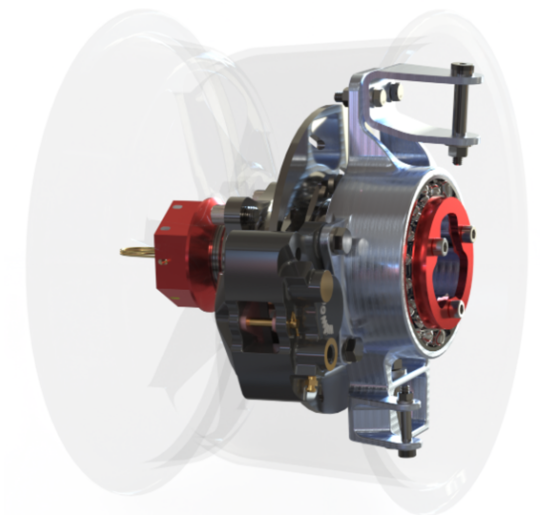
Málaga Racing Team

Case Study: Upright



November 2025

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Introduction

Additive manufacturing (AM) is a crucial aspect of contemporary science and engineering, enabling the layer-by-layer production of components. The past two decades have witnessed a surge in the development of AM processes for metal materials, which offer numerous advantages over conventional manufacturing processes such as casting, forging, and machining. AM has proven to be particularly effective in reducing material wastage, optimizing material properties, and shortening lead production times to meet component requirements. As a result, it has been widely adopted across various industries, including in aerospace, biomedical, marine and offshore, energy, and automotive applications [1].

The Andalusian based company, Meltio, takes metal AM to the next level by developing and manufacturing high-performance, affordable, and easy-to-use metal 3D printing solutions using Wire-Laser Metal Deposition (LMD) technology.

Prototype race car development is, and has always been in the forefront of innovation and technology development for the automotive industry. While not cost efficient in their own right, these prototype programs continuously generate substantial long-term value by fostering research, experimentation, and the validation of cutting-edge technologies under real-world conditions. They serve as an experimental platform where novel concepts in materials, aerodynamics, powertrain, and manufacturing can be tested and refined before being adopted in commercial applications.

Within this context, Formula Student plays a fundamental role in bridging the gap between academia and industry. It challenges university teams from around the world to design, manufacture, and race small-scale formula-style vehicles that comply with strict technical and economic regulations. This hands-on approach promotes not only technical excellence but also teamwork, project management, and innovation — all essential skills for the next generation of engineers.

The student organization MART FS designs and develops a new fully electric Formula-style race car each year to compete in the international Formula Student competition. As one of the most established teams in Spain, MART FS continuously strives to enhance vehicle performance through advanced engineering practices and the integration of emerging technologies such as AM.

This document outlines the collaboration between MART FS, the Formula Student Team of the University of Málaga, and Meltio, one of the world's leading metal additive manufacturing companies. The report covers the entire process — from the initial research on AM to the successful integration of additively manufactured components into the MA25RT prototype race car.

2

MART Formula Student

2.1 Formula Student

Formula Student, also known as Formula SAE, is an international motor racing competition between universities that promotes excellence in engineering through the study, design, development and manufacture of a single-seater racing car. Universities from around the world take on the challenge of building a open-wheel car to compete in a series of static and dynamic tests that push the limits of the future bright minds of engineering.

At a professional level, the aim of the competition is to produce a single-seater car that delivers high performance in terms of acceleration, braking and stability. This is done in accordance with regulations designed to ensure the smooth running of the event and promote ingenuity in problem solving.

On a personal level, the mission is to captivate young engineering students by offering them an ideal yet demanding opportunity to prove themselves and apply the extensive knowledge they have acquired during their studies in collaboration with their teammates.

Its history began in 1979, when the University of Houston and the Society of Automotive Engineers (SAE) decided to hold a university championship in which a vehicle based on Indianapolis single-seaters had to be built and raced. Since that first competition, participation and popularity in these events have grown exponentially, with countless championships springing up on most continents and federations being obliged to establish quotas and pre-qualification exams.

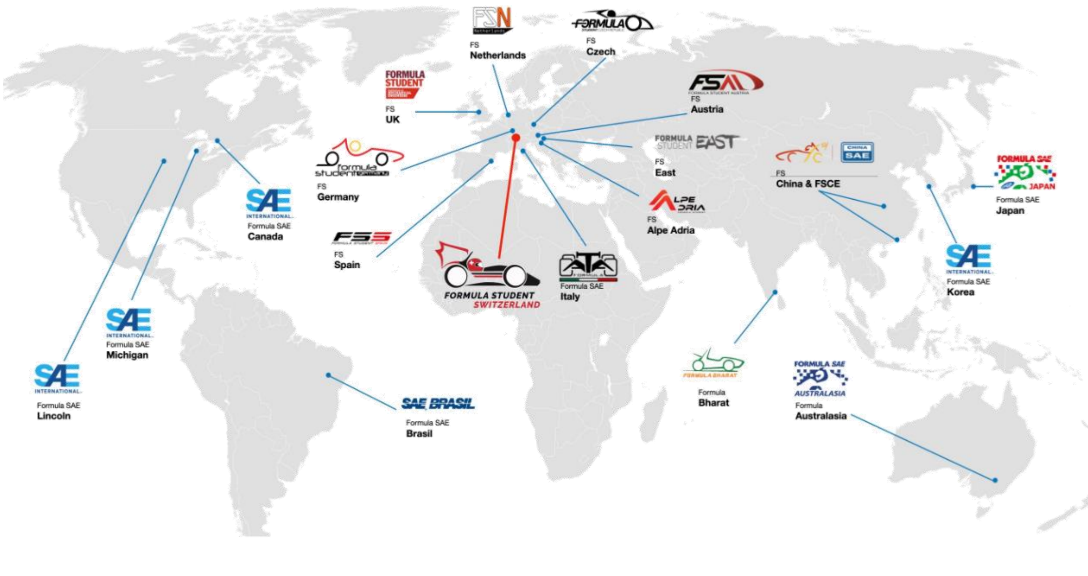


Figure 1. Map of FSAE Competitions. (Source: FSG)

One of the main reasons for their rapid growth and interest is the excellent formation that participants receive. For many, it is their first contact with the world of competition, a world that often arouses a notable predilection among engineering students.

Each competition is organised into a series of tests that award a limited number of points, and the team with the highest score at the end of the event is declared the winner. There are two types of tests: dynamic tests, which evaluate the car's performance, and static tests, which evaluate the car's design, the team's business plan and cost management.

"There are two really innovative forms of motorsport left. One of them is Formula 1 and the other one is Formula Student". - Ross Brawn.

2.2 Team's Development

In 2016, a group of 15 engineering students embarked on the adventure of creating their own Formula Student team at the University of Malaga. This led to the creation of MART FS, a racing team run entirely by students who, after years of novelty, motivation and uncertainty, managed to present their first complete single-seater in 2021.

The virtue and motivation of each and every one of the first members of the team is noteworthy, as it took five years from the conception of the project to the development of something tangible that reflected the dedication of all the members. During those long years of waiting, numerous prototypes were developed which, despite not having their own engines and therefore not being eligible for dynamic testing, allowed the team to be present in the competitions.

The team won its first trophy even before it had a car with its own engine. For its exemplary behaviour, motivation and sportsmanship, it was awarded the Spirit of Competition Award in the 2020 & 2021 Spanish championships.

After many years of waiting, 2021 was the year in which the team managed to shake off the bad omen of not having competed after trying for half a decade. The MA21RT was born, and it was good. A light, fast and reliable car. Perfect for consolidating knowledge and channelling development for the fleet of single-seaters that were about to come.

The 2022 season marked a surprising step forward in terms of performance and management. The experience gained with the MA21RT was reflected considerably in all departments, and our second car, the MA22RT, sent our reputation skyrocketing. That year, when we entered the competitions, we were one of the least experienced teams, having only been manufacturing cars for two years. However, that did not deter us, as we achieved a P5 in Formula Student Spain and a P6 in Formula Student Netherlands, which earned us a ‘One To Watch’ status and the respect of many teams across Europe.

Naturally, things continued on track and in 2023, with the MA23RT, we managed to establish ourselves, in just our third year competing, as one of the best teams in Europe, achieving a P2 in Formula Student Spain and a P12 in our debut in the prestigious Formula Student Germany, the competition par excellence.

Having established ourselves as one of Europe's leading teams in combustion cars, and aware of the great future potential of electric cars as a means of transport, we decided to embark on the adventure of developing electric single-seaters for 2024. Due to the characteristics of Formula Student vehicles, electric motorization represents a clear improvement in performance, which is why the teams from the best universities opt for them.

Although it is by far the biggest challenge the team has ever faced, the switch to electric powertrains allows us to take another step forward in terms of performance and compete head-to-head with the best teams on the continent. In terms of results, the last two years have been a setback, forcing us to go back to our roots, but on a larger scale, as we are developing a car without experience and competing against teams that not only have much more experience and budget than us, but are also some of the best in the world. The learning curve is as steep as ever, but we have been able to reinvent ourselves in the past, so we have no doubt about our capabilities.

Figure 2. MART FS's Milestones.

2.3 Present and Future

Formula Student, like any good motorsport competition, perfectly reflects economic adversity and the notable differences between teams in terms of budget. Since our inception, we have had to constantly reinvent ourselves to move forward with projects that not only made us extremely proud, but also challenged leading teams with much more experience and, more importantly, much larger budgets.

