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MORGAN
MOTOR COMPANY

Comparing Manufacturing Methods for the Morgan Plus Four Lower Control Arm

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Abstract

This dissertation presents a comparative evaluation of the manufacturing methods for the Lower Control Arm (LCA) of the Morgan Plus Four. The LCA is a critical structural element that connects the wheel hub to the chassis and absorbs diverse, dynamic loads from braking, cornering, and road irregularities. Therefore, this study focuses on transitioning from traditional hand-fabricated steel assemblies to advanced manufacturing techniques for this key component. The study investigates cast aluminium, additive manufacturing via Laser Powder Bed Fusion (LPBF), and CNC billet milling as alternative production routes. Detailed 3d CAD models were developed for each method, incorporating generative design where applicable to minimise mass while maintaining structural integrity. Finite Element Analysis (FEA) assessed static structural performance under representative automotive load cases. Manufacturing feasibility was critically analysed in terms of tooling requirements, production scalability, material efficiency, and cost. Results indicate that additive manufacturing and CNC-milled designs achieved the highest weight reduction and structural performance, albeit with higher production costs. Cast aluminium, optimised for low-pressure die casting, provided an effective balance between performance, manufacturability, and price, making it the most viable solution for Morgan's low-volume, bespoke production model. The findings support a strategic move towards integrating advanced manufacturing techniques to reduce manufacturing costs and component lead time while enhancing component performance, reducing unsprung mass, and aligning with evolving industry standards while maintaining Morgan Motor Company's traditional craftsmanship ethos.

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1.0 Introduction and Project Rationale

Morgan Motor Company, established in 1909, is renowned for its dedication to handcrafted automotive manufacturing, combining traditional craftsmanship with contemporary performance standards. The company's history is deeply rooted in an artisanal approach to manufacturing, and this commitment is reflected in its vehicles, notably the Morgan Plus Four. This model, in particular, stands as a testament to the company's unique fusion of classical styling and advanced engineering. The Plus Four features the advanced CX-Generation bonded aluminium chassis, significantly enhancing torsional stiffness and reducing weight compared to the previous steel structures. Despite this innovation, key components such as the Lower Control Arm (LCA), essential in the double-wishbone suspension system, are still produced using conventional hand-welded steel assemblies, reflecting Morgan's commitment to artisanal manufacturing.



Figure 1 Image of a Morgan Plus Four (Source: Pistonheads, 2021: online)

The LCA is a critical structural element that connects the wheel hub to the chassis and absorbs various dynamic loads from braking, cornering, and road irregularities. Consequently, exceptional structural integrity, fatigue resistance, and weight

optimisation are required to minimise unsprung mass, which is crucial for vehicle dynamics. Unsprung mass refers to the weight of the components not supported by the suspension system, such as the wheels, tires, and brakes. Minimising unsprung mass is essential, allowing the suspension to react quickly to road irregularities, enhancing traction and ride comfort. However, Morgan's traditional method, involving welding tubular or pressed steel segments, presents significant drawbacks. While suitable for low-volume, bespoke manufacturing, this technique is labour-intensive, results in heavier components, and imposes limitations on scalability, precision, and efficiency.

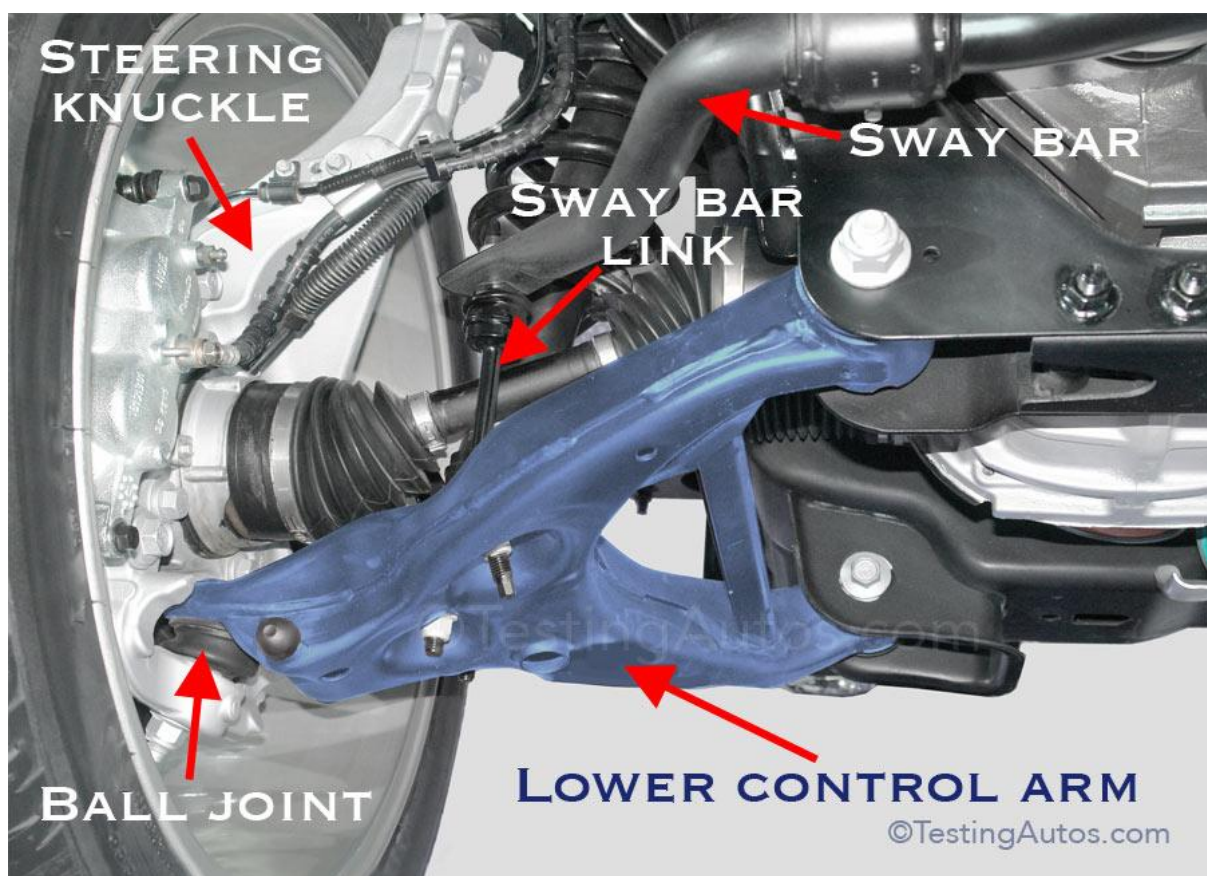


Figure 2 Image of Lower Control Arm in suspension assembly (Source: TestingAutos, 2020: online)

Morgan faces pressure to innovate while maintaining its heritage identity, as the automotive market increasingly demands lighter, stronger, and more efficient components. However, transitioning to alternative manufacturing techniques such as cast aluminium and Additive Manufacturing (AM) offers compelling opportunities. These methods promise significant advantages in weight reduction, enhanced

mechanical properties, and the ability to achieve intricate, topology-optimised geometries that are unattainable through traditional fabrication.

Cast aluminium offers superior grain orientation and mechanical properties, increasing fatigue resistance and durability. These attributes make the cast LCAS particularly suited to high-performance driving conditions. In contrast, AM methods, notably Laser Powder Bed Fusion (LPBF), provide unprecedented design flexibility, enabling intricate, lightweight structures optimised through generative design. This technological approach significantly reduces weight, enhances performance, and supports complex geometries without the constraints of conventional tooling.

Complemented by advanced simulation technologies, generative design has significantly benefited automotive applications. It enables the creation of organically shaped, high-performance components that mimic natural structures. These designs significantly reduce material usage and weight while preserving structural strength, enhancing vehicle dynamics and efficiency. The automotive industry increasingly utilises AM and generative design, from high-performance motorsport applications to advanced experimental vehicles.

Adopting these technologies aligns strategically with Morgan's vision of modern craftsmanship, allowing the company to maintain its artisanal ethos while integrating cutting-edge manufacturing methods. The flexibility of AM in producing small batches economically, without expensive tooling, aligns perfectly with Morgan's bespoke production model. This alignment should reassure the audience about the company's direction and commitment to its brand identity, demonstrating that Morgan is not just adapting to industry changes but is leading the way in integrating tradition and innovation.

This study evaluates the feasibility and implications of adopting these advanced manufacturing methods for Morgan's LCAS. It investigates cast aluminium, AM, and CNC milling to assess structural performance, weight optimisation, and production viability. Through detailed computational simulations including finite element analysis and fatigue testing, the study benchmarks each approach against Morgan's traditional hand-fabricated method.

The primary objective of this study is to determine whether these alternative manufacturing routes can achieve superior performance, reduced weight, and

enhanced durability, all of which are favourable for future high-performance models and potential motorsport applications, whilst costing less to produce and in a shorter amount of time. The project critically examines manufacturing feasibility by considering tooling costs, scalability, material efficiency, and overall integration into Morgan's low-volume, high-customisation manufacturing environment. The potential for superior performance and enhanced durability should instil confidence in the prospects of the new manufacturing methods.

Ultimately, this investigation aims to recommend a production strategy that harmonises with Morgan's long-standing heritage of craftsmanship while embracing modern manufacturing capabilities. It seeks to position Morgan Motor Company competitively in the evolving automotive landscape, meeting contemporary performance demands without compromising its distinctive identity and traditional values.

2.0 Aims and Objectives

The primary aim of this project is to assess and compare modern manufacturing techniques for producing the Lower Control Arm (LCA) for the Morgan Plus Four, to improve component performance, reduce mass, and streamline production processes while remaining aligned with Morgan Motor Company's traditional craftsmanship ethos and low-volume manufacturing model. Morgan employs a labour-intensive method for LCA production, relying heavily on manually welded steel assemblies. While this method remains true to Morgan's heritage and brand philosophy, it introduces significant weight, repeatability, production time, and scalability challenges. As the automotive industry continues its shift towards lightweight structures, enhanced performance, and digital integration, it becomes essential for heritage brands like Morgan to adopt advanced manufacturing methods that meet modern engineering standards without compromising their distinctive identity.

This project focuses on three alternative manufacturing methods: casting aluminium, metal-based additive manufacturing (3d printing) and CNC milling. These alternatives offer the potential for significant improvements in structural integrity, fatigue life, weight reduction, and design freedom. The aim is to compare these techniques from structural and manufacturing perspectives and evaluate their practical viability within Morgan's bespoke, low-volume production environment.

Several detailed technical and research-based objectives were defined to meet the overall aim. First, a comprehensive review of manufacturing methods was undertaken, covering traditional hand-welded steel fabrication, CNC milling (both 2.5-axis and 5-axis techniques), and metal additive manufacturing processes such as Laser Powder Bed Fusion (LPBF), Electron Beam Melting (EBM), and Directed Energy Deposition (DED). This research evaluated critical technical factors such as grain structure alignment, residual stresses, dimensional tolerances, and standard failure modes associated with each manufacturing method.

Following the literature review, multiple LCA designs were developed. These included a generatively designed LCA tailored for CNC milling, additive manufacturing, and casting, alongside the traditional steel-welded LCA used on the current Plus Four model. All designs were created to ensure full dimensional compatibility with Morgan's

existing chassis and suspension mounting points, facilitating a direct and fair comparison without requiring a complete vehicle redesign.

Fusion 360 was used to create generative design techniques for the additive manufacturing concept. The goal was to minimise weight while preserving required stiffness, respecting constraints such as factor of safety, and simulating manufacturability restrictions specific to casting, additive processes and CNC milling, such as draw directions, overhangs, and build orientation considerations. These designs aimed to deliver high-performance, organically optimised structures that could only be feasibly produced through modern manufacturing techniques.

Finite Element Analysis (FEA) simulations were carried out for all designs under real-world load cases, including braking, cornering, bump loads, and combined dynamic inputs representing worst-case scenarios. Key performance indicators such as stress and strain concentrations and compliance (deflection under load) were assessed for each concept.

In parallel, a manufacturability and production feasibility analysis was conducted. This evaluation encompassed tooling requirements, material handling efficiency, cycle times, post-processing demands, and integration considerations within Morgan's existing bespoke manufacturing workflow. Special attention was devoted to challenges unique to each method, such as surface roughness and internal porosity for additive parts or tool accessibility and fixturing for CNC-milled components.

Cost analysis formed another core objective, with estimations for tooling investments, unit production costs at low and medium volumes, material and energy consumption, labour inputs, and quality assurance expenses. This analysis was carefully tailored to Morgan's low-volume, high-customisation business model, ensuring that recommendations were commercially realistic.

Finally, the project benchmarked each design and manufacturing method against Morgan's existing hand-fabricated LCA, evaluating mass savings, structural performance, manufacturing complexity and cost-effectiveness. Based on this holistic assessment, a data-driven recommendation for an optimal manufacturing route was formulated.

3.0 Literature Review

3.1 Traditional Manufacturing at Morgan Motor Company (Plus Four)

Morgan Motor Company is renowned as a coachbuilder, priding itself on hand-crafted vehicles. Morgan touts itself as "the world's pre-eminent coachbuilder, providing a fitting antidote to mass-produced automotive manufacturing" (Morgan Motor Company). Every Morgan car is primarily built by hand, reflecting craftsmanship over automation. The Morgan Plus Four combines traditional build methods with an updated design. The Plus Four sits on Morgan's new bonded aluminium CX-Generation chassis, which is twice as stiff as the old steel ladder frame yet weighs only ~97 kg (Morgan Plus Four 2025 review – traditional charmer has modern appeal | evo). At each corner, it uses double-wishbone suspension – a notable change from Morgan's vintage sliding-pillar front suspension (an archaic design with no lower control arm) (Morgan Plus Four 2025 review – traditional charmer has modern appeal | evo) (Morgan goes modern: After 84 years, aluminium chassis replace steel frames | The Online Automotive Marketplace | Hemmings, The World's Largest Collector Car Marketplace).



Figure 3 Image showing Morgan's traditional manufacturing methods (Source: CarMagazine, 2020: online)

Despite the new aluminium chassis, Morgan has retained a traditional fabrication approach for many components. The lower control arms on the Plus Four are handmade, welded steel assemblies rather than cast or forged in large batches. Morgan's engineers cut and form steel pieces (often tubes or sheet steel profiles) and weld them into the A-arm shape in low-volume production. This process is labour-intensive but allows Morgan to avoid expensive tooling. It aligns with their ethos of craftsmanship – skilled welders ensure each LCA meets design specs. The result is a robust, if somewhat heavier, component. Notably, the Plus Four's suspension was engineered to accommodate Morgan's classic styling cues (including wire wheels on some models) (Morgan Plus Four 2025 review – traditional charmer has modern appeal | evo), which required clever engineering despite the old-fashioned appearance. The hand-fabricated steel LCAS provides the necessary strength. It allows Morgan to make minor design adjustments by hand-fitting during assembly – a flexibility not easily achieved with hard-tooled mass-production parts.

