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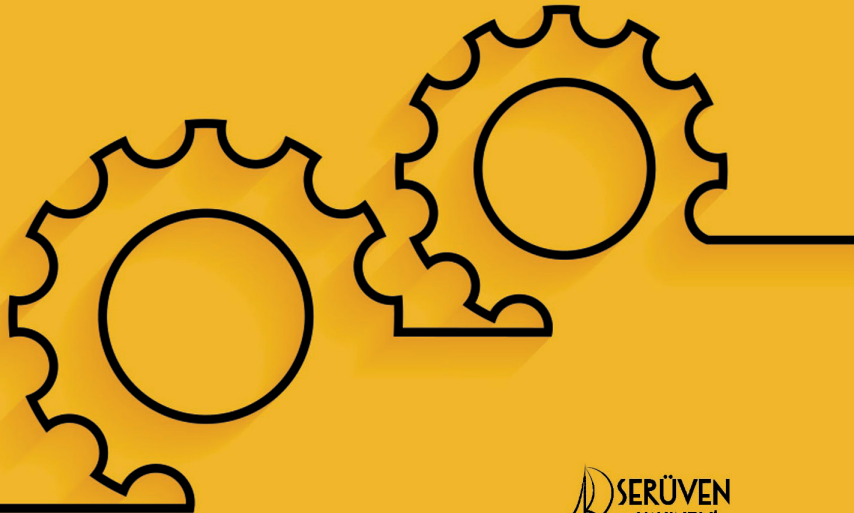
INTERNATIONAL ACADEMIC RESEARCH AND STUDIES IN

MECHANICAL ENGINEERING

EDITORS

PROF. DR. COŞKUN ÖZALP

PROF. DR. SELAHATTİN BARDAK



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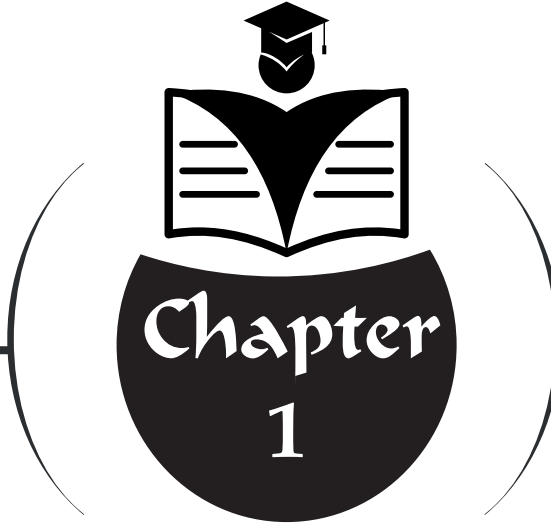
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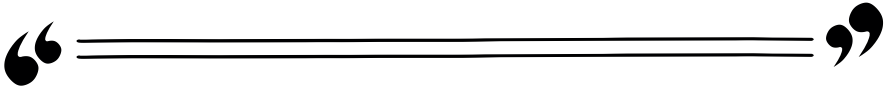
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NUMERICAL INJECTION ANALYSIS OF THIN-WALLED PLASTIC PART USING SOLIDWORKS PLASTICS



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1. INTRODUCTION

Plastic injection molding is a widely used manufacturing method in industry that enables the high-precision and economical production of thermoplastic parts with complex geometries. This process is based on injecting molten plastic raw material into a mold under high pressure, then cooling it to solidify its shape. However, ensuring high part quality requires the ability to predict material flow behavior, filling times, mold temperature distribution, and potential defects in advance (Osswald and Hernández-Ortiz, 2006).

Filling errors, air traps, weld line formation, and filling deficiencies that may occur during the injection process can negatively affect both product functionality and aesthetic appearance. Therefore, simulations performed prior to injection play a critical role in optimizing mold and product design. Flow analysis software enables the virtual modeling of the injection molding process, thereby reducing trial-and-error processes and lowering production costs (Bejan, 2013).

One of the software programs developed for this purpose, SolidWorks Plastics, offers comprehensive simulation tools for injection molding processes. Fully integrated with the SolidWorks CAD environment, this software enables moldability analyses, particularly in the early stages of the product development process. The software provides detailed control over parameters such as material selection, gate placement, fill time estimation, temperature distribution, and detection of potential surface defects (Dassault Systèmes, 2023). This allows designers to optimize mold design prior to production, thereby improving quality and saving time and money.

In his study, Yakut examined the filling analysis of a plastic cup during the injection molding process through simulation. Using Autodesk Moldflow software, he evaluated how the plastic raw material (PS – Polystyrene) flows into the mold cavity. During the analysis, factors such as gate selection, filling time, temperature distribution, and air traps were taken into account. The results obtained were used to anticipate potential problems that may be encountered in production and to create a more efficient mold design. The study emphasized the importance of simulation analyses in the injection molding process (Yakut, 2014). Tie and colleagues used 3D FEM to compare the prediction of flow, temperature, and pressure distribution in complex geometries with classical models. They noted that the 3D FEM method provided more accurate results than classical models (Tie et al. 2006). Moayyedean and colleagues aimed to reduce internal/external defects in thin-walled polypropylene parts by modifying geometric and process parameters using SolidWorks Plastics. They tested experimental parameter combinations using the Taguchi method

(Moayyedian et al. 2021). Chen and colleagues targeted both experimental and SolidWorks Plastics-based numerical optimization of process parameters to address issues such as cracking (“rupturing”) and warpage during the PET preform filling stage (Chen et al. 2023).

In this study, a filling analysis was performed on a specific plastic part using SolidWorks Plastics. The analysis stages were explained step by step through the program. Based on the analysis results, improvement suggestions were made in terms of part design and parameter selection. The findings reveal how the injection molding process can be made more efficient and controlled through digital simulation.

2. MATERIAL AND METHODS

In this study, a plastic injection flow analysis was performed on a mouse cover designed using SolidWorks 2023 software, utilizing the SolidWorks Plastics menu. Standard ABS material was selected as the plastic material for the analysis. The injection parameters were selected based on the parameters automatically provided by the program. The analysis steps are provided step by step.

2.1. Activating SolidWorks Plastics

Before starting the plastic flow analysis, the plastic part to be analyzed is opened in the SolidWorks program. If the SolidWorks Plastics menu is not active, it is activated. The SolidWorks Plastics menu is enabled from the Options/Add-ins menu. After activation, the SolidWorks Plastics Menu is added to the Command Tab. Select SolidWorks Plastics from the Command tab and enter the flow analysis menu using the New Study command from the Command manager menu. The flow analysis menu opens in the Feature Manager section (Figures 1, 2).

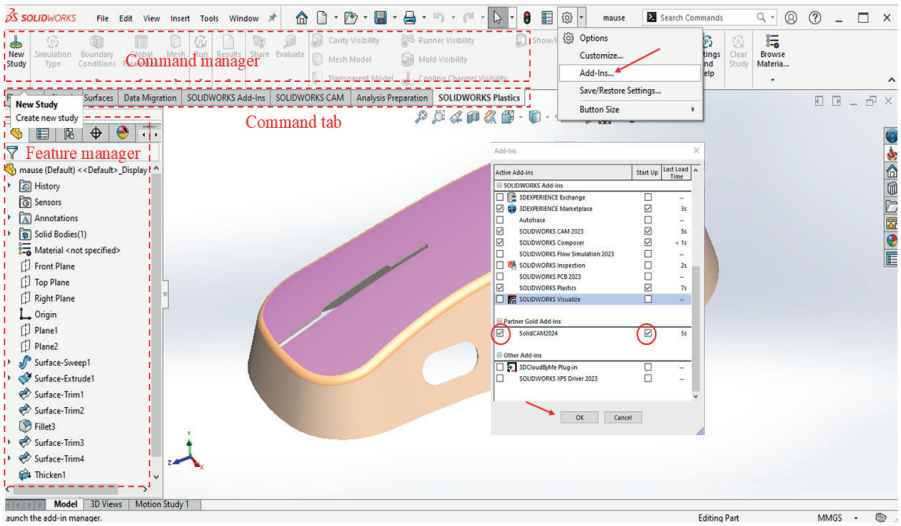


Figure 1. Enabling SolidWorks Plastics

2.2. Determination of Analysis Methods

First, in the Feature Manager section, select how many material injections will be made from the Injection Process menu. Determine whether a single plastic or multiple plastics will be used during filling. In the Analysis Procedure section, determine whether the plastic sample will be produced using the Solid or Shell method. Solid is a method used for solid parts with higher thickness. Shell is a method used for parts designed with elements such as shells with a specific thickness. Solid can also be used for thin parts, but the Shell method is generally preferred to obtain faster results. In this study, the Shell method was used for the plastic flow analysis of part (Figure 2). After the selections are made and confirmed, the feature manager section displays the process tree (Figure 3).

option opens a window for selecting the polymer material. Select the plastic material to be used in printing from the default database or user-defined database section. The material can be selected from the sort by family or sort by company options. If a second plastic material will be injected in the sample, select the set coinjection and 2nd options. The same material selection process is performed for the second material. The first and second materials selected are listed at the top of the window. If the desired material is not in the library, a new material definition process is performed by adding a project from the User-defined data section. In the newly opened window, the material name, temperature values, and all mechanical properties can be entered manually (Figure 4).

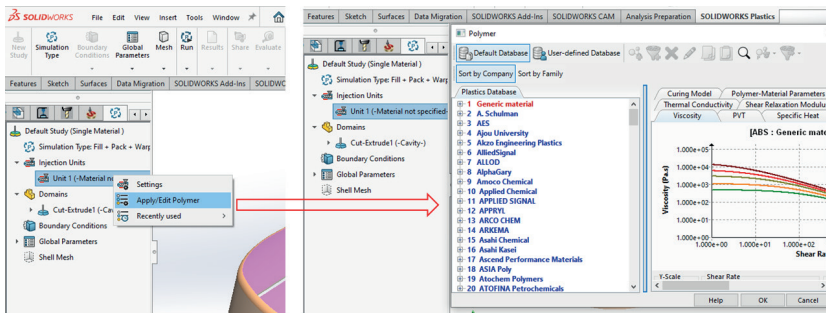


Figure 4. Material selection

After selecting the materials, the filling settings are configured by selecting Settings from the Injection Unit menu. The program automatically provides the filling settings. If the Automatic option is deselected and the User defined option is selected, the melt temperature, mold temperature, and filling pressure amount can be entered manually. The Flow Rate Profile Settings menu displays a graph showing the percentage of filling that will occur and the details of the filling amount per second. The mold temperature can be adjusted graphically in the Mold Temperature Profile section. The Recently Used menu allows you to select the last used polymer materials and perform the analysis based on these materials. After confirmation, the filling settings are complete (Figure 5).

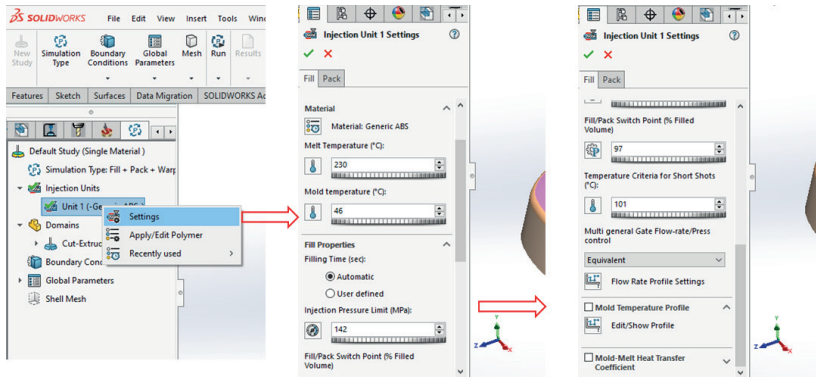


Figure 5. Determining temperatures for plastic material and mold

2.4. Boundary Conditions Settings

After defining the material and filling settings, the Boundary Conditions option is used to determine the filling location (Injection Location), piston control settings (Control Valve), mold wall temperature setting (Mold Wall Temperature), and clamp force settings (Clamp Force). Right-click on the Boundary Condition menu and first use the Injection Location command to determine the filling location(s) on the part. When selecting the filling location, the location of the injection density must be determined correctly. The location determination is initially done approximately, but the location determined based on the analysis results can be changed. The program estimates suitable filling locations in the form of points and displays them on the part. Either a single point or multiple filling points can be selected. This number varies depending on the complexity of the part geometry and the injection parameters. For this application, three separate points have been selected for the filling location, as indicated in Figure 6. The injection position is clicked on the part, and the selected points are displayed in the Selection window. The Predict Fill Pattern command can be used to view the simulation of the injection based on the selected filling locations (Figure 6). After entering any other necessary settings in the Boundary Condition menu, the command is confirmed, and the process moves on to the next step, the Mesh operation.

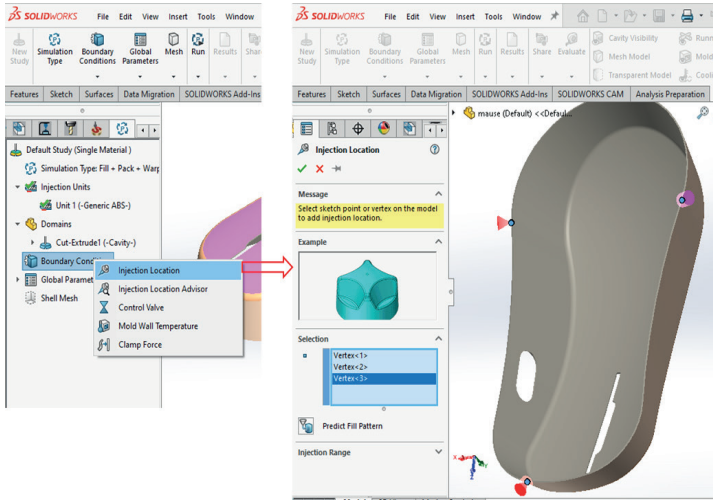


Figure 6. Boundary Condition settings

2.5.Mesh Settings

In this step, the Mesh assignment process is performed on the part to be injected. Right-click on the Shell Mesh command and select the Create Mesh command to enter the Mesh menu. The coarse or fine setting of the mesh to be assigned is made using the Surface Mesh ruler in the menu. If the scale is moved closer to the Fine section, a more precise Mesh operation is performed. Within the Mesh menu, the mesh operation can be completed without making any settings using the Create option, as shown in Figure 7. Here, the program performs an automatic Mesh assignment operation appropriate for the part. The assigned Element and Node counts are displayed on the right side of the drawing screen in Figure 7 As these numbers increase or decrease, the analysis completion time changes. If the numbers increase, the analysis time also increases, and we obtain a more accurate analysis. The biggest advantage of this method is that the program performs the mesh creation itself, enabling a faster process.

