Identifying and analyzing lightweight materials for automobile wheel rims using the finite element method

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Abstract. This study employed finite element analysis (FEA) to evaluate the mechanical performance of AZ91D magnesium alloy reinforced with 1.5 wt.% titanium diboride (TiB_2) nanoparticles, fabricated through stir casting, for potential use in automotive wheel rims. Unlike most rim analyses that focus on aluminium alloys, this work benchmarks a magnesium-titanium diboride (Mg-TiB_2) nanocomposite against Al6061 and A356 under identical geometry, loading and boundary conditions. The AZ91D/1.5 wt.% TiB_2 composite exhibited a maximum deformation of 0.055 mm, von Mises stress of 10.85 MPa and elastic strain of 2.31 x 10^{-4}, compared with 0.0374 mm, 10.88 MPa and 1.58 x 10^{-4} for Al6061 and 0.0575 mm, 11.05 MPa and 2.51 x 10^{-4} for A356. All values were well below the respective yield strengths, confirming safe elastic behaviour. The composite also achieved an approximate 31% reduction in density compared with Al6061, offering potential improvements in acceleration, braking and fuel efficiency. Argon gas was used to minimize oxidation as casting occurred while preheating TiB_2 powder before mixing. The stir rate was set so that a sufficient rate of particle dispersion was maintained. The FEA results look promising for lightweight rims, but proper fatigue and impact tests are still needed to confirm real-world performance.

1 Introduction

Tires are not the only part of how a wheel performs on roadways, but the rim that fits around a tire has a direct impact on how it brakes, turns, or accelerate during acceleration. This is why the weight of the rim is important in providing stability and control while driving, since if the rim is too heavy or too soft, the handling of the vehicle is going to be different from if it had the proper weight or stiffness. Therefore, material considerations in building modern vehicle rims must be considered carefully. For many years, steel rims were popular due to their strength, however, they are also considerably heavier, which has become an issue now that everybody's looking for lighter vehicles that provide better fuel economy. Interest in using aluminium and magnesium alloys has gone up recently. Magnesium has been gaining attention due to its lightweight property of only 1.74 g/cm^3 compared to aluminium (2.7

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g/cm^3) or steel (7.86 g/cm^3) [1], means that the wheels on a car are now able to go further, stop quicker and use less fuel when accelerating.

Nowadays, engineers do not typically build as many physical prototypes as in the past due to improved computer modelling methods that allow for simulations of designs. One of the most popular types of simulation used by engineers to determine the performance of the wheel rim when subjected to various loads is the use of finite element analysis (FEA). Several earlier studies show the usefulness of this approach. Ansari et al. [2], for example, developed rim designs in CATIA and evaluated their static, harmonic, modal and fatigue behaviour in ANSYS using aluminium, steel and magnesium alloys. Other researchers studying high-load or high-speed conditions have also reported that magnesium alloys typically show lower stress levels and offer noticeable weight savings compared with more common metals [2,3]. These outcomes indicate that magnesium can meet the mechanical demands of wheel rims while reducing overall mass.

Most of the available research, however, still concentrates on magnesium as a single-phase alloy. Recently, there has been more interest in improving its properties by adding ceramic reinforcement. Titanium diboride (TiB_2) is one such material and is often selected because it has a high melting point (~2790 °C), high hardness (~960 HV) and bonds well with magnesium. Studies suggest that small additions of TiB_2 help improve load transfer and keep the particles well dispersed. When the reinforcement level is much higher, problems such as particle clustering, poor wetting and reduced ductility have been reported [4–6].

Studies on aluminium matrix composites also show the benefits of ceramic reinforcement. TiB_2-reinforced Al2024 alloys, for example, have shown improvements in hardness and better wear performance under dry sliding conditions [7]. Even so, aluminium's higher density (~2.7 g/cm^3) limits the weight reduction that can be achieved. This is why magnesium-based composites have become a promising alternative, as they have the lightweight advantage and gain strength and wear resistance from the TiB_2 particles.

Researchers have also studied other reinforcement options to develop lightweight composite systems. Borosilicate-glass-reinforced aluminium alloys, for instance, have shown improvements in strength without a large increase in density [8]. These developments reflect the broader effort to combine low mass with improved mechanical behaviour. Nanocomposites based on magnesium follow the same idea and may offer an attractive option for components where weight needs to be minimised.