Historically, Morgan's reliance on welded steel structures served well for durability. The old steel chassis with sliding pillar suspension had been virtually unchanged for decades (Morgan goes modern: After 84 years, aluminium chassis replace steel frames | The Online Automotive Marketplace | Hemmings, The World's Largest Collector Car Marketplace). The handmade nature meant craftsmen could subtly tweak each chassis or suspension part. However, hand-welding can introduce variability and residual stresses, and it is not as weight-optimised as modern methods. Morgan's move to a new chassis and double wishbones acknowledges the need for modernisation. However, the company still leverages its small-scale fabrication skills for parts like LCAS. In summary, Morgan's Plus Four demonstrates a traditional manufacturing technique – cutting and welding steel – applied to a modern suspension design, preserving the hand-built character (Morgan Motor Company). This stands in contrast to the highly automated processes used by larger OEMS, and it sets the stage for discussing those standard methods next.

3.2 Casting

Most mass-produced automobiles manufacture control arms using either casting (often for aluminium alloys) or welded or stamped steel segments. Each process has distinct technical characteristics, material choices, and industry practices:

Casting involves pouring molten metal into a mould to form the LCA shape. This is commonly done with aluminium alloys to achieve weight savings. For example, many passenger cars use cast aluminium LCAS made of alloys like A356-T6 or A357, which offer good strength after heat treatment. The casting process (e.g. gravity sand casting or high-pressure die casting) allows complex geometric shapes, integrating features like a boss for ball joints and ribbing for stiffness.

The metal solidifies into a crystalline structure in casting with no oriented grain flow (The technical forging | FORGING industry). This means the microstructure is relatively isotropic but not reinforced in preferred directions. Castings are susceptible to internal defects: porosity, shrinkage cavities, or inclusions can form during solidification (The technical forging | FORGING industry). Manufacturers mitigate these issues through process control, using degassed molten metal, controlled cooling rates, and sometimes squeeze casting or vacuum casting to reduce porosity. Still, a cast LCA typically has lower fatigue strength than a forged one of the same material due to the lack of aligned grain and potential microscopic defects.

What is Metal Casting?

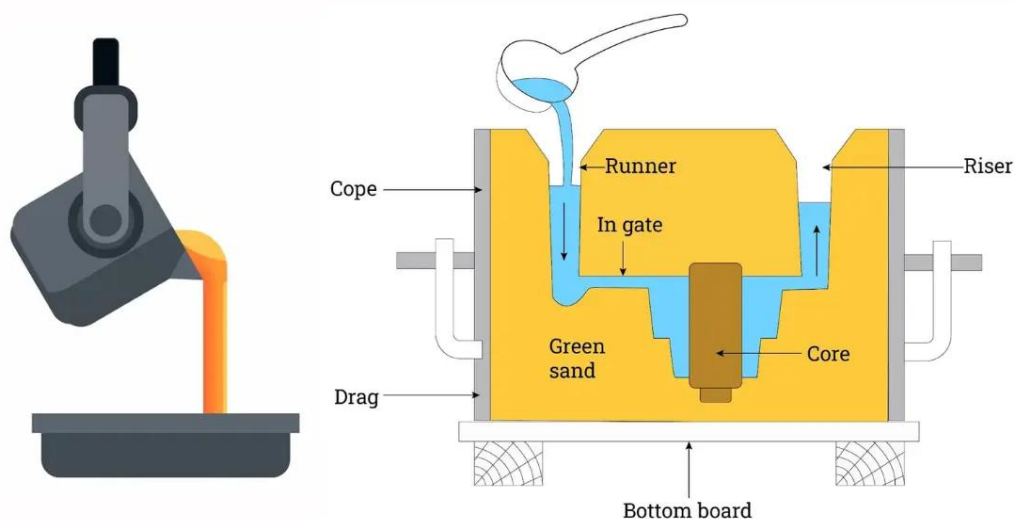


Figure 4 Diagram of Casting process (Source: MechDaily, n.d: online)

Technical parameters for casting LCAS include the melting temperature of the alloy (e.g. $\sim 660^{\circ}\text{C}$ for aluminium), mould material (steel die for high-pressure die casting or sand for gravity casting), and cooling rate (which affects microstructure and

properties). Cast aluminium LCAS are heat-treated (T6 temper) to improve strength, achieving tensile strengths at 250–300 MPa (A356 Aluminium Die Casting: Best Alloy for Automotive and Aerospace). Industry practice often favours casting for high-volume production of complex-shaped control arms. Once the tooling (dies) is made, each part can be produced relatively quickly and with minimal machining.

An example is the BMW 5 Series, which uses cast aluminium alloy front control arms for reduced unsprung mass. The casting process also allows for integrating bushing housings and gussets in one piece. The downside is the initial tooling cost and the need to carefully inspect cast parts (via X-ray or ultrasound) for internal flaws that could lead to premature failure.

3.3 Generative Designs for LCAs

Generative design technologies have surged in developing lighter, more efficient control arm designs. These techniques use software algorithms (often evolutionary or gradient-based topology optimisation) to remove unnecessary material and produce organic, high-performance shapes. The resulting geometries usually resemble bone-like or lattice-like structures that radically differ from conventional designs – they can look as if they were "grown" by nature rather than engineered in CAD (2021 Czinger 21c First Look Review). Such geometries often require advanced manufacturing methods (like casting with careful gating or additive manufacturing) to be realised because they may include curved ribs, hollow sections, or complex surfaces not achievable via simple machining.



Figure 5 Image showing Generative Design evolution of a component (Source: Sculpteo, n.d: online)

General Motors has reported using generative design for chassis components. For example, a Cadillac concept control arm was produced using generative design and then cast in aluminium as a single piece, achieving significant mass reduction (specific citation beyond 2020 would illustrate this, though details may be proprietary). In research, the study by Sookchanchai effectively showed a lightweight control arm design for stamping, indicating that even traditional processes benefit from generative design when constraints are applied. The optimised design had a skeletal form that could be realised by welding stamped high-strength steel pieces, marrying the new design with the existing process.

Generative design shines when paired with Additive Manufacturing (AM) because AM imposes fewer geometric limitations. An extreme real-world example is the Czinger 21c hypercar. This low-volume vehicle uses 3d-printed metal suspension components that were algorithmically optimised. The front upper control arms of the Czinger 21c are hollow, organically curved structures produced by laser powder-bed fusion. They have an internal lattice that conventional methods could never create (2021 Czinger 21c First Look Review). As MotorTrend described, the 21c's "spidery suspension arms" look as if they have "been grown rather than cast or machined or stamped", with a biomorphic appearance and internal truss-like features (2021 Czinger 21c First Look

Review). These generatively designed arms are significantly lighter yet stronger than traditional designs, illustrating the power of free-form optimisation when AM lifts manufacturing constraints. Kevin Czingier (the founder) even remarked that the parts "look like something from nature because nature competes for material and energy. It has to be efficient." (2021 Czingier 21c First Look Review) This perfectly encapsulates how generative design mimics evolutionary efficiency.

In 2024, Ferrari unveiled the F80 supercar, which features additively manufactured suspension arms. Although Ferrari has not published the design methodology, generative design and optimisation tools were likely employed to create those AM suspension links, given their weight reduction and performance mandate. Ferrari reports that the F80 is the brand's first road car to have 3d-printed structural suspension components, with the double wishbone suspension arms produced through Additive Manufacturing (Ferrari F80 Showcases Additive Manufacturing in Suspension System - 3d Printing). This highlights an industry trend: generative-designed, 3d-printed suspension parts moving from concept and hypercars into (elite) production vehicles.



Figure 6 Image of Ferrari F80 suspension arm (Source: 3DPRINTING.COM, 2023: online)



Figure 7 Image of Ferrari F80 suspension assembly (Source: 3dSPRO, 2024: online)

McLaren has also joined the wave of generative design for suspension systems in developing the W1, a concept platform used internally to explore next-generation vehicle architectures. The W1 incorporates lightweight, functionally integrated suspension components designed using generative algorithms. According to engineering leads at McLaren, the front and rear control arms on the W1 are digitally optimised for mass and stiffness and then produced using hybrid AM and subtractive finishing processes. While the W1 remains a technology demonstrator rather than a

production car, the control arms reportedly achieve double-digit weight savings over traditional forged aluminium parts and incorporate novel internal channels for weight reduction and stiffness tuning. McLaren's use of generative design in a real vehicle platform signals their intent to transition such components into future supercars, aligning with the industry's growing confidence in generative AM for structural parts.



Figure 8 Image of McLaren W1 front upright (Source: *tctMagazine*, 2024: online)



Figure 9 Image of McLaren W1 front suspension (Source: *Topgear*, 2024: online)

3.4. Additive Manufacturing Methods for LCAS (LPBF, EBM, DED)

The maturation of metal additive manufacturing (AM) has opened doors for creating complex, load-bearing automotive components such as lower control arms (LCAS). With high design flexibility and increasing material capabilities, AM supports applications beyond prototyping, especially in low-volume or performance-focused sectors. Three primary AM processes stand out for producing LCAS: Laser Powder Bed Fusion (LPBF), Electron Beam Melting (EBM), and Directed Energy Deposition (DED). Each offers distinct principles, advantages, limitations, and relevant automotive use cases.

3.4.1 Laser Powder Bed Fusion (LPBF)

Laser Powder Bed Fusion (LPBF), also referred to as Selective Laser Melting (SLM), is an additive manufacturing technique where thin layers of metallic powder (typically 20–60 μm thick) are selectively melted by a high-energy fibre laser, building parts layer-by-layer within an inert atmosphere, commonly argon or nitrogen, to prevent oxidation. The process begins with the powder being spread over a build platform using a recoater blade, followed by laser scanning according to the slice geometry

from the CAD model. Successive layers are built upon the previous solidified structure, achieving acceptable resolution and enabling the manufacture of highly complex geometries, including hollow lattices, integrated cooling channels, and topology-optimised load paths. Materials typically used in LPBF include AlSi10Mg aluminium alloy (offering ~320 MPa UTS after T6 heat treatment), Ti-6Al-4V titanium alloy (exceeding 900 MPa UTS after HIP treatment), and nickel-based superalloys like Inconel 718, chosen for their high strength-to-weight ratios and corrosion resistance. LPBF can achieve near-fully dense parts (>99.5%). However, defects such as keyholing porosity, lack of fusion, and microcracking may occur if parameters such as laser power (~200–400 W), scan speed, hatch spacing, and layer thickness are not optimally controlled. The build orientation significantly affects mechanical anisotropy, where vertically built parts exhibit slightly reduced ductility compared to horizontally built samples due to columnar grain growth aligned along the build direction. Thermal stresses accumulate due to the rapid localised heating and cooling, necessitating support structures to anchor parts and resist warping. Post-processing heat treatments like stress relief annealing are often required to ensure the quality of the final product. The surface finish directly off the machine is typically rough ($R_a \sim 10\text{--}20\text{ }\mu\text{m}$), requiring CNC machining of critical mating surfaces such as ball joint seats and bushing housings in LCAS.

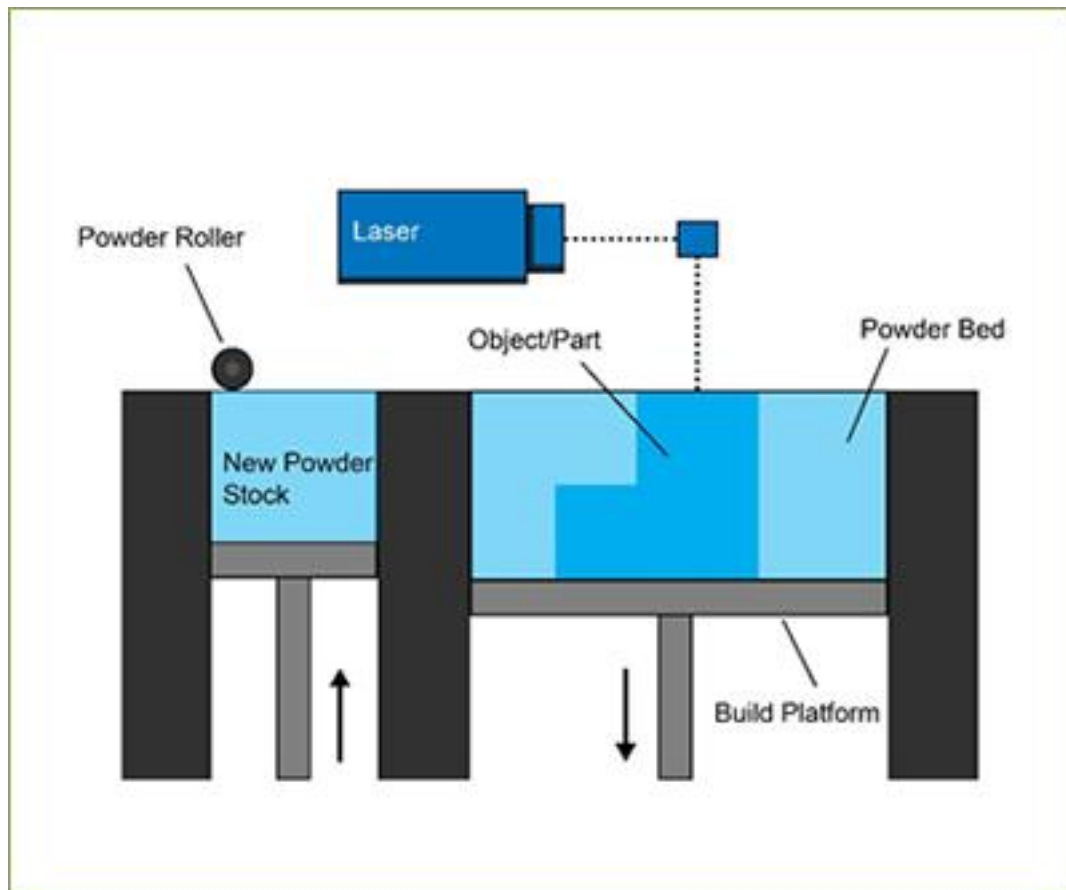


Figure 10 Diagram of LPBF 3d printing (Source: Loughborough University, n.d: online)

3.4.2 Electron Beam Melting (EBM)

Electron Beam Melting (EBM) is another powder bed fusion technology. However, it uses a focused electron beam, operating at 30–60 kV, to selectively melt metallic powders under high-vacuum conditions ($\sim 10^{-5}$ bar), making it particularly suited to reactive metals like titanium (Ti-6Al-4V) and cobalt-chrome alloys. Unlike LPBF, EBM preheats the entire powder bed to elevated temperatures ($\sim 600\text{--}800$ °C) before melting, drastically reducing thermal gradients and thus minimising residual stresses and the risk of part warping. This intrinsic stress relief allows the production of significant, dense components without needing separate post-build annealing steps. The higher layer thickness ($\sim 50\text{--}100$ μm) and beam power enable faster build rates. However, the resulting surface roughness is significantly higher ($R_a \sim 20\text{--}40$ μm), often requiring more aggressive surface finishing or machining for tight-tolerance automotive interfaces. Because the surrounding powder is partially sintered during preheating, parts are effectively self-supported, enabling complex overhangs without

dedicated support structures—a significant advantage for generatively designed LCAS with organic branching geometries. Material microstructure in EBM typically shows a fine acicular α' martensitic phase for Ti-6Al-4v, improving strength but sometimes reducing ductility unless post-processed. EBM-processed Ti-6Al-4v parts often reach mechanical properties comparable to forged equivalents (UTS ~930 MPa, elongation ~10%). However, dimensional tolerances are less precise than LPBF (typically ± 0.3 mm versus LPBF's ± 0.1 mm), making EBM less suitable for incredibly intricate thin-walled components but ideal for robust suspension parts or large chassis nodes. Aerospace industries have pioneered EBM, notably for orthopaedic implants and aircraft brackets. Automobile applications are emerging, with concepts like titanium control arms and heavy-duty chassis nodes for low-volume performance vehicles. Companies like Arcam (now part of GE Additive) have demonstrated EBM's feasibility for critical load-bearing structures in demanding environments, suggesting its suitability for future LCAS subjected to fatigue-critical dynamic loads.

