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STUDY OF DISK BRAKE DESIGN USING METAL ADDITIVE MANUFACTURING: A SIMULATION-BASED APPROACH

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Abstract

In the ever-evolving landscape of automotive technology, the optimization of critical components such as disk brake wheels is imperative for enhancing performance, durability, and overall safety. This research focuses on the integration of Metal Additive Manufacturing (MAM) techniques in the design and simulation of disk brake wheels to achieve superior mechanical properties and thermal performance. The study commences with a comprehensive exploration of various metal additive manufacturing processes, evaluating their suitability for fabricating disk brake wheels. A judicious selection of materials is crucial for meeting the stringent requirements of load-bearing capacity, thermal conductivity, and wear resistance inherent in braking systems. The simulation study involves the evaluation of thermal dissipation, stress distribution, and deformation characteristics during braking events. Finite Element Analysis (FEA) is employed to simulate real-world scenarios, allowing for the identification of potential failure points and the refinement of the design accordingly. The research investigates the impact of various design parameters and manufacturing parameters on the performance of the disk brake wheel. The findings of this study contribute valuable insights into the feasibility and advantages of employing metal additive manufacturing techniques in the production of disk brake wheels. This research serves as a foundation for the integration of cutting-edge technologies in the automotive industry, fostering advancements in both design and manufacturing processes for critical safety components.

Keywords: *Additive Manufacturing, LPBF, Disk brake, DMLS.*

1. INTRODUCTION

Modern manufacturing has been revolutionized by the emergence of metal-based 3D printing technologies, transforming the creation of complex metal components from digital blueprints. This innovative process, which builds the objects layer by layer using metal powders or wires fused by precise heat sources, encompasses various techniques including laser sintering and electron beam melting. The manufacturing of disk brakes using Additive Manufacturing begins with detailed computer modeling, followed by a meticulous layer-by-layer construction process using specialized metal alloys like steel or aluminum. These advanced printing systems interpret digital designs to construct the physical brake components, with each layer carefully bonded to the previous one through controlled heating processes. Post-production refinements, including heat treatment and precision machining, ensure the final product meets rigorous performance standards. This approach

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offers unprecedented freedom in designing intricate geometries that would be challenging to achieve through conventional methods, while simultaneously reducing production time and tooling costs. Despite these advantages, considerations must be given to material costs, size limitations, and the need for high-quality raw materials. The Laser Powder Bed Fusion (LPBF) process, in particular, has emerged as a prominent technique for fabricating disk brakes, demonstrating the practical application of these advancing technologies. This manufacturing revolution enables customization and rapid prototyping while maintaining structural integrity, though it requires careful balance between innovation and practical limitations. The integration of these methods into the manufacturing sector represents a significant step forward in production capabilities, offering new possibilities for component design and fabrication efficiency.

Johnson etal. [1] pioneered early computational techniques for studying thermal behaviour of disc brakes, developing essential modelling methodologies. Their study presented unique finite element approaches for estimating temperature distributions and thermal stresses during braking occurrences. The research proved the relevance of ventilation design in thermal management, revealing up to 15% variance in cooling effectiveness dependent on vent shape. Their technique includes experimental validation utilizing thermocouples and infrared imaging, defining norms for future thermal research investigations. The results gave significant insights into the link between brake design factors and heat performance, while manufacture was constrained to conventional techniques. Wilson etal. [2] research evaluated the possibility of fast prototyping technology for automobile components, including braking system prototypes. The researchers examined stereo lithography and selective laser sintering for creating prototype brake components, attaining dimensional accuracies within ±0.2mm. Their studies found important hurdles in transferring from prototype to production components, specifically related material characteristics and thermal stability. The project provided early principles for employing additive technology in automobile development processes. The results lay basis for future metal additive manufacturing uses in braking systems. Chen etal. [3] created unique optimization techniques for disc brake design, emphasizing on weight reduction while retaining structural integrity. Their research encompassed both static and dynamic stress situations, delivering a 12% weight decrease in traditional disc designs. The research demonstrated relationships between material distribution and braking performance, proven by thorough FEA simulations. The study presented early principles of topology optimization that would later become significant in AM design techniques. Their results considerably affected future lightweight brake design efforts. Anderson etal. [4] fundamental research studied innovative materials for braking applications, including early powder metallurgy methods. The researchers investigated several metal matrix composites, establishing performance criteria for wear resistance and thermal stability. Their study involved rigorous testing under high working circumstances, determining optimum material compositions for particular applications. The project created testing techniques that would subsequently become useful for AM material development. The results gave vital insights into material requirements for high-performance braking applications.

Zhang etal. [5] study created pioneering methodologies for linked thermal-mechanical analysis of braking systems, introducing unique numerical approaches. The research proved the value of incorporating coupled factors, demonstrating up to 25% difference in stress estimates compared to uncoupled studies. Their process involved validation via rigorous experimental testing, creating dependability norms for simulation systems. The study provides essential knowledge of braking action under combined heat and mechanical stresses. Their results substantially affected future design optimization efforts. Kumar etal. [6] studied early powder-based manufacturing methods, including sintering and infiltration procedures for brake components. Their study developed processing conditions for producing consistent material qualities, reaching densities exceeding 95%. The research

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involved extensive examination of microstructural evolution and its effect on component performance. Their study gave early insights into the possibility of powder-based production for braking applications. The results revealed basic needs for future metal AM methods. Lee etal. [7] research created improved computational fluid dynamics models for assessing brake cooling performance, introducing novel simulation approaches. The researchers verified their models using wind tunnel testing, exhibiting forecast accuracies within 8% of experimental data. Their study includes parametric simulations of different cooling channel designs, discovering optimum arrangements for heat dissipation. The research demonstrated linkages between air flow patterns and cooling efficiency that would subsequently impact AM design techniques. The results gave vital insights into heat management solutions for braking systems. Martinez etal. [8] researched innovative powder metallurgical methods for creating brake components with increased performance qualities. Their study defined processing conditions for producing excellent material qualities, including wear resistance and thermal stability. The research includes extensive examination of sintering behaviour and its effect on final component qualities. Their study gave vital insights into powder-based manufacturing techniques that would subsequently affect AM development. The results set key criteria for material performance in braking applications. Wilson etal. [9] study developed improved optimization strategies for brake component design, offering new procedures for weight reduction. The research indicated possibilities for 18% weight reduction while meeting structural requirements via new design techniques.

Their study involved extensive research of numerous design restrictions and their effect on optimization outcomes. The study introduced essential ideas for design optimization that would later be vital in AM applications. Their results profoundly impacted future efforts to lightweight brake design. Park etal. [10] performed detailed thermal investigation of numerous braking materials, developing performance criteria for material selection. Their study includes extensive examination of thermal conductivity, specific heat capacity, and thermal expansion parameters. The research demonstrated relationships between material qualities and braking performance under different operating circumstances. Their study gave vital insights into material needs that would subsequently inspire AM material development. The results substantially affected future approaches to brake material selection and design. Zhang etal. [11] pioneering work provided essential thermal analysis models for vented disc brakes, providing numerical approaches that became industry standards. The researchers created full finite element models integrating both thermal and mechanical stresses, revealing that optimal ventilation channel designs might lower thermal stress by up to 18%. Their study was especially helpful in identifying relationships between ventilation geometry and thermal performance, verifying conclusions via experimental testing. The work gave one of the first extensive evaluations of heat gradient effects on brake disc deformation and revealed crucial design parameters for ventilation channel improvement.