Our approach has always been based on continuous improvement and on laying the foundations for exponential performance growth. Fortunately, we have been lucky to count on brilliant minds within the team who have driven the car's development and capabilities to grow by leaps and bounds, quickly establishing us as one of the best combustion teams both nationally and internationally, even with a constrained budget.

As mentioned above, the switch to electric powertrains allows us to take another step forward in performance and compete head-to-head with the best teams on the continent. Although it is a temporary setback in terms of results, it is the only way for new members to keep reinventing previous concepts and avoid reaching a bottleneck where the car's performance is severely halted by the combustion powertrain, allowing only marginal improvements each year.

Fame follows success. Following the excellent results achieved in our early years, the team's reputation grew enormously and, as a result, we now receive more than 100 applications every year from students eager to join the team. Today, MART FS is no longer a small group of 15 students wanting to start a project, but a professional team of more than 80 brilliant students all pulling in the same direction.

The main challenge of racing an electric car is the weight of the batteries, which means that the weight of every other component must be minimized to keep the car competitive. With such a strong team and the solid foundations laid in previous years, we can now take calculated risks and focus on developing cars that prioritize performance over reliability, aiming for a greater weight reduction every year.

Our desire to innovate, improve performance and expand our knowledge – as true students of engineering – drives us to adopt new technologies such as AM. We are deeply grateful to Meltio for collaborating with us and allowing us to continue reinventing the development of our single seaters.

MA25RT (2025)

86	300	18th	34th
KW	Kg	FSS	FSN

Figure 3. MA25RT.

3

Materials and Methods

3.1 Additive Manufacturing – AM

Additive Manufacturing (AM), commonly known as 3D printing, refers to a group of manufacturing processes that create parts by depositing material layer by layer, directly from a digital model. Unlike traditional subtractive methods, such as machining, or formative processes like casting and forging, AM builds components additively, allowing for unprecedented design freedom and material efficiency. This technology has transformed the way engineers and designers approach product development, enabling rapid prototyping and the production of highly complex geometries that were previously impossible or economically unfeasible to manufacture. [2][3]

Over the past two decades, AM has evolved from a prototyping tool into a robust industrial manufacturing solution. Advances in materials science, process control, and computational modelling have expanded its applications from polymers to high-performance metals and composites. Metal AM technologies, such as Laser Powder Bed Fusion (LPBF), Directed Energy Deposition (DED), and Wire-Laser Metal Deposition (LMD), are now capable of producing fully dense, high-strength components suitable for structural and functional applications. These processes are increasingly adopted in sectors such as aerospace, automotive, biomedical, and energy, where performance, weight reduction, and customization are key drivers. [3][4]

One of the primary advantages of AM lies in its ability to reduce material waste and shorten lead times, especially in low-volume or highly customized production. Since material is only deposited where it is needed, buy-to-fly ratios (the proportion of raw material used compared to the final part weight) can be significantly improved compared to conventional machining. Moreover, AM enables design for performance rather than design for manufacturability, allowing the integration of topology optimization, lattice structures, and multifunctional features directly into the component. [4][5]

Despite its many benefits, AM still faces challenges that limit its widespread adoption. These include high production costs, limited build volumes, surface finish quality, and residual stress formation during processing. Post-processing steps such as heat treatment, machining, and surface finishing are often required to achieve the desired mechanical properties and tolerances. Nonetheless, continuous improvements in machine reliability, process monitoring, and hybrid manufacturing systems are progressively overcoming these limitations, positioning AM as a cornerstone technology for the future of advanced manufacturing. [6][7]

A classification of additive techniques is presented based on data from scientific publications on AM. Additive manufacturing techniques are classified according to three criteria [3]:

- Methodology of the product formation.
- Type of base material used.
- Processing method.

The diagram presented in Figure 4 illustrates the categorization of additive manufacturing techniques:

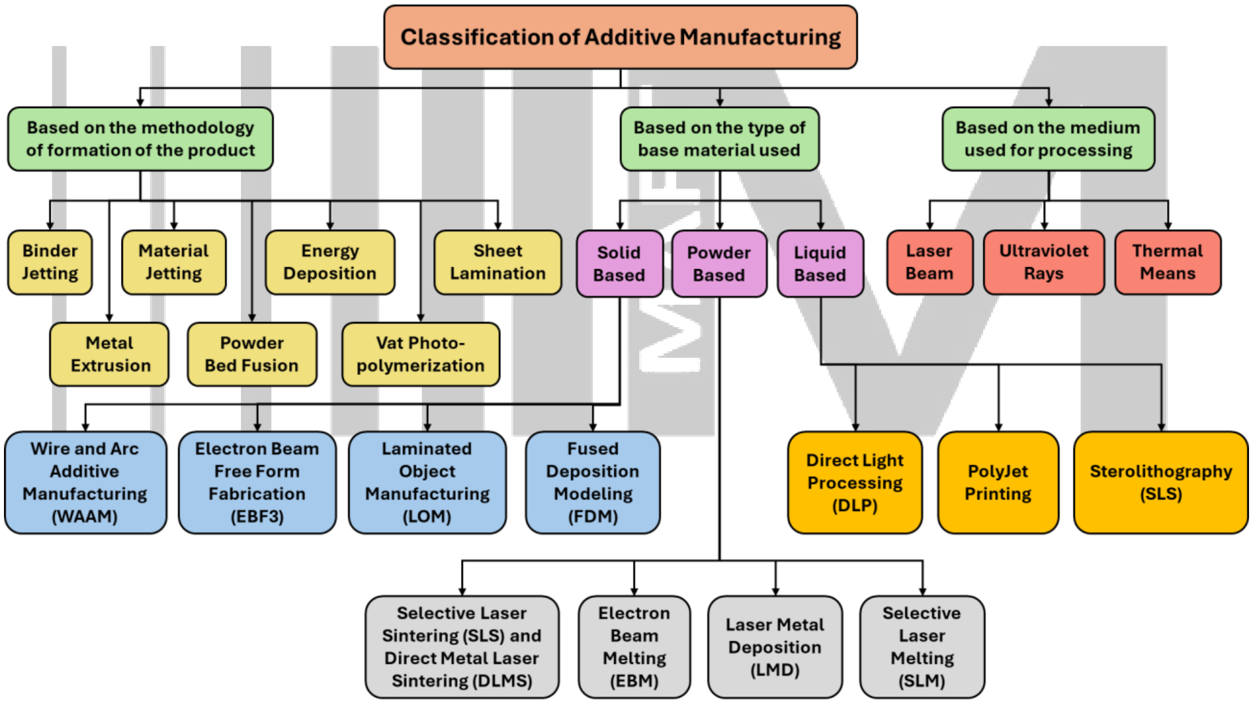


Figure 4. Categorization of Additive Manufacturing Techniques.

As can be observed, there are numerous types of AM, each suited for specific applications. Since the scope of this project focuses on only one of these technologies, the following sections will exclusively address that particular process.

3.2 Laser Metal Deposition – LMD

Laser Metal Deposition (LMD) is an additive manufacturing process in which a high-power laser beam is used as the energy source to create a melt pool on the surface of a metallic substrate. Into this melt pool, metallic powder is injected through a carrier gas stream and subsequently melted. By depositing successive layers, it is possible to build near-net-shape metallic components directly from three-dimensional CAD models, making LMD a true free-form fabrication method. [3][8]

To prevent oxidation during deposition, the melt pool must be protected from atmospheric contamination. For this reason, LMD is typically carried out either inside a sealed chamber filled with inert gas or under local shielding provided by an inert gas flow. The use of an appropriate shielding atmosphere is particularly critical when processing reactive alloys such as titanium or aluminium. [4][7][9]

An LMD system is composed of several core elements: a laser source (commonly fibre, CO_2, or diode), a coaxial or lateral nozzle for powder or wire feeding, an inert gas flow to protect the molten pool, and a multi-axis motion platform that ensures precise control of the deposition path. The selection of laser type and feed method directly affects deposition efficiency, melt pool stability, and the overall quality of the fabricated part. [8][9]

During the deposition process, complex thermo-fluid dynamics take place within the melt pool. Convection driven by Marangoni forces, steep thermal gradients, and high solidification rates strongly influence grain growth, microstructural morphology, and the distribution of residual stresses in the deposited material. To better understand and optimize these effects, thermal–fluid numerical models and solidification simulations are widely employed. [10]

LMD offers three main application domains:

- Repair of high-value components, such as turbine blades, dies, and molds.
- Functional cladding, where wear- or corrosion-resistant coatings are applied to improve surface performance.
- Direct AM of complex metal parts for various industrial sectors.