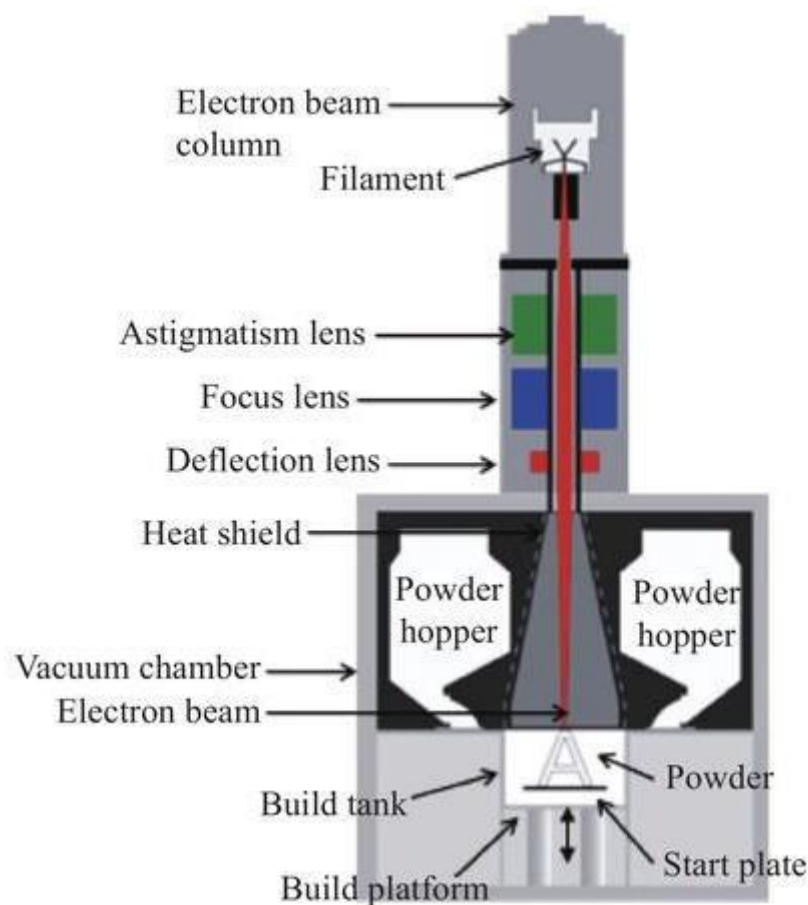


Figure 11 Diagram of EBM 3d printing (Source: AM-Material, n.d: online)

3.4.3 Directed Energy Deposition (DED)

Directed Energy Deposition (DED) represents a family of metal additive manufacturing techniques where material, fed either as powder or wire, is melted by a focused thermal energy source, commonly a laser (Laser Metal Deposition, LMD), electron beam (Electron Beam Additive Manufacturing, EBAM), or electric arc (Wire Arc Additive Manufacturing, WAAM), and deposited layer-by-layer to create near-net-shape parts. Unlike powder bed systems, DED systems are often mounted on robotic arms or multi-axis CNC platforms, allowing freeform fabrication without the constraints of a static powder bed. DED supports a broad range of materials, including steels (e.g., 17-4ph, maraging steels), titanium (e.g., Ti-6Al-4v), aluminium (e.g., 6061, 7075), and nickel-based superalloys, with deposition rates ranging from 10–50 g/min depending on the system and material. Key technical advantages include building vast structures (up to several meters) and performing in-situ repairs, such as rebuilding worn-bearing seats or reinforcing stressed regions on LCAS. However, DED typically produces coarse microstructures due to slower cooling rates than LPBF or EBM, resulting in lower resolution (minimum feature sizes $\sim 2\text{--}5\text{ }\mu\text{m}$) and rougher as-built surfaces ($R_a \sim 30\text{--}50\text{ }\mu\text{m}$). Dimensional tolerances are broader ($\pm 0.5\text{ mm}$ or more), and finishing via machining is usually necessary for precision features. Thermal management is crucial; significant thermal gradients can lead to anisotropic mechanical properties, large columnar grains, or residual stresses without careful process control. Advanced DED systems like WAAM3D and Sciaky's EBAM incorporate closed-loop thermal feedback and path planning strategies to mitigate such issues, ensuring more uniform material properties. DED is particularly attractive in the automotive context for producing oversized parts like subframes, tubular LCA blanks, and heavy-duty suspension links, where complex internal geometries are unnecessary. For instance, large WAAM-produced blanks can be CNC-machined down to final suspension geometry, significantly reducing the material waste compared to billet machining from solid aluminium or titanium. Emerging hybrid manufacturing concepts, such as Divergent 3d's node-link architecture, combining LPBF-printed critical nodes with carbon composite or WAAM-formed tubular links, point towards a future where DED enables scalable, cost-effective production of lightweight chassis and suspension systems.

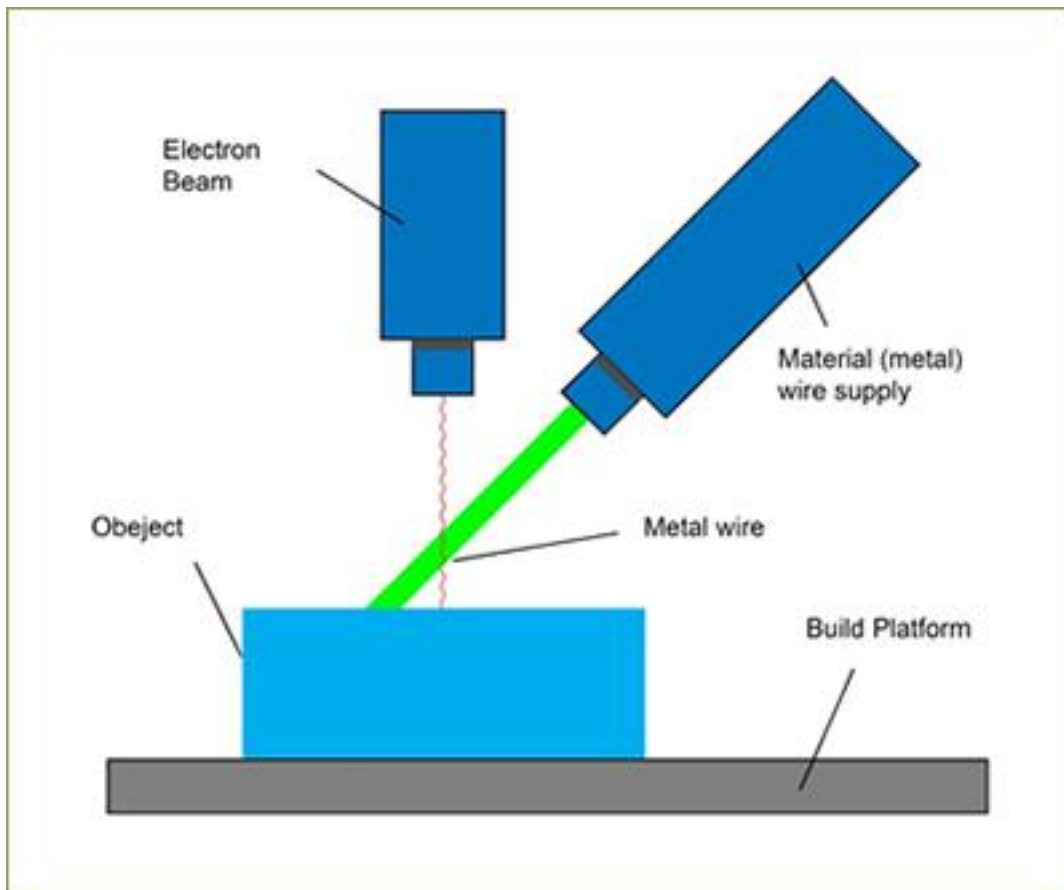


Figure 12 Diagram of DED 3d printing (Source: Loughborough University, n.d: online)

3.4.4 Additive manufacturing summary

Additive Manufacturing is revolutionising the design and production of LCAS by enabling novel geometries, lightweight, and material efficiency. LPBF leads in resolution and complexity, making it ideal for performance suspension arms. EBM offers better thermal management and faster builds for specific high-end materials like titanium. DED's unparalleled scalability and deposition rates open large, custom, or repair parts possibilities.

As costs decrease and printer technologies evolve, such as multi-laser LPBF systems and improved robotic DED heads, AM adoption in the automotive industry is poised to expand. While currently concentrated in motorsports and exotic vehicles, AM-based suspension components may soon see broader use, especially as hybrid approaches (combining DED and LPBF) emerge. However, AM parts must meet rigorous structural validation before integration—an essential step discussed in subsequent sections of this report.

3.5 CNC Milling

CNC (Computer Numerical Control) milling is a subtractive manufacturing method widely used to create precise, complex parts from solid material blocks. It utilises rotating cutting tools, guided by computer-generated instructions, to systematically remove material and achieve the desired geometry. Due to its precision, repeatability, and versatility, CNC milling is valued across various sectors, notably automotive, aerospace, and medical industries.

CNC milling machines are categorised primarily by their axis capabilities—commonly 3-axis, 4-axis, and 5-axis configurations.

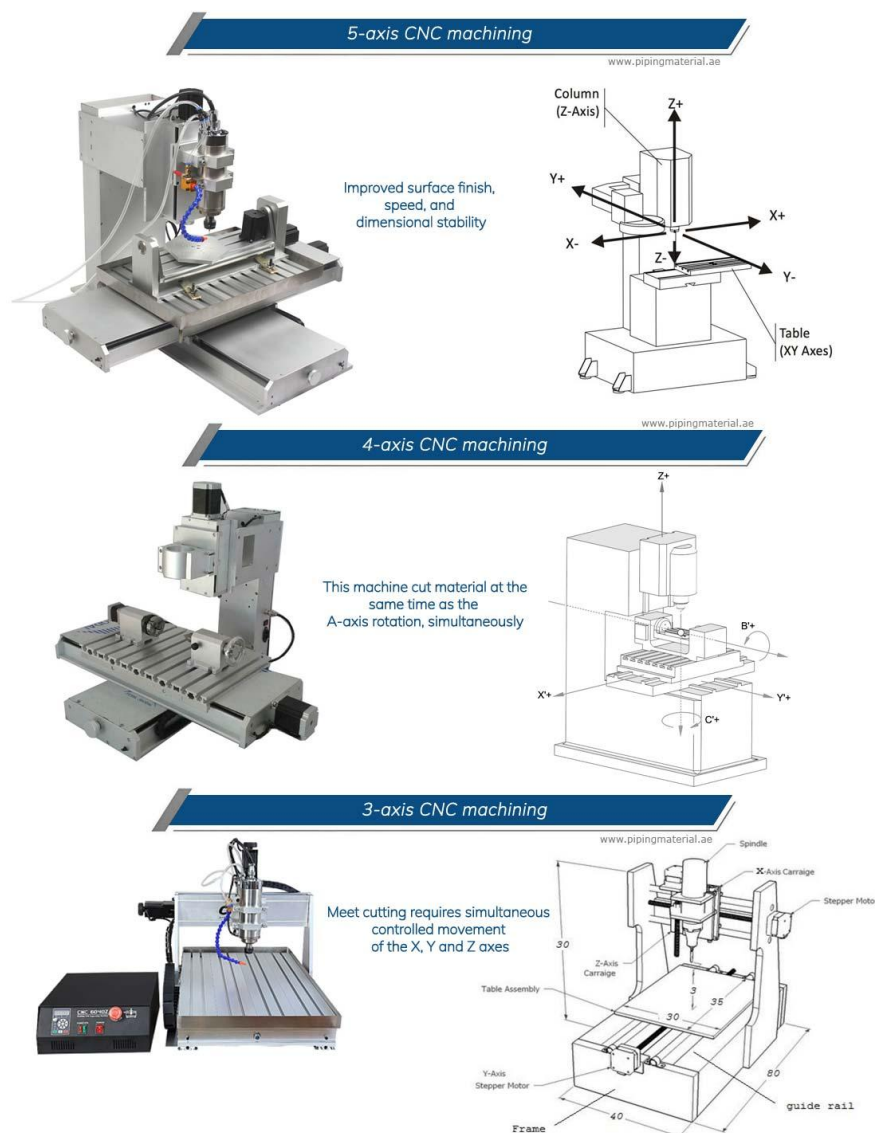


Figure 13 Image comparing 3,4, and 5-axis CNC machines (Source: pipingmaterial.ae, n.d: online)

The 3-axis CNC milling machine operates along the X, Y, and Z linear axes, suitable for manufacturing simple parts with straightforward geometries such as plates, brackets, or bare control arms. These are parts that do not have complex shapes or features. It is cost-effective, easy to operate, and highly reliable for producing components with accessible geometries. However, it has limitations in complexity, as it requires manual repositioning for multi-face operations, which increases setup time and introduces potential inaccuracies.

4-axis CNC milling enhances capability by introducing a rotational axis (typically the A-axis), allowing parts to be rotated around the X-axis. This facilitates machining features on multiple sides without manual repositioning, significantly reducing setup time and enhancing precision for multi-faced parts. It excels in producing cylindrical or helical features such as shafts, camshafts, or moderately complex automotive suspension parts like lower control arms that need machining from multiple angles. Despite its advantages, 4-axis milling machines introduce higher complexity and cost than 3-axis machines.

5-axis CNC milling machines represent the pinnacle of CNC milling capability, adding another rotational axis and allowing cutting tools to approach from virtually any angle. This level of flexibility supports the manufacture of highly complex geometries, intricate features, and optimised shapes typically impossible with fewer axes. Automotive components, such as highly optimised suspension arms and engine components, benefit significantly from 5-axis milling due to reduced setup times, improved accuracy, superior surface finish, and minimised machining errors. While 5-axis CNC milling offers unparalleled advantages for complex components, it is associated with higher costs, increased programming complexity, and more stringent operator skill requirements.

CNC milling is particularly advantageous in manufacturing vehicle lower control arms (LCAS) because it can precisely control dimensional accuracy and produce optimised, lightweight structures. Using multi-axis milling machines, particularly 5-axis configurations, manufacturers can produce LCAS with complex, optimised shapes designed for reduced weight and improved strength. This allows for better vehicle handling, enhanced safety, and performance gains. The ability to precisely machine critical areas such as bushing housings, ball joint mounts, and intricate load-bearing

features makes CNC milling a preferred method for prototyping and low-volume production runs in performance-focused automotive applications.