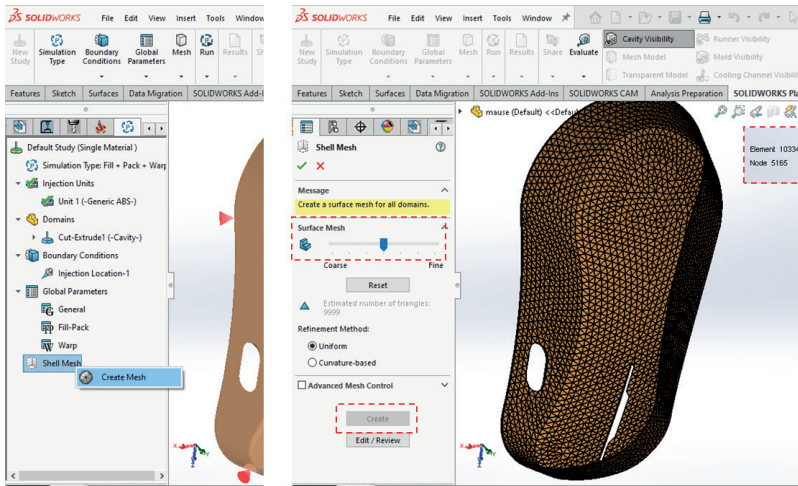


Figure 7. Mesh menu

If the Advanced Mesh Control option is enabled, the mesh settings can be manually adjusted on the desired surfaces of the part. This provides a more flexible mesh system. The selected surfaces appear in the window under the Advanced Mesh Control menu. The triangle sizes that make up the mesh can be manually specified using Mesh Size. The Gradation option specifies how the transitions between meshes will occur. Whether it should be smooth or sharp is adjusted using this scale. After entering the necessary parameters, clicking the Mesh tab creates the mesh on the part. Changes can be made to the assigned Mesh operations using the Edit/Review menu. The Summary menu displays data related to the mesh. The most important sections here are Bad Elements and Very Bad Elements. These values should be zero. If they are not zero, it indicates that there are some problems with the mesh assignment. The mesh process is checked and corrected (Figure 8).

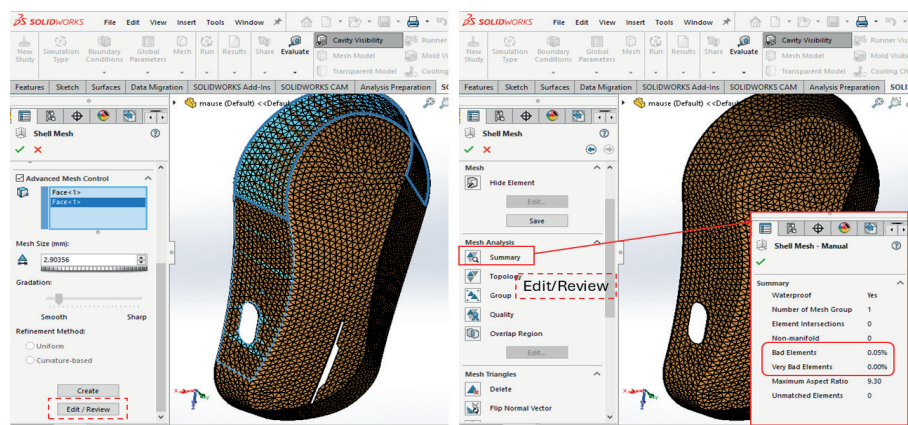


Figure 8. Mesh settings

2.6. Running the Analysis

After the mesh operation is also completed, the analysis is run. As shown in Figure 9, right-click on the Default Study option in the Feature Manager section and select the analysis you want to run from the Run command. There are three analysis options available here: Fill, Fill+Pack, and Fill+Pack+Warp. Select the desired analysis from here. The analysis time may vary depending on the complexity of the part, the assigned mesh density, and the hardware specifications of the computer.

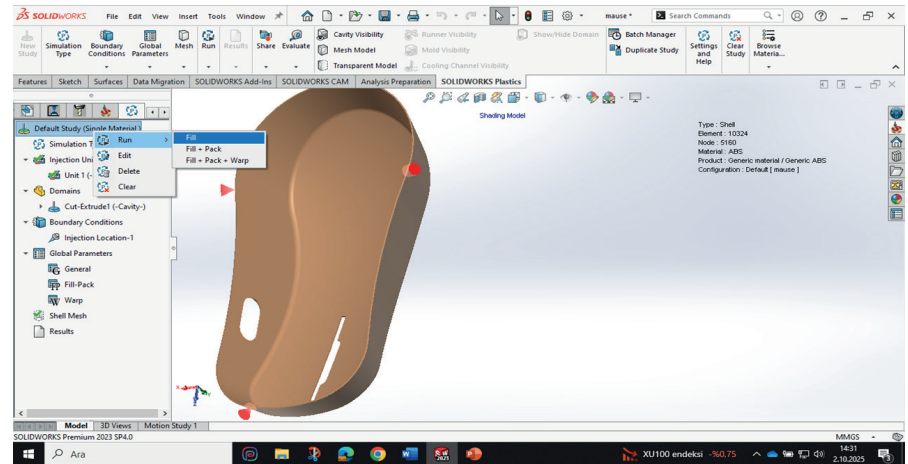


Figure 9. Running the analysis

When the analysis is complete, two windows open on the right and left (Figure 10). The test results are displayed under Available Results in the left window. Analysis results such as filling time, filling end pressure, filling center

temperature, and filling end average temperature can be examined separately. The desired result can be selected and the filling stage can be viewed instantly using the play button below the window. The right window contains a result advisor for each analysis result. This window contains general explanations about the analysis. It provides information such as whether the values are appropriate, how the results should be interpreted, and how the tests were performed. The red, yellow, and green lights on the window indicate whether the analysis was successful. A green light means that the analysis was largely successful. In this example, a red light is visible, and the error in the analysis is displayed below. This analysis warns that an axis selection is required for Clamp Force. In such a case, the Clamp Force settings must be made in the Boundary Conditions menu, and the analysis must be run again.

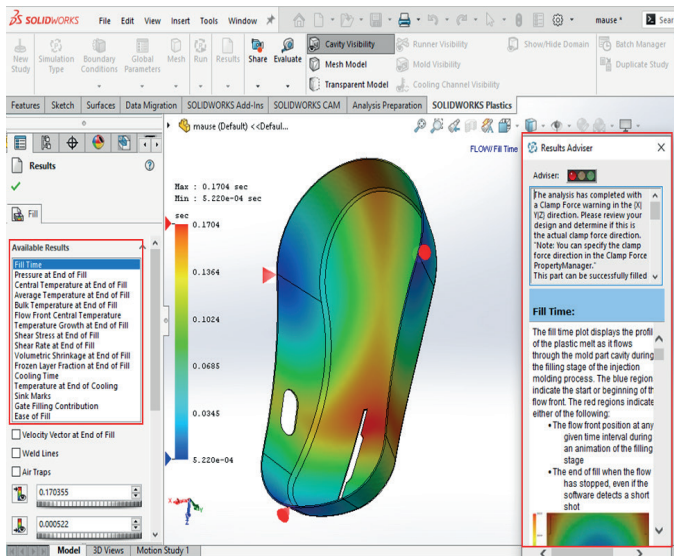


Figure 10. Analyzing the results

When the “Velocity Vector at End of Fill” command located in the middle section of the Results window is selected, the vector representation of the plastic flow during filling can be observed. Based on this analysis, flow directions and density can be examined, and necessary adjustments can be made.

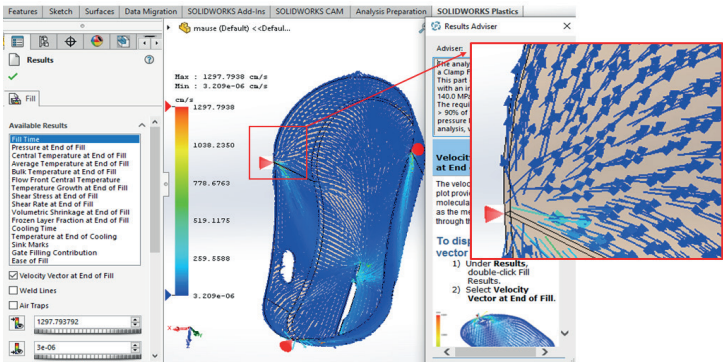


Figure 11. Image of the Velocity Vector

When the “Weld lines” option is enabled, the locations where weld lines (seam lines) may appear on the part are displayed. Since weld lines are undesirable, necessary precautions are taken based on this prediction. If the weld line is very prominent, the parameters must be adjusted. Figure 12 shows that weld lines are visible on the sample. To resolve this issue, the melting temperature of the plastic material to be injected and the mold temperature can be increased, or the plastic selection may be incorrect. Additionally, the injection pressure can be increased, and the specified filling points can be changed.

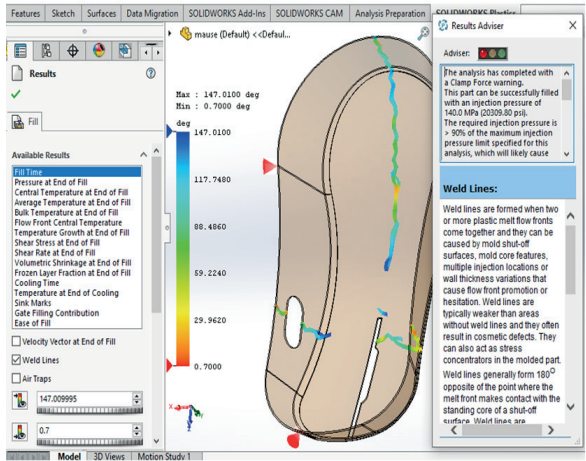


Figure 12. Image of the Weld Lines

The “air traps” command is also used to detect gas bubbles. Gas bubbles

form because air trapped inside cannot escape during filling. This command estimates the location of gas bubbles. When designing the mold, vent channels must be opened at these locations to eliminate gas bubbles. As seen in Figure 13, only one gas void was observed on the sample. When designing the mold based on this part, a vent channel must be opened in the area where the gas void is observed. The analysis results can be reviewed from the Results option in the Feature Manager menu.

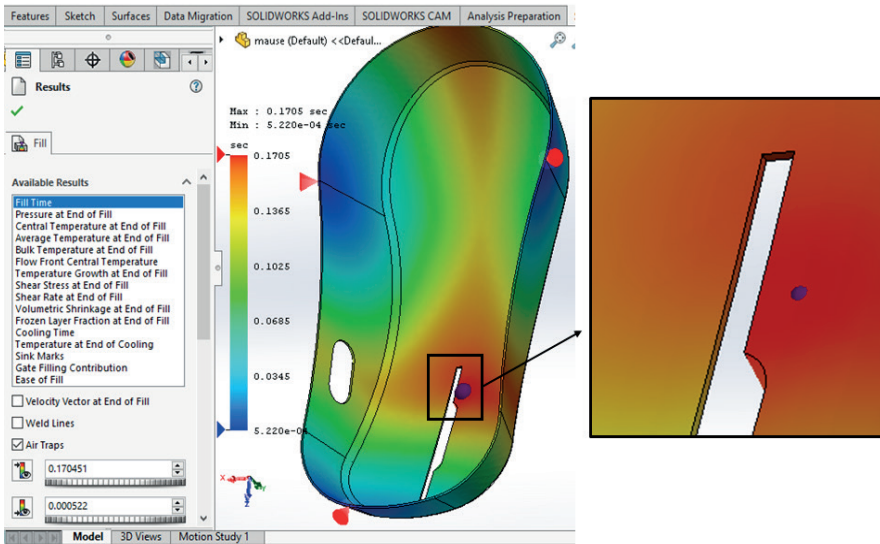


Figure 13. Image of the Air Traps region

3. RESULTS AND RECOMMENDATIONS

In this study, the plastic filling analysis of the mouse cover designed using SolidWorks 2023 was performed using the SolidWorks Plastics menu. The stages of the analysis are presented under the following headings. In the study, Fill, Pack, and Warp analyses were examined at the end of the injection molding process using ABS material.

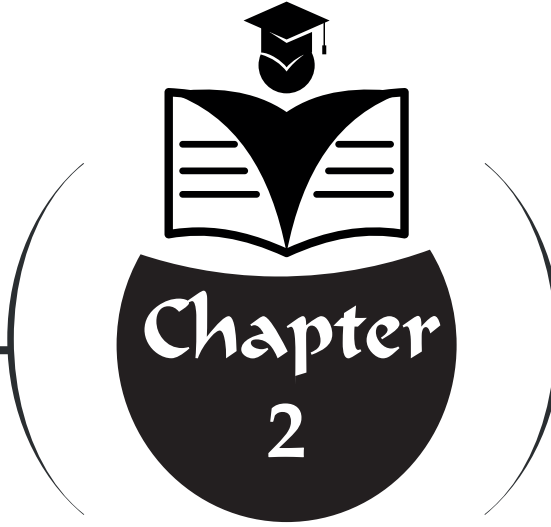
- Welding defects and air traps were identified on the plastic sample. Based on the data obtained, it was observed that a air trap formed at only one point on the sample. This situation should be taken into account when designing the mold, and an air vent should be made in that area of the mold.
- Weld lines are large and prominent on the sample. To resolve this issue, the plastic material can be changed, or the melting temperature, mold temperature, and injection pressure can be adjusted.