Compared to other deposition processes, LMD provides several advantages. It enables highly localized material deposition with minimal waste and allows for the use of multiple materials within a single component. Its relatively low heat input produces a smaller heat-affected zone, minimizing substrate distortion and reducing the thermal impact on surrounding material. Moreover, the higher cooling rates typical of LMD promote the formation of fine microstructures, which generally enhance mechanical performance. [1][10]

Despite these benefits, LMD also presents certain limitations. The process can yield suboptimal surface finish and dimensional accuracy, and defects such as pores or microcracks may arise if parameters are not properly controlled. As a result, post-processing operations—

such as heat treatment, machining, and surface finishing—are often necessary to achieve the required tolerances and functional properties. [5][10]

Today, LMD has become a key technology in sectors such as aerospace, energy, and biomedical engineering, where the repair and customized production of high-performance metallic components are of critical importance. Its versatility, combined with the ongoing development of hybrid additive–subtractive systems, positions LMD as one of the most promising technologies within the field of advanced manufacturing. [2][4]

3.3 Ti6Al4V (Grade 5)

Titanium alloys have become essential materials in several high-performance sectors — including the automotive, aerospace, petrochemical, offshore, and biomedical industries — due to their exceptional strength-to-weight ratio, excellent corrosion resistance, and biocompatibility. Among these alloys, Ti-6Al-4V (an α + β titanium alloy) stands out as the most widely used, offering an optimal balance between mechanical performance, corrosion resistance, and manufacturability. [3][7]

This alloy possesses mechanical strength comparable to that of steel while maintaining a density of less than 40% of it, resulting in substantial weight reduction, lower replacement costs, and extended service life. Furthermore, Ti-6Al-4V forms a stable, adherent oxide film on its surface, which provides outstanding corrosion resistance—allowing the material to endure exposure to seawater up to 15 times longer than conventional steels. Consequently, its industrial usage has grown significantly over the past two decades, particularly in applications demanding high performance and reliability. [7][8] [9]

Within the field of LMD, Ti-6Al-4V has become the most studied and commonly processed material, especially in aerospace and biomedical applications. The combination of LMD with titanium alloys enables the fabrication and repair of complex geometries with minimal material waste, eliminating the need for expensive forging or extensive subtractive machining. [4]

During deposition, titanium experiences rapid melting and solidification, resulting in high cooling rates that promote the formation of a fine martensitic α′ (alpha prime) microstructure. While this microstructure enhances strength and hardness, it also reduces ductility and toughness. To restore a better balance of mechanical properties, post-deposition heat treatments—such as annealing or solution-aging treatments—are typically applied to transform the α′ phase into a more stable α + β structure, improving both ductility and fatigue resistance. [9]

The quality and integrity of LMD-deposited titanium components depend strongly on the processing parameters and the shielding environment. Titanium's high reactivity with oxygen and nitrogen makes inert gas protection (commonly argon or helium) indispensable to prevent oxidation and contamination. Insufficient protection can result in porosity, cracking, and the formation of brittle oxide layers, all of which degrade the mechanical performance of the final part. [7] [9]

Experimental and numerical studies highlight the importance of optimizing laser power, scanning speed, and powder feed rate to achieve consistent layer fusion and minimize porosity. Additionally, the use of controlled interlayer dwell times—cooling periods between consecutive layers—helps manage thermal gradients, microstructural evolution, and residual stresses. When these parameters are properly optimized and combined with suitable heat treatments, LMD-fabricated Ti-6Al-4V parts can attain mechanical properties comparable to those of conventionally forged components. [7]

The application of LMD to titanium alloys is expanding rapidly across multiple sectors. In aerospace, it is used to repair turbine blades, compressor components, and structural parts; in the biomedical field, it enables the manufacture of customized implants with patient-specific geometries and biocompatible surfaces. Despite these advances, challenges persist — primarily in reducing porosity, enhancing fatigue life, achieving process certification, and integrating LMD with hybrid manufacturing systems that combine additive and precision subtractive operations. [5]

In conclusion, LMD of Ti-6Al-4V represents one of the most promising pathways for advanced titanium processing. It allows for localized material control, customized microstructure tailoring, and efficient repair of high-value components. Nevertheless, achieving isotropic, reproducible, and certifiable material properties demands careful management of process parameters, atmosphere control, post-deposition heat treatment, and precision finishing operations. When these factors are properly addressed, LMD can deliver titanium components that meet or exceed the standards of traditional manufacturing methods while offering superior design flexibility and sustainability [4] [9]

4

Design Process

4.1 Preliminary Review

Additive manufacturing is no longer just a sophisticated process reserved for high-end applications. It has evolved into a widespread technology that enhances component performance and, in many cases, reduces production costs. This is achieved by simplifying tasks that would traditionally require multiple steps into a single operation.

The process proves most advantageous compared to traditional methods when production volumes are low, typically no more than a few dozen units, as is common in prototype development. For this reason, in a field like Formula Student, AM remains as a highly competitive solution. Despite the challenges this technology may pose for a group of students without prior experience, the opportunity to improve the design process and harness its benefits represents a significant step forward in enhancing overall performance. [11] [12][13]

Consequently, when we were given the opportunity to collaborate with Meltio, a leading company in the AM sector, we decided to seize this valuable chance without hesitation. This collaboration not only allowed us to enhance the performance of our race car but also to massively expand our knowledge of one of the most promising technologies shaping the future of manufacturing.

Given that our team is composed entirely of students and considering that AM is still a relatively recent technology—one that is not yet part of most standard university curricula—we had to undertake the challenge of learning an entirely new manufacturing methodology from the ground up.

After a thorough review of the Direct Energy Deposition (DED) process, and specifically the LMD technique, an initial study was carried out by master's students to identify which components could achieve the most significant improvements by replacing conventional manufacturing processes with AM. The results of this study are summarized in the table below.

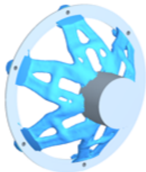
LMD CANDIDATES				
	Wheel Centre	Upright	Steering Support	Rocker
Components				
Loads	Medium	High	Low	Low
CNC Machining Complexity	Low	High	Low	Low
Weight Optimization	Medium	High	Low	Low
Other Inconveniences	Forced to Buy New Rims	New Manufacturing Methodology for a Complex Part	To be Done in a Very Short Window of Time	-

Table 1. LMD Candidates

After an extensive study, it was concluded that the upright was the component with the greatest potential for weight optimization, presented the fewest drawbacks, involved the most complex CNC manufacturing process among the three candidates, and was by far the most dynamically loaded part. Therefore, we decided to proceed with the design and manufacturing of the uprights using the LMD process.

4.1.1 Uprights

In a vehicle with a suspension system, it is possible to distinguish between the masses present depending on how they are supported. The suspended mass corresponds to the elements supported by the suspension itself – such as the bodywork, engine and chassis – which are protected from road surface disturbances. On the other hand, the unsuspended mass includes those components that are directly connected to the wheels, such as the steering knuckle, hub and brake disc.

.Figure 5. Sprung Weight vs Unsprung Weight. (Source: Dwarf Racing)

When encountering a bump in the road, compression is generated in the tyre, which translates into a force exerted on the vehicle. The suspension system is responsible for preventing this force from spreading to the components that make up the suspended mass; however, nothing prevents this force from acting directly on the components that make up the unsuspended mass. Consequently, as they are not supported by any component and are located close to the wheel, all the components that make up the unsuspended mass are often critical in terms of stress. They must therefore be selected after a thorough stress analysis and, if necessary, design analysis, as they must withstand the continuous vibrations and disturbances transmitted from the wheel.

In sports cars or high-performance vehicles, weight reduction is crucial for achieving extremely fast and precise response. However, reducing a specific amount of unsprung mass does not have the same impact on vehicle dynamics as reducing the same amount of sprung mass. The latter has a much greater influence [14]. Specifically, for Formula Student vehicles, a 1 kg reduction in unsprung mass is equivalent, in terms of dynamic behaviour, to a 25 kg reduction in sprung mass [15]. A useful analogy would be that of an athlete and their footwear: the lighter they are, the better their performance will be. For this reason, optimising the weight of the elements that make up the unsprung mass is crucial.

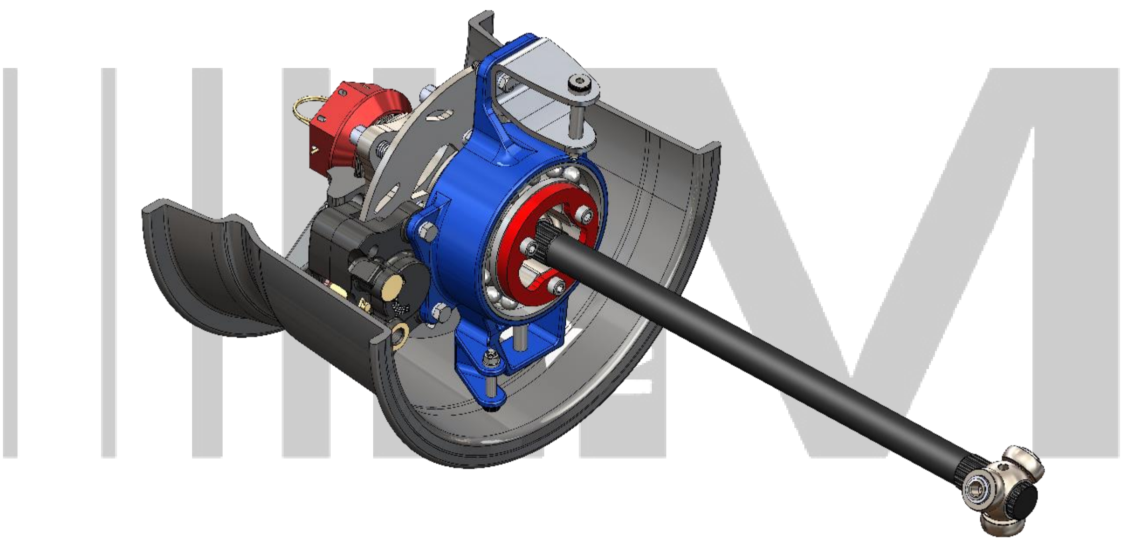


Figure 6. MA25RT's Rear Wheel Assembly (With the Upright in Blue).