CNC milling provides superior accuracy, repeatability, and design flexibility, enabling precise dimensional tolerances and complex geometries for critical automotive components. Nevertheless, CNC milling also involves higher initial investments and operational complexity, with increased material waste compared to additive manufacturing techniques. Consequently, selecting CNC milling, especially between 3-axis, 4-axis, and 5-axis options, depends on the specific geometric complexity, production volume, precision requirements, and budget constraints.

3.6 Structural Analysis of LCAS in Automotive Suspension

The Lower Chassis Arm (LCA) constitutes a primary load-bearing element within a vehicle's suspension architecture, transmitting forces between the chassis and wheel assembly. The LCA must endure a complex superposition of dynamic loads due to its critical function, including vertical impacts from road irregularities, lateral cornering forces, longitudinal braking and acceleration inputs, and vibrational excitations. Consequently, comprehensive structural analysis is imperative to ensure mechanical robustness, fatigue resistance, and vibrational integrity across the intended vehicle.

A rigorous structural validation methodology integrates advanced computational simulations, Finite Element Analysis (FEA), fatigue life estimation, and modal analysis, with empirical validation through physical testing. Each technique provides unique insights into the mechanical performance envelope of the component, collectively enabling robust and optimised design solutions.

Finite Element Analysis (FEA)

Finite Element Analysis is a foundational computational tool used to predict the static structural response of the LCA under various operational load cases. A meshed finite element model replicates the geometry and material behaviour, enabling the simulation of stresses, strains, and displacements arising from applied boundary conditions and external forces.

Typical load cases for LCA analysis encompass:

- Longitudinal braking forces inducing axial tension or compression,

- Lateral cornering loads generate significant bending and shear stresses,
- Vertical bump impacts simulate road surface irregularities,
- Combined dynamic conditions are representative of aggressive driving manoeuvres.

Boundary conditions are meticulously defined to emulate realistic interfaces, such as rigid chassis mounting points and compliant ball joint constraints. The FEA outputs include Von Mises stress distributions, total deformation fields, and safety factors, thereby identifying critical stress concentrations that inform iterative design improvements.

Additionally, compliance assessments are conducted to evaluate deflections under operational loads. Excessive LCA flexibility can adversely affect suspension kinematics, leading to degraded handling precision and unpredictable vehicle dynamics. Compliance targets guide structural stiffness optimisation, typically specified in millimetres of lateral and longitudinal deflection under defined loads.

FEA also enables topology optimisation studies, where the material is strategically redistributed based on load paths to minimise weight while preserving structural performance. Notably, FEA-driven optimisation has demonstrated mass reductions exceeding 40–50% in control arms without compromising mechanical safety margins.

Fatigue Life Prediction

Given the cyclic nature of automotive loading, fatigue failure remains a dominant failure mode for suspension components. Fatigue analysis employs stress-life (S–N) or strain-life (ϵ –N) methodologies, utilising material-specific fatigue curves to predict the number of cycles to failure under given stress amplitudes.

High-cycle fatigue (HCF) and low-cycle fatigue (LCF) regimes are considered, particularly at stress concentrators identified via FEA. Critical regions such as weld toes (in fabricated designs), fillet radii, or thin rib junctions are meticulously assessed for an LCA.

Modern fatigue assessments often incorporate:

- Mean stress correction models, such as Goodman or Gerber relationships,

- Multiaxial fatigue criteria, such as critical plane methods,
- Probabilistic fatigue life estimation to account for material and loading variability.

Achieving a design life consistent with vehicle durability targets—often exceeding 10^6 load cycles—while maintaining acceptable safety factors (typically >1.5 for fatigue) is essential for structural certification.

Modal Analysis and Vibrational Integrity

The vibrational behaviour of the LCA is evaluated through modal analysis to prevent detrimental resonance phenomena. The component's natural frequencies and mode shapes are computed, considering free-body conditions or, preferably, realistic chassis attachments.

Suspension components must avoid modal frequencies that coincide with operational excitation sources:

- Road-induced vibrations (<30 Hz),
- Engine harmonics (typically between 40–200 Hz),
- Brake judder or driveline excitations.

First bending and torsional modes are of particular concern, as amplification of these modes under operational inputs can lead to fatigue, the component's poor ride quality and undesirable NVH (Noise, Vibration, Harshness) characteristics.

Strategies to optimise modal behaviour include:

- Geometric stiffening through strategic rib placement,
- Material selection balancing mass and stiffness,
- Integration of passive damping treatments if necessary.

A modal separation margin of at least 20–30% relative to dominant excitation frequencies is typically targeted to ensure robustness against resonance.

Physical Validation and Model Correlation

Following computational analyses, physical prototypes undergo validation testing, encompassing:

- Static load testing to verify ultimate strength and deformation under peak loads,
- Fatigue testing under controlled cyclic loading profiles,
- Modal impact testing uses accelerometers and modal hammers to experimentally identify eigenfrequencies and mode shapes.

Discrepancies between experimental and computational results necessitate Finite Element Model Updating (FEMU), wherein model parameters such as bushing stiffnesses and joint constraints are refined to better correlate simulation outputs with physical test data. High-fidelity model correlation is critical for ensuring predictive simulation reliability in subsequent design iterations.

4.0 Methodology

This project adopted a comprehensive and iterative engineering methodology, integrating theoretical research, computational simulation, and manufacturability analysis. The primary objective was to explore alternative manufacturing methods for the Morgan Plus Four Lower Control Arm (LCA), ensuring that proposed designs would be technically robust, manufacturable within Morgan's bespoke production environment, and benchmarked rigorously against traditional fabrication approaches.

4.1 CAD Modelling and Initial Concept Development

The initial phase involved developing detailed 3d CAD models. A baseline model replicating the traditional hand-fabricated steel LCA was first found. Autodesk Fusion 360 was then used to create generatively designed components optimised for casting, additive manufacturing, and CNC milling using manufacturing-specific constraints such as overhang limitations for additive manufacturing and tool accessibility constraints for CNC milling. Throughout the modelling process, key constraints such as compatibility with Morgan's existing chassis mounting points, preservation of suspension kinematics, and packaging for component clearance were carefully maintained. The casting-optimised design incorporated features such as draft angles and simplified forms to facilitate manufacturability, whereas the additive and CNC designs were consciously shaped to exploit the capabilities and overcome the limitations inherent to each respective production method. The output geometries achieved substantial mass reductions while maintaining necessary structural performance, ensuring the designs remained technically optimal and adaptable to different manufacturers for Morgan's production environment.

4.2 Finite Element Analysis (FEA) for Structural Evaluation

Each LCA design underwent a rigorous structural evaluation using Finite Element Analysis (FEA) conducted with the industry-standard ANSYS Mechanical. The simulations included static structural analysis under combined longitudinal, lateral, and vertical loading scenarios and assessments of stress distribution, elastic strain, and total deformation. Material properties were carefully assigned based on the intended production method and material choice, including A356-T6 for cast components and AlSi10Mg for additive-manufactured arms. Boundary conditions were modelled to replicate realistic chassis and ball joint connections. This simulation phased each

design's mechanical performance, ensuring that only feasible and structurally sound concepts proceeded to the manufacturability and cost assessment stages.

4.3 Manufacturability Assessment

After simulation validation, each LCA concept underwent a critical assessment for manufacturability. This comprehensive evaluation considered the required tooling, equipment, material efficiency, cycle times, post-processing needs, and overall suitability for integrating Motor Company's low-volume, highly bespoke manufacturing model. Special attention was given to practical factors such as fixturing complexity for CNC milling, support removal and surface finishing requirements for additive manufacturing, and mould preparation for casting. This assessment provided a realistic evaluation of how each manufacturing method could be adapted to meet technical and operational demands without compromising the company's artisanal ethos.

4.4 Cost Analysis

A detailed cost analysis was undertaken to evaluate the approach's feasibility further. This analysis considered various financial factors, including initial capital equipment investment, setup and programming costs, material costs based on volume and material type, labour costs for fabrication or operation, post-processing expenses, and quality assurance requirements. Prototype-level and low-to-medium-volume production costs were estimated to enable Morgan's bespoke manufacturing scale. The financial analysis clearly understood the trade-offs between traditional fabrication methods and the advanced manufacturing options under investigation.

5.0 Project Timeline

The project timeline was systematically structured to ensure a coherent, phased progression aligned with the research objectives. Between October and December, an extensive literature review was undertaken, critically analysing traditional and advanced manufacturing methods for Lower Control Arms (LCAS), complemented by the initial development of detailed CAD models and the definition of technical requirements. January focused on finalising the LCA designs, including cast aluminium, additive manufactured, and CNC milled variants, followed by a comprehensive finite element analysis (FEA) to assess static performance and modal characteristics under representative load cases. In February, a detailed manufacturability assessment was conducted, evaluating tooling demands, material efficiency, scalability, post-processing requirements, and alignment with Morgan Motor Company's low-volume, bespoke production model. March was dedicated to a rigorous comparative benchmarking exercise, analysing structural performance, mass reduction, fatigue resistance, production complexity, and cost-effectiveness across all manufacturing methods. These results were used for evidence-based recommendations for optimal future manufacturing strategies. In April, the report was refined through iterative refinement, incorporating final edits, comprehensive proofreading, and formatting to meet the institution's submission standards. Effective time management, adaptability to emerging technical insights, and a focus on technical depth were consistently maintained throughout the project. The phased approach ensured that each stage contributed meaningfully to the overarching objective: to evaluate and recommend advanced manufacturing methods capable of enhancing LCA performance while preserving Morgan Motor Company's traditional ethos of craftsmanship.

6.0 Resources and Requirements

The successful execution of this project has relied heavily on a combination of specialised software, technical facilities, academic support, and well-defined project-specific requirements. These requirements, tailored to the engineering nature of the study and focused on CAD design, simulation, and manufacturability analysis, ensured the thoroughness of the project. Access to robust digital tools and physical infrastructure was critical at every stage.

SolidWorks and Fusion360 were employed for 3d CAD modelling for software resources to create detailed Lower Control Arm (LCA) designs across different manufacturing methods, including cast aluminium, additive manufacturing and CNC milling. SolidWorks allowed precise parametric modelling, ensuring full compatibility with the Morgan Plus Four chassis layout and seamless export to simulation platforms. ANSYS Mechanical was the primary simulation tool, facilitating static structural analysis under representative load cases. These tools enabled constraint-driven design generation, applying load-path optimisation, minimum member sizing, specific constraints for overhangs and drawing directions to ensure manufacturability. For managing the cost analysis and report writing, Microsoft Excel and Word were utilised to create comparative tables, charts, and structured content for the final dissertation submission.

7.0 Component design

7.1 Simulation set up

To accurately assess the structural performance of each Lower Control Arm (LCA) design, a meticulously detailed Finite Element Analysis (FEA) workflow was established using ANSYS Mechanical. The simulation setup was structured to ensure consistency, replicability, and technical robustness across all design variants, supporting credible comparative evaluations between manufacturing approaches.

7.1.1 Geometry Preparation

All LCA geometries, including the traditionally welded design, the cast-optimised model, the additive manufacturing (AM) topology-optimised design, and the CNC-milled designs, were imported into ANSYS as clean, defeatured STEP files. Non-critical features such as small fillets, manufacturing tabs, and tiny holes were suppressed where they did not affect structural performance. This approach improved meshing efficiency while maintaining the integrity of load paths and critical features essential for accurate simulation outcomes.

7.1.2 Material Assignment

Each LCA design was assigned material properties appropriate to its intended manufacturing method. The traditional welded steel LCA was modelled using mild steel, assuming a yield strength of approximately 250 MPa. The cast aluminium version was assigned properties for A356-T6 aluminium alloy, with comparable yield strength, while the AM design employed AlSi10Mg properties following post-heat treatment. The CNC-milled design used 7075-T6 aluminium alloy, offering a significantly higher yield strength of around 500 MPa. Each material's elastic modulus, Poisson's ratio, and density were defined based on industry-standard data to ensure accurate predictions of stiffness, mass, and structural behaviour.

7.1.3 Meshing Strategy

An acceptable mesh strategy was implemented to capture stress concentrations accurately, particularly around critical features such as mounting holes, load paths, and interfaces. Quadratic tetrahedral elements were utilised throughout, with element

sizing refined to 1mm. Mesh independence studies were conducted, particularly on the generatively designed AM and cast models, confirming that key results varied by less than 5% with further refinement. This level of variation is within the acceptable range for FEA studies, indicating the reliability and robustness of our simulation results.

7.1.4 Boundary Conditions

Realistic automotive suspension boundary conditions were meticulously applied to replicate operational constraints. Fixed supports were assigned to the chassis mounting points, simulating rigid connections. At the same time, calculated forces were used at the ball joint interface to allow force application without excessive over-constraint. Although bolt preloads were not explicitly simulated, they were considered negligible relative to operational loads. All contact surfaces were bonded to represent the stiffness provided by bushings and ball joints during typical driving conditions.

7.1.5 Loading Conditions

Vehicle load transfer calculations were conducted to determine realistic worst-case loading scenarios on the Lower Control Arm (LCA) during aggressive driving conditions. These calculations accounted for dynamic effects from braking, cornering, and vertical bump events, ensuring that the applied loads accurately represented peak operational demands on the component. For instance, during aggressive cornering, the LCA experiences a lateral force reaching up to 10,600 N, simulating severe cornering loads. Similarly, a longitudinal force of 9,200 N is applied during challenging braking conditions, and during bump or rebound impacts from road irregularities, a vertical force of 3,000 N is applied. This multi-axial loading configuration was applied at the ball joint location and directed through the wheel hub interface, reflecting the suspension load paths observed in real-world dynamic events. Applying these peak forces provided a conservative and robust basis for evaluating the structural performance of all LCA design variants.

7.1.6 Solution Settings

All simulations utilised static structural solvers within ANSYS Mechanical. Extensive deflection analysis was activated, particularly for lightweight AM and CNC designs where geometric non-linearities could influence results.. Solver settings were program-controlled to optimise stability and efficiency. Key outputs included maximum

Von Mises stress, elastic strain, and total deformation, with particular attention to stress concentrations at cantilevered or thin-rib regions in the generative designs.

7.1.7 Post-Processing

Post-processing activities involved a comprehensive extraction and comparative evaluation of simulation results across all designs. Critical metrics were recorded, including maximum Von Mises stress, maximum elastic strain, and total deformation. Stress distribution plots were scrutinised to identify potential failure initiation sites and compliance issues, ensuring a thorough analysis.

