, structural resilience, intelligent guidance, and advanced manufacturing technologies are co-optimized to meet the demands of next-generation hypersonic defense systems.

Keywords: Defensive missiles; Adaptive structures and controls; Additive technologies

1. Introduction

The evolution of modern defense capabilities is increasingly shaped by operations in extreme environments, particularly within the hypersonic regime, thereby necessitating missile systems that are capable of operating with a high degree of autonomy, robustness, and precision (Chen et al., 2020). Achieving optimal performance in defensive missiles demands a highly integrated and complex design process that spans three core domains: structural integrity, aerodynamic efficiency, and advanced guidance and control systems (Cui et al., 2010). However, as noted by Yusuf et al. (2019), conventional subtractive manufacturing (SM) and experimental testing approaches are often constrained by high production costs, extended development cycles, and limited capability to rapidly prototype and iterate intricate geometries that are characteristic of modern missile designs.

In this context, the convergence of Additive Manufacturing (AM), also referred to as additive structures or additive technologies, with missile design and testing represents a significant strategic shift in defense engineering. The United States Department of Defense (DoD) has identified both hypersonic technologies and advanced materials manufacturing methods, including AM, as critical enablers for maintaining technological superiority and strategic competitiveness (Cho, 2025).

Accordingly, this study examines the role of AM in facilitating advanced structural optimization and enabling the rapid development of specialized testing infrastructure for defensive missile applications. Emphasis is placed on computational optimization techniques for improving aerodynamic performance, alongside the implementation of robust nonlinear adaptive guidance laws capable of accurately intercepting highly maneuverable targets. Ultimately, the progression of next-generation defensive missile systems is shown to rely on rigorous, multidisciplinary research that tightly integrates aerodynamic efficiency, structural resilience, and autonomous control within a unified engineering framework.

2. Classification of Missiles

The study of missile technology encompasses a wide range of classifications that are typically defined by parameters such as speed, mission profile, warhead type, and structural configuration. In general terms, a missile is defined as a self-propelled, guided weapon system designed to deliver a payload or warhead to a designated target with a high degree of accuracy. Missile classification is therefore multifaceted and may be based on factors including the intended target type, operational range, propulsion and control systems, guidance methodology, and flight trajectory. These classification frameworks provide a systematic basis for understanding missile capabilities, performance limitations, and application domains, and they form an essential foundation for both design and analytical studies in missile engineering (Khan and Rao, 2018).

Missiles may also be classified according to their flight trajectory, which strongly influences their operational characteristics and mission roles. Ballistic missiles are launched to deliver warheads along a largely ballistic path, with most of their flight occurring outside the Earth's atmosphere along a predictable, arched trajectory. A well-known example is the LGM-30G Minuteman III Intercontinental Ballistic Missile (ICBM), which follows a high-altitude exo-atmospheric trajectory before re-entering the atmosphere near the target (Chen et al., 2020).

In contrast, cruise missiles, which are typically non-hypersonic, are air-breathing, engine-powered vehicles that remain within the atmosphere throughout their flight. They rely on aerodynamic lift and propulsion to maintain a relatively constant altitude and speed while homing toward the target. The Tomahawk Land Attack Missile (TLAM), a subsonic cruise missile, is a representative example of this class (Khan & Rao, 2018).

Another category is the glide missile, which is initially launched at a steep ascent angle to reach a designated altitude before transitioning into an unpowered or low-powered glide phase toward the target. Hypersonic Glide Vehicles (HGVs) fall within this category and are characterized by their ability to sustain hypersonic speeds during the glide phase, offering high maneuverability and reduced predictability compared to traditional ballistic trajectories (Ukirde et al., 2023).

Figure 1. Tomahawk missile (Khan and Rao, 2018).

Finally, skip missiles operate by being launched to high altitudes where the atmosphere is relatively thin, after which they repeatedly "skip" along the upper atmospheric layers. This skipping motion extends their range and complicates interception by conventional defense systems, making them suitable for long-range and high-speed missions.