More recent investigations further support the potential of magnesium nanocomposites. Liu et al. (2023) [4] reported grain refinement and increased strength in Mg-Al-Si alloys with TiB_2 nanoparticle additions. Rahman et al. (2025) [9], who compared different wheel-rim materials, also noted that lighter alloys can improve fatigue life. Together, these studies indicate that magnesium-based composites could serve as alternatives to aluminium alloys in situations where both strength and low weight are important.

In this context, the present study evaluates the mechanical performance of AZ91D magnesium alloy reinforced with 1.5 wt.% TiB_2 nanoparticles (<80 nm) fabricated by stir casting. The novelty of this work lies in being the first to apply FEA to a realistic 19-inch wheel rim geometry made from an AZ91D/TiB_2 nanocomposite and to benchmark its performance against two widely used aluminium alloys (Al6061 and A356) under identical loading and boundary conditions. The analysis considers deformation (mm), von Mises stress (MPa) and elastic strain (mm/mm) to determine whether Mg-TiB_2 nanocomposites can deliver a superior stiffness-to-weight ratio and thus support the development of lighter, more efficient and high-performance wheel rims.

2 Materials and methodology

2.1 Materials preparation

AZ91D magnesium alloy was selected as the base material for its low density, high strength-to-weight ratio and good castability, making it suitable for lightweight automotive components [1]. Its chemical composition is shown in Table 1.

Table 1. Chemical composition of the AZ91D magnesium alloy used as the base material in this study. Values are given in weight percentage (wt.%); the remainder is magnesium.

Elements	Al	Zn	Mn	Si	Cu	Fe	Ni	Others	Mg
Content %	8.3-9.7	0.35-1	0.15-0.50	0.1	0.03	0.005	0.002	0.02	Remainder

To improve mechanical performance, TiB_2 nanoparticles (<80 nm, 98% purity) were introduced as reinforcement. A concentration of 1.5 wt.% was chosen to achieve uniform dispersion without the ductility loss reported at higher particle contents [5,6]. The morphology of TiB_2 nanoparticles observed by Field Emission Scanning Electron Microscopy (FESEM) is shown in Figure 1.

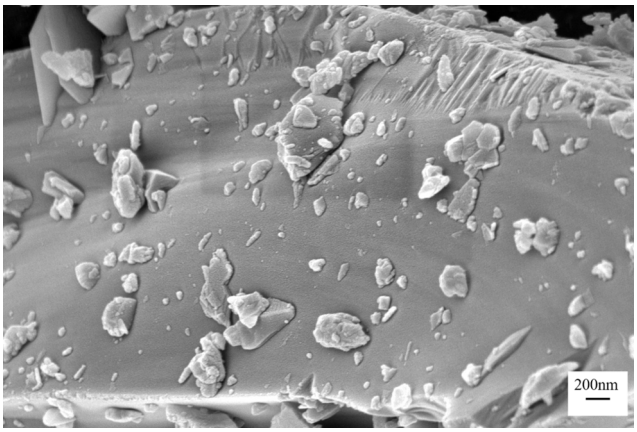


Fig. 1. FESEM micrograph of TiB_2 nanopowder showing predominantly angular particle morphology with nanoscale dimensions, used as reinforcement in the AZ91D alloy.

The composite was fabricated using stir casting. AZ91D ingots were melted in a graphite crucible at 750 °C under an argon-SF_6 protective atmosphere to suppress oxidation and burning of the melt. TiB_2 nanoparticles were preheated to 250 °C to improve wettability and reduce thermal shock before addition. They were introduced gradually into the vortex created by mechanical stirring at 600 rpm for 5 minutes. This approach minimised clustering of particles and promoted uniform dispersion. The molten slurry was then poured into a preheated steel mould to form billets, which were machined into test specimens.

Stir casting of magnesium composites presents challenges such as poor nanoparticle wettability, particle agglomeration and porosity formation. In the present work, these were addressed by:

- using a protective Ar-SF_6 gas mixture to prevent melt oxidation;
- preheating TiB_2 nanoparticles to enhance wetting and dispersion;
- optimising stirring speed and time to reduce agglomeration; and
- preheating the steel mould to minimise shrinkage porosity [4,5].