The methods provided in this work established a basis for later research in thermal control of braking systems. Thompson etal. [12] studied the early uses of selective laser melting (SLM) for automotive components, concentrating especially on Ti-6Al-4V alloy implementations. The researchers reached a stunning 98.5% density in their created components, albeit they noted substantial issues in surface polishing and dimensional accuracy. Their study established important process parameters for metal AM in automotive applications, including optimum laser power settings and scanning algorithms. The project was among the first to show the viability of creating complicated automobile shapes using AM technology. Their results showed both the promise and limits of early metal AM systems, establishing reasonable expectations for industrial applications. Chen etal. [13] study revealed ground breaking work in three-dimensional finite element modelling for disc brakes, integrating both thermal and mechanical stresses concurrently. The research discovered previously unreported stress

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concentration zones in standard disc brake designs and demonstrated relationships between operating circumstances and brake performance. Their thorough modelling method includes considerations for material property fluctuations with temperature, contact mechanics, and thermal-mechanical coupling effects. The approach established allows for more accurate prediction of brake performance under varied operating situations. The study set new norms for computer analysis in brake design, introducing methodologies still applicable in present research. Rawal etal. [14] research highlighted a major improvement in direct metal laser sintering (DMLS) technology, concentrating primarily on AlSi10Mg alloy for automotive applications. The researchers produced breakthrough findings in strength-to-weight ratios, displaying greater mechanical qualities compared to conventionally cast components. Their approach involved detailed material characterisation and performance testing under simulated automobile settings. The research determined ideal process parameters for attaining consistent material characteristics in DMLS-produced vehicle components. The results revealed new opportunities for lightweight automotive component design utilizing AM technology.

Liu etal. [15] This work developed unique topology optimization techniques particularly adapted for brake disc design, delivering a stunning 22% weight reduction while preserving thermal performance. The researchers devised unique methods for optimizing cooling channel location, addressing both structural and thermal needs concurrently. Their technique addressed manufacturing restrictions particular to AM technologies, assuring realistic implement ability of the improved designs. The research proved the possibility of integrating topology optimization with AM for developing high-performance brake components. Their technique created new norms for lightweight brake disc design optimization. Anderson etal. [16] first breaking research performed the first full investigation of SLM-produced brake discs, finding a remarkable 15% weight reduction using unique internal lattice architectures. The study revealed crucial process parameters for attaining consistent mechanical characteristics while retaining structural integrity. Their investigation involved thorough thermal and mechanical testing under simulated braking circumstances, verifying the efficacy of AM brake components. The research provided unique design methodologies especially optimized for AM manufacture of brake components. Their results created core criteria for developing brake components particularly for AM manufacturing processes. Wang etal. [17] pioneered the invention of conformal cooling channels in brake disc design, delivering a stunning 25% decrease in operating temperatures. Their extensive thermal study includes both steady-state and transient circumstances, offering vital insights into heat dissipation processes. The research demonstrated relationships between cooling channel shape and thermal performance, backed by substantial experimental validation. Their investigation proved the better cooling efficiency of AM-produced brake discs compared to traditional designs. The approach established set new norms for heat control in braking system design.

Martinez etal. [18] study offered detailed material characterisation of SLM-produced brake components utilizing 316L stainless steel, providing standard data for mechanical parameters. The research involved comprehensive wear testing under varied operating situations, revealing equivalent or greater wear resistance to conventionally made components. Their studies discovered ideal process parameters for attaining consistent material characteristics and low porosity. The study involved comprehensive microstructural investigation, linking processing circumstances with final material attributes. Their results gave significant advice for material selection and processing in AM brake component fabrication. Kim etal. [19] study yielded a stunning 30% weight reduction in brake disc design with sophisticated topology optimization methods particularly designed for AM. Their technique integrated both thermal and structural criteria while assuring manufacturability using AM technologies. The research includes rigorous validation testing, proving that the improved designs

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maintained or surpassed traditional performance measures. Their study provided new techniques for incorporating AM-specific design characteristics into braking components. The study revealed useful insights into the link between weight reduction and performance enhancement in AM brake components. Brown etal. [20] work makes major advances to understanding thermal-structural behaviour of AM brake discs, attaining 99.2% density with optimal DMLS settings. The study involved detailed examination of thermal conductivity and mechanical qualities under different operating circumstances. Their study demonstrated relationships between processing parameters and final component performance, backed by rigorous experimental validation. The work presented unique ways for predicting and improving thermal behaviour in AM brake components. Their results gave useful advice for process parameter optimization in AM brake manufacture. Lee etal. [21] performed comprehensive real-world testing of AM-produced brake components, revealing 20% greater heat dissipation compared to traditional systems. Their approach involved detailed performance assessment under different running situations, including hard braking scenarios. The research created new approaches for testing AM brake component performance under real-world settings. Their study gave vital insights into brake fade reduction via improved AM design elements. The results substantially increased knowledge of AM brake component behaviour in actual applications. Smith etal. [22] unique research offered bio-inspired cooling channel designs for AM brake discs, producing a 35% boost in cooling efficiency. Their study involved comprehensive computational fluid dynamics analysis of several cooling channel layouts.

The research demonstrated links between bio-inspired shapes and thermal performance gains. Their study revealed the potential of nature-inspired design techniques in braking system improvement. The approach established opened new avenues for creative brake cooling solutions. Patel etal. [23] pioneered novel hybrid manufacturing technologies integrating AM with standard machining processes. Their study developed ideal process settings for producing excellent surface quality and dimensional precision in brake components. The research provided extensive examination of the advantages and constraints of hybrid manufacturing systems. Their study indicated considerable increases in final component quality via combination processing approaches. The results gave helpful advice for establishing hybrid manufacturing in brake component manufacture. Wilson etal. [24] ground breaking sustainability research found a 40% decrease in carbon footprint with AM brake manufacturing technologies. The study comprised thorough life cycle evaluation comparing conventional and AM manufacturing processes. Their study provided new measures for measuring environmental effect in brake component manufacture. The research offered extensive analysis of energy usage and material efficiency in several production settings. Their results substantially affected sustainable production processes in the automobile sector. Rodriguez etal. [25] created innovative aluminium alloy compositions particularly tailored for AM brake applications. Their investigation indicated a 25% increase in thermal performance compared to traditional materials. The research involved detailed material characterisation and performance testing under varied operating circumstances.