As a result of the analyses conducted, determining the correct material and process parameters to be used in the production process has become

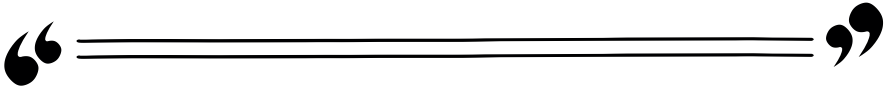
significantly easier. This contributes to increasing process efficiency and optimizing costs. Furthermore, the analyses provide important inputs for the mold design process, enabling the evaluation of fundamental elements such as the suitability of geometric structures, heat transfer, fluid behavior, and stress distributions. This makes it possible to develop mold designs that are more efficient both functionally and economically.

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WELDABILITY OF LOW CARBON STEELS AND FIBER LASER WELDING TECHNOLOGY



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1. Introduction

Steel materials are among the most widely used metallic materials in engineering applications due to their advantages such as high strength, ductility, machinability, and cost-effectiveness(Ishfaq et al., 2021). Carbon content, one of the primary classification criteria for steels, is a directly determining factor for weldability, as well as for mechanical and thermal properties. In this context, low-carbon steels, which contain approximately less than 0.25% carbon, hold a significant place in many industries such as automotive, white goods, construction, agricultural machinery, and energy systems(Zahner, 2020). The reasons for preferring low-carbon steels include high formability, easy machinability due to low hardness, good surface quality, and relatively low production cost. Furthermore, the low carbon content reduces the risk of hardening cracks during welding, making this material group advantageous for welding processes(Odebiyi, Adedayo, Tunji, & Onuorah, 2019).

In industry, traditional welding methods such as MIG/MAG (Metal Inert/Active Gas), TIG (Tungsten Inert Gas), arc welding, resistance welding, and submerged arc welding have been successfully used for a long time to join these types of steels(Singh, 2020). However, increasing quality expectations, tight tolerances, high repeatability, and the need for automation in modern production lines reveal some limitations of these conventional methods. Laser welding technologies have come to the fore as an alternative to traditional methods by offering more precise, faster, and lower distortion joining capabilities. Fiber laser welding systems are widely preferred in recent years due to advantages such as high beam quality, energy efficiency, small focal spot diameter, and compact system design. Thanks to its high energy density, fiber laser welding creates a narrow Heat-Affected Zone (HAZ), keeping post-weld distortion to a minimum and allowing fine-grained weld beads to be obtained(Deepak, Anirudh, & Sundar, 2023; Katayama, 2013).

In the case of laser welding low-carbon steels, the rapid heating and cooling cycle can lead to significant microstructural changes in the weld zone. These changes can directly affect the mechanical properties of both the weld bead and the heat-affected zone of laser welding low-carbon steels, the rapid heating and cooling cycle(Mao et al., 2019). The literature shows that welding speed, beam power, and focal position parameters play a determining role on weld bead geometry, penetration depth, and hardness distribution(Esfahani, Coupland, & Marimuthu, 2014; Yilbas, Arif, & Aleem, 2010).

Within the scope of this section, the weldability characteristics of low-carbon steels are discussed based on theoretical and applied literature, and the welding process of these materials, specifically concerning the fiber laser welding method, along with its effects on microstructural transformations, mechanical performance, and weld quality, are examined in detail.

2. General Characteristics of Low Carbon Steels

Low carbon steels are generally defined as Fe-C alloys in a balanced state, containing less than 0.25% carbon by mass. This low carbon content plays a decisive role in the microstructure the material attains at room temperature after an unbalanced cooling process. The microstructure consists largely of the ferrite phase, also referred to as a carbon solution, which has a Body-Centered Cubic (BCC) crystal structure. The ferrite phase has a very limited capacity to dissolve carbon atoms in solid solution (up to about 0.022%). In these steels, which have a hypoeutectoid composition along the cooling curve, the remaining austenite transforms around the eutectoid temperature of approximately 723°C. This transformation results in the formation of the pearlite phase, where ferrite and iron carbide (cementite) are arranged alternately in thin layers. Thus, the final microstructure of low carbon steels consists of ferrite grains forming a ductile matrix and pearlite regions dispersed within this matrix. The amount of pearlite increases in direct proportion to the carbon content of the steel (Brooks, 1996).

This microstructural configuration is directly reflected in the mechanical properties of the material. The dominant ferrite phase allows for high mobility of dislocations on slip planes, thereby imparting high ductility (high elongation and reduction of area values) and high toughness (energy absorption capacity under load) to the material. However, the primary strengthening mechanisms, namely solid solution strengthening and grain boundary hardening, remain limited due to the low carbon content and relatively large ferrite grain size. Consequently, mechanical strength values such as tensile and yield strength remain at moderate levels, and their hardness is relatively low (Ai, Liu, Huang, & Yu, 2021; Brooks, 1996; Esfahani et al., 2014).

Thanks to their characteristic microstructure, low carbon steel offers several superior advantages that stand out in industrial applications. The high ductility, a natural result of their ferrite-dominated structure, makes these materials highly compatible with cold and hot forming processes. Therefore, they provide high efficiency and easy machinability in manufacturing processes requiring plastic deformation, such as drawing, deep drawing, bending, and Rolling (Demeri, 2013). Furthermore, the low carbon equivalent is another critical advantage that significantly enhances their weldability. This characteristic minimizes the risk of undesirable martensitic structure formation and associated cracking in the weld zone, eliminating the need for preheating, which is a costly and time-consuming process in most applications. When the economical production cost brought by the low alloying element content is added to all these processing conveniences, this group of steels becomes an indispensable choice for industry (Demeri, 2013; Katayama, 2013; Lu & Kujanpää, 2013).

However, these superior processability and economic advantages inevitably bring along some mechanical limitations. The relatively moderate mechanical strength caused by the low carbon content directly restricts the application range of these steels. They are not preferred for structural components under heavy loads, such as bridge cables, high-strength fasteners, etc., which require high yield and tensile strength, or in high-temperature conditions where they cannot demonstrate sufficient performance. The industrial applications of low carbon steels encompass a wide range, including automotive body panels, various pipes and profiles, white goods bodies, and reinforcing bars, where high strength is not required, but high production speed, easy formability, superior weldability, and low cost are prioritized (Ismael, 2022).

3. The Concept of Weldability

Weldability is defined as the ability of a material to be joined under suitable methods and parameters without the formation of cracks, pores, or serious defects. The weldability of steel is primarily directly related to its chemical composition, microstructure, and thermal behaviors.

Due to their low carbon content and limited alloying elements, low-carbon steels are one of the most easily weldable steel groups. The potential issues that may occur during welding in these materials are much more limited compared to high-carbon or alloy steels.

3.1. Carbon Equivalent (CE) and Preheating Requirement

One of the most used criteria for determining the weldability of steels is the Carbon Equivalent (CE) value. The CE value is an empirical calculation method that considers the hardening effect of alloying elements such as manganese (Mn), chromium (Cr), molybdenum (Mo), vanadium (V), and nickel (Ni), in addition to carbon (C). The generally accepted formula is (Rao, Syamsundar, & Narasaiah, 2022):

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

as follows.

CE provides a critical criterion for quantitatively evaluating the weldability of steels. Depending on the calculated CE value, the weldability of steels is classified into three basic categories. When the CE value is below 0.40, the material's weldability is considered very good. Under these conditions, the hardening tendency is low, and preheating is not required for most applications. For steels with a CE value between 0.40 and 0.60, weldability is at a moderate level. In such cases, preheating may become necessary depending on the section thickness and the corresponding cooling rate. In steels with

high carbon and alloy content where the CE value exceeds 0.60, the risk of hardening and crack formation in the weld zone increases significantly. Therefore, for a controlled welding process, strict measures including high preheating temperature, the use of low-hydrogen welding electrodes, maintaining a specific interpose temperature, and subsequent controlled cooling are mandatory (Kinsey, 2000).

In the literature, it is recommended in the structural codes of many countries that the CE value should not exceed 0.49, and it has been reported that exceeding this value reduces weldability due to high hardenability (Martínez, 1993; Scholz & Roberts, 2000). Similarly, it is emphasized that if the CE value exceeds 0.47, the formation of low-temperature transformation products such as bainite and martensite in the weld zone is inevitable (Ramirez, 2008). Therefore, measures such as preheating are necessary when welding high CE steels, but experimental studies have shown that even a preheat of 200°C may not be sufficient when the CE value reaches levels of 0.60 (Moustafa, Khalifa, El-Koussy, & Abd El-Reheem, 2016). Low carbon steels, however, generally have a $CE < 0.25$, resulting in a very low hardening tendency during welding and maintaining a high level of weldability.

3.2. Effect of Thickness and Cooling Rate

Thickness and cooling rate parameters play a decisive role in the microstructural characteristics and mechanical performance of welded joints (Poorhaydari, Patchett, & Ivey, 2005). As plate thickness increases in welded constructions, changes observed in thermal conductivity and heat distribution profiles cause a significant increase in the cooling rate. These high cooling rates can pave the way for the formation of undesirable hard and brittle martensitic phases, particularly in the weld bead and the heat-affected zone (Tayier, Tai, & Janasekaran, 2022). This microstructural transformation negatively affects the material's weldability performance and significantly increases the risk of cold cracking. Furthermore, with increasing plate thickness, the levels of residual tensile stresses trapped within the material after the welding process also rise. This situation creates a potential risk factor for the initiation of fatigue cracks under cyclic loads that the structure is exposed to throughout its service life. Therefore, in the welding processes of thick-section materials, it is essential to systematically apply additional procedures such as preheating, controlled cooling protocols, and interpose temperature optimization to control the cooling rate and minimize internal stresses (L. Wang & Qian, 2022).

However, when low carbon steels are concerned, these processes become relatively more favorable. The low carbon content in this steel group raises the critical cooling rate value and positively affects the microstructural transformation behavior. Even under rapid cooling conditions, the

microstructure largely consists of ductile ferritic and pearlitic phases, thereby keeping the hardening tendency and the associated risk of cracking at limited levels. This makes low carbon steels a more reliable alternative in terms of weldability for medium and thick-section applications. Nevertheless, the negative effect of increasing residual stress levels due to thickness increase on fatigue performance should not be ignored. Ultimately, the inherently low cracking risk of low carbon steels, when supported by appropriate welding parameters and procedures, allows these materials to be used safely in the manufacture of thick-section critical structures. In this context, it is of great importance to comprehensively evaluate the effects of the thickness variable in the development of welding procedures and quality control processes (Shams-Hakimi, Yıldırım, & Al-Emrani, 2017).

3.3. Weldability with Traditional Methods

Low carbon steels exhibit superior weldability characteristics due to their low carbon equivalent values. This material group can be joined seamlessly using numerous traditional welding methods widely used in industry (Deepak, Raja, Srikanth, Surendran, & Nickolas, 2021). MIG/MAG Welding is a preferred joining method for the manufacturing of thin sheets and automotive components, especially due to its high welding speed and operational flexibility (González-González, Los Santos-Ortega, Fraile-García, & Ferreiro-Cabello, 2023). TIG Welding, despite having a lower deposition rate, is often used for thin-section and high-quality joining applications requiring superior penetration and weld quality. Shielded Metal Arc Welding finds widespread application in the welded fabrication of thick-section structures, particularly due to its economic advantages and equipment simplicity (Rao et al., 2022). Resistance Spot Welding is a joining technique frequently applied in mass production processes, such as automotive body manufacturing, due to the high efficiency it provides for the serial production of thin sheets (B. Wang et al., 2022).

Low carbon steels exhibit superior weldability characteristics due to their low carbon equivalent values. This material group can be joined seamlessly using numerous traditional welding methods widely used in industry. In this context, cold-rolled steel grades according to European norms, such as DC01, DC03, DC04, and DC05, which stand out with their cold-rolled and ductile structures, are frequently preferred in applications requiring formability and weldability. MIG/MAG Welding is a preferred method for the manufacturing of thin sheet grades like DC01 and DC04 and automotive components, especially due to its high welding speed and operational flexibility. TIG Welding, despite having a lower deposition rate, is used for thin-section materials with superior ductility, such as deep-drawing quality DC05, and in applications requiring high-quality joining, due to the superior penetration and weld quality it provides. Shielded Metal Arc Welding, with its

economic advantages and equipment simplicity, finds widespread application in the welded fabrication of thick-section structures, including structural steel grades like S235JR and S355JR, which have a more common carbon content. Resistance Spot Welding is a joining technique frequently applied in mass production processes, such as automotive body parts made from DC03 and DC04 grade steels, due to the high efficiency it provides for the serial production of thin sheets (Deepak et al., 2023; Di, Sun, Wang, & Li, 2017; Krawczyk, Pańcikiewicz, Frocisz, Danielewski, & Furmańczyk, 2025; Shi, Fang, Zhu, Norwood, & Peyghambarian, 2014).

4. Fiber Laser Welding Technique

4.1. Working Principle of Fiber Laser

Fiber lasers are an advanced type of laser system belonging to the class of solid-state lasers, utilizing optical fiber technology for both the generation and transmission of light. Fundamentally, the laser beam is created within a glass fiber core doped with rare-earth elements (most commonly Ytterbium - Yb). This structure, which houses both the active region where light is generated and the path through which the light is guided within the same medium, offers a compact, efficient, and stable system. High-power diodes are used as an energy source in fiber laser systems. The pump light emitted by these diodes is directed into the fiber core. The core of the fiber is doped with additives like Ytterbium, which absorb the pump light and create the laser beam via stimulated emission. The resulting laser beam typically has a wavelength of 1.06–1.08 micrometers, which is highly absorbed by metal surfaces. This makes fiber lasers particularly ideal for metal welding and cutting processes. The basic working principle of fiber laser systems relies on the coordinated function of specific components. The starting point of the system is the pump diodes, which convert electrical energy into laser radiation. The light emitted from these diodes is injected into the active fiber core, doped with rare-earth elements like Ytterbium. The effective confinement and propagation of light within this core is made possible by the fiber cladding surrounding the core, which has a lower refractive index. The laser resonator structure is formed by Bragg gratings written directly into the fiber; these photonic elements allow photons of a specific wavelength to be selected and amplified, resulting in a coherent laser beam. Finally, the produced laser beam is collimated into a parallel beam and then focused onto the workpiece via a focusing lens, concentrating it into a high-intensity spot to perform the material processing task (Davim, 2021; Katayama, 2013; Shi et al., 2014). Since light generation and transport in fiber lasers occur entirely within the fiber medium, light loss is minimal, and the system's overall efficiency is very high. The electro-optical efficiency of a typical fiber laser system ranges between 25–30%. This rate remains around 10% for traditional CO₂ lasers. Furthermore, because heat dissipation within the fiber medium is controlled more effectively,

the system's cooling requirement is relatively lower (Li et al., 2016). Another significant advantage is the beam quality ($M^2 < 1.1$). This allows fiber lasers to achieve extremely fine focal spot diameters. A small focal spot diameter means higher energy density, deeper and narrower penetration, and more precise processing. This is of great importance, especially for the distortion-free welding of thin-section low-carbon steels.