Of all the elements that make up the suspension assembly, the upright – also known as the wheel carrier or knuckle — is considered the most crucial. It connects the rim, and the rest of components that rotate with it, to the suspension's fixed components, acting as the structural link between the wheel assembly and the control arms. This connection allows the wheel to rotate freely while transmitting braking, cornering, and vertical loads to the chassis.

In terms of stress, it is one of the most critical components of the car. It must be as light as possible, since it contributes to unsprung mass, yet sufficiently rigid and strong to withstand braking and traction forces, as well as to resist the transmission of loads from the tire to the suspension components. Consequently, it experiences high stress levels in both magnitude and variety.

From a manufacturing perspective, the upright's geometry is highly constrained, as it must accommodate numerous components within a limited space. This often results in a complex shape that presents significant challenges when produced using conventional methods. Typically, uprights are CNC-machined from high-strength aluminium alloys or fabricated from steel, depending on design constraints and performance goals. In FSAE applications, weight optimization, stiffness, and manufacturability are key design considerations, and many teams are transitioning to AM to fully exploit its advantages in upright design.

Figure 7. MA25RT's Rear Upright & Rear Wheel Assembly.

4.2 Material Selection

One of the most critical aspects of mechanical design is the selection of material, which is inherently dependent on the chosen manufacturing process. AM and traditional methods exploit different material capabilities and limitations. For conventionally machined uprights, aluminum alloys are typically the preferred option, offering an excellent balance between low weight, stiffness, and cost-effectiveness. However, when applied to AM, aluminum alloys exhibit notable drawbacks. Their low mechanical strength, which can further deteriorate after the heat treatments commonly required in AM processes, makes them less suitable for highly stressed components.

Furthermore, most high-strength aluminum alloys are not compatible with AM due to their high crack sensitivity. The presence of alloying elements such as silicon and magnesium, near concentrations corresponding to peak crack susceptibility, makes them prone to solidification cracking during processing. As a result, their printability and mechanical integrity are significantly compromised. [16]

An effective alternative for this application is Ti-6Al-4V (Ti64), a titanium alloy known for its low density, high strength, and excellent corrosion resistance. Ti64 provides superior fatigue resistance compared to other lightweight alloys, while being lighter than steels and superalloys. Components manufactured with Ti64 can be machined and polished both in the as-built and heat-treated conditions. Due to the layer-by-layer deposition nature of AM, some degree of anisotropy can appear in the final part; therefore, post-process heat treatment is recommended to relieve internal stresses and enhance ductility. [16]

As previously discussed, the combination of Ti64 with the LMD process represents one of the most promising approaches within the field of metal AM. Considering Meltio's extensive expertise in this technology and material system, Ti64 was selected as the material of choice for the upright fabrication.

4.3 Design Phase

The design phase is as shown in the following image:

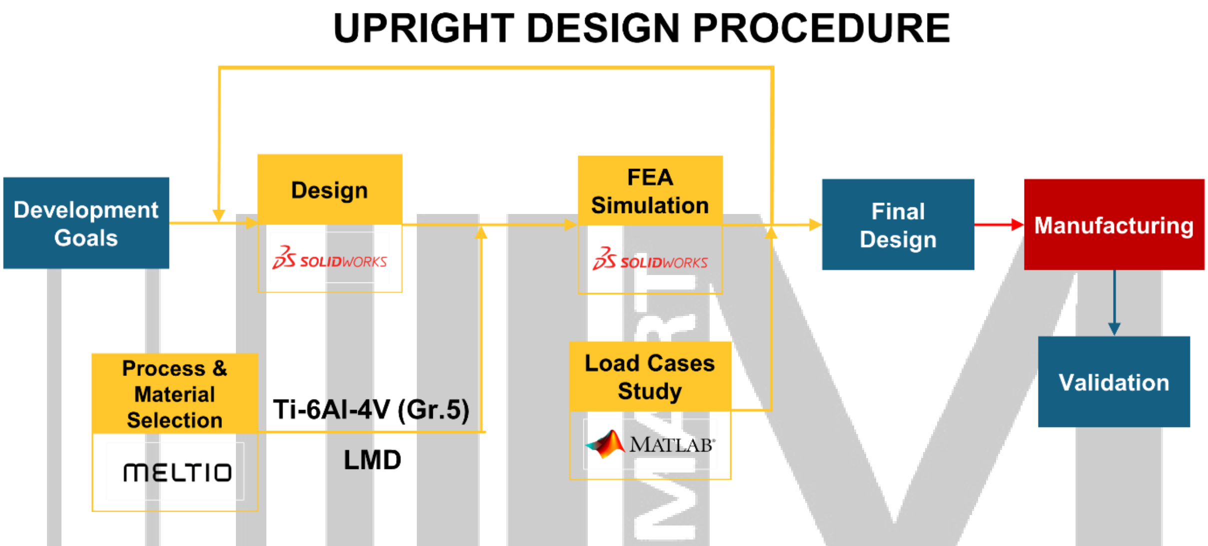


Figure 8. MA25RT's Upright Design Procedure.

Since the upright is the component of the wheel assembly that houses most of its parts and serves as the structural link between the wheel and the rest of the car, it is essential to define the design of all other components in the assembly before beginning the upright's design. Therefore, during that waiting period, a load study was carried out to determine the forces it would need to withstand.

As the forces acting on the car originate at the tire contact patches, the objective of the study was to calculate the loads on each tire's contact surface and extrapolate them to each wheel's upright. This allowed the design process to begin by determining key parameters such as geometry and bearing specifications. [17]

To achieve this, vehicle dynamics principles and data from previous tests were used to obtain the lateral, longitudinal, and vertical accelerations the car would experience under worst-case conditions. These accelerations were then converted into forces and, considering the dynamic weight transfer that occurs during motion, the loads at the tire contact surfaces were determined. [17]

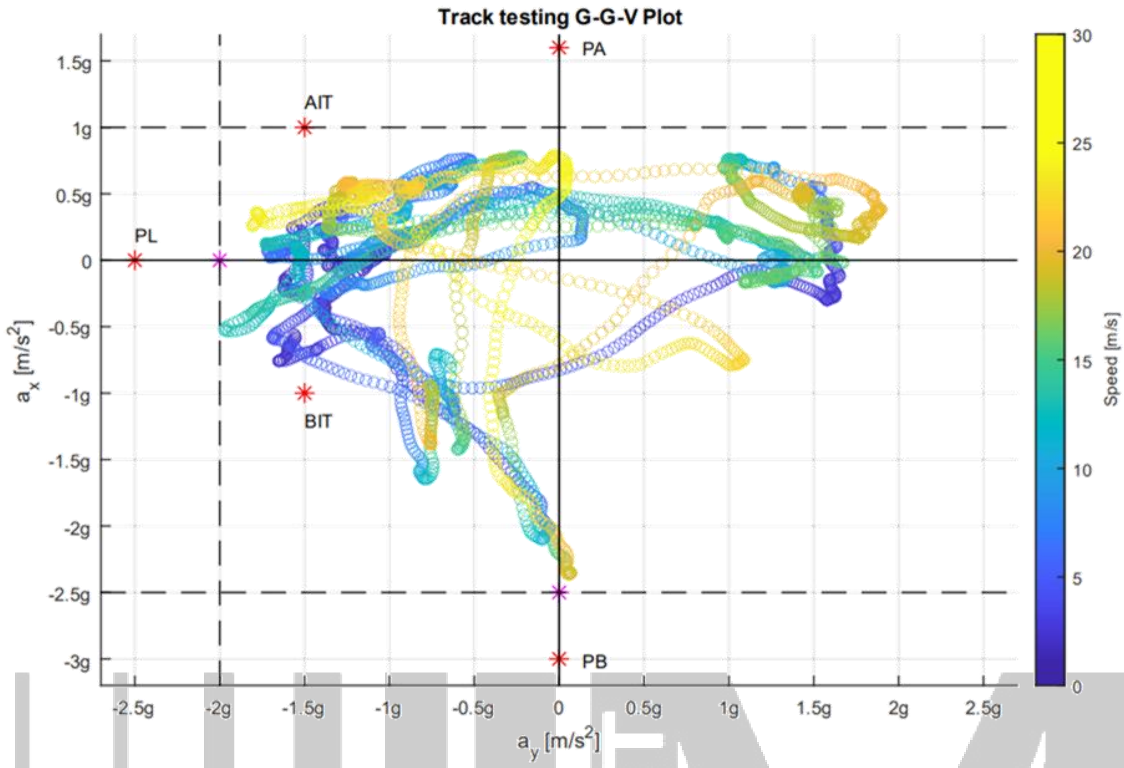


Figure 9. Longitudinal and Lateral Accelerations During Testing.