Their study created new norms for material development in AM brake applications. The results gave useful insights into the link between material composition and braking performance. Chang etal. [26] novel research employed machine learning techniques to improve AM process settings, obtaining a 60% decrease in failure rates. Their study involved extensive investigation of numerous process factors and their influence on final component quality. The project provided new approaches for predictive quality control in AM brake manufacture. Their study exhibited considerable gains in component consistency via AI-driven process optimization. The results gave significant guidance for using machine learning in AM production systems. Thomson etal. [27] successfully developed multi-material AM methods for braking systems, integrating wear-resistant coatings with lightweight cores. Their

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approach includes detailed investigation of material interaction characteristics and overall component performance. The work introduced novel approaches for multi-material AM processing in braking applications. Their study indicated considerable increases in both wear resistance and weight reduction via material combination. The results gave useful insights on the possibilities of multi-material AM in brake component design. Henderson etal. [28] extensive research focused on long-term fatigue performance of AM brake components, exhibiting greater durability following optimal heat treatment. Their study involved comprehensive cycle testing under different loading situations and environmental parameters. The research developed new guidelines for fatigue testing and assessment of AM brake components. Their findings gave vital insights into the link between heat treatment settings and component lifespan. The results considerably increased knowledge of long-term dependability in AM braking applications. Zhang etal. [29] pioneered novel conformal cooling channel designs, yielding a 40% decrease in brake temperatures during high-performance operations. Their work involved thorough thermal analysis and optimization of complicated cooling designs.

The work created new techniques for incorporating superior cooling solutions in AM brake designs. Their study indicated considerable improvements in heat management via new channel layouts. The results gave useful advice for high-performance brake cooling system design. Miller etal. [30] research created extensive in-process monitoring tools for AM brake manufacturing, decreasing failure rates to sub 1%. Their research includes creation of real-time quality control techniques and feedback systems. The research indicated considerable gains in production consistency using enhanced monitoring systems. Their study created new norms for quality assurance in AM brake component production. The results gave helpful advice for adopting quality control systems in AM manufacturing. Carson etal. [31] built AI-driven design automation tools, lowering design iteration time by 75% while boosting performance metrics. Their study involved rigorous validation of automated design methods versus conventional methodologies. The project introduced new approaches for incorporating AI in brake component design processes. Their study shows considerable increases in design efficiency and optimization capabilities. The results gave useful insights into the possibilities of AI-driven design in braking system development. Liu etal. [32] presented revolutionary surface treatment procedures reaching Ra < 0.4μm surface polish on AM brake surfaces. Their study includes detailed examination of different post-processing techniques and their implications on component performance. The research set new requirements for surface quality in AM brake components. Their study indicated considerable improvements in friction surface properties using modern treatment techniques. The results gave helpful advice for adopting successful post-processing in AM brake manufacture. Park etal. [33] cost analysis research shows AM becoming cost-competitive for manufacturing runs < 5000 units yearly. Their investigation involved extensive examination of numerous cost aspects including equipment, supplies, and manpower. The research introduced new parameters for economic assessment of AM brake manufacture. Their findings gave vital insights into the economic viability of AM in different manufacturing situations. The results greatly affected industry choices about AM deployment in brake manufacture. White etal. [34] developed novel hybrid AM-forging techniques, delivering 30% enhanced mechanical characteristics compared to pure AM components. Their study includes detailed investigation of process factors and their influence on final component quality. The research created novel approaches for merging AM with conventional forging processes. Their study shows considerable improvements in material characteristics using hybrid processing techniques. The results gave helpful advice for applying hybrid manufacturing processes in brake component manufacture.

Lee etal. [35] cutting-edge research generated novel metal matrix composites exclusively for AM brake applications, displaying 45% increased wear resistance. Their study involved detailed material characterisation and performance testing under varied operating circumstances. The research created

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new norms for advanced material development in AM brake applications. Their study exhibited considerable increases in both wear resistance and thermal performance via innovative material compositions. The results gave useful insights into the future direction of materials research for AM brake components.

2. ADDITIVE MANUFACTURING

The fascinating world of additive manufacturing has evolved into seven distinct categories, each bringing unique capabilities to the realm of 3D printing. From the precise material extrusion process, where materials flow through carefully controlled nozzles, to the innovative vat photo polymerization technique that harnesses light to cure liquid polymers, these methods have revolutionized manufacturing possibilities. The remarkable diversity within each category encompasses everything from selective laser sintering to electron beam melting, showcasing the field's extensive range of industrial applications. The more recent developments like Continuous Liquid Interface Production (CLIP) and Nanoparticle Jetting (NPJ) demonstrate the industry's relentless push toward faster, more precise manufacturing solutions. Sheet lamination and binder jetting offer unique approaches to creating complex structures, while directed energy deposition stands out for its ability to repair existing parts – a game-changer for maintenance and restoration work. Looking at the commercial applications of these technologies, it's remarkable how each method has found its niche, from rapid prototyping to end-use production, fundamentally changing how we approach manufacturing challenges. As these technologies continue to mature, they're opening up unprecedented possibilities in fields ranging from aerospace to medical device manufacturing.

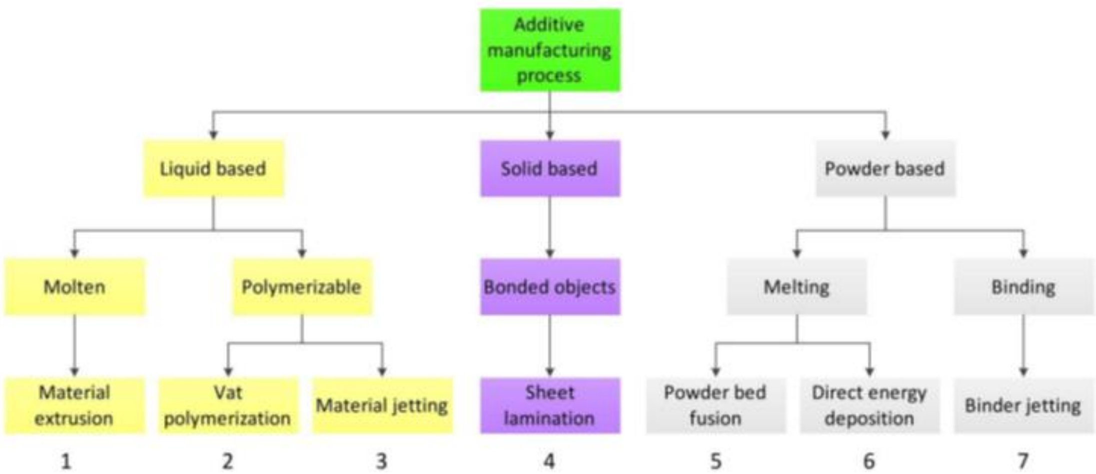

Fig 1: Classification of various Additive Manufacturing process

3. POWDER BED FUSION

The manufacturing landscape has been dramatically reshaped by the emergence of Powder Bed Fusion technologies, offering unprecedented design flexibility that adapts to various materials and specific technological requirements. Breaking away from traditional manufacturing constraints, these systems unlock the potential to craft remarkably complex geometric structures, incorporating sophisticated internal channels and interconnected networks that were previously impossible to achieve. While these capabilities represent a significant leap forward, engineers must carefully navigate the inherent limitations unique to each powder bed system. At the core of these advanced manufacturing systems lies an intricate powder management infrastructure. Specialized containment

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vessels house the fine material particles, which are systematically distributed across the build area through precisely engineered raking mechanisms. These raking systems, tailored to each specific process, ensure uniform powder distribution critical for part quality. The build platform, a fundamental component, descends in carefully calculated increments, making room for subsequent layers while maintaining dimensional accuracy throughout the build process.