The wavelength of fiber lasers (~1070 nm) provides very high absorption in ferrous materials (e.g., low-carbon steels). This enables a more controlled and efficient transfer of heat input into the material during the welding process. Simultaneously, working in harmony with the relatively low melting points and thermal conductivities of such steels, it reduces microstructural degradation and helps achieve high-quality weld beads. In conclusion, the working principle of the fiber laser, through the holistic advantages it provides in the processes of beam generation, transport, and focusing onto the workpiece, presents a highly suitable technological profile for the welding of low-carbon steels (Shi et al., 2014).

4.2. Comparison with Traditional Laser Systems

Fiber laser technology offers significant advantages compared to other laser types, especially in metal processing applications. Although traditional CO₂ lasers can achieve high output power, they operate at an infrared wavelength of 10.6 μm, which results in low absorption by metals. Additionally, their requirement for complex optical alignment, performance issues with reflective materials, high maintenance needs, and large physical footprints constitute major disadvantages. Nd:YAG lasers, while providing better absorption with a 1.064 μm wavelength and allowing fiber optic delivery, remain limited in continuous processing applications due to the complexity of their optical systems and their predisposition to operating in pulse mode. In contrast, fiber lasers stand out with their compact structure, superior beam quality, high energy efficiency (around 25-30%), long service life, and low maintenance requirements. Their wavelength of approximately 1.07 μm is highly absorbed by metals, significantly increasing process efficiency, while their easy integration with digital controls and robotic systems provides operational flexibility (Shi et al., 2014). Consequently, fiber lasers are rapidly replacing traditional laser systems for the precise, fast, and reliable welding of many metals, primarily low-carbon steels.

4.3. Welding of Low Carbon Steels with Fiber Laser

The fiber laser welding method allows for the joining of low-carbon steels with high precision and low deformation. The high energy density provided by fiber lasers results in a narrow and deep penetration, creating an intense and mechanically strong weld bead in the joint area. This characteristic enables the achievement of high-strength joints, particularly in thin-section structural

elements. During the welding process, the Heat-Affected Zone (HAZ) remains extremely narrow, which minimizes post-weld distortion and residual stress. Laser welding offers both time savings and quality advantages, especially in automotive, white goods, pipeline, and precision manufacturing processes. Furthermore, the high-level integration capability of fiber laser systems with robotic automation systems enhances process traceability and repeatability in Industry 4.0-focused production lines. This integration makes real-time quality control, digital management of production parameters, and reduction of error rates possible (Ai et al., 2021).

4.4. Limitations of Fiber Laser

While fiber laser systems offer numerous advantages, they also entail certain limitations. The first of these is the considerably high initial investment cost of the system compared to traditional welding methods. Another limiting factor is the requirement for precise control of laser parameters (power, focal position, travel speed, beam diameter, etc.). Inappropriate parameter combinations can lead to defects in the weld bead, such as spatter (scattering of molten metal particles), pore formation, lack of penetration, or excessive melt-through.

Furthermore, with materials possessing very high reflectivity (such as aluminum and copper), the low absorption of the laser beam at the initial moment of contact can cause focusing and stability issues at the start of the process. However, the surface properties of low-carbon steels are more tolerant against such absorption problems (Katayama, 2013; Lu & Kujanpää, 2013; Shi et al., 2014).

5. Welding Parameters and Effects

In fiber laser welding technology, performance criteria such as weld bead geometry, mechanical strength, and final quality are directly dependent on the applied process parameters (Steen & Mazumder, 2010). Fundamental variables such as laser power, welding speed, focal position, spot diameter, and shielding gas usage determine both the characteristics of the melt pool and the microstructure shaped by the heat input. Selecting these parameters in optimal combinations is of great importance for achieving high-quality and repeatable joints when welding low-carbon steels (Katayama, 2013).

5.1. Effect of Laser Power

Laser power refers to the total amount of energy transferred to the weld zone and is a direct determinant of penetration depth, bead width, and the thermal profile of the melt pool (Sharma & Molian, 2011). An increase in laser power enhances both the depth and width of the weld bead, making it possible to achieve full penetration, especially in thick-section components. However, with excessive power applications, controlling the melt pool becomes difficult,

and defects such as spatter, pore formation, melt ejection, or burn-through on the root side are observed around the weld bead (El-Batahgy & Kutsuna, 2009). On the other hand, insufficient power levels can result in incomplete melting of the material, leading to lack of penetration, poor fusion, and mechanical inadequacies. In the fiber laser welding of low-carbon steels, laser powers typically ranging from 500 W to 2000 W are preferred, and the power selection is optimized considering material thickness, welding position, and the targeted penetration depth.

5.2. The Role of Welding Speed

Welding speed determines the travel speed of the laser beam on the material surface and, together with laser power, controls the total heat input. At high welding speeds, the interaction time between the laser beam and the material decreases. While this can create a narrow and deep weld bead, it also carries the risk of insufficient heat input failing to achieve complete melting and resulting in lack of penetration.

At low welding speeds, the increased amount of energy transferred to the material leads to the formation of a wider melt pool. However, excessive heat input can cause the Heat-Affected Zone (HAZ) to widen and increase the risk of thermal distortion (Bunaziv, Akselsen, Ren, Nyhus, & Eriksson, 2021). When determining the optimum welding speed, factors such as material thickness, thermal conductivity, and mechanical requirements must be carefully evaluated alongside laser power.

5.3. Importance of Focusing and Spot Diameter

The efficiency and quality of the laser welding process largely depend on the focusing accuracy of the beam and spot diameter control. In fiber laser systems, optical assemblies consisting of a collimator and a focusing lens ensure that the laser beam is focused into a high-intensity spot on the workpiece. The penetration profile can be precisely controlled by adjusting the focal point position to be on, above, or just below the workpiece surface. Reducing the spot diameter causes the energy to concentrate in a narrower area, enabling the achievement of narrower and deeper weld beads. However, excessively small spot diameters can narrow process tolerances and increase sensitivity to surface irregularities on the part, negatively affecting process stability. On the other hand, incorrect focusing conditions prevent the effective transfer of laser energy to the desired area. This situation can result in significant weld defects such as irregular penetration depth, asymmetric bead profile, lack of fusion, and excessive spatter formation. Therefore, for optimum weld quality, the focal position and spot diameter must be optimized according to the material thickness and welding speed (Steen & Mazumder, 2010).

5.4. Examination of Shielding Gas Usage

The use of shielding gas plays a decisive role in the quality and efficiency of the fiber laser welding process. The primary functions of shielding gas are to protect the weld zone from oxidation and nitride formation caused by atmospheric gases, and to effectively suppress the plasma plume, which absorbs the laser beam and hinders energy transfer. This ensures the laser beam effectively reaches the material surface (Kuo, T. Y., & Jeng, S. L. (2011).

The choice of process gas varies depending on the chemical composition of the welded material and the desired penetration profile. Due to its low ionization potential and inert characteristics, argon is the most used gas for welding low-carbon steels. Helium, with its high thermal conductivity and ionization energy, can provide deeper penetration, but its high cost can be a limiting factor for process economics. Nitrogen gas is preferred particularly for austenitic stainless steels due to its effect of increasing corrosion resistance; however, its use is limited for low-carbon steels due to the risk of forming brittle nitride phases.

Optimization of shielding gas parameters is as critical as the gas selection itself. Parameters such as gas flow rate, flow regime (laminar/turbulent), application angle, and nozzle geometry directly affect weld quality. Flow rates below the optimal value lead to insufficient protection, while excessively high flow rates create turbulence, disrupting the protective zone and causing weld pool instability. Therefore, shielding gas parameters must be optimized in harmony with material thickness and welding speed.

5.5. Combined Effect and Optimization of Parameters on Low Carbon Steels

In the fiber laser welding of low-carbon steels, the interaction of process parameters with each other is of critical importance in determining weld quality (Katayama, S. (Ed.). (2013). *Handbook of Laser Welding Technologies*. Woodhead Publishing). An optimum parameter combination results in a narrow heat-affected zone, minimized thermal distortion, and a fine-grained homogeneous microstructure, whereas imbalances between parameters can lead to defects such as pore formation, lack of penetration, and excessive spatter.

Parameter optimization aims to systematically minimize these defects through the statistical design of fundamental variables like laser power, welding speed, and focal position, validated with experimental data. Although the low hardening tendency of low-carbon steels limits the risk of post-weld cracking, significant losses in mechanical properties in the weld zone can be observed under conditions combining high welding speed with low energy input (Sharma, R. S., & Molian, P. (2009).

Therefore, to ensure process reliability, parameter optimization must be supported by experimental studies and its continuity guaranteed through process control systems. In optimization studies, the use of statistical techniques like Response Surface Methodology offers significant advantages for modeling parameter interactions and simultaneously optimizing multiple outputs.

6. Microstructural and Mechanical Properties

Fiber laser welding enables superior microstructural control and mechanical performance in low-carbon steels compared to traditional welding methods, thanks to its characteristic low heat input and high energy density. The most distinct advantage of the process is the narrow HAZ resulting from localized heat application. This narrow zone limits degradations, such as excessive grain growth, in the ferritic-pearlitic microstructure of the base material, thereby preserving the overall mechanical strength of the welded joint.

The weld bead region exhibits a fine-grained and homogeneous weld metal microstructure because of rapid solidification. This refined and homogeneous microstructure allows critical mechanical properties of the joint, such as ductility, tensile strength, and especially impact toughness, to be maintained close to base material levels or even exceed them in some cases.

6.1. Heat-Affected Zone (HAZ) and Microstructural Transformations

The mechanical performance and integrity of welded joints are often determined by the microstructural evolution of the HAZ, which is typically the weakest link. The high energy density and localized heat input of fiber laser welding are the fundamental factors that directly control the extent and nature of these critical transformations occurring in the HAZ. The microstructural changes in this zone are shaped by parameters such as the material's carbon content, the experienced thermal cycle, and the cooling rate (Ismael, 2022; B. Wang et al., 2022). In low-carbon steels, HAZ is mostly characterized by the recrystallization of ferrite and pearlite phases. Due to the temperatures reached during welding, grain growth in ferrite and realignment of pearlite colonies can occur. However, the low carbon content ($C < 0.25\%$) limits the tendency for martensitic transformation, which significantly reduces the risk of post-weld cracking. The high travel speeds of the fiber laser welding method ensure the HAZ remains confined to a narrow region. This situation both reduces thermal distortion and increases mechanical continuity. Studies have reported that the HAZ width achieved with fiber laser welding is 30-50% narrower compared to MIG or TIG welding methods, and the microstructural integrity is better preserved (Saha et al., 2014).

Experimental studies in literature (Figure 1.a-c) (Atmaca & Kurt, 2021; Eroğlu et al., 1999; Mansur et al., 2021) clearly reveal the microstructural transformations occurring in the HAZ region of fiber laser welding. SEM examinations conducted on DP600 dual-phase steels have shown that parameters such as welding speed and focal distance directly affect the grain morphology and phase distribution in the HAZ (The Effects of Welding Speed and Focal Length on the Mechanical Characteristics of Fiber Laser-Welded Structures of DP600 Dual-Phase Steel). High welding speeds reduce the HAZ width and increase the cooling rate, thereby inhibiting excessive grain growth. Under these conditions, a microstructure consisting of spherical carbides dispersed within a fine-grained ferritic matrix has been observed. In low-carbon steels, it has been determined that the initial coarse grain size significantly influences the recrystallization behavior in the HAZ (Effect of coarse initial grain size on microstructure and mechanical properties of weld metal and HAZ of a low-carbon steel). SEM analyses have confirmed that in regions subjected to high thermal cycles, coarse ferrite grains recrystallize and transform into a finer and more equiaxed grain structure. This grain refinement mechanism improves the mechanical properties of the HAZ, particularly impact toughness and ductility. In the regions progressing from the weld metal towards the HAZ and the base material, SEM images reveal a gradual microstructural transition (Effect of laser welding on microstructure and mechanical behaviour of dual-phase 600 steel sheets). Moving away from the weld bead, a clear transition can be observed from the fine-grained structure characteristic of rapid solidification to the thermally recrystallized grains in the HAZ, and finally to the unaffected ferrite-pearlite microstructure of the base material. This gradual transition is an indicator that microstructural integrity is preserved thanks to the localized heat input of laser welding, and that mechanical performance can be maintained close to base material values.