LOAD CASES

Acceleration (g)	Max. Acc.	Max. Break.	Corner Entry	Corner Exit	Bump
Longitudinal – X	1.3	-1.5	-1.2	1	-1.2
Lateral – Y	–	–	2.1	1.7	2.1
Vertical – Z	–	–	–	–	5

Table 2. Worst Load Cases Combinations [17]

By obtaining these forces, we were able to correctly select the appropriate bearings for each wheel and therefore, define the inner geometry of the upright [18]. In addition, once the suspension arm geometry was defined, the loads acting on each individual suspension link were determined. These loads were then used as input for the Finite Element Analysis (FEA) of the upright. [19]

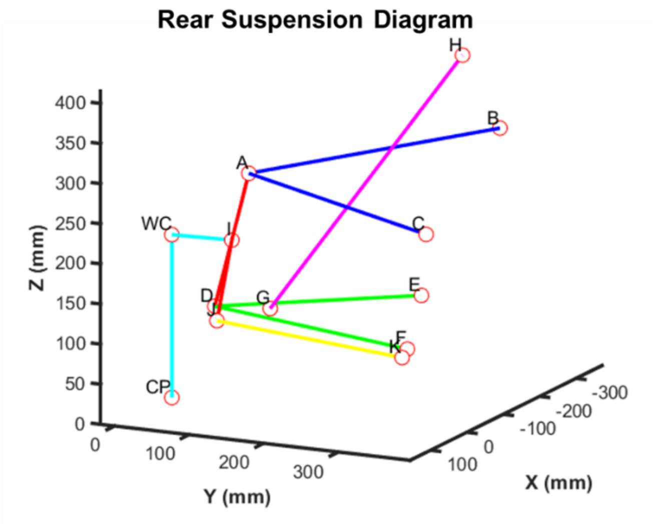


Figure 10. Rear Suspension Diagram Used to Calculate Suspension Link's Forces. [19]

Once the design of the remaining wheel assembly components was completed, and both the material and AM process had been selected, we proceeded with the upright's design stage. The preliminary sketches were reviewed and thoroughly reviewed and discussed, not only among the key members of the design team but also in collaboration with Meltio. Their technical feedback served as a catalyst for design optimization and fostered a deeper understanding of the LMD manufacturing constraints and opportunities.

An integrated approach between design and manufacturing was adopted, emphasizing the iterative relationship between both domains. This methodology involves first developing the optimal conceptual design and then applying the necessary geometric adaptations to ensure manufacturability without compromising performance.

The key principles of design for Additive Manufacturing (DfAM) can be summarized as follows [20][21]:

- Avoid relying on conventional design approaches.
- Exploit the full potential of AM technologies.
- Redefine the assembly through an integrated, freeform design perspective.
- Minimize raw material usage by optimizing for maximum strength-to-weight ratio.
- Take advantage of AM freedom—use undercuts, internal channels, and hollow structures when beneficial.
- Design the optimal shape of the part according to functionality.

With these guidelines in mind, a comprehensive redesign of the upright was carried out, resulting in a substantial evolution of the component's geometry and performance, as illustrated in Figure 11.

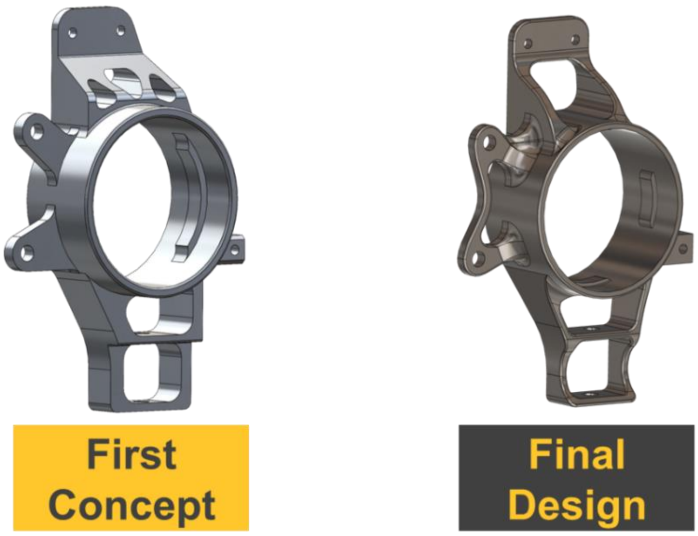


Figure 11. MA25RT Front Upright Design Phases.

Once the design phase was completed, final FEA and motion studies were conducted to validate the design and perform the necessary final adjustments. For the FEA simulations, the previously obtained contact patch forces were used as input. Additionally, the anisotropic material properties imposed by the manufacturing process were taken into account [22]. A safety factor of 1.5, commonly used in FSAE applications [15], was applied, and additional fatigue analyses were performed using force spectra gathered from previous testing (Figure 13). All of these analyses yielded positive results, confirming the structural integrity and reliability of the final design.

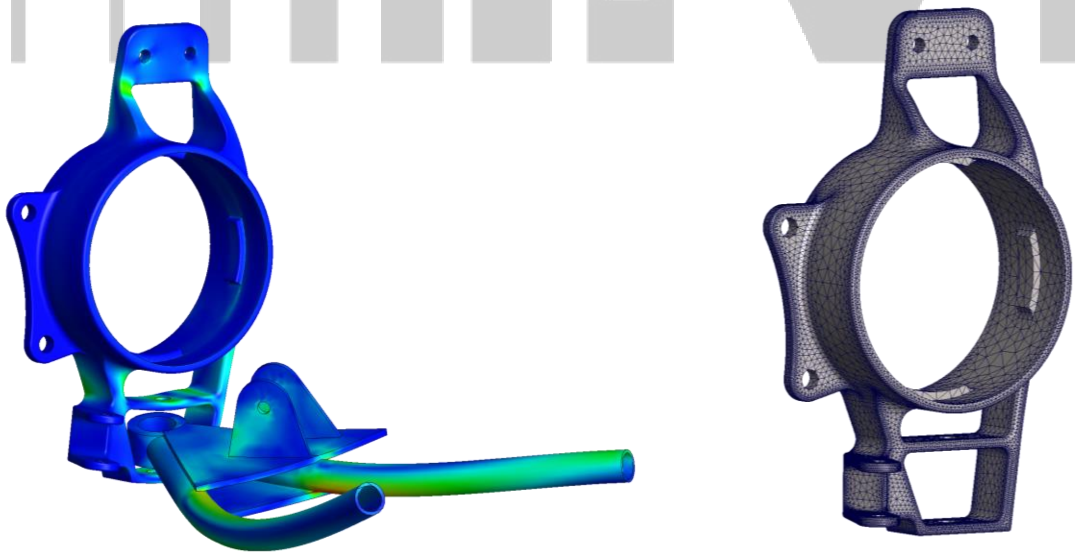


Figure 12. FEA Analysis of the Rear Upright.

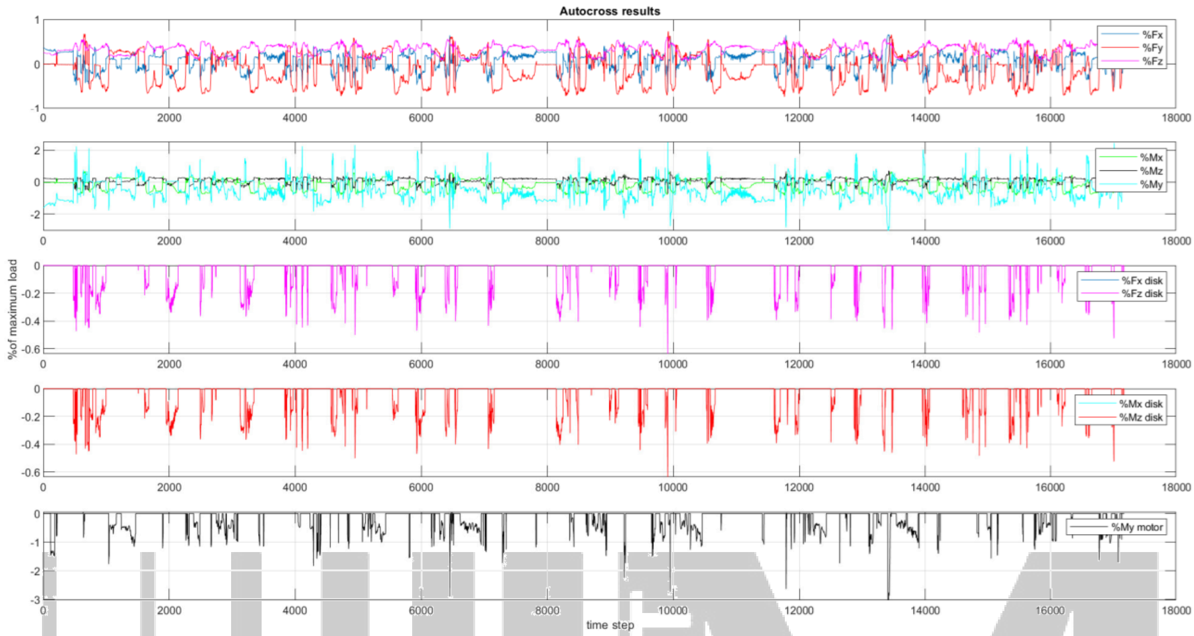


Figure 13. Force Spectra used for Fatigue Analysis.

5

Manufacturing Process

5.1 Uprights Manufacturing

After the completion of the design phase, the model was sent to Meltio for validation and subsequently manufactured using one of their in-house machines. The upright is a geometrically complex component, characterized by continuous variations in cross-section, multiple extrusion directions, thin wall regions, and interconnected narrow features. These aspects make the LMD process particularly challenging, as the process parameters – which are critical for achieving the desired mechanical properties and surface quality – cannot be easily predicted.