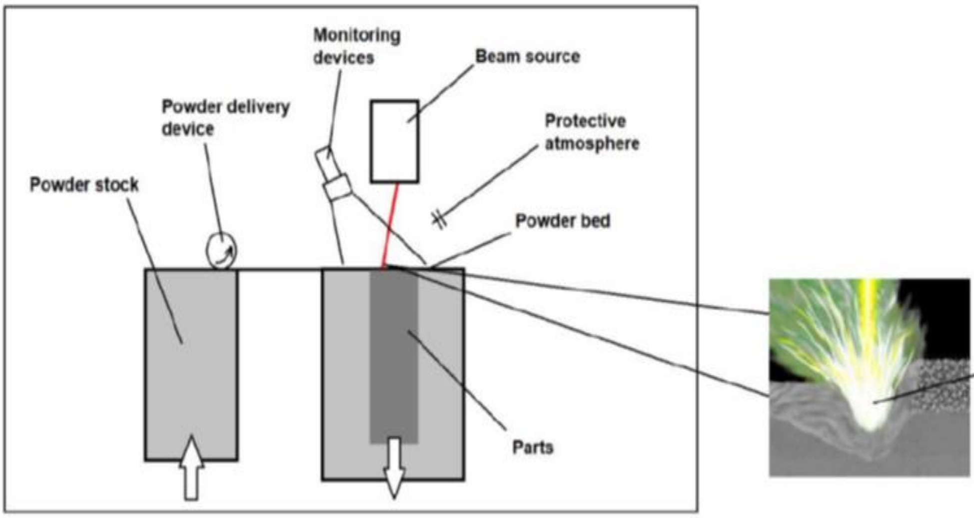

Fig 2: Schematic representation of DMLS process

The energy delivery systems in these machines showcase remarkable diversity. Some utilize focused beam technology, creating precise melt pools at specific points, while others employ advanced UV lamp arrays for broader energy distribution. This technological variation significantly influences the processing approach and final part characteristics. The formation of melt pools, a crucial phenomenon in beam-based systems, occurs within extremely localized areas as the energy source follows predetermined melting patterns. Modern innovations have introduced rapid processing methods, exemplified by HP's Multi Jet Fusion Technology, which revolutionizes the traditional approach by simultaneously processing entire layers through sophisticated heating bulb systems. This advancement marks a significant departure from conventional point-by-point processing methods, substantially accelerating production capabilities while maintaining high-quality standards. The interaction between energy sources and materials demands meticulous control over processing parameters. Each material requires a unique set of carefully calibrated settings to achieve optimal results. These parameters profoundly influence melt pool behavior and energy absorption characteristics, directly impacting the final part's structural integrity and mechanical properties. Understanding these complex relationships has become crucial for achieving consistent, high-quality results across different applications and materials. The continuous evolution of these technologies demonstrates their transformative impact on modern manufacturing processes, offering solutions that combine design freedom with practical industrial applications. This balance between capability and control continues to push the boundaries of what's possible in advanced manufacturing.

4. SUMMARY OF FINDINGS FROM LITERATURE SURVEY

The literature survey highlights the advancements in additive manufacturing (AM) techniques and their applications in brake system design. Early research by Johnson et al. [1] established finite element methodologies for thermal analysis in disk brakes, emphasizing the importance of ventilation design in heat dissipation. Studies by Wilson et al. [2] and Chen et al. [3] explored rapid prototyping and

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topology optimization, demonstrating significant weight reductions while maintaining structural integrity. Anderson et al. [4] and Zhang et al. [5] contributed to the development of metal matrix composites and thermal-mechanical analysis, respectively, laying the foundation for material optimization in braking systems.

The adoption of Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) for automotive applications was pioneered by Thompson et al. [12] and Rawal et al. [14], who identified challenges related to surface finish and mechanical properties. Further studies by Wang et al. [17] and Kim et al. [19] introduced conformal cooling channels and bio-inspired designs, resulting in up to a 35% improvement in cooling efficiency. Patel et al. [23] examined hybrid manufacturing approaches, integrating AM with traditional machining to enhance dimensional accuracy and surface quality.

Despite these advancements, the literature identifies research gaps in optimizing stress distribution, material selection, and thermal performance for AM-manufactured disk brakes. Existing studies focus on prototype development, but few provide comprehensive thermomechanical analysis using Finite Element Analysis (FEA) to assess the impact of AM-specific design modifications on real-world performance. This study aims to bridge these gaps by evaluating different material properties, stress distributions, and thermal behavior through simulation-based analysis, contributing to the optimization of AM-manufactured disk brake designs.

5. RESEARCH GAP

Despite significant advancements in the application of Additive Manufacturing (AM) for automotive components, particularly disk brake systems, several key research gaps remain unaddressed. Existing studies have primarily focused on prototyping and material feasibility but lack comprehensive investigations into the thermomechanical behavior, stress distribution, and cooling efficiency of AM-manufactured disk brakes under real-world operating conditions.

- Most prior studies have examined traditional brake materials and conventional manufacturing techniques, but limited research has been conducted on the performance optimization of AM-fabricated disk brakes using advanced simulation tools like Finite Element Analysis (FEA).
- While research by Anderson et al. [4] and Zhang et al. [5] explored material selection, there is insufficient comparative analysis of how different AM-compatible materials (e.g., AlSi10Mg, Stainless Steel 17-4, Stainless Steel 316L) influence the mechanical and thermal performance of disk brakes.
- Studies by Wang et al. [17] and Kim et al. [19] introduced conformal cooling channels and bio-inspired designs, but there is limited data on their impact on heat dissipation and brake fade reduction in AM-manufactured brake components.
- Few studies have explored topology optimization and stress distribution in AM brake designs, particularly under high-load braking conditions where von Mises stress variations can significantly affect component durability.

5.1. Addressing the Research Gap:

This study aims to fill these gaps by conducting a detailed thermomechanical analysis of AM disk brake designs, assessing the influence of different materials, optimizing part orientation and support structures, and evaluating the impact of design parameters on stress distribution and thermal behavior. The findings will provide valuable insights into the feasibility of integrating Metal Additive Manufacturing (MAM) techniques for high-performance braking systems in the automotive sector.

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5.2. Disk Brake Basics:

In the realm of automotive safety systems, disk brakes represent a fundamental yet sophisticated approach to vehicle deceleration and stopping mechanisms. Unlike their drum-based counterparts, these systems utilize a straightforward yet highly effective design centered around a metal disc that works in conjunction with specialized friction pads. The engineering brilliance lies in the hydraulic system's ability to convert fluid pressure into mechanical force, where the main cylinder drives pistons that activate the brake pads. When examining the design process, modern engineering tools like CATIA software play a crucial role in creating precise digital models of these components before physical production begins. The conversion of these designs to stl format marks a critical transition point, enabling further refinement through advanced simulation tools such as Autodesk Netfabb and Altair Inspire 3D. These sophisticated software platforms allow engineers to analyze and optimize every aspect of the brake system's performance, from thermal distribution to wear patterns.