Missiles may also be categorized beyond speed and trajectory, taking into account their structural configuration, mission function, and geometric characteristics. Defensive missiles, in particular, are designed to operate effectively in both offensive and defensive roles, with a critical defensive application being the interception of an incoming threat launched toward a protected platform, such as an aircraft. In such scenarios, a defensive missile may be deployed from the target aircraft itself to neutralize the approaching weapon. Extensive research in this area has led to the development of advanced guidance strategies, including the Command to Optimal Interception Point (COIP) guidance law, which is specifically formulated to safeguard non-maneuverable aircraft by optimizing interception geometry and timing.

In terms of geometry, most conventional missiles, such as Russia's Kh-47M2 and China's CJ-100, employ a simple circular cross-section due to its manufacturing simplicity and structural efficiency (Chen et al., 2020). However, increasing performance demands have motivated the exploration of noncircular cross-sectional geometries, including square, diamond, and elliptic profiles. These alternative shapes are proposed to enhance aerodynamic performance, support complex maneuvering, and enable extended cruise capabilities. Since the cross-sectional geometry directly influences aerodynamic forces, pressure distribution, and thermal loading, noncircular designs offer opportunities for performance gains, albeit at the cost of increased design complexity and manufacturing challenges.

Lastly, certain missile configurations are designed as spinning missiles, in which the vehicle is intentionally rotated about its longitudinal axis to enhance aerodynamic stability and controllability during flight. The induced spin provides gyroscopic stiffness, improving resistance to external disturbances and stabilizing the missile's attitude, particularly at high speeds or under asymmetric loading conditions. A representative spinning missile design incorporates a hemispherical nose cone, a cylindrical fuselage, and four fixed tail fins arranged to generate the required rolling moment. This configuration enables passive roll stabilization without the need for complex active control mechanisms, thereby simplifying the control system while maintaining reliable flight performance (Ukirde et al., 2023).

3. Aerodynamic and Structural Optimization for Missile Performance

Optimization approaches serve as powerful tools for improving the performance of missile and aircraft systems by systematically refining structural configurations, flight trajectories, and propulsion characteristics. In the context of cruise missiles, a key design objective is the maximization of the lift-to-drag ratio (L/D), as this parameter directly governs aerodynamic efficiency, cruise range, and maneuverability. A higher L/D ratio enables sustained flight with reduced energy consumption, enhances endurance, and improves the missile's ability to execute evasive or corrective maneuvers during mission execution, making it a critical performance metric in cruise missile design (Cui et al., 2010).

Traditional missiles employing circular cross-sections are often inadequate for meeting advanced maneuverability demands or extended cruise performance requirements. As a result, substantial research attention has shifted toward the development and optimization of noncircular missile forebody geometries. These configurations offer greater aerodynamic flexibility and the potential for improved lift, drag reduction, and control authority. To support this, an efficient and robust shape optimization framework has been developed using the Class/Shape Function Transformation (CST) method combined with power-law curves, enabling comprehensive and flexible parametric representation of complex forebody shapes. This approach facilitates systematic aerodynamic optimization while maintaining geometric smoothness and manufacturability, making it particularly suitable for high-speed missile applications (Chen et al., 2020).

Chen et al. (2020) conducted a detailed investigation into missile forebody shape optimization, with particular emphasis on improving aerodynamic efficiency in the hypersonic regime. The optimized forebody configuration achieved a substantial 33.3% increase in lift-to-drag ratio (L/D), improving from 1.8 to 2.4 under a Mach 6 cruise condition at an angle of attack of 6°. Beyond this design point, the optimized geometry consistently outperformed the baseline configuration across a broad operational envelope, spanning Mach numbers from 2 to 8 and angles of attack ranging from 0° to 30°. Although the noncircular forebody design resulted in a reduction in volumetric efficiency, the authors concluded that the aerodynamic gains—particularly the marked improvement in L/D—more than compensated for this drawback. As a result, the optimized configuration demonstrated strong potential for enhancing cruise efficiency, maneuverability, and overall mission performance in high-speed missile applications.