The uprights were manufactured on a build platform for several reasons. Firstly, the platform provides a stable base for material deposition, ensuring proper adhesion of the initial layers and preventing warping or detachment during the early stages of printing. Secondly, it acts as a heat sink, promoting more uniform heat dissipation and reducing thermal gradients, which in turn minimizes residual stresses and distortion. Thirdly, it facilitates accurate positioning and alignment of the component within the build envelope, which is particularly important for multi-axis deposition paths. Finally, the build platform simplifies post-processing operations, allowing for easier separation of the part, machining of reference surfaces, and inspection of dimensional tolerances once the build is complete. [16][23]

Figure 14. Manufactured Uprights.

5.2 Post-Treatment

Despite all the advantages that AM brings, the surface quality and tolerances achieved with such technologies remain relatively low. Consequently, an as-built AM part is rarely considered "finished" once the build process is complete. Tolerances are comparable to those achieved through casting (approximately 1 mm), and surface roughness tends to be significant. [6] [23]

Therefore, finishing treatments are essential to refine the part's geometry and improve fatigue performance, which is adversely impacted by the inherent surface characteristics of metal AM parts. The typical post-build workflow includes heat treatment (to relieve residual stresses), separating the part from the build platform, transferring the part to a CNC machine, and performing the machining process [16]. It is crucial to relieve residual stresses before machining; otherwise, stress release during machining can distort the part. Each component should be machined individually, even when multiple parts are produced on the same platform [23].

5.2.1 Heat Treatment

The LMD process, like most AM technologies, is characterised by non-uniform local heating of the buildup, which leads to stress distributions that may exceed the yield strength of the material and cause a loss of dimensional accuracy. In contrast to the temperature field, which disappears after cooling, the stress and strain fields remains due to its irreversible nature. Consequently, after complete cooling, residual strains and stresses remain within the fabricated part [10] and therefore, post-processing heat treatments are applied to promote the formation of an equiaxed grain structure and improve overall mechanical performance

The main factors affecting the stress and strain fields are the shape and the size of the buildup, the process parameters, the thermomechanical and the thermophysical properties of the deposited material and the interlayer dwell time. The study of the origin of the stress field is essential for solving a number of problems in AM, including: the assessment of cold and hot cracking; prediction of the fatigue resistance, and the stress corrosion cracking. [7][10]

Compared to other AM processes, LMD is generally less affected by residual stresses. It typically results in a relatively small heat-affected zone, reduced deformation, good surface finish, and high mechanical properties. In addition, its fractures—which usually initiate at pre-existing cracks—are mostly ductile, though some brittleness may still appear [9]. Furthermore, the upright, having numerous areas of reduced thickness, tends to develop lower residual stresses. This occurs because much of its surface is in direct contact with the air, promoting more uniform heat dissipation. As a result, the cooling rate is slower and the thermal gradient between different regions of the part is reduced, thus minimising the formation of residual stresses. [9][24]

Nevertheless, following consultation with Meltio, it was decided to apply a heat treatment. Although this manufacturing technology is not particularly prone to generating high levels of residual stresses, their presence cannot be completely avoided. Furthermore, the enhancement of the component's mechanical properties resulting from the treatment is considerable.

In general, two main thermal post-treatments are applied to LMD-fabricated titanium parts—Hot Isostatic Pressing (HIP) and annealing—both involving heat application but differing significantly in their mechanisms and effects.

Hot Isostatic Pressing (HIP) is a widely used post-processing method aimed at enhancing the density and mechanical properties of additively manufactured titanium alloys. The process combines high temperature and isostatic gas pressure (typically argon at 800–950 °C and 100–150 MPa) for several hours, enabling diffusion-driven closure of internal pores and defects formed during deposition. The simultaneous application of heat and pressure eliminates internal voids, promotes microstructural homogenization, and relieves residual stresses. It is usually applied to parts subjected to high fatigue loads, where structural integrity and long-term performance are critical. As a result, HIP-treated Ti-6Al-4V components exhibit higher ductility, improved fatigue life, and reduced variability in mechanical behaviour compared to as-built or conventionally heat-treated counterparts. However, because the process involves exposure to both elevated temperature and high pressure, slight dimensional distortions or shape deviations may occur, especially in thin-walled or geometrically complex parts. In addition, excessive thermal exposure may induce coarsening of the α/β lamellar microstructure, which can slightly reduce ultimate tensile strength if the cycle is not properly optimized. [25][26]

In contrast, annealing (conventional heat treatment) primarily aims to relieve residual stresses and transform the metastable martensitic α' phase, typical of the rapid solidification rates in LMD, into a more stable $\alpha + \beta$ equilibrium structure. Performed at lower temperatures (generally between 700 and 850 °C) and without applied pressure, annealing effectively enhances ductility and toughness, though it has limited impact on internal porosity, since diffusion alone cannot seal closed voids.[25][26]

While studying this phenomenon, research was conducted to determine the post-heat treatments that some AM companies applied to components manufactured using LMD. The results are shown in the table below. As can be seen, both treatments are widely used. [22] [27] [28] [29] [30]

HEAT TREATMENTS					
Company	**Meltio**	**Carpenter Additive**	**Arcam EBM**	**Zapp**	**ATI**
Process	A. Solution Annealing B. Age Hardening	A. Annealing B. HIP	HIP	A. Recrystallization Annealing B. Stress Relieve Annealing	A. Annealing B. Stress Relief Anneal C. Solution Heat Treatment D. Age Hardening
Temperature	A. 920ºC B. 460ºC	A. 593ºC B. 925ºC	1100ºC	A. 730ºC B. 650ºC	A. 1000ºC B. 700ºC C. 930ºC D. 550ºC
Time	A. 2h B. 8h	A. 2h B. 3h	3h	A. 6h B. 2h	A. 1h B. 5h C. 1h D. 7h
Cooling	A. To RT Outside B. To RT in Oven	A. To RT in Oven B. To 427ºC in Oven	To RT Outside	A. To RT Outside B. To RT Outside	A. To RT Outside B. To RT in Oven C. Sprayed with Water D. To RT Outside
Atmosphere	A. Vacuum B. Vacuum	A. Vacuum/Argon B. Vacuum/Argon	Vacuum	A. Vacuum/Argon B. Vacuum/Argon	A. Vacuum/Inert Gas B. Vacuum/Inert Gas C. Vacuum/Inert Gas D. Vacuum/Inert Gas
Typical Parameters for a Sample of 160x60x30mm					

Table 3. Heat Treatments Applied by Different Companies.

Overall, both HIP and annealing contribute to improving the structural integrity of LMD-produced Ti-6Al-4V components. HIP provides superior densification and fatigue resistance, albeit at a higher processing cost, while annealing offers a simpler and more economical route focused on microstructural refinement and stress relief. In industrial practice, the two treatments are often combined sequentially—with HIP used first to eliminate porosity, followed by annealing or aging—to achieve an optimal balance between mechanical strength, ductility, and dimensional stability. [25][26]

Given that we had no means in our university to apply HIP and that annealing was simpler and easier to carry out, we used an industrial furnace to apply annealing. The characteristics of the process can be seen in the table below:

HEAT TREATMENT PARAMETERS				
Process	**Temperature**	**Time**	**Cooling**	**Atmosphere**
Solution Annealing	800ºC	2h	To RT in Oven	Argon

Table 4. Heat Treatment Parameters.

Figure 15. Rear Uprights after Heat Treatment.

With the residual stress problem solved, we embarked on the next step, the use of hybrid manufacturing to obtain the finished parts.

5.2.2 Post-Manufacturing

The goals of finishing processes include enhancing aesthetics, achieving dimensional accuracy, reducing surface roughness, improving mating surfaces and features, enhancing part functionality, optimizing tribological properties, and extending fatigue life. If the objective is to reduce roughness while tolerances are less critical, abrasive finishing processes can be employed [9].

However, when tight tolerances are mandatory, machining with CNC machines becomes the only viable option. The combination of additive and subtractive manufacturing techniques is known as Hybrid Manufacturing (HM). Implementing HM is complex due to the inherent differences between additive and subtractive processes [23]:

- **Holding and fixing challenges:** The complexity and roughness of AM surfaces make it difficult to secure parts in the machine. Establishing datums and reference points for orienting and locating the part, as well as defining tool paths for the CNC machine, becomes particularly challenging after the part is separated from the build plate.
- **Vibration issues:** The low stiffness of AM parts can lead to vibrations during machining, reducing accuracy. While this may seem counterintuitive, it arises from the fact that AM parts are optimized for specific functional loads, resulting in low stiffness for other types of loads. To address this, additional features can be incorporated into the design to enhance stiffness during machining, or machining loads must be considered during the design's optimization phase.
- **Access limitations:** Intricate geometries may restrict access to certain areas with cutting tools.

As a conclusion, HM techniques are a potential solution but poses challenges such as fixing and holding complex parts, managing low stiffness (which causes vibrations), and accessing intricate geometries. Proper design considerations can mitigate these issues, ensuring better machining outcomes. [21][23]

Thus, it's important to adjust the shape of the component in a way that a traditional CNC machine can operate easily. Unfortunately, it's not an easy task because there's the risk of not fully exploiting the AM possibility. On the other hand, it can happen to increase too much the costs or the complexity of the CNC process. It's possible, for example, to introduce some sacrificial supports. These structures aim to secure the component in the CNC machine, providing support to be cut away at the end. It is very difficult to take into account these problems during the design phase because the production of support is usually automated by the software, and it is challenging to modify the shape as you want.