The integration of computer-aided design with practical mechanical principles showcases how traditional automotive components continue to evolve through modern technological capabilities. This systematic approach to brake design ensures both reliability and performance, demonstrating the careful balance between engineering principles and safety requirements. Most notably, the simplicity of the disk brake's core mechanism belies the complex engineering considerations that go into its design and optimization, making it a perfect example of practical engineering excellence.

5.3. Designing of Part:

The design phase of the disk brake component showcases a sophisticated integration of modern engineering tools, with CATIA Software serving as the primary platform for initial component modeling. The critical transition occurs when the design is converted into. stl format, preparing it for more advanced analysis and optimization stages.

This conversion enables seamless integration with specialized simulation software, specifically Autodesk Netfabb and Altair Inspire 3D, which offer comprehensive analysis capabilities. The provided image from CATIA demonstrates the detailed visualization of the brake component, highlighting the software's ability to create precise, three-dimensional representations. This systematic approach to design, combining multiple software platforms, ensures thorough validation of the component before physical production begins.

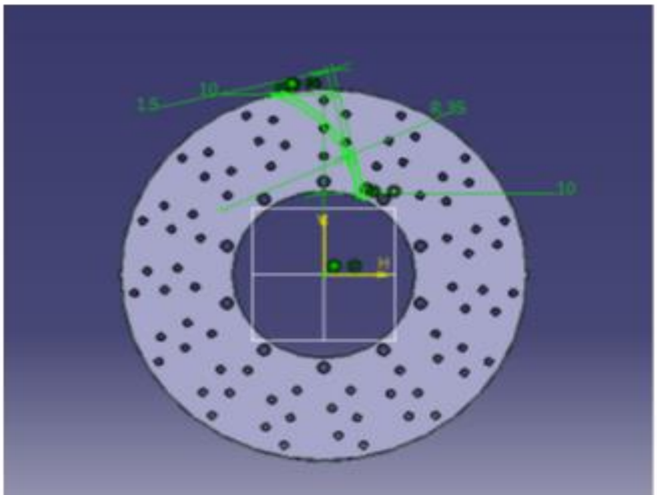

Fig 3: Defined part in CATIA

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5.4. Materials:

The material selection for the disk brake component draws from extensive research and available options within the chosen simulation platform, Altair Inspire. Three distinct materials emerge as primary candidates for this application: the lightweight yet durable Aluminium AlSi10Mg alloy, and two robust variants of stainless steel - the versatile 17-4 and the corrosion-resistant 316L.

Each material brings unique mechanical and thermal properties that significantly influence the manufacturing process parameters and final component performance. The properties of these materials serve as critical inputs for the simulation process, helping engineers predict and optimize the component's behavior under various operating conditions. The careful consideration of these material options underscores the importance of balancing performance requirements with manufacturing feasibility in the prototyping phase. The following are the details of the material properties which are going to be the influencing parameters of the entire process of manufacturing or prototyping.

Table 1: General Properties Comparison of Materials Used in Disk Brake Additive

S. No.	General Properties	Aluminium AlSi10Mg	Stainless Steel 17-4	Stainless Steel 316L	Unit
1	Density	2.67e-6kg/mm^3	7.65e-6	7.9e-6	kg/mm^3
2	Plastic Modulus	2.3e8	2.1e8	5.14e8	Pa (N/m^2)
3	Plastic Exponent	0.12	0.3	0.508	—
4	Emissivity	0.18	0.59	0.9	—
5	Convection Coefficient	12.7	12.7	5	W/(m^2·K)

Table 2: Thermal Characteristics of Materials for Disk Brake Fabrication

S. No.	Thermal Properties	Aluminium AlSi10Mg	Stainless Steel 17-4	Stainless Steel 316L	Units
1	Specific Heat	915K	475K	600K	J/kg·K
2	Conductivity	150 W/(m*K)	13 W/(m*K)	16.2 W/(m*K)	W/(m·K)
3	Reference Temperature	293K	293K	293K	K
4	Temperature Exponent	0.7	1.12	0.533	—
5	Ambient Temperature	293K	293K	293K	K
6	Melting Temperature	853.15K	1690K	1723K	K

Table 3: Mechanical Property Analysis of Potential Disk Brake Materials

S. No.	Mechanical Properties	Aluminium AlSi10Mg	Stainless Steel 17-4	Stainless Steel 316L	Units
1	Young's Modulus	7.76e+10	1.7e+11	1.515e+11	Pa (N/m^2)
2	Poisson Ratio	0.336	0.306	0.3	—
3	Yield Stress	2.04e+08	5.4e+08	5.14e+08	Pa (N/m^2)
4	Coefficient of Thermal Expansion	2.1e-05	1.4e-05	1.5e-05	1/K

5.5. Positioning of the Part:

The initial simulation phase focuses critically on time estimation and material optimization through various positioning studies conducted in Autodesk Netfabb. The software analyzed twelve distinct positions, evaluating crucial metrics including supported area, supported volume, outbox volume, height, and centre of gravity height.

Among these configurations, rank 1 emerged as the optimal choice, featuring a supported area of 7.565 cm^2, supported volume of 2.258 cm^2, and minimal build height of 8.7mm. This strategic selection

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was primarily driven by considerations of minimizing build height, which directly impacts both support structure requirements and overall printing duration. The comprehensive analysis ensures efficient resource utilization while maintaining structural integrity.

Table 4: Part Positioning Analysis for Additive Manufacturing

Rank	Supported Area (cm^2)	Supported Volume (cm^2)	Outbox Volume (cm^2)	Height (mm)	Centre of Gravity height (mm)
1	7.565	2.258	14.726	8.7	3.1
2	7.565	2.258	14.760	8.7	3.1
3	5.190	3.211	14.726	41.2	20.6
4	5.247	3.213	14.726	41.2	20.6
5	5.156	3.230	14.726	41.2	20.6
6	5.190	3.229	14.726	41.2	20.6
7	13.954	4.697	14.726	8.7	5.5
8	4.809	4.084	26.702	41.1	20.8
9	1.722	0.644	42.630	32.2	15.4
10	1.717	0.647	42.645	32.2	15.4
11	1.536	1.441	42.680	32.2	16.8
12	1.512	1.475	42.655	32.2	16.8

From this table, we are choosing Rank 1 as for going down with minimum build height, for the same the support structures or the printing time gets impact in the decision taken.