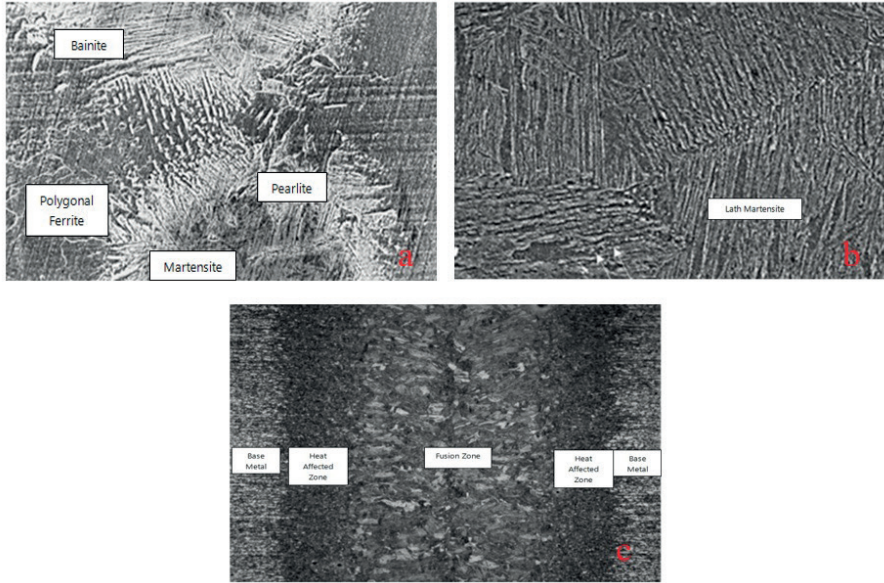


Figure 1. a-c) SEM investigations Adopted from (Atmaca & Kurt, 2021; Eroğlu, Aksoy, & Orhan, 1999; Mansur, de Figueiredo Mansur, de Carvalho, de Siqueira, & de Lima, 2021)

6.2. Hardness Profiles

The mechanical integrity of welded joints is directly related to the homogeneity of the hardness distribution. In traditional high heat input welding methods (such as MIG, shielded metal arc welding), significant hardness fluctuations are observed in the Heat-Affected Zone (HAZ) due to excessive grain growth or the formation of brittle phases. This heterogeneous hardness profile can cause stress concentrations in critical areas, shortening the fatigue life and promoting crack initiation in the transition zones. In contrast, the low and localized heat input of fiber laser welding provides an extremely homogeneous distribution across the weld zone. Microhardness measurements conducted on low-carbon steels show that the weld metal and HAZ hardness typically range between 160-180 HV, maintaining values close to the base material hardness (90-95% of it). This minimal hardness gradient reduces stress concentrations in the joint, thereby enhancing the structure's ductile behavior and, consequently, its toughness. As a result, the homogenized hardness profile contributes to increased reliability and service life of the welded joint by providing superior resistance to cracking, especially in applications under dynamic and impact loads (Ling et al., 2023; Pathak, Singh, Gaur, & Balu, 2021).

6.3. Mechanical Strength

The mechanical performance of fiber laser-welded low-carbon steel joints exhibit superior properties confirmed by laboratory tests and industrial applications. Tensile tests show that the ultimate tensile strength of welded specimens reaches levels equivalent to the base material strength, and in most cases, failure occurs in the base metal rather than in the weld bead. This behavior indicates high joint efficiency and the adequacy of the weld zone's load-bearing capacity. Impact toughness assessments have proven that, thanks to the fine-grained and homogeneous microstructure provided by fiber laser welding, a more ductile fracture behavior is achieved compared to traditional methods like MIG and TIG. This preserved microstructural integrity, despite the rapid thermal cycle, enhances the material's energy absorption capacity under impact loads. Particularly, Charpy-V tests conducted at low temperatures reveal that fiber laser-welded specimens achieve significantly higher impact energy values compared to their counterparts welded with traditional methods (Barbosa, de Godois, Bianchi, & Ruggieri, 2021; Huang et al., 2021).

7. Industrial Applications

The joining of low-carbon steels using fiber laser welding is widely preferred in many industrial sectors to increase production process efficiency, improve product quality, and reduce costs. Especially due to its high repeatability, narrow HAZ, high travel speed, and compatibility with automation, fiber laser welding has become a strategic solution for modern manufacturing systems.

7.1. Automotive Sector

The automotive industry is an area where high production volumes, tight geometric tolerances, and lightweight-strength optimization are critically important. In this context, low-carbon steels are widely used in applications such as chassis components, body panels, body reinforcement elements, and fuel system parts. Fiber laser welding technology demonstrates distinct advantages over traditional MIG/MAG methods, particularly in joining thin sheets. A narrow weld bead, minimized thermal distortion, and high surface quality are characteristic features of this method. The high repeatability of the process and its compatibility with robotic automation increase efficiency in mass production lines and facilitate quality control processes. Today, automotive manufacturers intensively use fiber laser welding for critical applications such as roof joints and door inner reinforcement elements (Dhamothara Kannan et al., 2024).

7.2. Pipe and Profile Manufacturing

Pipe and profile production is a sector where low-carbon steels are extensively used, both in structural applications and fluid transmission

systems. Fiber laser welding is effectively used in this field for manufacturing longitudinally welded and spiral welded pipes. The method's high penetration capability, providing full penetration in a single pass, leads to significant reductions in production times. The post-weld internal surface smoothness, minimal burr formation, and superior sealing performance offer decisive advantages for gas and liquid transport systems. Furthermore, the high degree of automation potential minimizes human intervention in continuous production lines and enhances process reliability and safety standards(Chaturvedi et al., 2022).

7.3. White Goods Sector

White goods manufacturing is a sector with high-quality expectations, both aesthetically and functionally. The low-carbon steel used are often galvanized, paintable, or stainless-coated types. Fiber laser welding allows for the joining of such coated sheets without damaging the coating. The low heat input minimizes degradation, color change, and deformation, especially on painted and coated surfaces. In applications with high aesthetic expectations for products (e.g., oven bodies, refrigerator doors, washing machine drums), laser welding provides clean and spatter-free seams. This method also reduces assembly time, increases production efficiency, and contributes to sustainability goals by lowering energy consumption(Liu et al., 2023).

7.4. Robotic Production Lines and Industry 4.0 Integration

In today's manufacturing systems, flexibility, speed, and digitalization are paramount. In this context, fiber laser welding systems have become an indispensable component of modern manufacturing due to their integrability into robotic production lines. Fiber laser systems integrated with robotic arms enable the precise 3D joining of parts with complex geometries. This structure is ideal for welding operations with tight tolerances and minimizes human error during production. Robotic welding systems supported by sensor technology and visual monitoring systems can provide real-time control, continuously monitoring weld quality. Within the scope of Industry 4.0, fiber laser welding machines can be equipped with advanced features such as cloud-based monitoring, automatic error analysis, data logging, and performance optimization. This makes production systems smarter, more adaptable, and error-free(Pires, Loureiro, & Bölmsjö, 2006).

8. Discussion and Future Perspectives

The fiber laser welding method provides significant microstructural and mechanical advantages for low-carbon steels. Features such as a narrow HAZ, low distortion, and high welding speed make this method particularly attractive in the automotive, pipe/profile, and white goods sectors. However, the high initial investment cost and the requirement for precise control of

welding parameters can create application limitations in some production environments. In this context, process optimization and operator experience emerge as critical factors directly affecting weld quality. Future studies are focusing on technological developments to enhance fiber laser welding performance. Hybrid laser-arc welding systems have the potential to provide deep penetration, especially in high-thickness materials, while minimizing thermal deformation and distortion due to low heat input. Furthermore, artificial intelligence and machine learning-based parameter optimization are reducing error rates in the welding process and significantly increasing production repeatability. Within the scope of Industry 4.0, robotic fiber laser welding lines equipped with sensor-based monitoring systems and intelligent control mechanisms enable the digitization of production processes and an increase in automation levels. These developments ensure that low-carbon steels are welded more efficiently, reliably, and sustainably in mass production. Finally, environmental criteria such as energy efficiency and waste minimization, in line with sustainable production goals, further highlight the advantages of the fiber laser welding method and contribute to increasing its adoption rate by industry in the future. Therefore, the development and widespread adoption of fiber laser welding technology is of strategic importance from both economic and environmental perspectives.

9. Conclusion and Recommendations

The use of fiber laser welding technology in low-carbon steels is currently creating a significant transformation in the welding industry. The narrow HAZ, high penetration capability, and low thermal effects provided by this method increase the mechanical strength of welded joints and preserve the material's original structural properties. Consequently, the rate of preference for fiber laser welding in applications of low-carbon steels in high-performance sectors such as automotive, pipe/profile manufacturing, and white goods is rapidly increasing.

The integration of fiber laser welding systems with robotic automation and Industry 4.0 technologies offers significant advantages in mass production by enhancing flexibility, speed, and quality control capabilities in manufacturing processes. AI-based parameter optimizations allow for the standardization of weld quality and the minimization of defects, thereby elevating production efficiency to higher levels. In this context, in the coming years, fiber laser welding systems supported by smart sensors, real-time data analysis, and autonomous control systems are expected to become standard practices in the industry.

On the other hand, limitations such as high initial costs and the need for precision in process parameters still pose obstacles to the widespread adoption of the technology. Therefore, research aimed at reducing costs and

the development of user-friendly control systems are critically important for increasing technology's accessibility. Furthermore, a more comprehensive investigation of fiber laser welding applications on different alloyed and surface-treated materials will contribute to expanding the technology's scope.

In conclusion, fiber laser welding technology stands out as an innovative method that enhances efficiency, quality, and sustainability in the welding processes of low-carbon steels. In line with academic studies and industrial applications, continuous improvement and integration efforts focused on the technology will ensure that welded production processes become faster, more economical, and environmentally friendly in the future.

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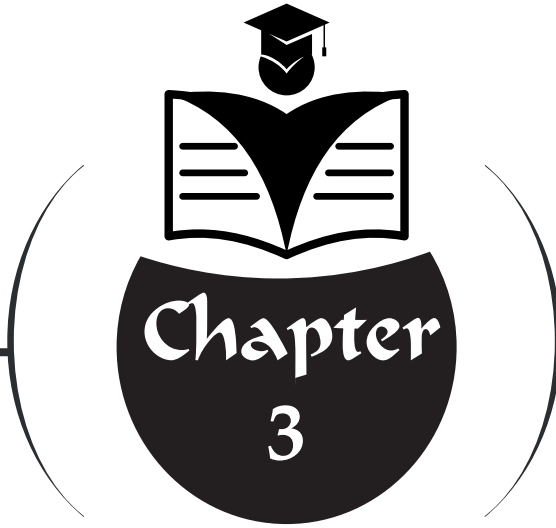
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LIGHTWEIGHT MATERIALS, TYPES AND THEIR USES

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1. Introduction

The demand for lightweight materials has become a central theme in contemporary engineering and industrial design, driven by performance optimisation and sustainability pressures. Lightweight materials reduce structural mass without compromising, and in many cases, enhance critical functional properties such as mechanical strength, stiffness, thermal stability, and energy absorption. Their adoption is strongly motivated by the global need for energy efficiency, reduced emissions, improved payload capacity, and enhanced durability across multiple engineering sectors, including aerospace, automotive, civil infrastructure, marine, and biomedical applications (Seo et al., 2008; Wang et al., 2008; Liu et al., 2019). Lightweight materials span in a wide range of materials, each offering unique advantages. Their categories, applications and benefits are summarised in Figure 1.

LIGHTWEIGHT MATERIALS

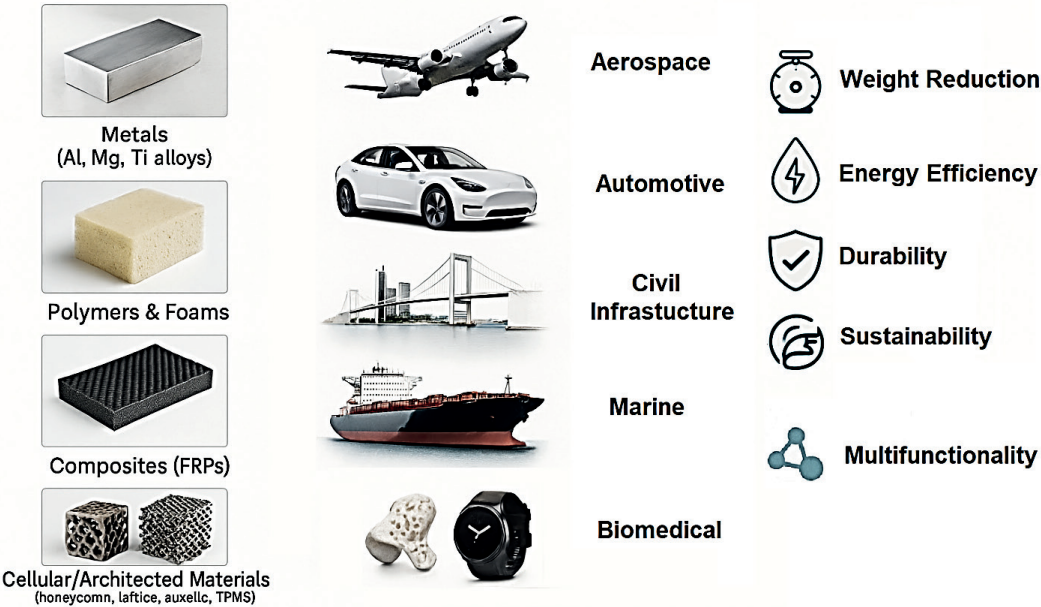


Figure 1: Lightweight Materials: Material Categories, Applications, and Benefits

Engineering systems, from aircraft and spacecraft to vehicles and building structures, face increasingly stringent requirements in terms of performance-to-weight ratio. In aerospace, for instance, even minor reductions in mass translate into substantial improvements in fuel economy, extended range, and reduced greenhouse gas emissions. In automotive engineering,

lightweighting supports the ongoing transition toward electric vehicles (EVs), where the weight of the battery pack necessitates compensatory reductions in chassis and body mass to achieve competitive efficiency and driving range. Similarly, civil and marine applications benefit from lightweight panels that combine structural integrity with reduced material consumption and easier installation. The biomedical sector also embraces lightweight solutions, with honeycomb-based and porous materials being integrated into implants and wearable technologies for improved biomechanical compatibility (Du & Li, 2019; Guo et al., 2021).