In our case, we aimed to adapt the optimized upright design to a more CNC-friendly geometry. Fortunately, thanks to the prior recommendations provided by Meltio, this redesign was successfully carried out without any significant increase in weight. After performing the corresponding heat treatment, we collaborated with one of our sponsors to separate the part from the build plate and machine its surfaces to achieve the required final finish.

Since titanium is considerably more challenging to machine than steel—mainly due to its low thermal conductivity, high mechanical strength at elevated temperatures, and tendency to adhere to cutting tools—the process proved to be quite demanding. It required the use of specialized tooling, such as a wire-cut system, low cutting speeds, and abundant cooling to ensure proper surface quality and dimensional accuracy. [16]

Given the extensive experience of the sponsor responsible for the machining process, the manufacturing strategy was fully defined by them. The approach consisted of profiling the upright contours using wire-cutting, applying all the required dimensional tolerances. Subsequently, the support structures were removed, the upright was separated from the build platform, and finally, the remaining geometry was profiled to achieve the final shape and surface finish.

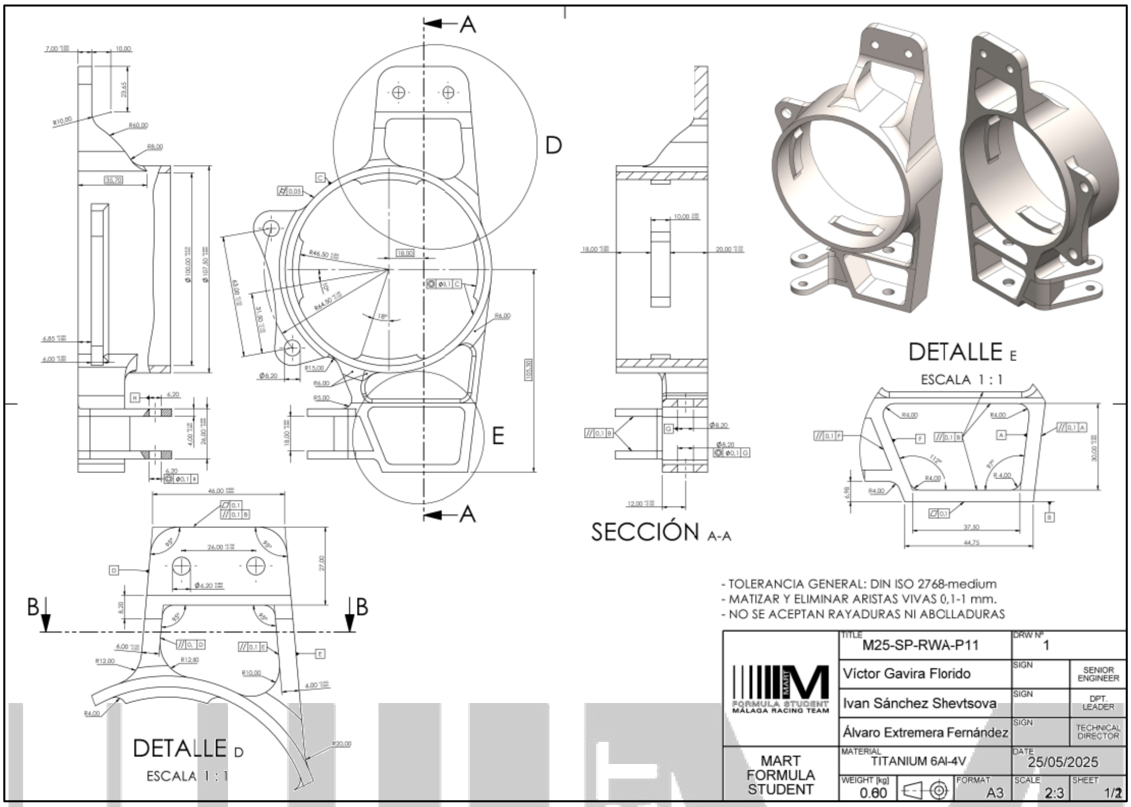


Figure 16. First Sheet of the Rear Upright's Manufacturing Drawing.

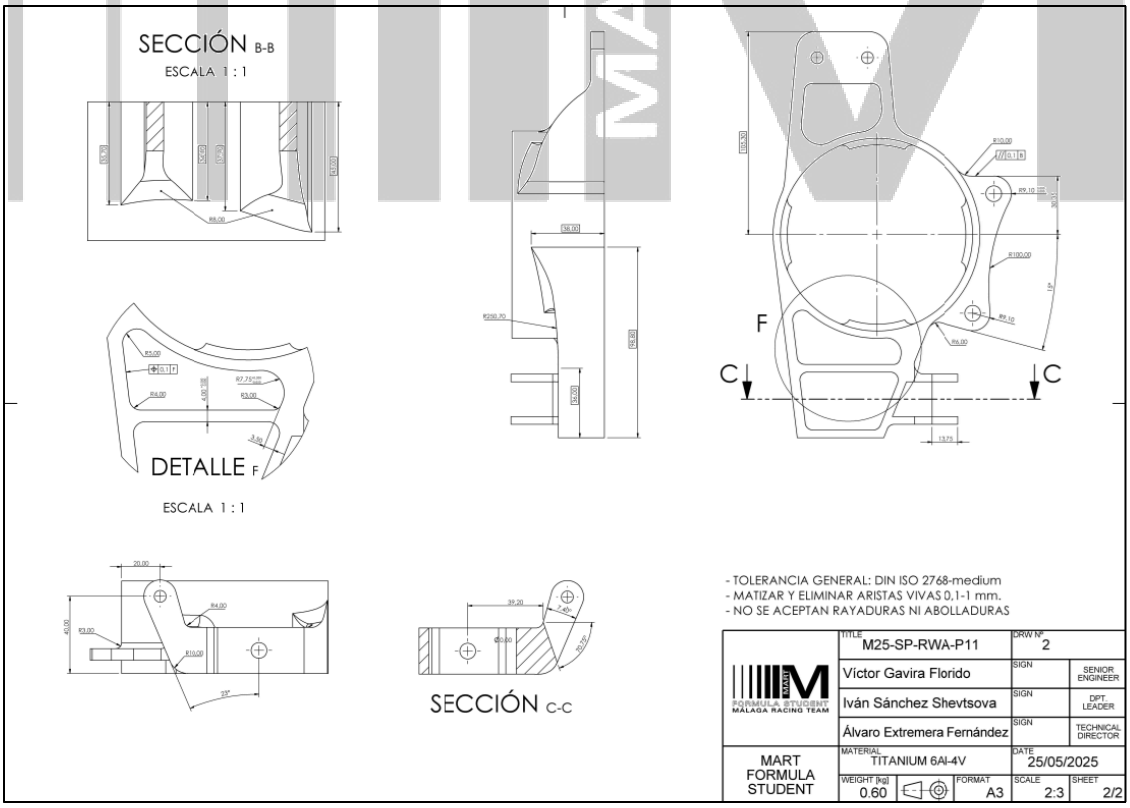


Figure 17. Second Sheet of the Rear Upright's Manufacturing Drawing.

6

Results

6.1 Comparison with Previous Years

As previously discussed, the use of AM redefines both the design and production processes of components, significantly enhancing vehicle performance. Thanks to the implementation of Meltio's technology, we were not only able to design lighter uprights but also to adapt an entire assembly to this manufacturing approach. This resulted in substantial improvements, particularly in terms of weight reduction and the decrease of unsprung mass. The reduction in wheel weight translated directly into a more agile and responsive vehicle, a difference that our driver immediately noticed during testing

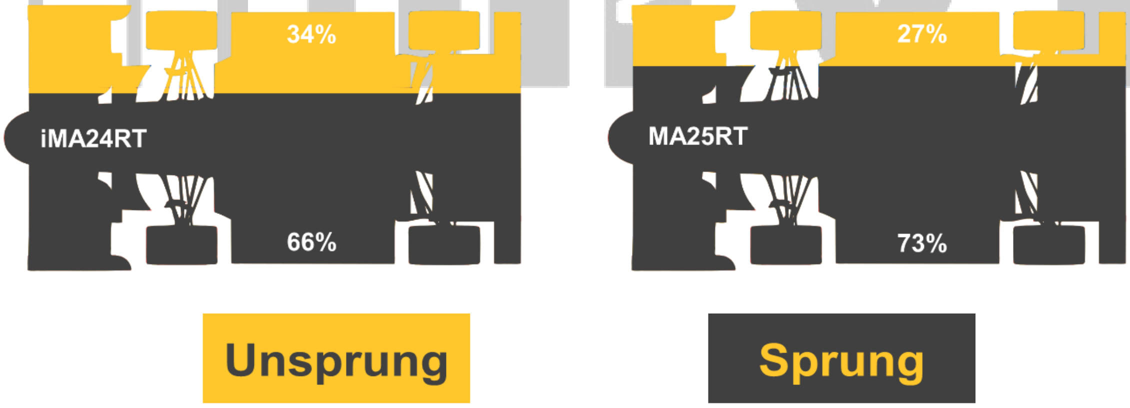


Table 5. iMA24RT vs MA25RT Weights Comparison.

At the beginning of the 2025 season, before the partnership with Meltio was established, an attempt was made to optimize the design of conventionally manufactured uprights by reducing weight without compromising stiffness and strength. However, the performance gains were minimal compared to the associated costs. This realization prompted us to explore alternative manufacturing processes, ultimately leading to the development of this project and the valuable collaboration with Meltio.