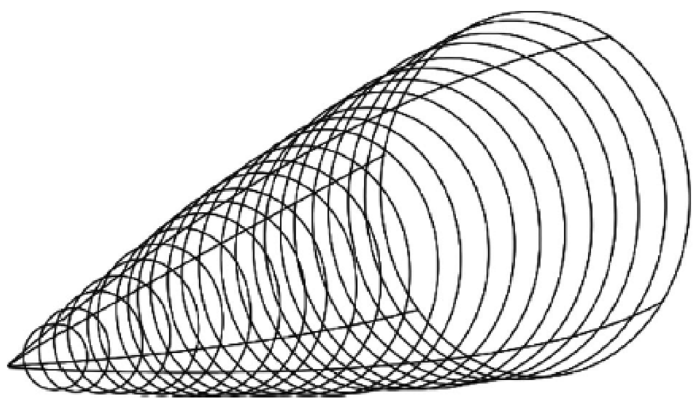

Figure 2. Schematic illustration of noncircular missile forebody (Chen et al., 2020).

For axisymmetric missile configurations, geometric constraints imposed by cylindrical launch tubes often necessitate the use of deployable or folding arc-wings. An optimization study on folding arc-wing geometries demonstrated that by refining the leading-edge profile and fixing the installation angle, δ, an improvement of approximately 8.76% in lift-to-drag ratio (L/D) at the design point could be achieved (Cui et al., 2010). The optimized results indicated a clear preference for sweep-forward wing configurations over sweep-back designs, as sweep-forward wings were more effective in capturing the high-pressure flow generated by the missile forebody. This interaction enhanced lift production and increased axial force, thereby improving overall aerodynamic efficiency.

However, practical implementation of the optimized sweep-forward configuration required further refinement. In particular, the wing segments intersecting with the forebody shock wave were trimmed to address structural safety and thermal concerns. The resulting trimmed wing configuration was ultimately favored over the fully optimized, untrimmed design, as it preserved a favorable L/D while reducing drag. Additionally, the reduction in wing area and span provided structural advantages by lowering bending loads and improving overall structural robustness (Huang et al., 2017).

Beyond rigid aerodynamic considerations, the influence of structural flexibility, referred to as static aeroelasticity, has been shown to play a significant role in missile control surface performance, particularly for components such as grid fins. Numerical investigations revealed that bending deformation of elastic grid fins induces an effective sweep-back behavior, leading to an increase in axial force. This deformation alters the local flow field and effectively increases the angle of attack, thereby contributing to changes in normal force and overall aerodynamic loading. These findings highlight the importance of accounting for aeroelastic effects in the integrated aerodynamic and structural design of high-speed missile control surfaces.

According to Shetty et al. (2025), nose cone geometry is a primary determinant of aerodynamic drag, thermal management, and shock–body interaction in both supersonic and hypersonic flight regimes. Comparative analyses conducted over supersonic Mach numbers ranging from 2.4 to 3.6 demonstrate that nose shape plays a dominant role in governing flow separation behavior and shock wave structure. Although sharp nose cones are effective in minimizing drag and enhancing lift, they generate strong shock interactions that impose severe thermal and pressure loads, rendering them unsuitable for prolonged high-speed operation. In contrast, blunt or bulbous nose geometries provide a critical aerodynamic–thermal compromise by attenuating shock strength and enhancing thermal robustness, albeit at the cost of increased wave drag.

4. Adaptive Guidance and Control Systems

The effectiveness of defensive missile systems is fundamentally dependent on autonomous guidance and control architectures capable of operating under the substantial uncertainties inherent in hostile engagement environments. In this context, the development of vision-based guidance and control systems represents a critical advancement toward achieving higher levels of autonomy in next-generation defense platforms. However, the design of such systems is particularly challenging because adversarial targets can execute highly aggressive and unpredictable evasive maneuvers. These maneuvers induce rapid, nonuniform variations in relative velocity that are difficult to observe, estimate, and model accurately in real time.