Lightweight materials represent not a single class of materials but a broad spectrum spanning metals, polymers, composites, foams, and architected cellular structures. Conventional lightweight metallic materials include aluminium, magnesium, and titanium alloys, which offer high specific strength and corrosion resistance in transport and aerospace sectors. Polymeric materials and foams provide excellent thermal insulation and impact absorption, while composites such as fibre-reinforced polymers (FRPs) achieve exceptional stiffness-to-weight ratios, making them indispensable in both aerospace and automotive structures (Liu et al., 2019; Xue et al., 2022). More recently, bio-inspired and architected cellular materials — particularly honeycombs, corrugated cores, lattice frameworks, and auxetic structures — have emerged as advanced lightweight solutions that deliver multifunctionality and superior energy absorption (Côté et al., 2006; Zaid et al., 2016; Hong-jun et al., 2021).

Among these, honeycomb sandwich structures exemplify the state-of-the-art in lightweight design. Inspired by natural hexagonal patterns, their geometry provides an optimal balance between mass efficiency and structural performance. Aluminium honeycombs, polymer foams, and Nomex-based cores are widely used for aerospace panels and protective applications, owing to their high stiffness-to-weight ratio and outstanding impact energy absorption capabilities (Guo et al., 2019; Liu et al., 2019; Xue et al., 2022). Recent developments in triply periodic minimal surface (TPMS) structures and other complex geometries, often enabled by additive manufacturing, further extend the design possibilities by combining lightweighting with tunable multifunctional properties (Fashanu et al., 2021; Hong-jun et al., 2021).

Beyond conventional structural roles, lightweight materials are increasingly expected to deliver multifunctional performance. For instance, modern aerospace systems require materials that not only provide structural integrity but also exhibit resistance to extreme temperatures, vibrations, and impact, while accommodating embedded sensing or actuation functionalities (Nezami & Gholami, 2015; Sharif et al., 2021). Lightweight panels with integrated smart materials, such as piezoelectric or magnetorheological

components, can actively modulate stiffness, dampen vibrations, or monitor structural health in real time. Similarly, architected composites incorporating natural fibres address sustainability goals by reducing dependence on energy-intensive metals and polymers while offering competitive mechanical performance (Hossain et al., 2023; Al-Azad et al., 2021).

The trajectory of lightweight material development illustrates a continuous balancing act between weight reduction, mechanical performance, manufacturability, and sustainability. Traditional lightweight alloys and composites are being complemented by advanced cellular structures that exploit both geometry and material innovation. Concurrently, manufacturing advances, particularly additive manufacturing, are expanding the design space, enabling previously unattainable core topologies such as auxetic and star-shaped lattices with tailored properties (Yang & Mao, 2024; Xu et al., 2024).

This chapter comprehensively overviews lightweight materials, their types, manufacturing methods, and applications. Section 2 categorises lightweight materials into metals, polymers, composites, and cellular/architected materials, highlighting their advantages and limitations. Section 3 discusses manufacturing techniques, including both conventional and advanced processes. Section 4 examines application domains across aerospace, automotive, civil, marine, and biomedical engineering. Section 5 focuses on performance considerations, including mechanical, thermal, acoustic, and sustainability aspects. Finally, Section 6 offers concluding remarks, underscoring current trends and future directions in lightweight materials. Through this structured synthesis, the chapter aims to provide an integrated perspective on how lightweight materials are shaping the evolution of modern engineering systems. By highlighting both well-established materials and emerging innovations, it underscores the transformative potential of lightweight design in achieving energy efficiency, sustainability, and multifunctional performance across diverse industries.

2. Types of Lightweight Materials

Lightweight materials encompass a diverse range of material families, each offering unique advantages in terms of density, mechanical properties, thermal behaviour, manufacturability, and cost-effectiveness. Their classification is typically based on the underlying material category—metallic, polymeric, composite, or architected structures—but their applications often overlap, especially when multifunctionality and sustainability are prioritised. Figure 2 provides a comparative overview of these categories, highlighting their representative features and key advantages. This section provides a comprehensive overview of the main categories of lightweight materials, outlining their fundamental characteristics, representative examples, and key engineering applications.

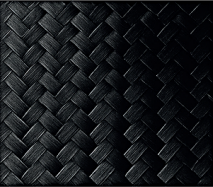
Metals	Polymers & Foams	Composites	Cellular/ Architected Materials
			
Low Density	Chemical Resistance	High Strength to Weight Ratio	Enhanced Compactness and Stiffness

Figure 2: *Classification of Lightweight Materials*

2.1 Metallic Lightweight Materials

Metallic alloys remain among the most widely used lightweight materials due to their excellent balance of mechanical strength, durability, corrosion resistance, and established manufacturing routes. Key metallic lightweight materials include aluminium, magnesium, and titanium alloys.

Aluminium has long been a cornerstone of lightweight engineering, especially in aerospace and transportation. With a density of $\sim 2.7 \text{ g/cm}^3$ (about one-third that of steel), aluminium combines low mass with high specific strength, good corrosion resistance, and excellent formability. Aluminium alloys are often classified into two main groups: wrought alloys (e.g., 2xxx, 6xxx, and 7xxx series) and casting alloys. In aerospace applications, aluminium honeycomb cores are widely utilised for their high stiffness-to-weight ratio and proven performance in sandwich panel configurations (Seo et al., 2008; Liu et al., 2019). Aluminium also exhibits favourable recyclability, aligning with sustainability goals in materials engineering.

Magnesium alloys are even lighter than aluminium, with a density of $\sim 1.8 \text{ g/cm}^3$, making them particularly attractive for applications where weight reduction is paramount. They also offer high specific strength, excellent machinability, and good damping capacity. Automotive and aerospace industries have increasingly adopted magnesium alloys for components such as gear housings, seat frames, and structural parts. However, magnesium's relatively low corrosion resistance and flammability under certain conditions limit its widespread use. Advances in alloying and protective coatings are gradually mitigating these issues.

Titanium alloys, with a density of $\sim 4.5 \text{ g/cm}^3$, are heavier than aluminium and magnesium but provide superior strength-to-weight ratios,

exceptional corrosion resistance, and high-temperature stability. Titanium is indispensable in aerospace applications, particularly for critical components such as turbine blades, landing gear, and high-stress structural parts. While their high cost and difficult machinability restrict broader use, the superior performance of titanium alloys makes them a material of choice in high-end engineering, biomedical implants, and defence applications.

Overall, metallic lightweight materials remain dominant in transport and aerospace, where established supply chains and extensive testing standards ensure reliability and safety. Their integration with other material classes, such as composites, further extends their application potential.

2.2 Polymeric and Foam-Based Materials

Polymers and polymer foams are essential in lightweight material design, offering low density, corrosion resistance, ease of processing, and cost-effectiveness. Thermoplastics (e.g., polyethylene, polypropylene, polycarbonate) and thermosets (e.g., epoxy, phenolic resins) are widely used for lightweight structures. Their densities typically range from 0.9–1.5 g/cm³, making them significantly lighter than metals. Thermoplastics are recyclable and can be reprocessed, while thermosets provide superior thermal stability and dimensional accuracy. These materials serve as matrices in fibre-reinforced composites and are also used in stand-alone applications such as automotive body panels, casings, and consumer products.

Polymeric foams (e.g., polyurethane, polystyrene, PVC foams) are particularly valued for their combination of low density, impact absorption, and thermal insulation. They are widely employed in packaging, thermal insulation panels, and as core materials in sandwich structures. Polymer foams provide tunable properties by adjusting cell size, density, and chemistry. For example, Nomex foams and cores are commonly employed in aerospace sandwich panels due to their high stiffness-to-weight ratio and flame resistance (Liu et al., 2019; Gao et al., 2019).

Polymeric lightweight materials provide significant advantages in applications where low density and multifunctionality are more critical than ultimate strength. However, their susceptibility to creep, limited high-temperature resistance, and environmental degradation (e.g., UV exposure) remain challenges.

2.3 Composite Materials

Composite materials combine two or more distinct phases—typically a reinforcement (e.g., fibres) embedded in a matrix (e.g., polymer, metal, or ceramic)—to achieve superior properties compared to the individual constituents. Composites have become synonymous with lightweight high-performance materials, especially in aerospace, defence, and automotive

sectors.

FRPs, particularly carbon fibre-reinforced polymers (CFRPs) and glass fibre-reinforced polymers (GFRPs), dominate the landscape of lightweight composites. CFRPs offer high stiffness-to-weight and strength-to-weight ratios, making them the material of choice for aerospace structures, UAV wings, and high-performance automotive components. GFRPs provide cost-effective alternatives with good mechanical and corrosion-resistant properties, though with lower stiffness than CFRPs.

Driven by sustainability concerns, natural fibre composites (NFCs) are gaining interest as eco-friendly alternatives. Materials such as flax, jute, and bamboo fibres embedded in polymer matrices provide competitive lightweight performance while addressing recyclability and life-cycle concerns (Al-Azad et al., 2021; Hossain et al., 2023). Natural fibre honeycomb (NFH) cores, for example, have shown potential in building, construction, and marine applications, though their durability under moisture and temperature fluctuations remains under investigation.

Hybrid composites combine synthetic fibres (e.g., carbon, glass) with natural fibres or metallic reinforcements to balance performance and sustainability. This strategy enhances mechanical properties while reducing environmental footprint. Additionally, foam-core composites and smart composites with embedded sensors or piezoelectric elements enable multifunctionality, such as vibration control and structural health monitoring (Nezami & Gholami, 2016; Sharif et al., 2021).

Overall, composites represent one of the most versatile families of lightweight materials, with tailored properties achievable through adjustments in reinforcement, matrix, and architecture.

2.4 Cellular and Architected Materials

Cellular materials derive their properties not only from material composition but also from geometry. Advances in both design and manufacturing have enabled a wide variety of cellular and architected structures, from conventional honeycombs to highly complex lattices.

Honeycomb materials are perhaps the most widely recognised cellular lightweight structures. They achieve exceptional stiffness-to-weight and strength-to-weight ratios by exploiting hexagonal cell geometries. Traditional honeycombs are manufactured from aluminium, Nomex, or paper, each with specific trade-offs in terms of density, damage tolerance, cost, and thermal stability (Liu et al., 2019; Guo et al., 2019). Honeycomb sandwich panels are standard in aerospace fuselages, UAV wings, and protective applications due to their excellent energy absorption under impact (Xue et al., 2022).

Corrugated cores and lattice structures extend beyond the hexagonal geometry, offering enhanced energy absorption and tailored stiffness. For instance, corrugated and diamond lattice cores have been shown to perform well under both static and dynamic loading (Côté et al., 2006; Zaid et al., 2016). These geometries provide alternatives for structural components in civil and marine applications, where vibration damping and thermal performance are also critical.

Auxetic materials exhibit negative Poisson's ratios, meaning they expand laterally when stretched. This unique behaviour provides superior energy absorption and fracture resistance, making auxetic honeycombs particularly promising for protective equipment and biomedical applications (Xu et al., 2024). Triply periodic minimal surface (TPMS) structures, often realised through additive manufacturing, offer continuous surfaces with high strength-to-weight ratios, excellent multifunctionality, and tunable properties (Fashanu et al., 2021; Yang & Mao, 2024).

Recent research has embraced bio-inspired and origami-inspired designs, where cellular materials mimic natural structures (e.g., bone, bamboo) or exploit folding geometries for enhanced compactness and stiffness (Wang et al., 2017; Hong-jun et al., 2021). These architected materials offer significant promise in aerospace and deployable structures where reconfigurability is required.

3. Manufacturing Methods for Lightweight Materials

The choice of manufacturing method is crucial in determining the performance, cost, and scalability of lightweight materials. While traditional methods such as casting, extrusion, and lamination dominate large-scale production, recent advances in additive manufacturing, resin infusion techniques, and origami-inspired design have significantly broadened the possibilities for creating innovative lightweight structures. This section reviews the key manufacturing approaches for lightweight materials, spanning conventional processes, advanced fabrication routes, and specialised methods developed for cellular and architected materials.

3.1 Conventional Manufacturing Processes

The conventional manufacturing methods of lightweight materials can be grouped into processes for metals, polymers/foams, and composites. These are summarised schematically in Figure 3, where key processes such as casting, extrusion, foaming, and hand lay-up are illustrated.

CONVENTIONAL MANUFACTURING OF LIGHTWEIGHT MATERIALS

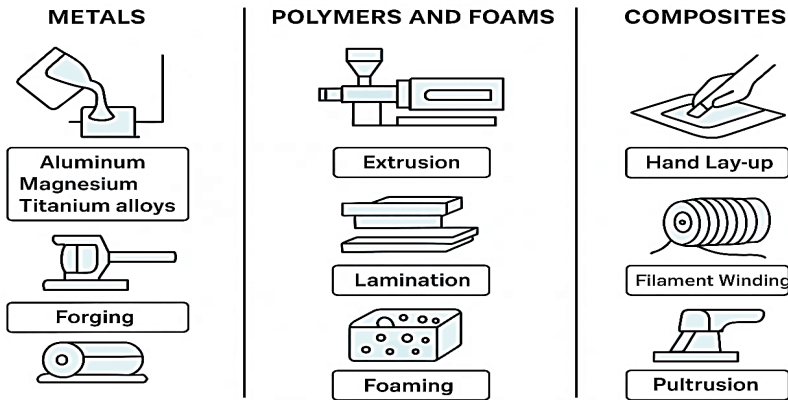


Figure 3: *Conventional Manufacturing Methods of Lightweight Materials*

Aluminium, magnesium, and titanium alloys—the three most important metallic lightweight materials—are traditionally processed through casting, extrusion, forging, and rolling. These methods allow the production of bulk and semi-finished products such as plates, sheets, and profiles used in transportation and aerospace sectors. For Aluminium alloys, extrusion processes produce complex geometries for automotive and aerospace applications, while forging ensures high strength and reliability in aerospace landing gear and structural components.

Magnesium alloys, while more difficult to process due to oxidation tendencies and limited ductility, are commonly manufactured by die casting. This method is favoured in the automotive industry for producing thin-walled, complex components such as engine housings and seat frames, where weight savings translate directly into improved fuel economy. Due to their high melting points and reactivity, titanium alloys often require specialised vacuum-based processes such as electron beam or plasma arc melting, followed by forging or rolling to achieve desired mechanical properties.