Similar stir casting challenges have also been reported in aluminium-based nanocomposites. For instance, an experimental study on Al_2O_3 and ZrO_2-reinforced Al-Mg-Si alloys highlighted issues of nanoparticle clustering and uneven distribution, which directly influenced mechanical performance [10]. Such findings reinforce that achieving uniform dispersion remains a universal challenge in stir-cast nanocomposites, underscoring the importance of the process controls adopted in the present work.

The measured mechanical properties of the fabricated AZ91D/1.5 wt.% TiB_2 composite, along with those of Al6061 and A356 alloys used for comparison, are presented in Table 2.

Table 2. Mechanical properties of the AZ91D/1.5 wt.% TiB_2 composite compared with Al6061 and A356 alloys. These baseline values (Young's modulus, yield strength, ultimate tensile strength and density) were used as material inputs for the FEA simulations.

Alloy	Young's modulus (GPa)	Yield strength (MPa)	Ultimate Tensile Strength (MPa)	Density (g/cm^3)
AZ91D/1.5wt% TiB_2	46.9	171.1	253.1	1.85
Al6061	68.9	276	310	2.70
A356	44.045	99	228	2.67

2.2 Wheel rim modelling

A 3D CAD model of a 19-inch alloy wheel rim was developed in Autodesk Fusion 360. This rim size is widely used in premium passenger vehicles (e.g., BMW, Audi, Volvo), making the design industrially relevant.

The rim design has a set of main spokes, eight of them and each one branches out into two smaller spokes, so it becomes sixteen in total. This layout was chosen because it keeps the rim strong without adding too much extra weight. The rim width is 250 mm and the thickness is about 6 mm, which is pretty normal for this type of wheel. It also uses a five-bolt setup with each bolt hole around 24 mm, so it can fit on most common car hubs. The finished 3D model can be seen in Figure 2 and the important measurements are listed in Table 3.

(a) (b)

Fig. 2. CAD model of 19-inch alloy wheel rim developed in Autodesk Fusion 360: (a) Perspective view with primary and secondary spokes, and (b) Side profile showing cross-sectional geometry.

Table 3. Dimensional parameters of the modelled 19-inch alloy wheel rim.

Sl. No.	Specification	Value
1	Rim width	250 mm
2	Wheel diameter	491 mm
3	Number of spokes	16
4	Rim thickness	6 mm
5	Bolt diameter	24 mm
6	Number of bolt holes	5

2.3 Finite element analysis setup

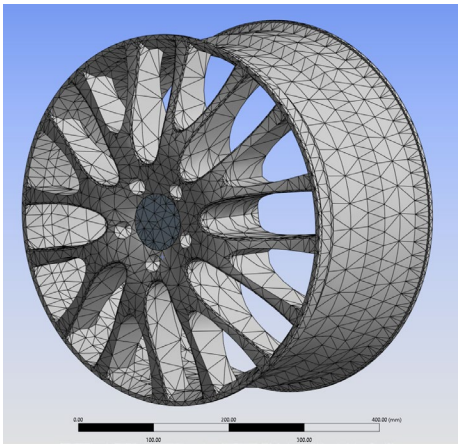
The CAD geometry was exported in IGES format and imported into ANSYS Workbench 2022 R2 for static structural analysis. The model was discretised using tetrahedral solid elements to capture complex geometries. An average element size of 5 mm was used, with local mesh refinement around bolt holes to resolve stress concentrations. A mesh convergence study confirmed that refining the element size below 5 mm changed stress results by less than 2%, validating numerical stability. The final mesh consisted of approximately 1.2 million elements and 2.3 million nodes, as shown in Figure 3a.

Boundary and loading conditions were applied as follows:

- Supports: All five bolt holes were constrained in all degrees of freedom to simulate a rigid hub connection (Figure 3b).
- Loading: A uniform pressure of 0.241 MPa was applied to the outer rim surface to simulate tyre contact at 32-36 psi inflation pressure (Figure 3c).

The solver was configured to calculate:

- Total deformation (mm) - to quantify displacement under the applied loading.
- Equivalent von Mises stress (MPa) - to evaluate yielding tendency.
- Equivalent elastic strain (mm/mm) - to determine elastic deformation capacity.