RESULTS

The following section presents the improvements achieved in both the upright's weight and the overall wheel assembly. A substantial reduction in weight has been accomplished without compromising the mechanical integrity of the system. As previously discussed, manufacturing the uprights using LMD technology has enabled a complete redefinition of the vehicle's drivetrain architecture. This redesign resulted in a reduction of approximately 2.5 kg per rear wheel assembly, which represents a significant improvement in performance terms.

FRONT WHEEL ASSEMBLY WEIGHT (g) (per wheel)		
Component	*iMA24RT*	*MA25RT*
Rim	1350	1150
Wheel	3630	3430
Wheel Hub	465	420
Brake Disc	640	595
Brake Calliper	405	405
Bearings	510	430
Upright	725	470
Total	7725	6900

REAR WHEEL ASSEMBLY WEIGHT (g) (per wheel)		
Component	*iMA24RT*	*MA25RT*
Rim	1350	1150
Wheel	3630	3430
Wheel Hub	2535	620
Brake Disc	500	422
Brake Calliper	420	420
Bearings	560	600
Upright	695	555
Total	9690	7197

Table 6. iMA24RT vs MA25RT Weights Comparison.

From the MART FS team, we express our sincere gratitude to Meltio — not only for the technological partnership that enabled a massive enhancement in one of the most geometrically and dynamically complex assemblies of the car, but also for their contribution to fostering advanced engineering knowledge in one of the most promising manufacturing technologies poised to revolutionize the industry.

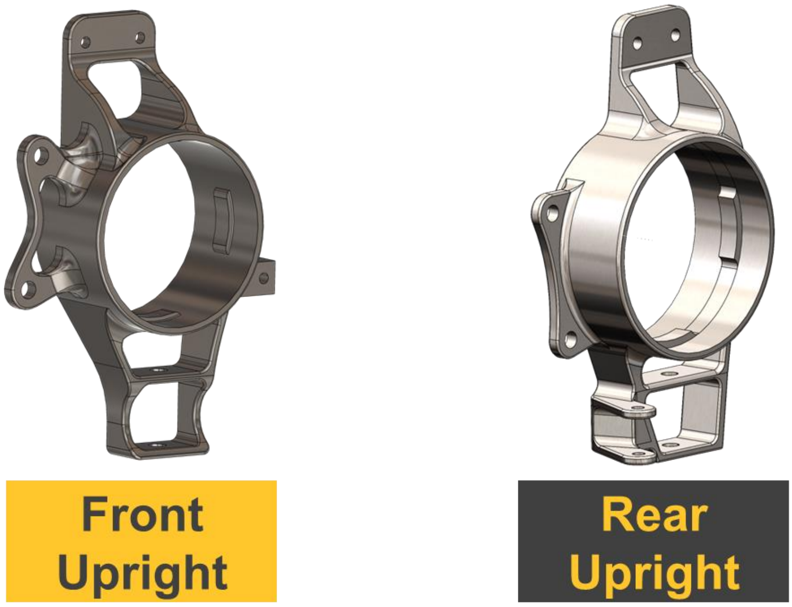


Figure 18. Final Uprights' Design.

6.2 Future Scope

The evolution of this partnership has followed a logical and steady path. At the beginning of the season, no member of the team had extensive knowledge of AM, which made the development of the upright a continuous learning process. Now, with a stronger understanding of the technology and a well-defined manufacturing methodology, the team feels optimistic about developing even more efficient components for the upcoming season. The goal is to fully exploit the principles of DfAM while minimizing valuable time intervals throughout the entire post-machining process.

As a result, the future direction is clear: to consolidate the knowledge acquired by the key members of the design department and effectively transfer it to new team members through documentation such as this report. This will empower future designers to explore and expand the implementation of AM technologies in the development of additional components.

Additionally, due to the short time frame available after the heat treatment process and scheduling incompatibilities with the testing department at our university, we were unable to perform non-destructive testing to fully verify the structural soundness of the component after machining. Consequently, this remains an open task for further analysis. Nevertheless, the upright has shown no issues or failures during the extensive testing hours conducted on the vehicle, confirming its satisfactory performance in real-world conditions.

6.3 Q&A

Although the answers to the questions provided by Meltio are scattered throughout the document, this subsection has been created to summarise the most valuable aspects.

Why did MART FS chose Meltio's industrial wire-laser technology?

Additive manufacturing is no longer just a sophisticated process reserved for high-end applications. It has evolved into a widespread technology that enhances component performance and, in many cases, reduces production costs. This is achieved by simplifying tasks that would traditionally require multiple steps into a single operation.

The process proves most advantageous compared to traditional methods when production volumes are low, typically no more than a few dozen units, as is common in prototype development. For this reason, in a field like Formula Student, AM remains as a highly competitive solution. Despite the challenges this technology may pose for a group of students without prior experience, the opportunity to improve the design process and harness its benefits represents a significant step forward in enhancing overall performance.

Consequently, when we were given the opportunity to collaborate with Meltio, a leading company in the AM sector, we decided to seize this valuable chance without hesitation. This collaboration not only allowed us to enhance the performance of our race car but also to massively expand our knowledge of one of the most promising technologies shaping the future of manufacturing.

What are the advantages that Meltio's new application brings to a Formula Student Team?

The main challenge of racing an electric car is the weight of the batteries, which means that the weight of every other component must be minimized to keep the car competitive. With such a strong team and the solid foundations laid in previous years, we decided to take calculated risks and focus on developing cars that prioritize performance over reliability, aiming for a greater weight reduction every year.

At the beginning of the 2025 season, before the partnership with Meltio was established, an attempt was made to optimize the design of conventionally manufactured uprights by reducing weight without compromising stiffness and strength. However, the performance gains were minimal compared to the associated costs. This realization prompted us to explore alternative manufacturing processes, ultimately leading to the development of this project and the valuable collaboration with Meltio.

The implementation of Meltio's LMD technology has transformed the way MART FS approaches both design and production. The possibility of manufacturing geometrically complex titanium parts directly from digital models allows for full exploitation of Design for Additive Manufacturing (DfAM) principles—reducing weight, consolidating multiple components into single parts, and improving stiffness-to-weight ratios. This directly translates into enhanced vehicle performance by reducing unsprung mass, improving dynamic response, and optimizing packaging within the car's wheel assemblies.

Moreover, the collaboration has provided team members with hands-on experience in advanced manufacturing, bridging the gap between academic knowledge and industrial practice. This exposure to real-world additive processes represents a significant educational benefit and aligns perfectly with Formula Student's mission to prepare future engineers for cutting-edge technologies.

Could MART FS provide statements presenting the strengths and value proposition of Meltio's application?

Thanks to Meltio's new application, the team gains several key advantages:

- **Significant weight reduction:** Meltio's technology allows us not only to lighten individual components but also to redesign entire assemblies to optimize the vehicle's overall weight. This directly improves car performance, enabling better acceleration, agility, and energy efficiency. The weight optimization can be seen in Table 6.
- **Complex design optimization:** Metal additive manufacturing enables geometries that are impossible or very costly to achieve with traditional processes. This allows components to be designed to withstand loads only where necessary, eliminating unnecessary material.
- **Innovation and learning:** As engineering students, adopting advanced technologies like additive manufacturing is an opportunity to learn, experiment, and innovate. The collaboration with Meltio gives us access to cutting-edge processes that expand our technical knowledge and skills. This report reflects all the knowledge acquired during our partnership.
- **Development agility:** The ability to iterate quickly on complex designs reduces development time and allows us to test new ideas faster, facilitating continuous improvement of components and vehicle performance.
- **Competitive advantage:** In an environment where every gram matters, the ability to manufacture lighter, optimized components gives us a direct advantage over teams that rely on traditional manufacturing methods. Thanks to the improvement in the wheel assemblies, we achieved one of the top steps in the Engineering Desing Event in Formula Student Spain.

On our side, thanks to the collaboration, we have achieved better results in both static and dynamic testing, significant weight optimization, and the acquisition of highly valuable knowledge about a technology that is set to revolutionize the industry. Additionally, we are aware that Meltio has also benefited from this partnership, as they had the opportunity to experiment with the manufacturing of a particularly complex component, characterized by continuous variations in cross-section, thin-wall regions, and interconnected narrow features. These aspects made the LMD process particularly challenging and helped them gain a clear understanding of the process parameters required for components with such geometry.

RESULTS

Does this application have future evolution and improvement? In what aspects?

Absolutely, Laser Metal Deposition (LMD) is a versatile additive manufacturing process with significant potential for future development. Although its layer-by-layer deposition currently limits production speed, advances such as higher-power lasers, multi-head systems, and optimized powder delivery are expected to enhance efficiency. Material versatility is also expanding, with ongoing research on novel alloys, multi-material deposition, and improved microstructural control aimed at enhancing mechanical properties. Simultaneously, advancements in laser optics, adaptive process control, and real-time monitoring are enabling greater precision, reduced surface roughness, and the production of complex geometries with minimal post-processing.

Regarding our partnership, the future direction is clear: to consolidate the knowledge acquired by the key members of the design department and effectively transfer it to new team members through documentation such as this report. This will empower future designers to explore and expand the implementation of Meltio's advanced additive manufacturing technologies in the development of additional components, as exemplified in Table 1. The results of this collaboration have had a highly positive impact on MART. Professionally; we successfully optimized a complex assembly for the first time in our brief history. On a personal level, we gained invaluable knowledge that is not yet taught in university courses, significantly enriching the expertise of our team.

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