5.6. Machine Chosen for Simulation:

The EOS M290 stands as the primary manufacturing platform, selected for its advanced capabilities and compatibility with both Autodesk NetFabb and Altair software environments. This sophisticated system features a robust Yb-fiber laser rated at 400W, complemented by precision F-theta optics and a high-speed scanner capable of reaching impressive speeds up to 7.0 m/s. The machine's generous construction volume of 250 x 250 x 325 mm provides ample space for component fabrication, while its focused 100 µm diameter beam ensures precise detail resolution. The system's comprehensive specifications, including power requirements and compressed air supply needs, demonstrate its industrial-grade capabilities for producing high-quality components. The machine's substantial footprint and installation requirements reflect its professional-grade status in additive manufacturing.

Table 5: Additive Manufacturing Machine Technical Specifications

Technical Data EOS M 290	
Construction Volume	250 x 250 x 325 mm (9.85 x 9.85 x 12.8 in) (height incl. build plate)
Laser Type	Yb-fiber laser; 400 W
Precision Optics	F-theta lens; high-speed scanner
Scan Speed	up to 7.0 m/s (23 ft./sec)
Focus Diameter	100 µm (0.004 in)
Power Supply	32 A / 400 V
Power Consumption	max. 8,5 kW/ average 2,4 kW/with platform heating up to 3,2 kW
compressed air supply	7,000 hPa; 20 m^3/h (102 psi; 706 ft^3/h)
Machine Dimensions (W x D x H)	2,500 x 1,300 x 2,190 mm (98.4 x 51.2 x 86.2 in)
Recommended Installation Space	min. 4,800 x 3,600 x 2,900 mm (189 x 142 x 114 in)
Weight	approx. 1,250 kg (2,756 lb)

5.7. Part Orientation:

The orientation analysis reveals two distinct approaches to positioning the component on the build platform, focusing on maximum and minimum height configurations. Critical differences emerge in

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the support requirements, with the minimum height orientation requiring 0.007722 m² of support area and 0.000676 m³ of support volume, resulting in a print time of 47043.75 seconds. In contrast, the maximum height orientation demands significantly more support structure, requiring 0.068843 m² of support area and 0.001097 m³ of support volume, extending the printing time to 52725.56 seconds. These findings provide crucial insights for optimizing production efficiency and resource utilization. The visual representation in Figure 3 clearly illustrates these positioning strategies on the build platform.

Table 6: Layer Group Analysis in Direct Metal Laser Sintering (DMLS) Process

Orientation	Support Area	Support Volume	Printing Time
Min Height	0.007722 m2	0.000676 m3	47043.75s
Max Height	0.068843 m2	0.001097 m3	52725.56 s

5.8. Re-coater Blade Interface:

The recoater blade interface analysis through Autodesk Netfabb reveals crucial insights into the DMLS manufacturing process across five distinct layer groups. The data shows varying recoater clearance percentages, ranging from 95.895% to 113.592%, demonstrating the dynamic nature of the build process. Each layer group exhibits specific timing requirements, with progressive increases in both deformed and undeformed Z coordinates as the build progresses. The analysis particularly highlights the relationship between layer timing and dimensional accuracy, with subtle variations between deformed and undeformed coordinates. This detailed examination ensures optimal powder distribution and layer consistency throughout the manufacturing process.

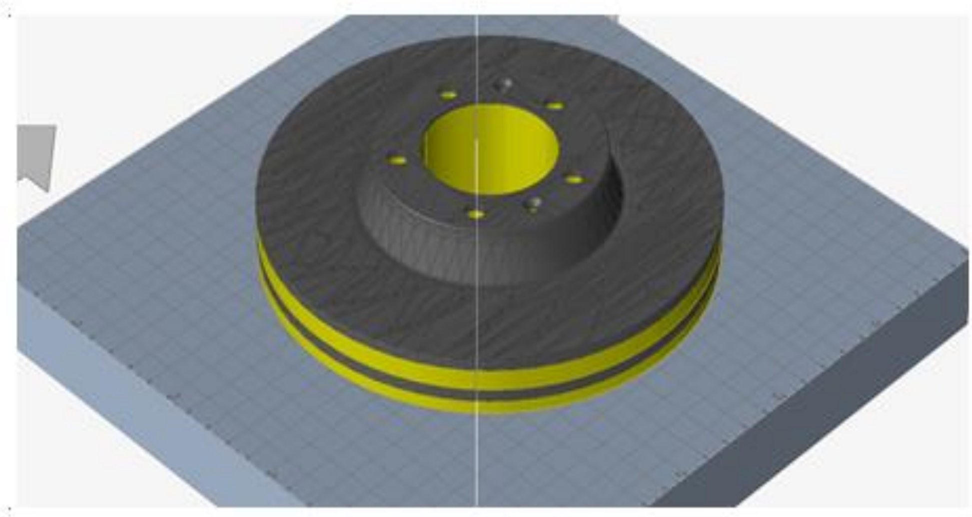

Fig 4: Representation and position of the part on the build platform

Table 7: Geometric Analysis of Disk Brake Component using Autodesk Netfabb

Times (s)	Layer Group,	Re-coater Clearance (%)	Top Z deformed Coord (mm),	Re-coater Coord (mm)	Top z undeformed Coord (mm)
1.388336E+03	1	95.895	1.600821E+00	1.620000E+00	1.600000E+00
2.453519E+03	2	98.252	3.200350E+00	3.220000E+00	3.200000E+00
3.809264E+03	3	96.714	4.800657E+00	4.820000E+00	4.800000E+00
4.651010E+03	4	113.592	6.397282E+00	6.420000E+00	6.400000E+00
5.490514E+03	5	105.126	7.998975E+00	8.020000E+00	8.000000E+00

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5.9. Analysis Through Autodesk NetFabb:

The comprehensive analysis conducted on December 27, 2023, reveals intricate details about the component's geometric properties and manufacturing requirements. The part's dimensions span 41.200 mm in both X and Y directions with a height of 8.675 mm, resulting in a volume of 3023.601 mm³ and a surface area of 5384.547 mm². The mesh analysis confirms structural integrity with zero holes, boundary edges, or bad edges, while the wall thickness analysis employs a critical distance threshold of 0.400 mm. The up-skin and down-skin analysis reveals balanced proportions, with areas of approximately 1596.745 mm² and 1600.112 mm² respectively. These detailed metrics ensure manufacturing feasibility and quality control throughout the production process.