The resulting uncertainty in target kinematics significantly complicates state estimation and degrades the effectiveness of conventional guidance and control laws, especially during high-speed intercept scenarios. Furthermore, the depth associated with visual features is time-varying and often poorly known, introducing additional ambiguity into the perception and estimation process. Prior studies have shown that many reactive guidance strategies are unable to robustly accommodate these unknown and rapidly changing target motions, frequently leading to large miss distances, particularly when engaging highly maneuverable targets (Mehta et al., 2011).

Defensive missile technology is currently defined by the rapid development of hypersonic systems, primarily categorized as Hypersonic Cruise Missiles (HCM) and Hypersonic Glide Vehicles (HGV) (Herath, 2024). HCMs utilize air-breathing scramjet engines to maintain high-speed atmospheric flights, while HGVs are typically launched via rocket boosters into the upper atmosphere before gliding at speeds exceeding Mach 5. Specialized airframe designs, such as the bank-to-turn (BTT) missile, use aerodynamic control surfaces to achieve precise heading changes (Mehta et al., 2011). Moreover, innovative configurations like folding arc-wing missiles have been engineered to fit within constrained launch tubes, deploying their wings only after launch to maximize cruise efficiency.

Modern missile flight control systems (FCS) are rapidly evolving to cope with extreme operational conditions, particularly within the hypersonic flight regime where velocities exceed Mach 5 (Herath, 2024). The overarching objectives of these systems are to preserve dynamic stability, accurately track prescribed trajectories, and retain high levels of maneuverability despite severe aerodynamic forces and intense thermal loading (Horing, 2025). In this context, conventional reactive guidance laws are increasingly regarded as inadequate for engaging highly agile and evasive targets, prompting a transition toward nonlinear and adaptive control frameworks. Such advanced architectures are required to fuse high-fidelity feedback, most notably vision-based sensing, with robust estimation and control strategies to accommodate unknown target maneuvers and environmental disturbances, including atmospheric turbulence and wind gusts (Mehta et al., 2011).

The architecture of a modern missile control system is founded on advanced navigation and guidance subsystems that enable precise, autonomous operation throughout the flight envelope. At its core is the Inertial Navigation System (INS), which estimates the missile's position, velocity, and attitude by integrating measurements of linear acceleration and angular rate. These measurements are typically obtained using high-performance inertial sensors, including fiber-optic gyroscopes (FOGs), ring laser gyroscopes (RLGs), and micro-electromechanical system (MEMS) accelerometers.

As noted by Herath (2024), a key advantage of INS lies in its self-contained operation, requiring no external references, which makes it particularly robust in contested or signal-denied environments. Nevertheless, INS performance is inherently limited by sensor biases and noise that accumulate over time, leading to navigation errors commonly referred to as drift. To mitigate these long-term inaccuracies, INS is frequently integrated with Global Navigation Satellite Systems (GNSS), such as GPS, which provide periodic absolute position updates to correct error growth.

In operational scenarios where GNSS signals are unavailable, degraded, or deliberately denied due to electronic warfare or environmental constraints, alternative aiding techniques become essential. One widely adopted approach is Terrain-Contour Matching (TERCOM), in which real-time radar altimeter measurements of the underlying terrain are correlated with pre-stored digital elevation maps to continuously update and refine the missile's estimated trajectory and maintain navigational accuracy.

Guidance laws serve the critical function of translating navigation information and engagement objectives into executable control commands. Although Proportional Navigation (PN) continues to be widely adopted for conventional offensive strike missions, it is increasingly inadequate for defensive interception scenarios involving agile and evasive targets, thereby necessitating the development of more sophisticated guidance strategies (Mehta et al., 2011). One such example is the Command to Optimal Interception Point (COIP) guidance law, which applies differential game theory to compute optimal interception strategies, originally formulated to protect nonmaneuverable target aircraft against pursuing threats (Venkatesan & Sinha, 2015).