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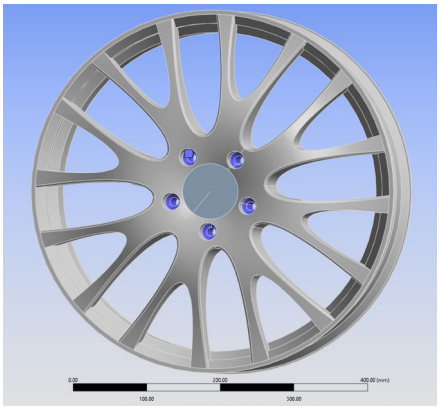

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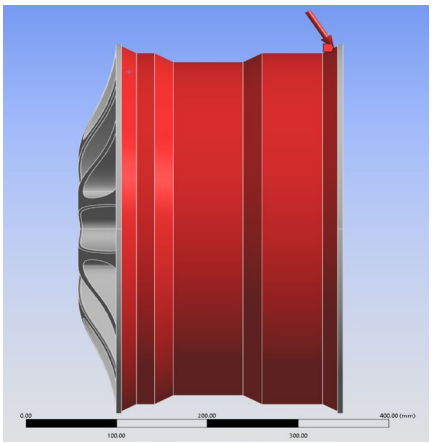


(c)

Fig. 3. Finite element model of the wheel rim: (a) Mesh with refinement near bolt holes; (b) Applied boundary conditions with bolt holes fully constrained, and (c) Uniform pressure of 0.241 MPa applied on the outer rim surface to simulate tyre inflation pressure.

2.4 Output evaluation

Simulation results for the AZ91D/1.5 wt.% TiB_2 composites were compared with those of Al6061 and A356 under identical conditions. Deformation, stress distribution and strain were assessed to evaluate the suitability of Mg-TiB_2 as a lightweight, high-strength material for wheel rims.

3 Results and discussion

Finite element analysis (FEA) was carried out to evaluate the mechanical behaviour of AZ91D reinforced with 1.5 wt.% TiB_2 nanoparticles, compared with Al6061 and A356 alloys under identical loading and boundary conditions. For clarity, the key mechanical properties and simulation outputs of all three materials are shown in Table 4, enabling a direct comparison of stiffness, strength and deformation behaviour. The parameters studied were

total deformation, equivalent von Mises stress and equivalent elastic strain, as shown in Figures 5-7.

Before running the main analysis, the mesh was adjusted a few times to check whether the results were changing. After a certain refinement, the variation dropped to below about 2% which was taken as a sign that the mesh was stable enough. Keeping the same mesh settings for all three materials helped maintain a fair comparison. These FEA simulations were fully deterministic so there was no need to include statistical variation or standard-deviation values.

3.1 Total deformation

The overall results for total deformation provide some insight into how well a material performs under load, in this instance the AZ91D alloy containing 1.5 wt.% of TiB_2 showed about 0.055 mm total deformation. Although it is below A356 (0.0575 mm) but above Al6061 (0.0374 mm), Al6061 will bend less because it has a higher modulus - close to 69 GPa - but its higher density (2.70 g/cm^3) does have its associated disadvantages. By contrast, the composite remains significantly lighter at 1.85 g/cm^3.

Also, while wheel rims are considered 'stiff', the stiffness of a wheel rim is not the only factor. If a wheel rim is too stiff and also very heavy, this can alter the way in which a vehicle handles and rides (e.g., with more resistance). This balance is important and earlier work by Ansari et al. [2] also mentions that magnesium alloys can still hold their form even if they flex a bit more. In our simulation, the 0.055 mm deformation falls inside the usual working range seen in similar studies, roughly 0.04-0.06 mm [11]. This suggests that the composite behaves in a practical zone where the rim remains stable but still manages small road vibrations without issue.

3.2 Equivalent von mises stress

The von Mises stress values for the three materials turned out to be very close to each other. In the simulation, the AZ91D/TiB_2 composite showed 10.85 MPa, Al6061 showed 10.88 MPa and A356 was slightly higher at 11.05 MPa. These numbers are all quite small when we compare them with the yield strengths of the materials. For reference, the composite has a yield strength of about 171 MPa, Al6061 is around 276 MPa and A356 is roughly 99 MPa. So none of them came anywhere near their yielding point under this particular load, which was expected.