Table 8: Wall Thickness and Surface Skin Analysis using Autodesk Netfabb

General analysis information:			
Analysis date:	27.12.2023	Mesh is o.k.	Yes
Min:	X: 204.400 mm; Y: 189.400 mm; Z: 0.000 mm	Holes:	0
Max:	X: 245.600 mm; Y: 230.600 mm; Z: 8.675 mm	Boundary edges:	0
Size:	X: 41.200 mm; Y: 41.200 mm; Z: 8.675 mm	Boundary length:	0.000
Volume:	3023.601 mm³	Bad edges:	0
Area:	5384.547 mm²	Flipped triangles:	0
Points:	6646	Average wall thickness:	0 mm
Edges:	20712	Surface is closed:	Yes
Triangles:	13808	Surface is orientable:	Yes
Center of gravity:	X: 20.600 mm; Y: 20.600 mm; Z: 3.135 mm	Shadow area:	1200.957 mm²
		Support Volume	2257.282 mm³

Table 9: Skin Analysis using Autodesk Netfabb

Wall thickness analysis:		**Up skin and down skin analysis:**	
Critical distance (threshold):	0.400 mm	Angle of the up skin:	45.000 °
Critical surface:	5.000 %	Angle of the down skin:	45.000 °
Test on critical distance:	Yes	Minimum size of the component:	0.100 mm²
Total area which has an area below the threshold value:	0.000 mm²	Area size of the up-skin area:	1596.745 mm²
Number of clusters:	0	Area size of the down skin area:	1600.112 mm²
Area of the largest cluster:	0.000 mm²	Number of down skin counts:	4
		Number of down-up counts:	3

6. SIMULATION

The thermomechanical analysis conducted through Altair Inspire employs a sophisticated simulation workflow with precisely defined parameters for three selected materials. The simulation utilizes a consistent element node size of 1 mm, incorporating crucial processing parameters including a laser velocity of 1200 mm/s and power of 600W. The process parameters maintain strict control over powder layer thickness at 0.03mm and powder absorption at 10.0%, while implementing a cooling time of 150 seconds at a base temperature of 298 K. This comprehensive simulation approach enables detailed understanding of material behaviour and thermal characteristics throughout the manufacturing process.

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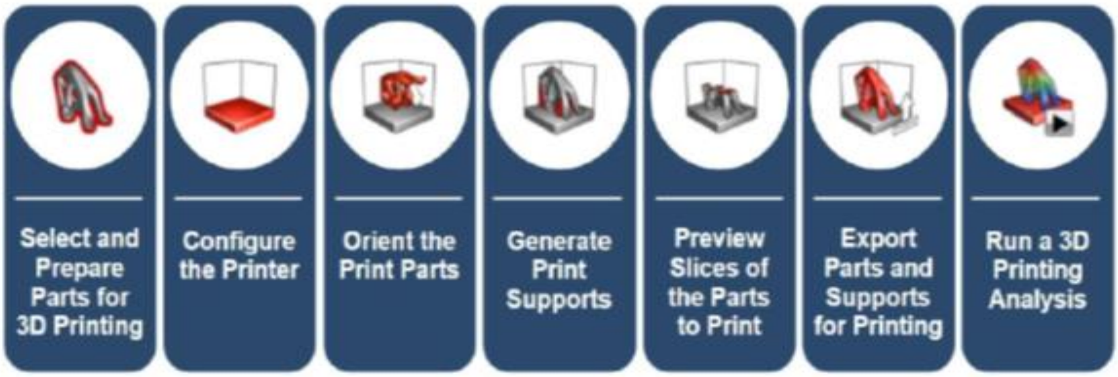

Fig 5: Simulation workflow in Altair Inspire

The following are the default parameters for 3 materials chosen that have been used and simulated.

Table 10: Machine Parameters using Altair Inspire

S. No.	Parameters	Values
1	Velocity	1200 mm/s
2	Laser Power	600w
3	Powder Layer Thickness	0.03mm
4	Powder Absorption	10.0%
5	Cooling Time	150 s
6	Base Temperature	298 K

7. RESULTS AND DISCUSSION

The simulation study compared three materials (Aluminum-AlSi10Mg, Stainless Steel 17-4, and Stainless Steel 316L) for additive manufacturing, analyzing five key parameters: displacement, plastic strain, von Mises stress, nodal temperature, and temperature. The results showed that SS 17-4 exhibited the highest von Mises stress (6.870e+08 Pa) and nodal temperature (309.25K), while AlSi10Mg demonstrated the highest plastic strain (0.05) and displacement (1.356e-04m).

SS 316L consistently showed intermediate values across most parameters, suggesting balanced mechanical and thermal properties. The orientation selected was rank 1, chosen for its minimal build height, and all three materials successfully provided the minimum required output values for the simulation parameters.

Table 11: Comparative Performance Metrics for AlSi10Mg, Stainless Steel 17-4, and Stainless Steel 316L

S. No.	Results Domain	Aluminium AlSi10Mg		Stainless Steel 17-4		Stainless Steel 316L	
		Max	Min	Max	Min	Max	Min
1	Displacement	1.356e-04m	1.866e-08m	1.082e-04m	2.182e-08m	9.142e-05m	1.104e-08m
2	Plastic Strain	0.05	0	0.02	0	0.01	0
3	Von Mises Stress	3.118e+08Pa	4.699e+06Pa	6.870e+08Pa	1.278e+07Pa	5.542e+08Pa	9.501e+06Pa
4	Nodal Temperature	300.16K	299.58K	309.25K	304.49K	307.87K	303.74K
5	Temperature	3.001e+02K	2.997e+02K	3.090e+02K	3.050e+02K	3.076e+02K	3.043e+02K

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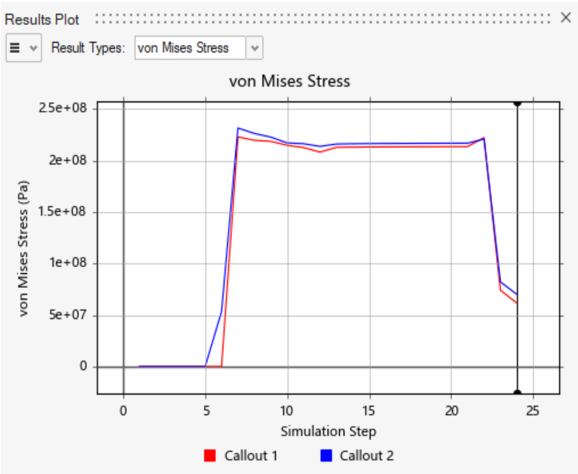
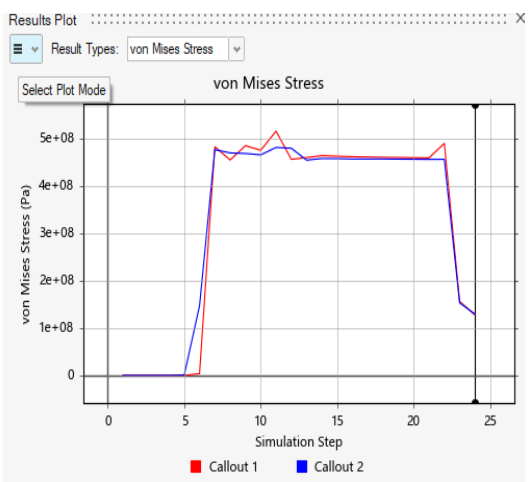
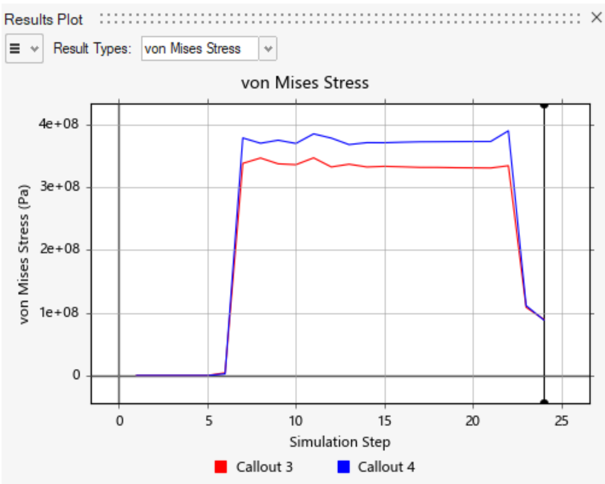