In parallel, significant research effort has been directed toward nonlinear adaptive visual servo guidance laws for bank-to-turn (BTT) missile configurations. These approaches exploit monocular vision data acquired from an optical imaging seeker to generate real-time feedback for guidance and control. To address uncertainties arising from highly unpredictable target kinematics, particularly variations in relative velocity, unknown system dynamics are approximated using power series expansions in conjunction with continuous adaptive parameter update laws. Experimental and simulation results reported by Mehta et al. (2011) demonstrate that such adaptive compensation schemes can reduce miss distances by more than a factor of seven when compared to uncompensated guidance systems.

The actuation subsystem is responsible for executing guidance commands through a coordinated combination of aerodynamic and propulsion-based control mechanisms (Ukirde et al., 2023). As outlined by Mehta et al. (2011) and Blades and Newman (2007), bank-to-turn (BTT) missile configurations primarily achieve heading and trajectory changes via the deflection of aerodynamic control surfaces, including canards, wings, and tail fins, to regulate roll, pitch, and yaw moments. In recent designs, unconventional control surfaces such as grid fins, also referred to as lattice fins, have gained increased adoption due to their favorable stall characteristics, compact stowage, and enhanced control effectiveness at high angles of attack.

The actuation subsystem is responsible for executing guidance commands through a coordinated combination of aerodynamic and propulsion-based control mechanisms (Ukirde et al., 2023). As outlined by Mehta et al. (2011) and Blades and Newman (2007), bank-to-turn (BTT) missile configurations primarily achieve heading and trajectory changes via the deflection of aerodynamic control surfaces, including canards, wings, and tail fins, to regulate roll, pitch, and yaw moments. In recent designs, unconventional control surfaces such as grid fins, also referred to as lattice fins, have gained increased adoption due to their favorable stall characteristics, compact stowage, and enhanced control effectiveness at high angles of attack.

A major challenge in the design of advanced missile control systems lies in accurately capturing the coupled effects of aerodynamics and structural response. Aeroelastic phenomena, namely the deformation of the missile airframe and control surfaces under aerodynamic loading, can significantly modify control effectiveness and, if unaccounted for, degrade guidance performance. For example, in spinning missile configurations, the interaction between body roll and a nonzero angle of attack generates rotational lift forces that can introduce destabilizing moments and adversely affect dynamic stability.

Similarly, static aeroelastic effects acting on unconventional control surfaces, such as grid fins, can lead to increases in axial force and unintended shifts in the effective angle of attack. These effects alter the nominal aerodynamic coefficients and necessitate high-fidelity fluid–structure interaction (FSI) modeling to preserve control accuracy and robustness (Huang et al., 2017). To mitigate the resulting modeling uncertainties and nonlinear disturbances, stabilizing feedback terms must be incorporated into the guidance and control laws. Such compensation mechanisms are essential to counter parameter identification errors and ensure that the closed-loop system satisfies uniformly ultimately bounded (UUB) stability throughout the missile's operational envelope (Mehta et al., 2011).

5. Materials and Structures

Material science constitutes the final cornerstone of defensive missile development, as hypersonic vehicles are routinely exposed to extreme aerothermal environments in which stagnation temperatures can approach or exceed 10,000 °C. To survive such conditions, structural and thermal protection materials must combine low density with exceptional thermal stability and mechanical integrity. Historically, carbon–carbon (C/C) composites have been the material of choice for aeroshells and leading-edge components due to their favorable strength-to-weight ratio and their ability to retain structural properties at temperatures approaching 2,000 °C.