Polymers and polymer foams are produced using extrusion, lamination, and foaming techniques. Extrusion of thermoplastics allows continuous production of sheets and films, while foaming processes—such as chemical or physical blowing—introduce cellular structures that dramatically reduce density. Several manufacturing methods are applied in composites depending on the performance requirements and application field. Lamination techniques are widely employed, where fibre layers (carbon, glass, or natural fibres) are impregnated with resin matrices and cured under heat and pressure. Hand lay-up is the simplest and most traditional method, where resin is

manually applied to fibre layers, making it cost-effective for low-volume or large structural parts. Resin Transfer Moulding (RTM) enables higher production efficiency by injecting resin into a closed mould containing dry fibres, offering good dimensional accuracy and surface finish. Pultrusion is used for continuous profiles, where fibres are pulled through a resin bath and then through a heated die to form constant cross-sectional components such as beams and rods. Filament winding is particularly suited for cylindrical or spherical structures, as resin-impregnated fibres are wound around a rotating mandrel in precise orientations, yielding components with excellent strength-to-weight ratios. Autoclave curing remains the gold standard for aerospace-grade composites, ensuring high fibre volume fractions, low porosity, and superior mechanical properties.

Traditional honeycomb sandwich panels, a hallmark of lightweight construction, are produced by bonding thin face sheets (e.g., aluminium, carbon/epoxy) to lightweight cores such as Aluminium honeycombs, polymer foams, or Nomex honeycomb. This process ensures excellent stiffness-to-weight ratios, making them indispensable in aerospace fuselage panels and marine structures (Seo et al., 2008; Liu et al., 2019). Adhesive bonding remains critical for ensuring load transfer and durability at the core–face interface, and process-induced defects (e.g., voids, weak bonding) must be carefully controlled.

3.2 Advanced Manufacturing Techniques

Vacuum-assisted resin transfer moulding (VARTM) and related infusion techniques have become increasingly important for manufacturing composite sandwich structures. These methods involve placing dry fabric or honeycomb cores into a mould and infusing resin under vacuum pressure. Compared to autoclave curing, VARTM offers lower cost, reduced tooling requirements, and scalability for large structures, making it suitable for marine, wind turbine, and civil applications (Eum et al., 2005; Vasanthanathan & Kumar, 2021). While VARTM structures may exhibit slightly lower mechanical performance than autoclave-cured composites, advances in resin chemistry and process optimisation are narrowing this gap. In parallel, automated and digital manufacturing technologies are increasingly shaping the production of high-performance composites. Automated Fibre Placement (AFP) and Automated Tape Laying (ATL) enable precise, computer-controlled deposition of fibre tows or tapes, allowing complex geometries, optimised fibre orientations, and high repeatability for aerospace and defence components. These techniques improve production speed and consistency compared to manual lay-up while reducing material waste. 3D printing for composites—including both short-fibre-reinforced thermoplastic printing and continuous-fibre additive

manufacturing—has emerged as a disruptive approach, enabling rapid prototyping, lightweight lattice structures, and customised components that would be difficult or impossible to produce with conventional methods.

Additive manufacturing (AM) has emerged as a transformative approach for fabricating complex lightweight geometries that are impossible or prohibitively expensive to achieve through conventional processes. Techniques such as selective laser melting (SLM), fused deposition modelling (FDM), stereolithography (SLA), and electron beam melting (EBM) allow the direct fabrication of intricate honeycomb, lattice, and TPMS cores.

AM enables unprecedented design freedom, including graded architectures, hierarchical cores, and auxetic geometries (Fashanu et al., 2021; Hong-jun et al., 2021). For example, triply periodic minimal surface (TPMS) structures fabricated via 3D printing demonstrate excellent stiffness-to-weight ratios and energy absorption capacity, outperforming conventional hexagonal honeycombs in some applications. Origami-inspired designs, realised by AM, offer further opportunities for reconfigurable and deployable lightweight structures (Wang et al., 2017).

Despite its promise, AM faces challenges in ensuring repeatability, controlling surface finish, and minimising defects such as porosity and anisotropy. Furthermore, scaling AM for high-volume production remains costly compared to established processes. Hybrid strategies combining AM with conventional processes are increasingly explored to balance design flexibility with manufacturability.

Origami-inspired fabrication uses folding and tessellation principles to create lightweight cores with high stiffness and compact stowage capability. These structures have gained attention in aerospace applications, particularly for deployable systems such as solar UAV wings and space structures (Hong-jun et al., 2021). Bio-inspired designs mimic natural cellular geometries (e.g., trabecular bone, bamboo fibres), enabling highly efficient load distribution and damage tolerance. Such approaches often combine computational design with AM, bridging the gap between natural inspiration and practical engineering application. All these emerging processes are summarised schematically in Figure 4, which illustrates automated fibre placement (AFP), automated tape laying (ATL), 3D printing of composites, additive manufacturing of lattices, and origami/bio-inspired fabrication strategies.

ADVANCED MANUFACTURING TECHNIQUES FOR LIGHTWEIGHT MATERIALS

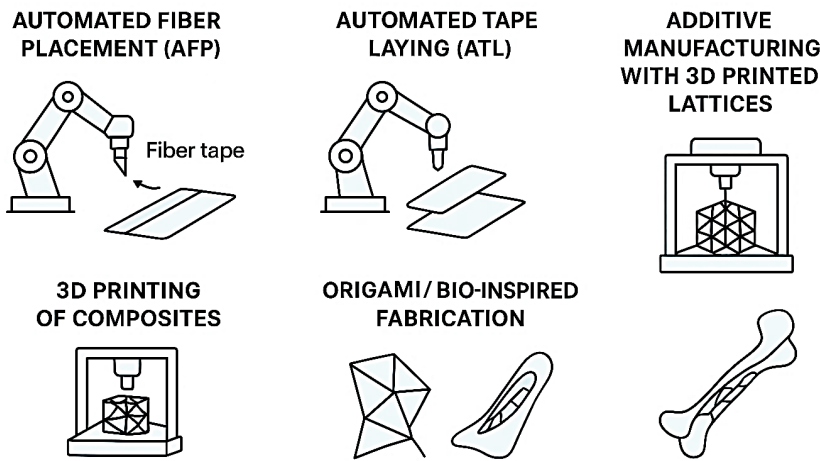


Figure 4: *Advanced Manufacturing Techniques for Lightweight Materials*

3.3 Challenges in Manufacturing Lightweight Materials

While significant progress has been made in processing lightweight materials, several challenges persist. Manufacturing processes can introduce defects that compromise the structural integrity of lightweight materials. For instance, milling imperfections in Aluminium honeycomb cores reduce mechanical properties by initiating localised stress concentrations and premature failure (Wu et al., 2023). In composites, incomplete resin infiltration, void formation, or delamination at core–face interfaces can severely degrade fatigue performance and impact resistance (Zhang et al., 2023).

The core–face interface is a critical weak point in sandwich structures. Adhesive degradation due to temperature cycling, moisture ingress, or mechanical fatigue can lead to delamination, reducing stiffness and load-carrying capacity. Non-destructive evaluation (NDE) methods such as laser ultrasonics and ultrasonic guided waves are being developed to detect disbonding and core damage (Dong et al., 2023; Sikdar et al., 2016). However, reliable repair strategies for damaged sandwich panels remain a challenge.

While AM and VARTM expand the design space, scaling these methods to industrial production poses significant cost and throughput challenges. Autoclave curing, though reliable, is energy-intensive and expensive, limiting its feasibility for cost-sensitive industries such as automotive. Developing

scalable, cost-effective processes without sacrificing quality remains a central concern.

Lightweight materials, particularly polymeric foams and natural fibre composites, often suffer from reduced durability under environmental exposure. Moisture absorption, UV degradation, and temperature cycling can weaken materials and compromise adhesive bonds. To establish standardised design guidelines, life-cycle testing and accelerated durability studies are essential (Hossain et al., 2023). Figure 5 illustrates the key challenges encountered in manufacturing lightweight materials, including process-induced defects, bonding/interface reliability, scalability and cost, and long-term durability under environmental conditions.

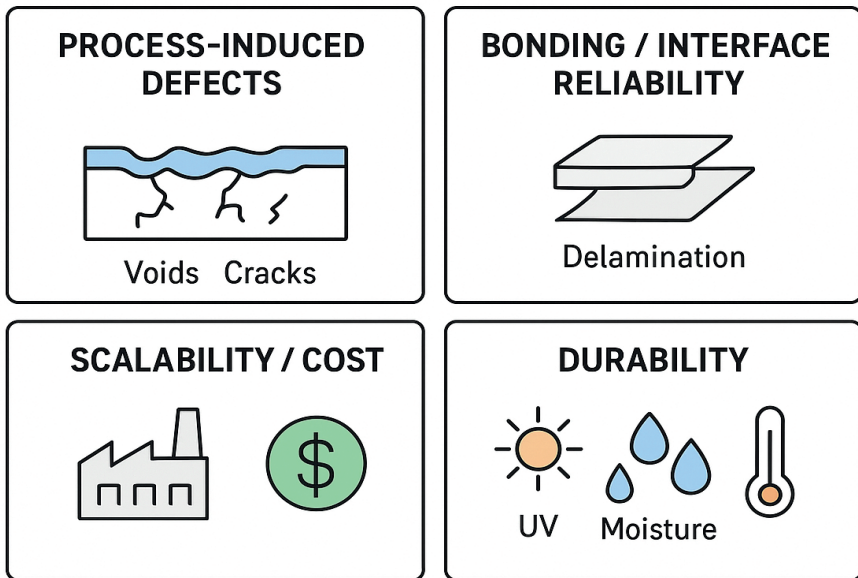


Figure 5: *Challenges in Manufacturing of Lightweight Materials*

3.4 Integration of Smart Manufacturing and Multifunctionality

The future of lightweight materials manufacturing lies in integrating multifunctional capabilities with structural performance. Embedding sensing, actuation, and thermal management features during fabrication is an emerging strategy to create intelligent lightweight structures. For example, piezoelectric patches integrated into honeycomb sandwich beams enable active flutter control in aerospace structures (Nezami & Gholami, 2015; Nezami & Gholami, 2016). Magnetorheological cores, fabricated through specialised infusion methods, provide adaptive stiffness and vibration damping under magnetic fields (Sharif et al., 2021). These multifunctional strategies require

advanced manufacturing routes that ensure compatibility between structural and functional components.

In parallel, digital manufacturing and data-driven approaches are enhancing process control. Machine learning algorithms applied to AM and composite curing processes can predict defect formation, optimise parameters, and ensure repeatability. This convergence of materials science, manufacturing, and artificial intelligence is expected to accelerate the deployment of next-generation lightweight materials (Feng et al., 2020).

4. Applications of Lightweight Materials

The adoption of lightweight materials has transformed numerous engineering sectors by enabling reductions in structural mass, improved energy efficiency, enhanced safety, and greater design flexibility. The performance benefits extend beyond weight savings alone; lightweight materials often provide superior impact absorption, thermal insulation, vibration damping, and multifunctionality. This section surveys the major application domains, with emphasis on aerospace, automotive, civil and construction, marine, and biomedical engineering. Figure 6 provides an overview of the major engineering sectors where lightweight materials play a transformative role, highlighting key benefits such as fuel efficiency, crashworthiness, thermal insulation, corrosion resistance, and biocompatibility. The following subsections expand on these applications in detail.

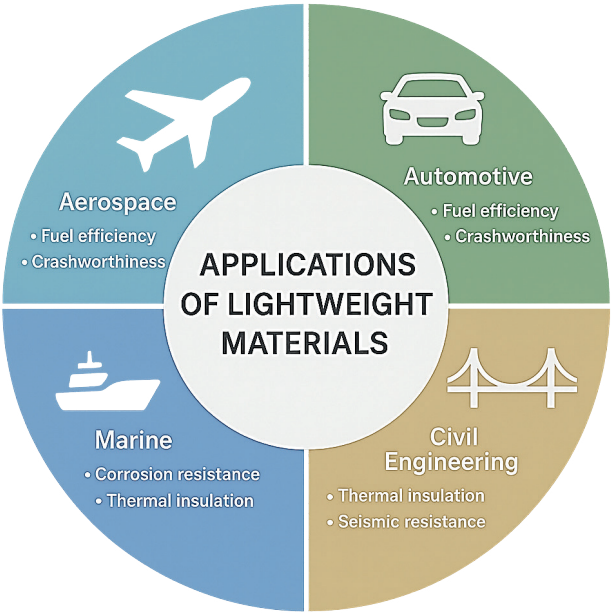


Figure 6: Applications of Lightweight Materials Across Engineering Sectors

4.1 Aerospace and Aviation

Aerospace engineering has historically been the primary driver of lightweight material development. The stringent requirements for fuel efficiency, payload optimisation, and structural performance make lightweighting an indispensable design paradigm. Aluminium alloys have traditionally dominated the aerospace industry, with their high specific strength, corrosion resistance, and established processing routes. Honeycomb sandwich panels with Aluminium or Nomex cores bonded to carbon fibre face sheets are widely used in fuselages, control surfaces, and flooring systems (Seo et al., 2008; Liu et al., 2019). These structures combine stiffness, energy absorption, and impact resistance while minimising fuel consumption.

Lightweight composites and architected materials are especially critical in UAV applications, where endurance and payload capacity are directly linked to mass. Origami-inspired and TPMS core structures fabricated via additive manufacturing have been employed in UAV wing designs to reduce mass while ensuring aerodynamic stability (Hong-jun et al., 2021).

Spacecraft components, including satellite panels and thermal shields, benefit from honeycomb sandwich structures due to their excellent stiffness-to-weight ratio and ability to withstand extreme thermal cycling (Tang et al., 2016). Emerging auxetic and multifunctional cores further provide opportunities to enhance vibration resistance and thermal protection in space missions (Xu et al., 2024). Lightweight honeycomb panels also play a crucial role in crashworthiness and impact energy absorption, ensuring passenger safety. The capacity of paper and polymer honeycombs to dissipate energy under impact loading makes them attractive for secondary aerospace structures, packaging, and protective housings (Guo et al., 2019; Ji et al., 2021).