7.2 Existing design (Hand-Fabrication/Welding)

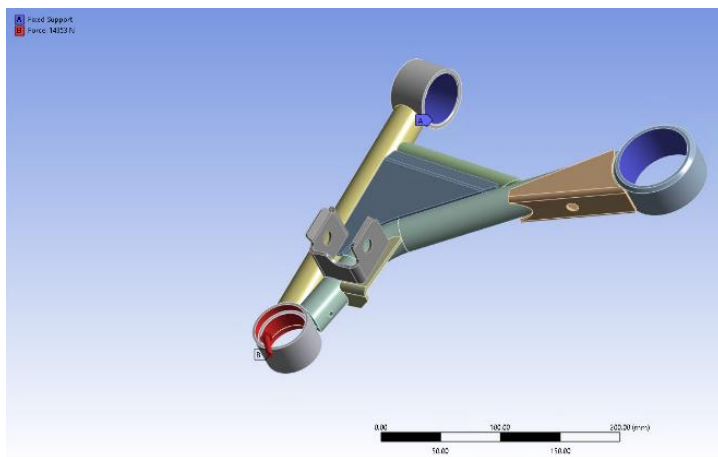


Figure 14 Image of the setup of the existing components' static structural simulation

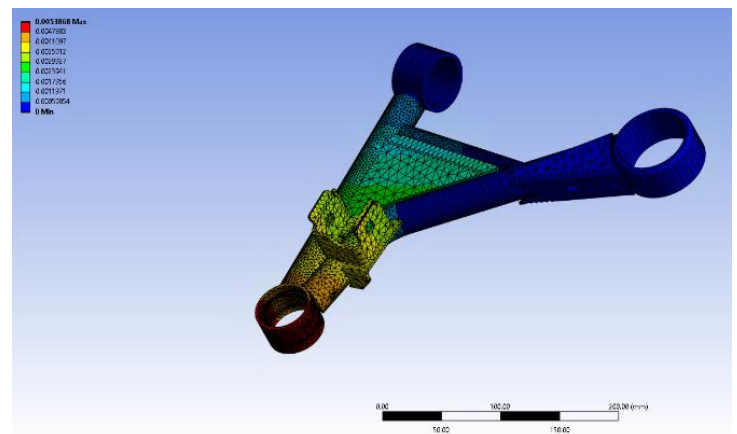


Figure 15 Image of the existing components' maximum deformation

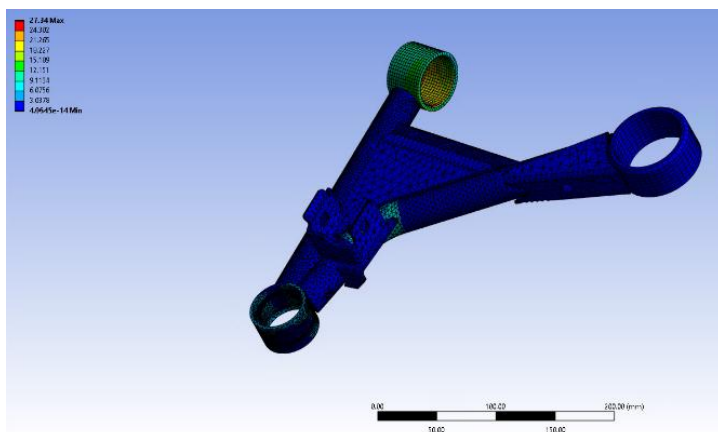


Figure 16 Image of the existing components' maximum Von Mises stress

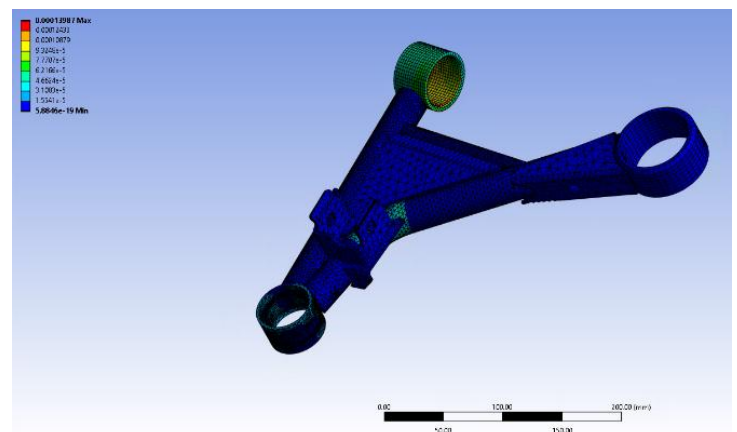


Figure 17 Image of the existing components' maximum Von Mises stress

The traditionally manufactured lower control arm design was created following conventional engineering principles, using straightforward geometrical forms and

established fabrication techniques. The geometry prioritised manufacturability through stamping, forging, or basic machining, resulting in a design characterised by flat sections, simple fillets, and clear load paths. While adequate regarding production ease and robustness, this conventional design was not optimised for mass efficiency or minimum material usage compared to the generative designs. For instance, the traditional design may use more material due to its conservative approach, while the generative design, with its topological optimisation, can achieve the same strength with less material.

The traditionally manufactured component's finite element analysis (FEA) showed a **maximum equivalent (Von Mises) stress** of **27.34 MPa**. This relatively low stress level indicates the structure is highly conservative, with a significant margin, before reaching the material's yield strength. Such conservative design, typical in traditional automotive suspension components, reassures us of its reliability, where safety factors are often prioritised over material efficiency.

The **maximum elastic strain** was recorded at **0.00013987 mm/mm** or **0.013987%**. This very low strain value highlights the component's substantial stiffness, instilling confidence in its performance and confirming that minimal elastic deformation occurs under load, which is advantageous for maintaining suspension geometry and vehicle handling characteristics.

The **total deformation** under the applied loading conditions was measured at **5.3868 mm**. This is noticeably higher than the deformation in the generative designs, reflecting the increased mass and lack of topological optimisation in the traditional approach. Despite the greater deformation, the structural integrity of the arm remained fully intact, and the deformation values are still within acceptable limits for vehicle operation. However, this higher deformation can increase wear and tear and reduce component lifespan.

Overall, while the traditional lower control arm design offers simplicity, high stiffness, and ease of manufacture, it is considerably heavier and less material-efficient than the advanced generative designs developed in later sections. However, its simplicity may provide comfort due to its familiarity.

7.3 Generative Design Studies

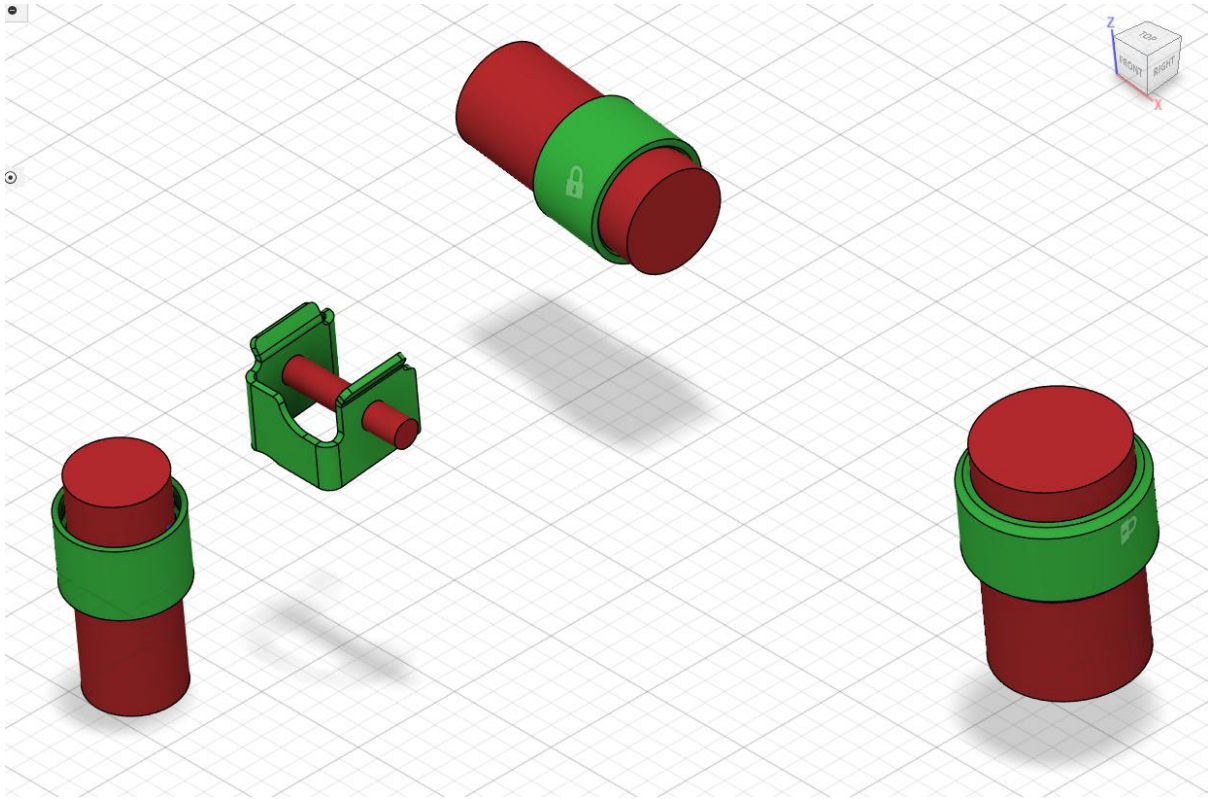


Figure 18 Image of the setup of Fusion360 Generative design study

Generative design tools were utilised to create optimised LCA geometries tailored to each proposed manufacturing method. Autodesk Fusion 360's Generative Design platform enabled the development of distinct lower control arm designs, each balancing mass reduction, structural performance, and manufacturability according to the constraints and capabilities of casting, additive manufacturing, and CNC milling processes.

7.3.1 Design Space and Load Case Definition

The generative design process began with importing a simplified baseline CAD model of the existing LCA into Fusion 360. A design space was defined, encompassing all critical structural regions that required preservation, including chassis mounting points, the ball joint interface, and the coilover bracket. Clearance envelopes were established to ensure full compatibility with suspension articulation and wheel movement. Precision constraints were then applied to preserve key mating interfaces, ensuring that any generated geometry would seamlessly integrate with the Morgan Plus Four's existing chassis and suspension system. The generative design solver

was subsequently tasked with optimising material flow paths based on realistic suspension load cases reflective of braking, cornering, and bump forces.

7.3.2 Generative Design Parameters

Separate generative studies were conducted for each targeted manufacturing method, with appropriate constraints applied. For the casting-oriented design, a single draw direction constraint was imposed to ensure mouldability, with a minimum member size of 10 mm to avoid thin, uncastable features. The material specified was A356-T6 aluminium alloy, with the optimisation objective focused on mass reduction while maintaining a safety factor above 2.0. The additive manufacturing (AM) study removed draw constraints to fully leverage LPBF's design freedom, with a minimum member sizing set between 4 mm and 6 mm to accommodate thin ribs and hollow structures typical of AM production. AISi10Mg was selected as the material, and extreme mass reduction was prioritised. For the CNC milling study, tool accessibility constraints suitable for 3-axis and 5-axis milling were applied, prohibiting internal voids and limiting undercuts, with a minimum member size of 8 mm to ensure machinability. The selected material was 7075-T6 aluminium, with the optimisation goal again focused on weight reduction without compromising manufacturability on standard CNC platforms.

7.3.3 Advantages of Using Fusion 360's Generative Design

Fusion 360's Generative Design platform offered several critical advantages throughout optimisation. It enabled the rapid exploration of hundreds of design iterations, balancing mass efficiency with practical manufacturing constraints. Built-in manufacturability features ensured that outcomes were not merely theoretical but realistically achievable. Integrated cloud computing resources accelerated complex simulation tasks, significantly reducing development time. Furthermore, Fusion 360's direct linkage between topology optimisation outputs and subsequent finite element validation allowed for a seamless and iterative refinement. This approach ensured that all generated LCA designs delivered significant structural improvements over the baseline, with optimisations that remained feasible for the respective manufacturing strategies.

7.4 Generative Design for Casting

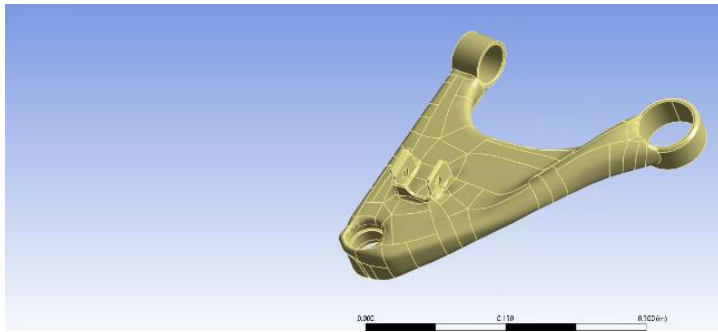


Figure 19 Image of the setup of the cast components' static structural simulation

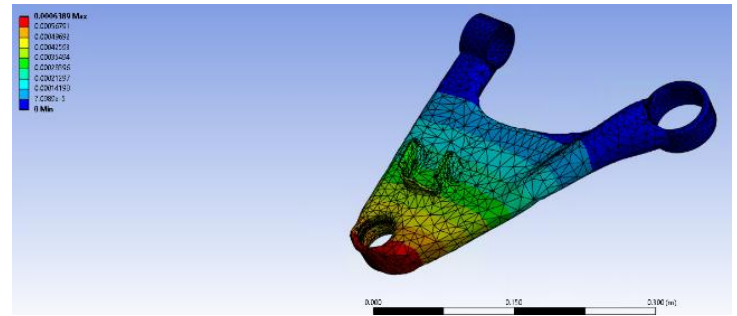


Figure 20 Image of the cast components' maximum deformation

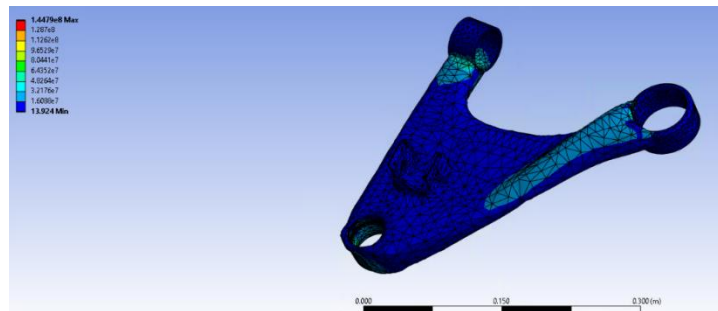


Figure 21 Image of the cast components' maximum Von Mises stress

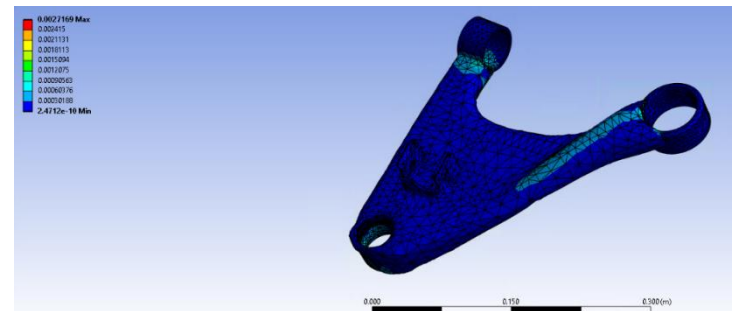


Figure 22 Image of the cast components' maximum Von Mises strain

The generative design adapted for aluminium casting focused on manufacturability using low-pressure die casting of A356-T6. The design retained key mounting features while incorporating tapered ribs and curved arms conducive to mould extraction, draft angles, and gating systems.

Under standard multi-axial load conditions, the **maximum equivalent Von Mises stress**, a measure of the material's resistance to deformation, reached approximately **98.86 MPa** ($9.886\text{e}+007$ Pa). This is well below the typical yield strength of A356-T6 (~ 250 MPa), indicating a robust safety margin for static loading.

The **maximum elastic strain** was **0.001365 mm/mm** or **0.1365%**. These strain values remain within the elastic regime and confirm suitable stiffness for operational performance, instilling confidence in its functionality.