Despite these advantages, carbon-based materials are inherently vulnerable to oxidative attack, with oxidation initiating at temperatures as low as approximately 370 °C. This susceptibility necessitates the application of protective systems, such as silicon carbide (SiC) coatings or silica-forming impregnates, to limit surface recession and preserve structural integrity during prolonged high-temperature exposure. In flight regimes where surface temperatures exceed 3,000 °C, designers increasingly turn to ultra-high-temperature ceramics (UHTCs), including zirconium diboride (ZrB_2) and hafnium carbide (HfC). These materials exhibit exceptional melting points, thermal stability, and oxidation resistance, making them well suited for sustaining performance under the most severe hypersonic aerothermal loads (Peters et al., 2024).

According to Davis et al. (1974) to maintain structural integrity while minimizing weight, modern missiles incorporate honeycomb sandwich panels into their primary structures. Titanium honeycombs are specifically valued for providing high wing stiffness, which is essential to prevent wing flutter during high-speed maneuvers. Conversely, Nomex honeycombs, manufactured from aramid fiber paper are utilized for their excellent fire resistance and impact energy absorption, making them ideal core materials for internal protective panels and impact-resistant components (Wan A Hamid et al., 2025).

6. Additive Manufacturing: Strategic Implementation and Structural Reliability

The integration of Additive Manufacturing (AM) represents a transformative shift in the development of modern defensive systems, moving away from traditional subtractive manufacturing (SM) methods that are often limited by high overhead costs and excessive lead times. The Department of Defense (DOD) specifically identifies AM as a critical technology area required to maintain a competitive strategic edge in the hypersonic regime. Unlike conventional machining, which involves removing material from a solid block, AM allows for the rapid fabrication of complex geometries with high design freedom and cost-effective production cycles. This capability is essential in research environments where frequent design modifications and rapid prototyping are necessary to validate new missile configurations under extreme operational conditions.

One of the most significant applications of AM technology is the development of specialized experimental infrastructure, such as modular, axisymmetric hypersonic wind tunnels (HSWTs) (Cho, 2025). These facilities are vital for validating computational fluid dynamics (CFD) simulations and assessing how new missile geometries perform at speeds of Mach 5 and above. Axisymmetric designs provide a distinct aerodynamic advantage over standard rectangular tunnels by ensuring highly uniform flow characteristics and eliminating the corner-induced distortions that can skew data during the testing of radially symmetric bodies, such as nose cones and missile fuselages.

Using AM to construct these test sections significantly reduces fabrication complexity and enables a modular approach to tunnel design. Modular sections can be produced, replaced, or reconfigured rapidly to meet different experimental goals without requiring extensive retooling of the facility. This flexibility not only increases experimental efficiency but also lowers the barriers to entry for advanced hypersonic research by making testing infrastructure more accessible and shortening development cycles through iterative prototyping.

Ensuring structural integrity is a primary challenge when selecting AM materials for components exposed to the harsh environments of HSWT operation. These environments involve severe thermal gradients, large pressure differentials, and temperatures that can drop as low as 200 K. While Direct Metal Laser Melting (DMLM) for 316 stainless steel is a common choice for high-strength applications, structural analyses indicate that high-performance thermoplastics like ULTEM™ 9085, used in Fused Deposition Modeling (FDM), offer a feasible and efficient alternative (Cho, 2025).

Although stainless steel possesses higher tensile strength and stiffness, ULTEM™ 9085 shells have demonstrated the ability to maintain stress levels safely below their yield and ultimate strength limits under combined thermal and pressure loading. The primary advantage of utilizing this thermoplastic lies in its drastically reduced manufacturing time compared to metal-printed components. This balance of adequate mechanical performance and rapid production makes it an ideal material for experimental infrastructure where frequent design iterations are expected.

Beyond testing infrastructure, metal AM has proven its reliability for the fabrication of load bearing, mission-critical aerospace structures. Electron Beam Melting (EBM) is highlighted in the literature as an exceptionally effective process for producing metallic components with intricate geometries. A landmark example of this technology's success is the manufacture of Ti-6Al-4V alloy brackets for the Juno spacecraft (Rawal et al., 2013). As stated by Rawal et al. (2013) and Yusuf et al. (2019), this near-net-shape fabrication method allowed for a dramatic reduction in material wastage, bringing scrap rates down to below 10%, compared to the 80–90% wastage typical of conventional subtractive processes.