4.2 Automotive and Transportation

The automotive sector has rapidly adopted lightweight materials, particularly as manufacturers aim to reduce fuel consumption and adapt to electric vehicle (EV) demands. Aluminium alloys have become standard in automotive lightweighting and are used in chassis, body panels, and suspension systems. Magnesium alloys are increasingly considered for interior and structural components, though cost and corrosion resistance remain challenges. Composites, particularly GFRPs and CFRPs, are employed in high-performance vehicles for body panels, roofs, and crash structures.

Lightweight honeycomb cores and polymer foams are integrated into automotive crash boxes, bumpers, and side-impact structures, where their ability to absorb kinetic energy reduces occupant injury (Chang et al., 2024). CFRP-reinforced sandwich panels are also applied in electric vehicle battery casings, where they provide both protection and thermal insulation.

Lightweight materials extend beyond automobiles to buses and rail transport. Honeycomb and corrugated sandwich structures are increasingly used in floor panels, doors, and partition walls of trains and trams, reducing overall system weight and improving energy efficiency.

4.3 Civil and Construction Engineering

In civil engineering, lightweight materials provide advantages in reducing structural loads, improving thermal insulation, and enhancing energy efficiency. For example, polymeric foams and honeycomb panels are widely used for thermal insulation and acoustic damping in building envelopes. Green sandwich structures incorporating natural fibres provide eco-friendly alternatives for walls, partitions, and roofing, offering favourable mechanical and thermal performance (Hossain et al., 2023).

Lightweight composites are employed in pedestrian bridges, roofing systems, and façade elements. Aluminium honeycomb cores, for example, serve as cladding panels due to their high stiffness and weather resistance (Konka et al., 2015).

In earthquake-prone regions, lightweight composites reduce inertial loads while maintaining structural stiffness. Honeycomb and corrugated cores offer energy absorption benefits, mitigating damage during seismic events. Drop-impact studies confirm the suitability of paper and polymer honeycombs in protective civil structures (Ji et al., 2021).

Natural fibre honeycombs (NFHs) represent an emerging approach for eco-friendly construction, though challenges remain in ensuring long-term durability under moisture and UV exposure (Al-Azad et al., 2021). Nevertheless, their renewable and biodegradable nature positions them as promising alternatives in sustainable infrastructure development.

4.4 Marine Applications

Marine environments impose unique challenges, including corrosion, hydrodynamic loading, and weight restrictions. Lightweight materials are increasingly adopted to improve vessel efficiency and durability. Aluminium alloys are commonly employed in marine vessels for hulls, decks, and superstructures, reducing displacement and increasing speed. Sandwich panels with polymer or Aluminium honeycomb cores are used for floors, bulkheads, and doors, where weight reduction enhances fuel economy and payload (Vasanthanathan & Kumar, 2021).

CFRP composites offer high stiffness-to-weight ratios and superior corrosion resistance compared to metallic alternatives, making them attractive for offshore platforms and marine equipment. Research into natural-fibre-reinforced honeycomb cores shows promising thermo-mechanical behaviour

for building and marine applications, though performance in demanding marine contexts remains under investigation (Hossain et al., 2023).

4.5 Biomedical and Wearable Technologies

Biomedical engineering increasingly leverages lightweight materials for implants, prosthetics, and protective equipment. Honeycomb sandwich structures have been explored for vertebral implants, where their porous geometry provides mechanical support while allowing bone ingrowth and integration (Guo et al., 2021). Additively manufactured auxetic and lattice structures are also employed in orthopaedic implants for enhanced shock absorption and biocompatibility.

Honeycomb-based sandwich structures are applied in thermal protective clothing, where they provide insulation and impact resistance. For instance, aramid and composite honeycomb cores integrated into textiles enhance protection against heat and mechanical impact in firefighting and military gear (Du & Li, 2019).

Lightweight composites and foams are used in exoskeletons, prosthetics, and wearable devices, balancing structural support with comfort. Their low density ensures minimal burden on the wearer, while multifunctional composites allow integration of sensors for health monitoring.

5. Performance Considerations

The selection of lightweight materials is not governed by density alone; rather, their adoption depends on how effectively they balance mass reduction with mechanical, thermal, and environmental performance under service conditions. Performance considerations also extend to durability, repairability, and sustainability. This section synthesises the critical performance attributes of lightweight materials, focusing on their mechanical, impact, thermal, acoustic, and environmental behaviour as illustrated in Figure 7.

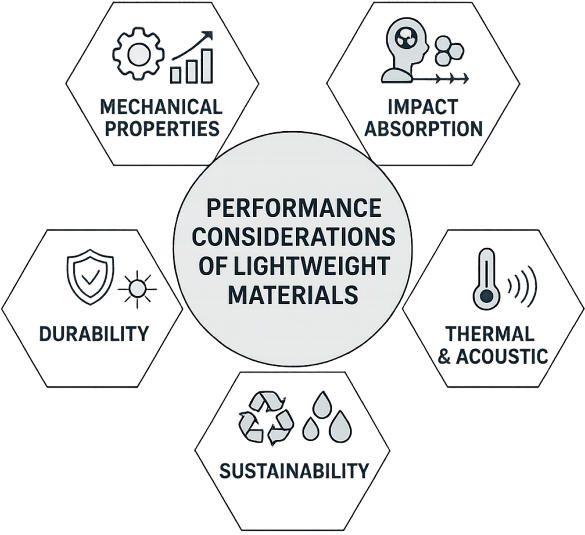


Figure 7: *Performance Considerations of Lightweight Materials*

5.1 Mechanical Properties and Structural Efficiency

A primary advantage of lightweight materials is their high strength-to-weight and stiffness-to-weight ratios, enabling them to achieve structural efficiency without excessive mass. Aluminium honeycomb panels, for instance, deliver stiffness comparable to solid Aluminium sheets at a fraction of the weight (Seo et al., 2008). Similarly, CFRP composites provide stiffness-to-weight ratios several times higher than steel or aluminium, making them indispensable in aerospace structures (Liu et al., 2019; Xue et al., 2022).

Honeycomb sandwich structures exhibit exceptional bending stiffness due to the load-bearing synergy between the thin face sheets and lightweight cores. Studies on corrugated and lattice cores confirm enhanced shear and compressive resistance compared to conventional hexagonal honeycombs (Côté et al., 2006; Zaid et al., 2016). In compression, Nomex and Aluminium honeycombs show predictable progressive failure modes, whereas TPMS and auxetic structures exhibit superior energy dissipation with tunable stiffness (Fashanu et al., 2021; Xu et al., 2024).

Fatigue resistance is another critical factor, especially in aerospace and automotive contexts where cyclic loading is unavoidable. CFRPs demonstrate high fatigue resistance compared to metals, while metallic honeycombs are more prone to crack initiation at cell walls under repeated loading (Niu et al., 2024). Hybrid designs, such as carbon-fibre laminates bonded to aluminium or natural-fibre cores, aim to improve fatigue life while reducing cost.

5.2 Impact Energy Absorption and Crashworthiness

Lightweight honeycomb and corrugated cores have been extensively studied for their impact energy absorption capacity. Under drop and crash loading, paper and polymer honeycombs exhibit progressive crushing, dissipating energy efficiently (Guo et al., 2019; Ji et al., 2021). Corrugated and diamond lattice structures provide superior crashworthiness compared to conventional hexagonal geometries (Chang et al., 2024).

In defence and aerospace safety, honeycomb sandwich structures are often filled with advanced materials to improve impact resistance. For example, honeycombs filled with reactive powder concrete prisms have shown enhanced ballistic resistance (Jin et al., 2017). Similarly, CFRP and aramid fibre face sheets bonded to honeycomb cores increase protection against high-velocity impacts.

Residual strength after impact is a key metric for assessing the reliability of lightweight structures. Honeycomb composites subjected to lightning strikes, bird strikes, or foreign object impacts may suffer core crushing or delamination that reduces residual load-carrying capacity. Experimental and numerical studies confirm that residual strength depends strongly on core density, adhesive quality, and face sheet toughness (Wang et al., 2022; Zhang et al., 2023).

5.3 Thermal and Acoustic Behaviour

Thermal insulation and stability are vital in aerospace, civil, and marine structures. Honeycomb panels, by virtue of their air-filled cells, provide excellent thermal insulation, which can be enhanced through polymer coatings or core filling (Konka et al., 2015). CFRPs exhibit good thermal stability up to moderate temperatures, while metallic alloys such as titanium withstand high-temperature environments, making them ideal for jet engines and spacecraft structures.

Honeycomb and TPMS structures are increasingly valued for their acoustic damping properties. Lightweight sandwich panels with embedded damping materials can reduce vibrations and noise transmission in aerospace cabins, automotive interiors, and building façades. Due to their unusual deformation behaviour, auxetic structures also show promise in acoustic attenuation and vibration control.

5.4 Durability and Environmental Resistance

Environmental durability is a major concern, especially for polymeric foams and natural fibre composites. Exposure to moisture, UV radiation, and temperature cycling can degrade mechanical properties, reduce bonding at core–face interfaces, and accelerate fatigue. For example, natural-

fibre honeycomb (NFH) cores are highly susceptible to moisture-induced degradation unless properly treated (Al-Azad et al., 2021).

Damage tolerance is crucial in applications where lightweight materials are exposed to impacts or harsh environments. Honeycomb cores often fail through localised buckling or crushing, while composites may experience delamination. Non-destructive evaluation (NDE) techniques such as ultrasonic guided waves and laser ultrasonics enable early damage detection (Dong et al., 2023; Sikdar et al., 2016). However, repairability remains challenging, especially for adhesively bonded sandwich panels, where disbonds are difficult to re-establish.

Thermal protection is essential in aerospace and civil engineering. Nomex honeycomb cores offer inherent flame resistance, while Aluminium and titanium alloys retain mechanical properties at high temperatures. Polymer foams, however, require flame-retardant additives or coatings to meet safety standards.

5.5 Sustainability and Life-Cycle Performance

Sustainability considerations are reshaping material selection. Natural-fibre composites and honeycomb cores offer renewable, biodegradable alternatives to synthetic materials (Hossain et al., 2023). While NFHs show promise in civil and marine applications, their performance in demanding aerospace environments remains limited due to durability challenges.

Metals such as aluminium and magnesium are highly recyclable, making them attractive in circular economy frameworks. CFRPs, while offering superior performance, present recycling challenges due to thermoset matrices. Thermoplastic composites are increasingly explored for their reprocessability and potential in high-volume automotive applications.

Life-cycle assessment (LCA) is essential to quantify the environmental footprint of lightweight materials. Studies highlight that although composites reduce energy consumption during operation (e.g., lighter vehicles and aircraft), their end-of-life management remains problematic (Feng et al., 2020). Integrating recyclability and eco-friendly processing into design frameworks will be critical for the sustainable adoption of lightweight materials in future engineering systems.

6. Conclusion

Lightweight materials have emerged as one of the most transformative enablers of modern engineering. Their importance lies not simply in reducing mass but in redefining how structures are designed, manufactured, and applied across diverse industries. From aerospace and automotive to construction, marine, and biomedical applications, the integration of lightweight materials

has reshaped engineering solutions by achieving an optimal balance between performance, efficiency, and sustainability.

This chapter has presented an overview of the major classes of lightweight materials, including metallic alloys, polymers, composites, and cellular or architected structures. Each material family contributes distinctive advantages: metals such as aluminium and magnesium provide durability and recyclability, polymers and foams offer impact absorption and insulation, composites deliver unmatched strength-to-weight ratios, and cellular materials such as honeycombs and TPMS lattices exploit geometry to unlock multifunctional performance. Increasingly, hybrid systems combine these classes to achieve tailored solutions for demanding applications.

Manufacturing methods play a decisive role in realising the potential of lightweight materials. Conventional techniques such as casting, lamination, and autoclave curing continue to ensure large-scale reliability, while advanced approaches such as resin infusion, additive manufacturing, and origami-inspired fabrication expand design freedom and enable novel topologies. Despite these advances, challenges remain in defect control, bonding reliability, scalability, and cost reduction. Addressing these issues is critical for transitioning from laboratory-scale innovation to widespread industrial deployment.

Applications across sectors demonstrate the versatility of lightweight materials. In aerospace, they enable high-performance aircraft, UAVs, and space systems by improving fuel efficiency and payload capacity while ensuring safety and thermal resilience. Automotive design leverages lightweight materials to enhance energy efficiency, safety, and adaptability to electric mobility. Civil and construction engineering benefits from lightweight panels that reduce loads while improving insulation and sustainability. Marine applications highlight the need for corrosion resistance and structural efficiency, while biomedical engineering demonstrates how lightweight, bio-inspired structures can improve implants, prosthetics, and protective equipment. These diverse applications confirm that lightweight materials are not niche solutions but foundational technologies for future engineering.

Performance considerations underline that lightweight materials must be evaluated holistically. Strength-to-weight and stiffness-to-weight ratios determine their structural efficiency, but equally important are fatigue life, impact energy absorption, thermal and acoustic properties, and long-term durability. Repairability and fire resistance add further complexity. Sustainability and recyclability are now indispensable considerations as industries align with global environmental goals. Natural-fibre composites, recyclable thermoplastics, and green sandwich structures point toward a more sustainable future, though long-term durability remains a barrier to adoption in highly demanding sectors.

The evolution of lightweight materials is also characterised by multifunctionality. No longer limited to passive load-bearing roles, these materials increasingly integrate smart functions such as sensing, actuation, and vibration damping. The convergence of structural performance with adaptive and intelligent behaviours represents the next frontier in lightweight design, where materials not only withstand external demands but also actively contribute to system performance and resilience.

In summary, lightweight materials are redefining engineering possibilities by reducing weight while enhancing performance, extending service life, and contributing to sustainability. They represent the foundation upon which modern aerospace, automotive, civil, marine, and biomedical systems are built. The continued development of advanced manufacturing techniques, hybrid material systems, and sustainable design frameworks will further expand their impact.

Ultimately, the future of lightweight materials lies in integration: integration across material families, across manufacturing methods, across functional domains, and across industries. When viewed as part of a unified framework, lightweight materials are not merely alternatives to conventional materials but essential components of innovative, efficient, and sustainable engineering solutions for the challenges of the 21st century.

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