Also, this behaviour matches what other researchers have seen. For example, Ariyarit et al. (2023) [11] reported that Mg-TiB_2 combinations usually stay well within the elastic region under similar loading. Our results follow the same trend and there was nothing unusual or unexpected in how the stresses developed here.

3.3 Equivalent elastic strain

Elastic strain is basically how much the material stretches in proportion to its original size. In our results, the AZ91D-TiB_2 sample showed a strain of 2.31 x 10^{-4} mm/mm, which is a little lower than A356 (2.51 x 10^{-4}) but still higher than Al6061 (1.58 x 10^{-4}). Compared to A356, this slight decrease indicates that TiB_2 particles provide increased rigidity by assisting grain refinement and redistributing some weight to smaller grain construction.

According to previous research, including Liu et al.'s (2023) [4] and Meher et al.'s (2020) [5], it is known that the addition of less than 2 wt. % of TiB_2 to magnesium alloys normally helps refine the grain structure of the alloy. The variation in behaviour among the three alloy types can primarily be traced to their respective internal structures. As a result of the unique

internal structure of each alloy type, Al6061 will exhibit the least amount of stretch due to the stiffness of the α-Al matrix. Due to having more ductile concentrations of eutectic silicon in its structure, A356 exhibits slightly greater elongation at fracture. Meanwhile, the AZ91D composite occupies an intermediate position; due to the fine-dispersion of its grain structure, the composite exhibits an increase in strength compared to pure magnesium, but the composite can't fall below a specific amount of strain due to the lower modulus of the magnesium compared to the modulus of the aluminium.

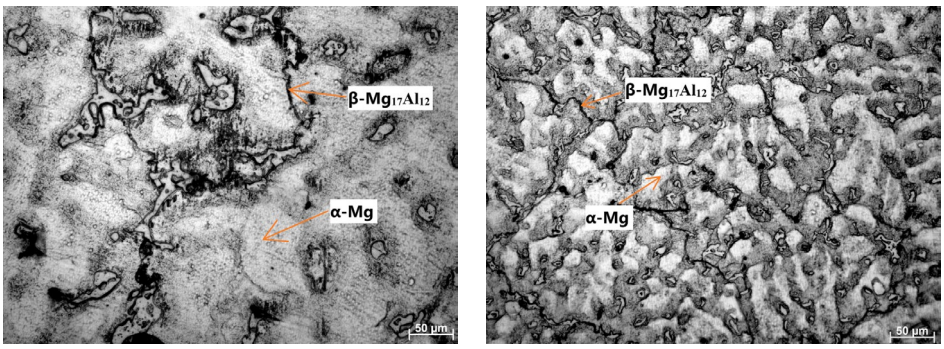
3.4 Strengthening mechanisms

There are several contributors that have led to an increase in stiffness in the AZ91D alloy-composite with disruption by 1.5 wt% of TiB_2, rather than identifying the single most significant contributor. One of the more intuitive mechanisms at play is that the TiB_2 particulates, which are significantly higher in hardness than magnesium matrix, will share a portion of the load being placed on the alloy due to it being the weak link in the composite system. The matrix is no longer precluded from having to take the complete load (and thus limit the ability of that matrix to deform).

Further, these small, fine particles act as an impediment to dislocation motion. Small size dislocations do not have enough space in which to move freely through a material, so they must go around particles or in some cases become obstructed. This is typically associated with the Orowan mechanism [6,12]. The result is that dislocations impede the ability of the alloy to stretch or bend easily.

There is a stage of solidification. When TiB_2 is introduced into the melt, the grain growth is limited and much smaller grain sizes are created. The number of grain boundaries also increases, which leads to increased strength due to more dislocations being impeded when they try to pass through the grain boundaries. Hangze et al. (2025) [12] observed the same trend for AM60B Alloy where grain refinement and particle effects worked together for the transformation of the microstructure.