Mechanical testing of these EBM processed components has revealed that their properties are nearly equivalent to those of wrought and conventionally machined specimens. These findings confirm that metal AM can meet the stringent structural and fatigue requirements demanded by advanced missile and space systems. Ultimately, the implementation of AM provides both economic advantages and the technical ability to produce high-performance hardware capable of surviving the intense mechanical and thermal loading of the hypersonic environment.

7. Conclusion

In conclusion, it shows that the development of modern defensive missile systems requires an integrated engineering approach rather than focusing on individual components separately. As missile threats continue to evolve into the hypersonic speed range, it becomes increasingly difficult to treat aerodynamics, materials, structures and manufacturing as independent fields. Instead, these elements must work together as a complete system. The overall performance of a defensive missile depends on achieving a good balance between aerodynamic efficiency, structural strength and reliable guidance and control.

Aerodynamic design plays an important role in improving missile performance at high speeds. Noncircular missile geometries optimized using the Class/Shape Function Transformation (CST) method were shown to improve the lift-to-drag (L/D) ratio. A higher L/D ratio helps the missile maintain better efficiency and maneuverability during flight. This is especially important when intercepting fast and evasive targets. However, while noncircular shapes offer aerodynamic advantages, they also lead to uneven pressure and heating on the missile surface. This increases the structural and thermal loads acting on the airframe, which must be carefully considered during the design process. To withstand these extreme conditions, appropriate material selection is essential. Hypersonic missiles are exposed to very high temperatures, particularly at stagnation points where airflow slows down. In some cases, surface temperatures can reach extremely high values. Advanced materials such as Carbon–Carbon (C/C) composites are commonly used because they can retain their strength at high temperatures. Protective coatings are applied to reduce oxidation and material degradation. For areas exposed to even higher heat, Ultra-High Temperature Ceramics (UHTCs), such as zirconium diboride (ZrB_2), provide additional thermal resistance. The use of these materials helps ensure that the missile structure remains stable and does not fail during high-speed flights.

Manufacturing methods also have a strong influence on how these advanced designs are realized. Additive Manufacturing (AM) has become increasingly important in aerospace applications due to its ability to produce complex geometries with reduced material waste. Compared to traditional subtractive manufacturing, AM allows parts to be produced faster and with lower cost, which is useful during the testing and development stage. AM is also widely used to fabricate experimental equipment, such as components for hypersonic wind tunnels. The use of high-performance thermoplastics like ULTEM™ 9085 shows that AM can provide sufficient strength for testing purposes while significantly reducing production time.

The final goal of combining aerodynamic design, material selection and advanced manufacturing is to achieve accurate and reliable missile guidance. Modern defensive missiles must be able to track and intercept highly maneuverable targets under uncertain conditions. This requires guidance and control systems that can process sensor data and respond effectively during flight. By integrating navigation systems with strong structural design, missiles can maintain stability and accuracy throughout the mission. Overall, it was highlighted that successful defensive missile development relies on the effective integration of multiple engineering disciplines rather than improvements in a specific area.

References

[1] Chen, J., Fan, X., Xiong, B., & Wang, Y. (2020). Shape optimization of the cross-section for noncircular hypersonic missile forebody. *International Journal of Aerospace Engineering, 2020*, Article 8885494. https://doi.org/10.1155/2020/8885494

[2] Cho, H. S. (2025). Design and analysis of a modular additively manufactured axisymmetric Mach 5+ hypersonic wind tunnel [Master's thesis, Naval Postgraduate School]. NPS Archive: Calhoun.