Maximum deformation was found to be **0.6389 mm** ($6.389\text{e}-004$ m). This low deflection highlights the component's structural rigidity, providing a sense of security about its stability, with most deformation occurring near extended arms and the coilover bracket interface.

Though heavier than additive or milled versions, the cast design offered excellent mechanical performance at lower production cost, with better fatigue resistance than welded counterparts due to its monolithic form and homogeneous microstructure.

7.5 Generative Design for Additive Manufacturing

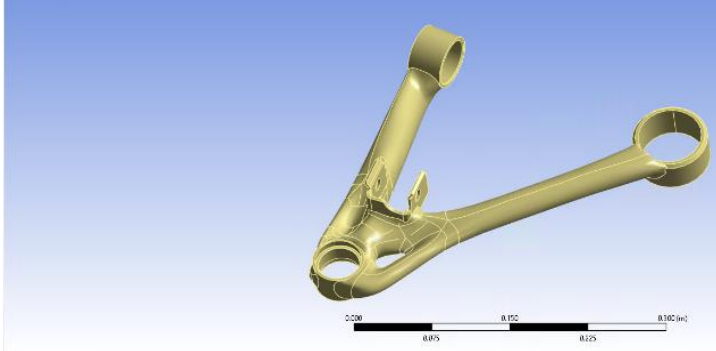


Figure 23 Image of the setup of the additively manufactured components' static structural simulation

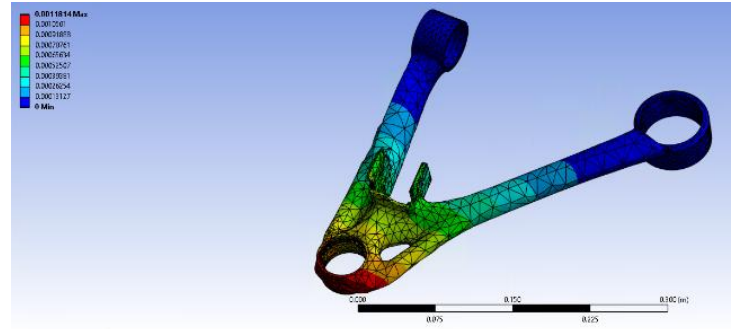


Figure 24 Image of the additively manufactured components' maximum deformation

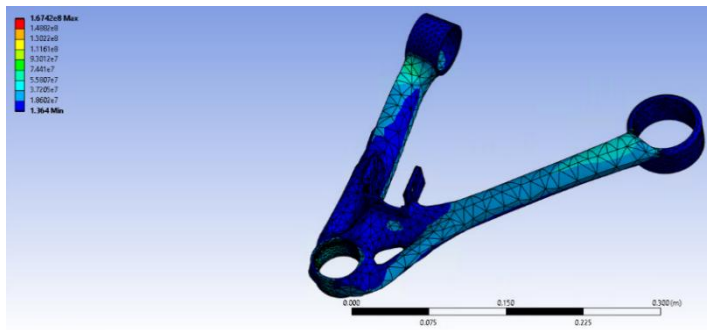


Figure 25 Image of the additively manufactured components' maximum Von Mises stress

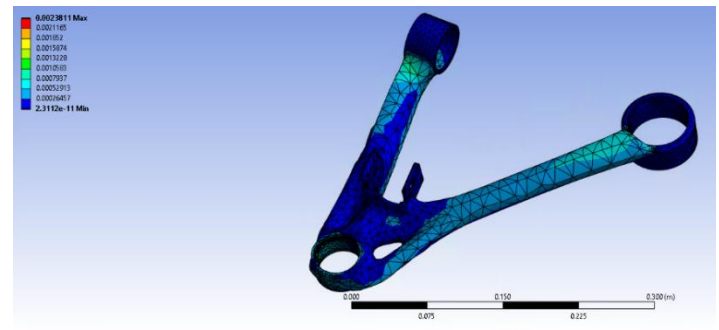


Figure 26 Image of the additively manufactured components' maximum Von Mises strain

Using topology optimisation unconstrained by subtractive or casting limitations, a design was generated for production via Laser Powder Bed Fusion (LPBF) in AlSi10Mg. This allowed complex load-path optimised forms, including hollow ribs and integrated shock mounts.

FEA simulation revealed a **maximum Von Mises stress** of approximately **128.78 MPa** (1.288×10^8 Pa), within safe limits for AlSi10Mg's post-treated yield strength (~250 MPa). Stress concentrations appeared near thin rib junctions and mounting bosses.

The **maximum elastic strain** observed was **0.00206 mm/mm** or **0.206%**. The structure remained fully elastic under loading, confirming sufficient ductility and safety.

Total deformation peaked at **1.77 mm**, concentrated around the coilover bracket and cantilevered ends. While this is slightly higher than the cast version, it remains acceptable due to the structure's enhanced compliance and weight savings.

The AM design resulted in an estimated **50% mass reduction** over the steel baseline. Although more expensive and slower to produce, it delivered the best performance-to-weight ratio with the potential for integrated sensor pathways and further functionalisation.

7.6 Generative design for milling

7.6.1 5 Axis Milling

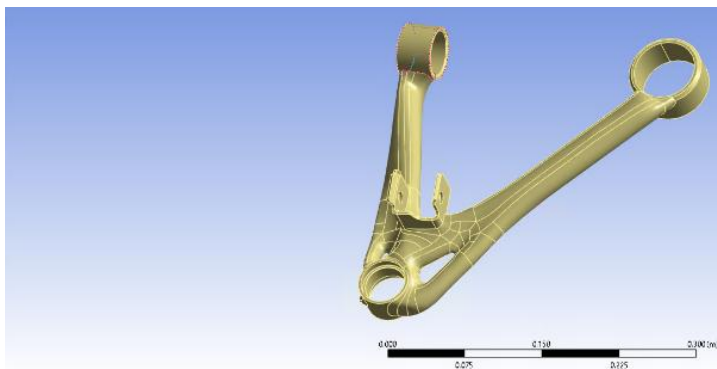


Figure 27 Image of the setup of the 5-axis milled components' static structural simulation

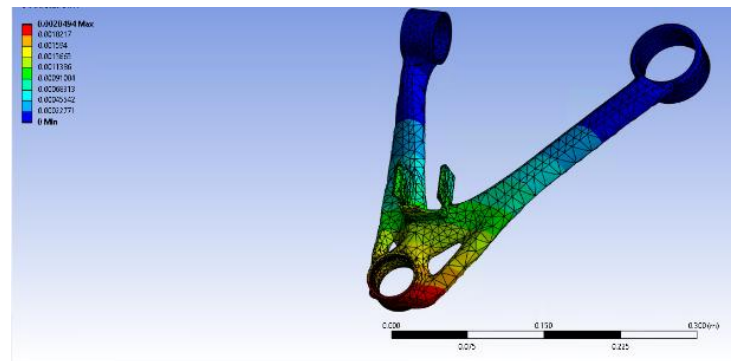


Figure 28 Image of the 5-axis milled components' maximum deformation

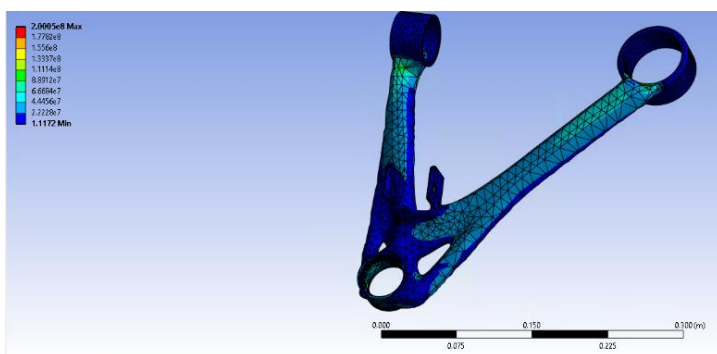


Figure 29 Image of the 5-axis milled components' maximum Von Mises stress

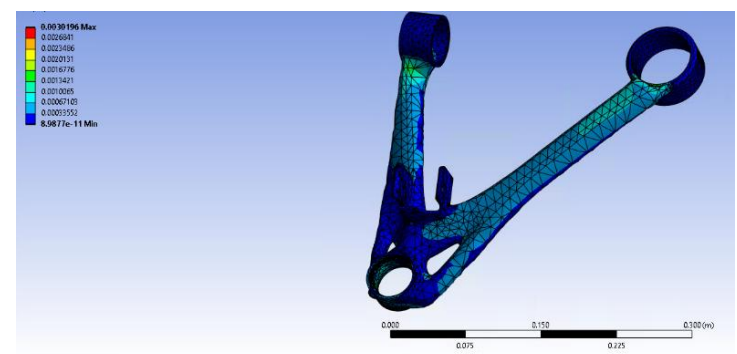


Figure 30 Image of the 5-axis milled components' maximum Von Mises strain

A generative solution was developed with subtractive manufacturing constraints, optimised for 3-axis CNC milling of 7075-T6 aluminium billet. This led to a less organic yet highly refined form, balancing tool accessibility and geometric efficiency.

The **maximum Von Mises stress** recorded was **128.78 MPa** (1.288×10^8 Pa). This consistent peak value across cases likely reflects standardised boundary conditions and loading but remains safely below 7075-T6's yield strength (~500 MPa).

The **maximum elastic strain** reached **0.00206 mm/mm**, similar to the AM design. However, strain distribution was more uniform, owing to simpler geometry and consistent material properties.

Total deformation was 2.05mm, suggesting comparable stiffness. However, the machined form benefits from better dimensional control and surface finish, enhancing fatigue resistance and component longevity.

The milled design compromises AM's flexibility and casting's cost-efficiency. While it results in higher material wastage, it supports higher volumes with existing manufacturing capabilities and superior repeatability.

7.6.2 2.5 Axis Milling

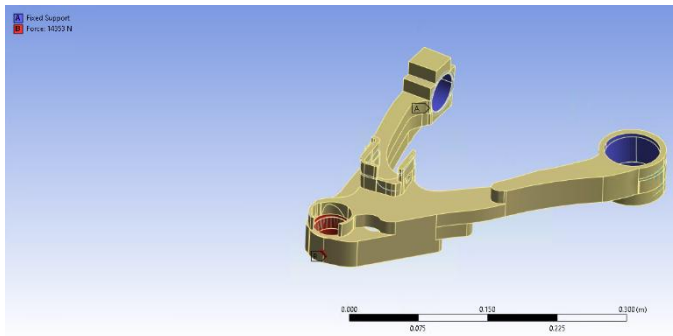


Figure 31 Image of the setup of the 2.5-axis milled components' static structural simulation

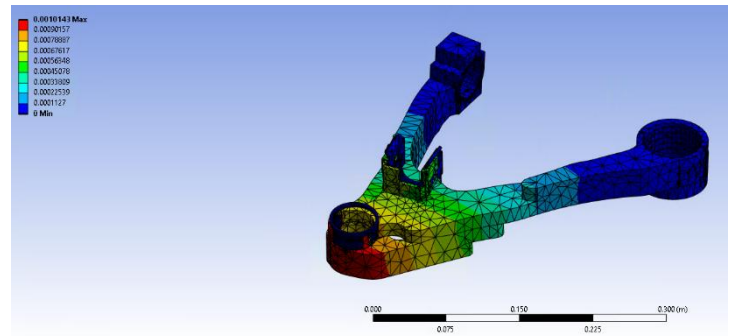


Figure 32 Image of the 2.5-axis milled components' maximum deformation

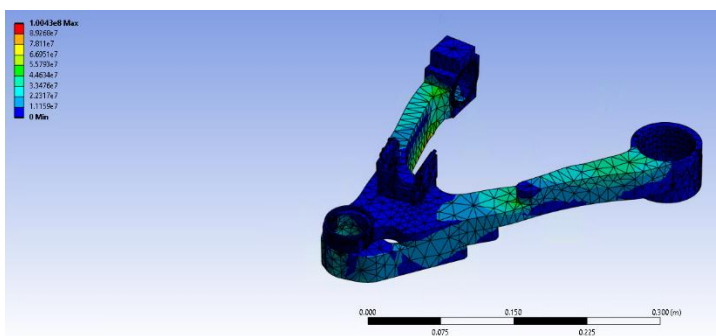


Figure 33 Image of the 2.5-axis milled components' maximum Von Mises stress

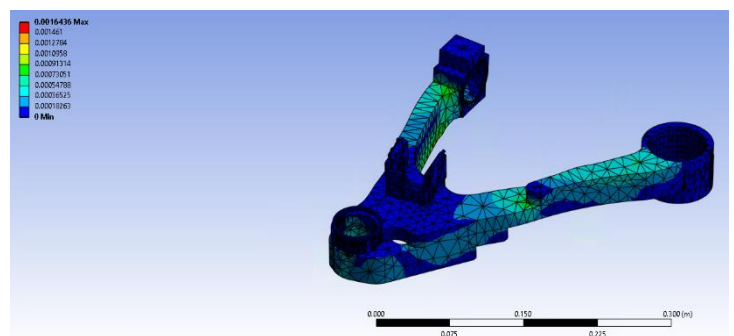


Figure 34 Image of the 2.5-axis milled components' maximum Von Mises strain

The second machining-based generative design iteration was a resounding success, optimised explicitly for 2.5d **milling** processes. This approach, which restricted geometry to prismatic forms with variable depth cuts, significantly simplified toolpaths and reduced machining complexity compared to complete 3d multi-axis milling. The resulting structure maintained much of the original milled design's stiffness and load path efficiency, demonstrating the power of this approach. However, it was simplified into mostly flat-faced features with vertical walls and blended radii.

Finite element analysis (FEA) results for this 2.5d milled design indicated a **maximum equivalent (Von Mises) stress** of approximately **19.51 MPa**. Despite the geometric simplification, this value is substantially lower than the maximum stresses observed in previous designs, demonstrating that the part still effectively carries applied loads without critical stress concentrations.

The **maximum equivalent elastic strain** was **0.001925 mm/mm**, corresponding to **0.1925%**. This strain value, well within acceptable limits for typical aluminium alloys

used in automotive control arm applications, assures us that the material is operating safely below its yield threshold, reinforcing the reliability of our design.

The **total deformation** of the structure was recorded at **1.0413 mm** under the applied loading conditions. This deformation, while lower than the additive manufactured version, is slightly higher than the fully optimised 3d milled component. However, it is essential to note that this level of deformation still reflects a satisfactory balance between stiffness, manufacturability, and material usage for a 2.5d-machinable geometry, ensuring the part's performance is not compromised.

This optimisation demonstrates that with careful constraint application, which involves balancing design complexity with manufacturing feasibility, generative design can create highly efficient parts while remaining feasible for economical 2.5-axis CNC production. The design's relative simplicity reduces manufacturing costs and improves repeatability and quality control in production settings.

8.0 Manufacturing Process Evaluation

8.1 Hand Fabrication/Welding



Figure 35 Image showing welding process (Source: Sydney Welders, n.d: online)

Hand fabrication and welding involve manually constructing control arms by cutting, forming, and welding metal components, usually from steel tubes or plates. This method requires minimal capital investment, primarily involving basic welding equipment, cutting tools, and custom alignment jigs. It allows rapid design iteration and flexibility, which benefits prototypes, limited production runs, or custom applications. For instance, if a design change is needed, it can be implemented quickly and without significant cost, allowing for faster development and testing of new ideas.