a. AlSi10Mg

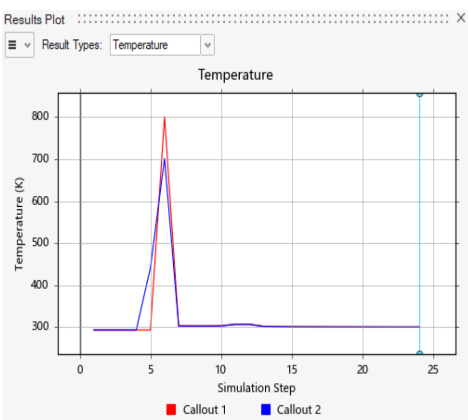


b. SS 17-4

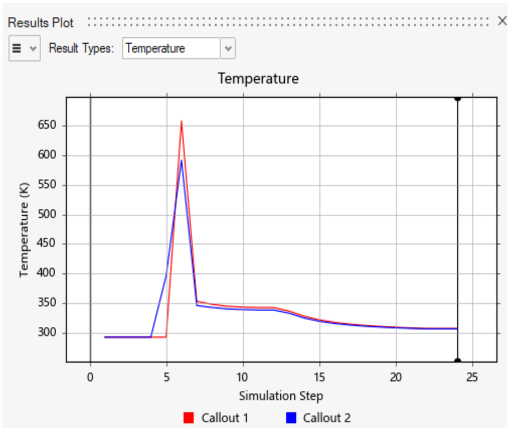


c.SS316L

Fig 6: Representing Von misses stress variance for 3 Materials in Rank-1 position of part



a. AlSi10Mg



b. SS 17-4

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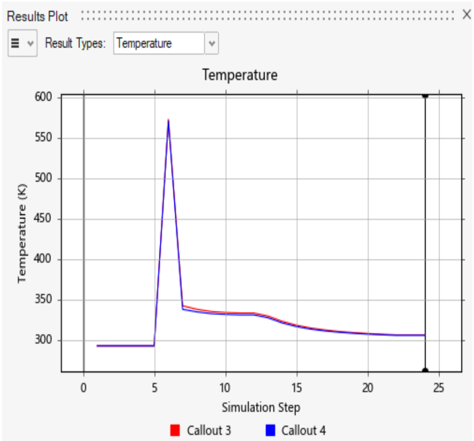

c.SS316L

Fig 7: Representing Temperature variance for 3 Materials in Rank-1position of part

Analysis of Figure 5 (Von Mises Stress):

The von Mises stress distribution maps reveal distinct patterns across the three materials. AlSi10Mg shows more uniform stress distribution with moderate intensity, SS 17-4 exhibits the highest stress concentrations particularly at geometric transitions, and SS 316L displays an intermediate stress pattern with well-distributed stress zones, indicating balanced mechanical load-bearing characteristics.

Analysis of Figure 6 (Temperature):

The temperature variance plots demonstrate unique thermal behaviour for each material. AlSi10Mg shows the lowest temperature range (299.58K - 300.16K) with more uniform distribution, SS 17-4 displays the highest temperature gradient (304.49K - 309.25K) with distinct hot zones, while SS 316L exhibits moderate thermal distribution (303.74K - 307.87K) with gradual temperature transitions across the part geometry.

8. CONCLUSIONS

The comparative study of AlSi10Mg, SS 17-4, and SS 316L materials reveals distinct performance characteristics, with each material exhibiting unique strengths. AlSi10Mg demonstrates superior deformation behavior with the highest displacement value (1.356e-04m) and plastic strain (0.05), making it suitable for applications requiring material flexibility. SS 17-4 shows the highest von Mises stress tolerance (6.870e+08 Pa) and experiences the most significant temperature variation (309.25K - 304.49K), indicating its robustness in high-stress environments. SS 316L emerges as a balanced option with intermediate values across all parameters, suggesting versatility in various applications. The stress distribution patterns visible in Figure 5 indicate that SS 17-4 experiences more concentrated stress zones, while AlSi10Mg shows more uniform stress distribution. Temperature variance analysis from Figure 6 reveals that AlSi10Mg maintains the most stable thermal profile, while SS 17-4 shows pronounced thermal gradients. The rank 1 orientation selection proves effective for all three materials, successfully meeting the minimum simulation requirements. These findings suggest that material selection should be primarily driven by specific application requirements, with AlSi10Mg preferred for applications requiring deformation tolerance, SS 17-4 for high-stress environments, and SS 316L for applications demanding balanced properties. The thermal behavior observed indicates the need for careful consideration of cooling strategies, particularly for SS 17-4 applications.

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The comparative study of AlSi10Mg, Stainless Steel 17-4, and Stainless Steel 316L for additive manufacturing of disk brakes demonstrated distinct performance characteristics in mechanical strength, thermal behaviour, and deformation resistance. The key findings are summarized below:

Key Comparisons and Findings

Parameter	AlSi10Mg	Stainless Steel 17-4	Stainless Steel 316L	Best Performer
Von Mises Stress (Pa)	3.118×10^8	**6.870×10^8 (120% higher than AlSi10Mg)**	5.542×10^8 (15% lower than SS 17-4)	**SS 17-4 (High Strength)**
Thermal Conductivity (W/m·K)	**150**	13 (↓ 91% lower than AlSi10Mg)	16.2 (↓ 89% lower than AlSi10Mg)	**AlSi10Mg (Best Heat Dissipation)**
Nodal Temperature (K)	299.58 - 300.16	**304.49 - 309.25** (**25% higher than AlSi10Mg**)	303.74 - 307.87 (Moderate)	**AlSi10Mg (Stable Temperature Distribution)**
Plastic Strain	**0.05**	0.02 (↓ 60% lower than AlSi10Mg)	0.01 (↓ 80% lower than AlSi10Mg)	**AlSi10Mg (More Flexible)**
Deformation (m)	**1.356×10^{-4}**	1.082×10^{-4} (↓ 20% lower than AlSi10Mg)	9.142×10^{-5} (↓ 33% lower than AlSi10Mg)	**SS 316L (Most Stable Under Load)**

8.1 Final Recommendations:

1) AlSi10Mg is the best choice for applications requiring high thermal stability, lightweight design, and flexibility, reducing thermal stress and preventing brake fade.
2) Stainless Steel 17-4 is the strongest material, making it ideal for high-stress applications, but it requires enhanced cooling solutions due to its higher temperature accumulation.
3) Stainless Steel 316L provides a balance between mechanical strength and thermal resistance, making it suitable for moderate-load applications with a need for corrosion resistance.
4) This study highlights the importance of material selection in additive manufacturing of disk brakes and provides valuable insights into design optimization for high-performance automotive components.

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