[3] Cui, K., & Yang, G. (2010). Shape optimization for hypersonic arc-wing missiles. *Journal of Aircraft, 47*(4), 1414–1426. https://doi.org/10.2514/1.45882

[4] Davis, R. A., Elrod, S. D., & Lovell, D. T. (1974). Titanium honeycomb structure (NASA Technical Report No. N74-30926). *National Aeronautics and Space Administration*. https://ntrs.nasa.gov/citations/19740022813

[5] Herath, C. L. (2023). Hypersonic Missile Technology: A Comprehensive Analysis. *International Journal of Research in Engineering and Science, 11*(1).

[6] Huang, C., Liu, W., & Yang, G. (2017). Numerical studies of static aeroelastic effects on grid fin aerodynamic performances. *Chinese Journal of Aeronautics, 30*(4), 1300–1314. https://doi.org/10.1016/j.cja.2017.04.013

[7] Kalvinkar, M., Jacob, K., Reddy, P., & R, K. (2024). Hypersonic High Speed Strike Weapons: Design, Research and Development. *Acceleron Aerospace Journal (AAJ), 3-5*.

[8] Khan, M. A. H., & Rao, T. A. (2018). Aerodynamic and Structural Analysis of a Land Attack Cruise Missile. *International Journal of Management, Technology And Engineering, 8*(12).

[9] Mehta, S. S., MacKunis, W., & Curtis, J. W. (2011). Adaptive vision-based missile guidance in the presence of evasive target maneuvers. *IFAC Proceedings Volumes, 44*(1), 5471–5476. https://doi.org/10.3182/20110828-6-IT-1002.01257

[10] Olson, N., Boghozian, T., Sidor, A., Larsen, G., Bouslog, S., & Venkatapathy, E. (2023, August 13–17). Development of additive manufacturing technologies for 3D printing of spacecraft heat shields [Conference presentation]. ACS Fall 2023: Poly, San Francisco, CA, United States.

[11] Orion_int. (2021, August 2). Demystifying the DF-100: A deeper look at China's mysterious cruise missile. *Overt Defense*. https://www.overtdefense.com/2021/08/02/demystifying-the-df-100-a-deeper-look-at-chinas-mysterious-cruise-missile/

[12] Peters, A. B., Zhang, D., Chen, S., Ott, C., Oses, C., Curtarolo, S., McCue, I., & Pollock, T. M. (2024). Materials design for hypersonics. *Nature Communications, 15*(1), Article 3433. https://doi.org/10.1038/s41467-024-46753-3

[13] Rawal, S., Brantley, J., & Karabudak, N. (2013). Additive manufacturing of Ti-6Al-4V alloy components for spacecraft applications. In *Proceedings of the 6th International Conference on Recent Advances in Space Technologies (RAST)* (pp. 5–11). IEEE.

[14] Shetty, S., Nagarkar, K., Khan, S. A., Aabid, A., & Baig, M. (2025). Analysis of flow characteristics around sharp, blunt, and bulb-shaped missile nose geometries. *International Journal of Thermofluids*, 28, Article 101321. https://doi.org/10.1016/j.ijft.2025.101321

[15] SOFREP. (2024, June 4). Kh-47M2 Kinzhal: An Air-Launched Hypersonic Missile. https://sofrep.com/news/kh-47m2-kinzhal-an-air-launched-hypersonic-missile/

[16] Ukirde, K. K., Pawar, S., Rahane, D., Sagar, B., & Shinde, T. (2023). Aerodynamic study of various fins for missile body. *International Journal for Research in Applied Science & Engineering Technology (IJRASET)*, 11(2). https://doi.org/10.22214/ijraset.2023.49235

[17] Wan A Hamid, W. L. H., Shaik Dawood, M. S. I., & Aminanda, Y. (2025). Symmetrical finite element model for out-of-plane crushing of Nomex honeycomb structure. *Advanced Materials Science and Technology*, 7(2). Omniscient Pte. Ltd.

[18] Yusuf, S. M., Cutler, S., & Gao, N. (2019). Review: The impact of metal additive manufacturing on the aerospace industry. *Metals, 9*(12), Article 1286. https://doi.org/10.3390/met9121286