However, this method relies on skilled labour, leading to higher per-unit costs. Fabrication quality can vary significantly due to manual processes, potentially resulting in inconsistencies and structural weaknesses at weld joints. These welded joints can introduce stress concentrations, reducing fatigue life and making the arms susceptible to corrosion. Additionally, welded LCAS generally require thicker sections or additional reinforcements, which increases overall weight, negatively impacting vehicle performance.

Hand fabrication and welding require a modest initial investment, involving equipment such as high-quality MIG or TIG welding machines (costing between £5,000 and £10,000), metal cutting tools (£1,000 to £2,000), and custom alignment jigs (£500 to £1,000). Labour costs are significant, as skilled welders are essential, typically earning £30 to £50 per hour, with each Lower Control Arm (LCA) requiring approximately 2–4 hours to fabricate, resulting in a labour cost range of £60 to £200 per component. Material costs are relatively low, with steel tubes and plates priced at £2–£3 per kilogram; an LCA generally consumes 2–4 kg of material, costing around £5–£10 per unit. Additional minor costs include welding consumables (£2–£5), corrosion protection treatments (£5–£10), and optional post-weld stress-relief processes (£10 per unit). Although the setup and tooling times are minimal, the manual nature of fabrication leads to higher per-unit production times. Overall, the total cost for a hand-fabricated and welded LCA typically ranges between approximately £100 and £250, providing a clear understanding of the financial investment required for fabrication.

8.2 Casting



Figure 36 Image of casting process (Source: 3erp, 2024: online)

Casting involves pouring molten metal, commonly aluminium, into moulds to solidify into the desired LCA shape. Sand casting is especially suitable for Morgan's moderate volume, offering lower initial tooling costs and considerable geometric flexibility,

including complex internal structures and ribbing. This flexibility empowers designers to explore a wide range of design possibilities, enhancing the appeal of the casting method.

The key drawbacks of casting include generally lower mechanical strength and fatigue resistance than forged parts. This means cast parts may not be as durable or long-lasting as forged ones and require more frequent replacements. To compensate for this, designers often increase wall thicknesses, resulting in heavier components. Casting processes are also prone to internal defects, such as porosity and inclusions, necessitating rigorous quality assurance and potentially costly inspection processes such as X-ray or ultrasonic testing. Cast LCAS requires additional post-casting machining operations to achieve precise tolerances and necessary surface finishes.

The casting process, particularly sand casting, involves a moderate initial investment primarily directed toward pattern making, typically costing between £2,000 and £5,000. Labour costs for sand casting are relatively high due to manual mould preparation and pouring, estimated at £20–£40 per component, whereas permanent mould methods reduce labour to around £10–£20 per part. Material costs for aluminium alloys such as A356 are typically £3–£5 per kilogram, with each LCA requiring 2–3 kg, costing approximately £6–£15 per unit. Additional expenses arise from necessary heat treatment (£5–£10 per arm), precision machining for critical surfaces (£10–£20 per arm), and quality assurance measures like ultrasonic or X-ray inspection (£5–£10 per unit). Sand casting, although labour-intensive with more extended cooling and handling times, suits Morgan's low-volume context, whereas permanent mould casting offers faster production at a higher tooling cost. The resulting production cost per LCA is estimated at £50–£80 for sand casting or slightly lower at £40–£60 when utilising permanent mould casting methods.

8.3 Additive Manufacturing

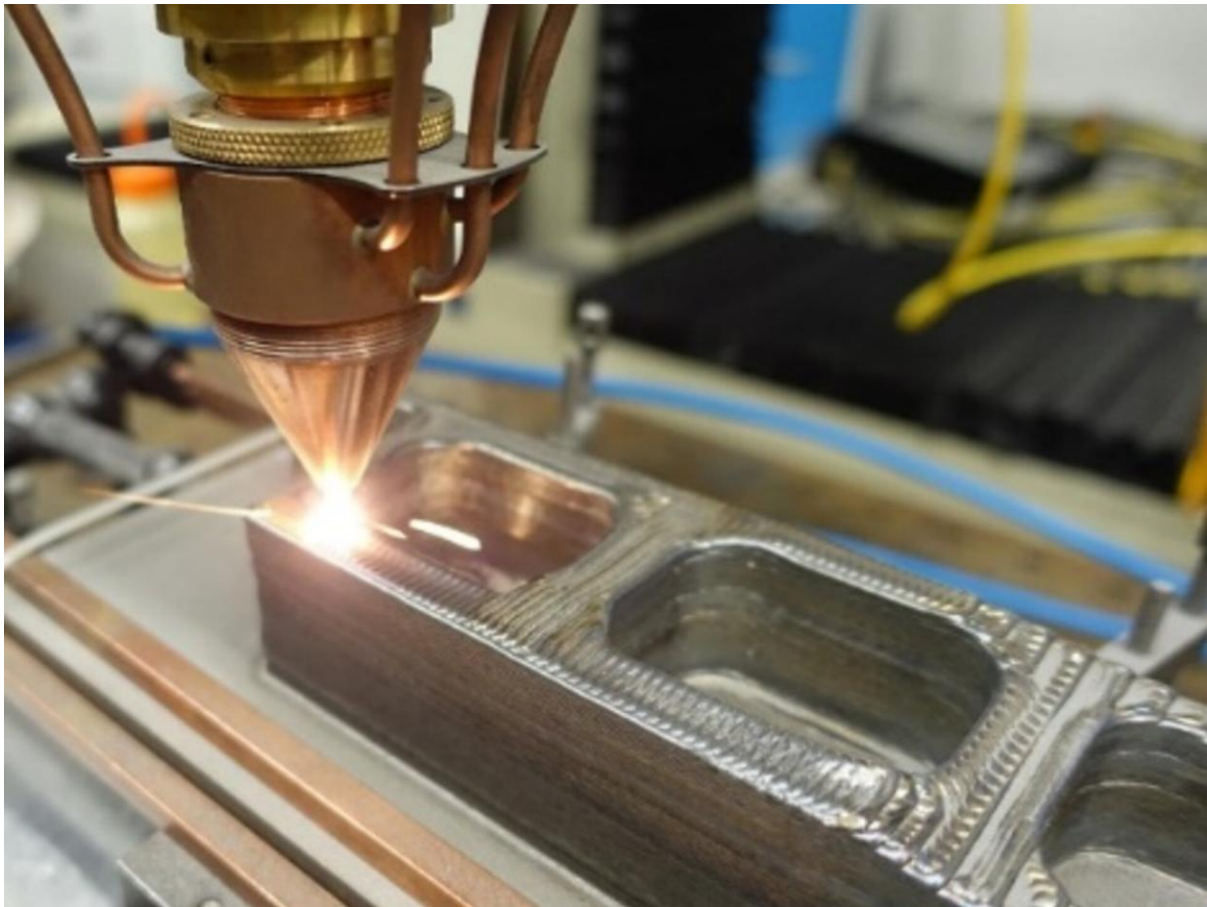


Figure 37 Image of metal 3d printing process (Source: ESA, 2018: online)

Additive manufacturing (AM), specifically metal 3d printing, builds LCAS layer-by-layer from metal powders, offering unmatched design flexibility. It enables complex, optimised geometries, including internal lattice structures, that conventional methods cannot replicate. AM requires no dedicated tooling, facilitating rapid prototyping, customisation, and design iterations with minimal waste.

Despite these advantages, AM remains economically impractical for automotive components due to extremely high equipment and material costs.

Additive manufacturing (AM) for LCAS, specifically using Laser Powder Bed Fusion (LPBF), demands very high capital investment, with industrial-grade metal 3d printers priced between £400,000 and £1,000,000, alongside necessary ancillary equipment such as powder handling systems and heat treatment furnaces costing an additional £50,000–£100,000. Labour costs are also elevated, with skilled technicians responsible for operating the machines, removing support structures, and overseeing

post-processing, typically contributing £100–£200 per unit. Material costs are significantly higher than conventional methods, with metal powders like AlSi10Mg priced between £50–£150 per kilogram; accounting for build supports and inefficiencies, each LCA consumes 3–5 kg of powder, resulting in material costs of £150–£500 per component. Post-processing costs, including stress-relief heat treatments (£20–£50 per batch), CNC machining of critical features (£50–£100 per unit), surface finishing (£10–£20), and detailed CT or ultrasonic inspections (£50–£100), further compound the total expenditure. Printing times of 10–20 hours per component and intensive post-processing limit scalability and throughput, making additive manufacturing viable only for highly specialised or ultra-low-volume applications. The total cost for an AM-produced LCA typically ranges between £2,000 and £3,000 per unit.

8.4 CNC Milling



Figure 38 Image of CNC milling process(Source: GEOMIQ, n.d: online)

8.4.1 5 Axis milling

5-axis CNC milling, known for its efficiency, is required to produce the fully optimised generative lower control arm design. Its ability to machine complex undercuts, freeform surfaces, and intricate rib structures ensures that the process is cost-effective in the long run. In a 5-axis system, the cutting tool moves simultaneously along the X, Y, and Z axes while rotating on two additional axes (A and B), allowing access to virtually any surface without repositioning the part.

However, the associated costs are significant. High-end 5-axis CNC machines typically range in price from £250,000 to £500,000, reflecting their size, brand, quality, and capabilities. Advanced CAM programming is required for these parts, with setup times often spanning 8 to 20 hours for initial configurations, while annual CAM software licences cost between £10,000 and £20,000. Machining costs add to the expense, with hourly rates typically falling between £75 and £125 to cover machine amortisation, operator wages, and overheads. Tooling and fixture requirements are also substantial; bespoke fixtures and specialised multi-flute cutting tools can add approximately £500 to £1,500 per project. Labour costs are elevated due to the high level of operator and programmer skill required, with annual salaries typically between £40,000 and £55,000. Post-processing, such as deburring, surface finishing, and inspection, can add £50 to £100 per part. Consequently, low-volume production costs for the generative control arm are typically in the region of £450 to £750 per unit, making 5-axis milling most suited to high-performance sectors like motorsport, aerospace, or prototype development, where maximum performance and minimum mass outweigh manufacturing cost concerns.

8.4.2 2.5 Axis milling

For the simplified generative design, 2.5-axis CNC milling was selected. In this process, the cutter performs two-dimensional operations in the X and Y axes with discrete plunges in the Z direction, which is ideal for machining pockets, profiles, and vertical features with flat bottom surfaces. No simultaneous multi-axis motion is required.

The costs associated with 2.5-axis CNC milling are much lower. Standard 3-axis CNC machines configured for 2.5-axis operations are significantly more affordable, typically costing between £60,000 and £120,000. Due to the simplicity of 2.5-axis toolpaths,

setup and programming times are also reduced considerably, with initial setups generally completed within 2 to 6 hours, and CAM software licences costing a more modest £5,000 to £8,000 annually. Machining costs are correspondingly lower, with hourly rates between £35 and £65, reflecting reduced capital and facility costs. Tooling and fixture requirements are minimal; off-the-shelf vices, clamps, and standard cutting tools suffice, with fixture costs rarely exceeding £200 to £400 per project. Labour costs are also lower, with operator wages typically between £30,000 and £40,000 annually, and multi-machine tending is common practice to increase efficiency. Post-processing requirements for parts produced via 2.5-axis milling are limited to basic deburring and dimensional inspection, costing around £20 to £50 per part. As a result, unit costs for this manufacturing route fall between £150 and £300 per part, depending on batch size, making 2.5-axis CNC milling a highly economical option for medium- to high-volume production where cost efficiency is critical.

9.0 Conclusions and Recommendations

This study has critically assessed four manufacturing approaches for the Morgan Plus Four's Lower Control Arm (LCA): traditional hand fabrication/welding, aluminium casting, additive manufacturing using Laser Powder Bed Fusion (LPBF), and CNC billet milling. Each method was evaluated through detailed CAD modelling, static structural Finite Element Analysis (FEA), manufacturability studies, and comprehensive cost analysis. The following sections provide detailed recommendations based on simulation performance, manufacturing practicality and costs, culminating in a final technical recommendation for Morgan Motor Company.

9.1 Recommendation Based on Simulation Results

From the structural simulation results, the topology-optimised **additively manufactured (AM)** design emerged as a beacon of innovation, delivering the **highest performance** across all critical metrics:

A ~50% mass reduction compared to the traditional welded steel arm was achieved, offering a significant decrease in unsprung mass, critical for enhancing suspension responsiveness, ride quality, and overall dynamic performance.

The maximum Von Mises stress observed was **128.78 MPa**, well within the AlSi10Mg alloy's post-heat-treated yield strength of approximately 250 MPa, providing a generous safety margin against failure even under worst-case combined dynamic loads.

The maximum total deformation recorded was **1.77 mm**, concentrated around cantilevered coilover mounting regions. Although slightly higher than the cast design, it remained within acceptable automotive limits.

The AM design displayed the most efficient material usage, with stresses distributed optimally along generatively designed load paths, resulting in lower peak stress concentrations than other designs.

The AM component's superior strength-to-weight ratio would substantially improve vehicle handling characteristics by reducing the unsprung mass. This reduction enhances the suspension's ability to respond quickly to road irregularities, improving

both comfort and grip, critical attributes for a vehicle like the Morgan Plus Four, which blends classic appeal with modern driving dynamics.

While the AM approach is structurally **ideal**, its **cost** and **time requirements** (unit cost £2,000–£3,000, production times exceeding 10–20 hours per component) significantly restrict its feasibility for anything beyond extremely low-volume or special-edition vehicles.

9.2 Recommendation Based on Manufacturing Process Evaluation and Cost Analysis

While AM achieved outstanding structural performance, its production costs, material inefficiency (due to unused powder waste), long cycle times, and post-processing requirements (stress relief, machining, surface finishing) make Morgan's primary production needs impractical.

When manufacturability and cost are prioritised, **Casting** emerges as the most favourable solution:

The cast aluminium design achieved a maximum Von Mises stress of **98.86 MPa**, substantially below A356-T6 aluminium's typical yield strength (~250 MPa). The maximum deformation was only **0.6389 mm**, indicating excellent stiffness and minimal deflection under peak loads.

Casting, particularly low-pressure die casting, suits Morgan's low-to-medium production volumes. It enables complex geometries optimised for weight reduction while being **much faster** and **more economical** per unit than additive manufacturing or billet milling.

With pattern tooling costs around £2,000–£5,000, and per-unit production costs between £40–£80 (including material, labour, heat treatment, and machining), casting offers a **5x–10x lower price per unit** compared to additive manufacturing and **lower cost than 5-axis billet milling** (£450–£750/unit), making it a financially sound choice.

Although castings generally exhibit lower fatigue resistance than forged or billet machined parts, the homogeneous solid structure and post-processing (T6 heat treatment) provide **adequate fatigue life** for road-going performance vehicles like the Plus Four.

Casting strikes a perfect balance, offering substantial weight reduction, sufficient structural integrity, and cost-effectiveness. The slightly higher mass compared to AM (~10–15% more) is a reasonable trade-off for the significant reduction in production cost and lead time.

9.3 Final Overall Recommendation

Considering both technical and strategic factors, including performance, manufacturability, cost, production volume, and Morgan's unique brand positioning, the final recommendation is that Morgan Motor Company should adopt a generatively designed aluminium Lower Control Arm produced via Low-Pressure Die Casting using A356-T6 alloy.

Although additive manufacturing yields the ultimate structural efficiency, Casting still performs well. The generative design, adapted for casting (with controlled draft angles and thickened critical regions), allows substantial mass savings (~30–40% weight reduction versus welded steel) without compromising structural integrity.

Casting's low per-unit cost makes it sustainable for production volumes suitable for Morgan's low-volume, high-value product strategy. It ensures Morgan can achieve profitability without passing excessive costs onto customers or requiring massive capital investment.

Casting supports design flexibility, moderate production automation, and minimal finishing compared to the manual, labour-intensive fabrication, modernising Morgan's production capabilities without sacrificing the craftsmanship ethos.

This approach preserves the spirit of "hand-crafted excellence" by allowing for visually stunning, organically shaped parts that still require finishing and fitting by skilled craftsmen, aligning tradition with innovation — a core element of Morgan's brand identity and a strategic fit for the company's production capabilities. **Future**

Furthermore, by adopting casting now, Morgan keeps the door open to **incremental integration of additive manufacturing** for future special models such as motorsport variants and limited-run performance editions, where absolute performance takes precedence over cost.

10.0 Further Work

While this report has successfully evaluated and compared multiple manufacturing routes for the Morgan Plus four Lower Control Arm (LCA), there are several opportunities for further development to build upon these findings and enhance the project's depth and industrial applicability.

10.1 Dynamic Load Simulation and Vehicle Integration

Looking ahead, integrating dynamic multi-body simulations with the LCA as a part of a complete suspension project holds immense potential. This approach would allow the possibility of simulating complex, real-world load cases such as bump impacts, curb strikes, and cornering transitions. Using software like MSC Adams, in conjunction with detailed FEA in ANSYS, could revolutionise our ability to predict the behaviour of the control arm under dynamic conditions, thereby enhancing the robustness of the design against peak and cyclic stresses.

10.2 Experimental Validation through Prototyping

It is crucial to note that the simulation results presented in this study would greatly benefit from physical validation. Manufacturing prototype LCAS via CNC milling, casting and additive manufacturing would allow static load testing, fatigue cycling, and modal analysis under controlled conditions. This experimental data could serve as a robust validation of the Finite Element Analysis (FEA) models, thereby ensuring the accuracy of our simulations and instilling confidence in the proposed designs.

10.3 Fatigue Simulation Testing in ANSYS

While our initial FEA efforts focused on static strength and deformation, we must recognise the need for a detailed fatigue life analysis within ANSYS in future work. By applying realistic loading spectra and using material-specific S–N (stress-life) or ϵ –N (strain-life) curves, we can predict the number of cycles to failure and identify fatigue-critical regions of the design. This step is crucial for understanding the control arm's long-term durability, particularly for lightweight aluminium and additively manufactured variants where fatigue behaviour can dominate.

10.4 Material Alternatives Exploration

Further work could investigate alternative materials beyond aluminium. Although more costly, titanium alloys offer exceptional fatigue strength and corrosion resistance, making them attractive for motorsport or high-performance applications. Additionally, hybrid solutions combining carbon-fibre composites with metallic inserts could be explored to reduce unsprung mass further.

10.5 Lifecycle Cost and Production Scalability Analysis

Future research should model production costs over larger volumes (e.g., 500 to 5000 units per year) to better understand how each manufacturing method scales economically. As additive manufacturing costs continue to decrease and print speeds improve, the long-term viability of AM for limited-series production could be re-evaluated.

10.6 Environmental Lifecycle Assessment (LCA)

A complete environmental lifecycle analysis comparing billet milling, casting, and additive manufacturing could provide insights into the sustainability of each approach. Factors such as embodied energy, material wastage, recycling potential, and carbon footprint should be assessed to support environmentally responsible manufacturing choices aligned with Morgan Motor Company's ethos.

10.7 Integration of Smart Features in Additive Designs

Additive manufacturing offers the possibility of embedding sensor pathways directly into structural components. Future work could explore the company's application of strain gauges, accelerometers, or load cells into the topology-optimised LCA designs, enabling real-time monitoring of suspension loads for predictive maintenance or motorsport telemetry.

10.8 Forging

Forging was not considered a primary manufacturing method within this project due to the nature of the generative design outputs, which typically produce highly complex geometries with intricate internal structures, non-uniform wall thicknesses, and undercuts incompatible with traditional forging processes. Conventional closed-die

forging best suits simpler, symmetric parts with gradual transitions. This would have significantly restricted the design freedom necessary to achieve the optimised lightweight structures targeted in this study. The high initial tooling costs and long lead times associated with die production made forging unsuitable for this project's low-volume, prototype-oriented focus. However, forging offers substantial mechanical performance advantages, particularly in grain structure alignment, fatigue resistance, and overall material strength. Future work could explore hybrid design strategies where generative geometries are constrained to be forgeable or investigate emerging techniques such as near-net-shape forging combined with secondary machining to achieve complex forms. Incorporating forging could unlock new opportunities for high-strength, cost-efficient mass production of lightweight structural components.

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12.0 Appendices

Parameter	Value
Max Vehicle Mass (m)	1300 kg
Gravity (g)	9.81m//s^(2)
Track Width (T)	1.455 m
Centre of Gravity Height (h)	0.3943 m
Wheelbase	2.52 m
Lateral Acceleration	1.5g=14.715m//s^(2)
Longitudinal Acceleration	1.3g=12.753m//s^(2)

$$\begin{aligned}
 \text{Static load per wheel} &= \frac{1300 \times 9.81}{4} \\
 &= \frac{12753}{4} \\
 &= 3188.25\text{N}
 \end{aligned}$$

$$\begin{aligned}
 F_{\text{lateral}} &= m \times (1.5 \times g) \\
 &= 1300 \times (1.5 \times 9.81) \\
 &= 1300 \times 14.715 \\
 &= 19130\text{N}
 \end{aligned}$$

$$\begin{aligned}
 F_{\text{longitudinal}} &= m \times (1.3 \times g) \\
 &= 1300 \times (1.3 \times 9.81) \\
 &= 1300 \times 12.753 \\
 &= 16579\text{N}
 \end{aligned}$$

$$\begin{aligned}
 \text{Lateral load transfer} &= \frac{m \times a_{\text{lat}} \times h}{T} \\
 &= \frac{1300 \times (1.5 \times 9.81) \times 0.3943}{1300 \times 14.715} \\
 &= \frac{1.455}{7553.45} \\
 &= \frac{1.455}{1.455} \\
 &= 5184\text{N}
 \end{aligned}$$

$$\text{Longitudinal load transfer} = 2594\text{N}$$

$$\begin{aligned}
 \text{Total load} &= 3188.25 + \frac{5184}{2} + \frac{2594}{2} \\
 &= 3188.25 + 2592 + 1297 \\
 &= 7077.25\text{N}
 \end{aligned}$$

$$\begin{aligned}
 \text{Total weight} &= 1300 \times 9.81 \\
 &= 12753\text{N}
 \end{aligned}$$

$$\begin{aligned}
 \text{Percentage} &= \frac{7077.25}{12753} \times 100 \\
 &= 55.5\%
 \end{aligned}$$

$$\begin{aligned}
 F_{\text{long tyre}} &= 16579 \times 0.555 \\
 &= 9200\text{N}
 \end{aligned}$$

$$\begin{aligned} F_{\text{lat tyre}} &= 19130 \times 0.555 \\ &= 10600\text{N} \end{aligned}$$

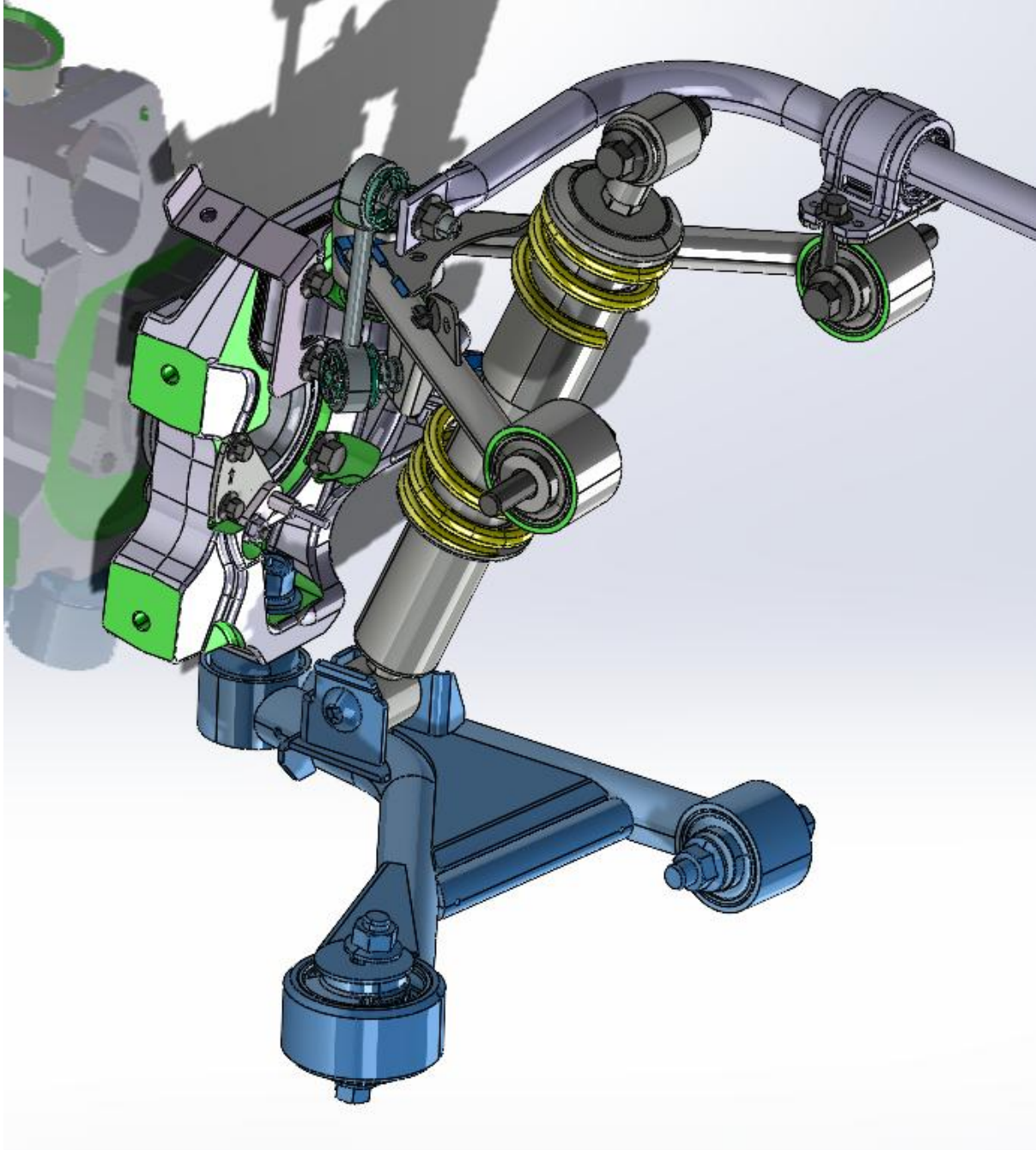


Figure 39 Image of the Morgan Plus Four suspension (LCA Highlighted) from behind

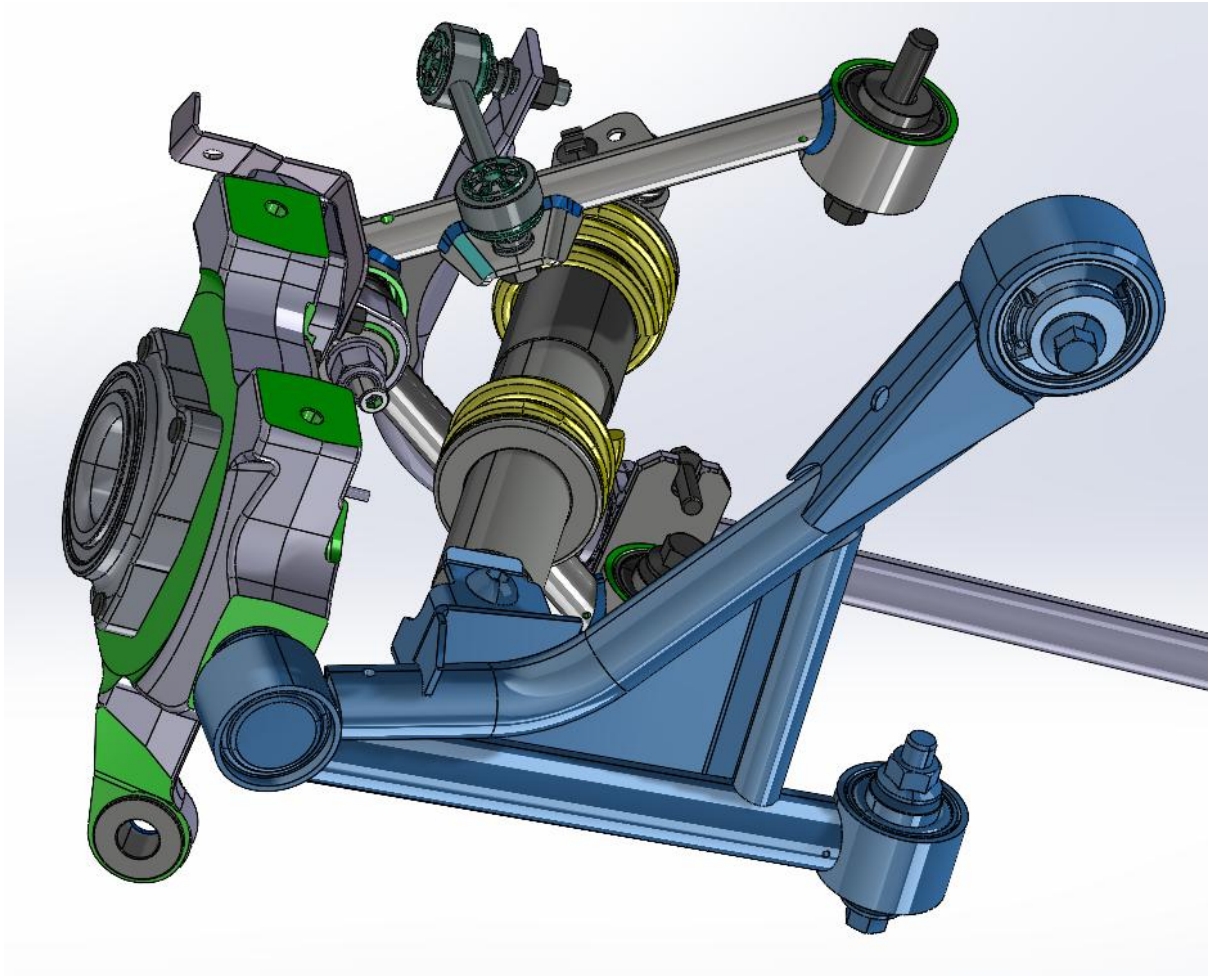


Figure 41 Image of the Morgan Plus Four suspension (LCA Highlighted) from underneath