The difference between the two alloys is also easily seen in our photographs (Figure 4). The plain AZ91D alloy has larger α-Mg grains with β-$Mg_{17}Al_{12}$ deposited on, or around, the grain boundaries. In comparison, the composite material has a considerably finer and more homogenous structure than this material. This agrees closely with Liu et al. (2023) [4], as well as Xiao et al. (2018) [6]. A similar trend is observed in the case of aluminium composites such as Al7075-SiC, with the particle reinforcement and load sharing resulting in an increase in hardness [13].



(a) (b)

Fig. 4. Optical micrographs at 50 µm scale: (a) The as-cast AZ91D Al alloy has a relatively coarse α-Mg grain structure, which consists primarily of coarse α-Mg grains with β-$Mg_{17}Al_{12}$ at grain boundaries, and (b) The AZ91D alloy, with 1.5 wt.% TiB_2, shows a more evenly distributed and finer grain structure, illustrating the effect of TiB2 in refining grains during solidification.

There were technical considerations with the production of uniform dispersion of nanoparticles in magnesium due to their low wetting ability and tendency to clump together. The process used by the author to achieve this uniformity included preheating the TiB_2 particles, maintaining a protective atmosphere surrounding the particles during stirring and controlling the stirring process.

3.5 Optimal reinforcement content

The 1.5 wt.% TiB_2 was chosen on purpose due to several studies indicating that a lower concentration would promote easier dispersion and not allow for the formation of clusters as is common with a higher concentration of the same material. Based on this study's observations, it was determined that a material containing both improved stiffness, but with minimal risk of becoming overly brittle and/or denser, is obtained with the use of 1.5 wt.% TiB_2.

3.6 Comparative advantage over existing alloys

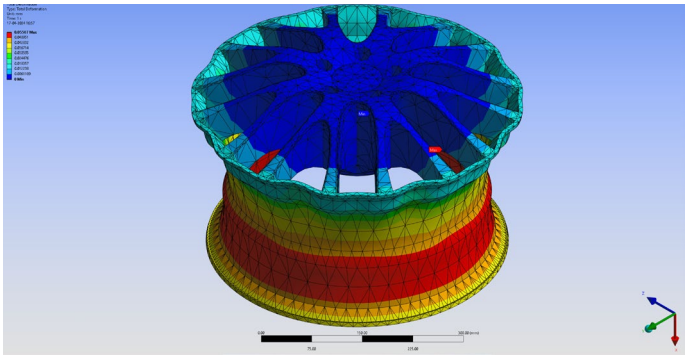
In comparing the stiffness and weight of AZ91D/ TiB_2 composite with those two other alloys, it positions itself much more favourably. In fact, it weighs approximately 31% less than Al6061; however, the amount of deformation that occurs on AZ91D/ TiB_2 composite when similar loads are applied is only about 0.018mm less than on Al6061. Thus, one could argue that although AZ91D/ TiB_2 composite has lower weight, its performance relative to Al6061 is nearly identical. Due to having slightly higher strain at a greater amount of deflection, A356 shows more than both of these types of aluminium in stiffness but is still much denser than the two types of aluminium alloys combined.

Many combinations of aluminum composites (AZ91D/TiB_2 and Al5052-TiB_2) have been found to have increased hardness and a reduction in friction [7,14]. The disadvantage of these combinations, however, is that they are still very "dense". They become more robust, yet they're also heavier. Although Mg-TiB_2 composites provide a similar degree of strengthening as compared to steel, they do so without being heavier than steel, which is really important in many ways, particularly for rotating components that require low mass (such as wheels) [5,11].

3.7 Engineering significance

The deformation value for the AZ91D/ TiB_2 composite was found to be 0.055 mm, which is within the range of 0.04-0.06 mm considered safe according to many studies regarding performance rims [11]. Therefore, 0.055 mm is accepted as an acceptable value for this rim composite.

The Mg-TiB_2 system's lightness compared to Al6061 means lighter weights directly help with faster acceleration and braking. Additionally, a lighter-weight suspension will have lesser performance requirements as a result of decreased mass to manage. Therefore it is concluded that Mg-TiB_2 systems can be developed to produce lightweight wheel designs, where high strength/low weight characteristics are essential and that Mg-TiB_2 systems provide enough strength to make wheels light enough (low weight/low mass) for use in high performance wheel applications.



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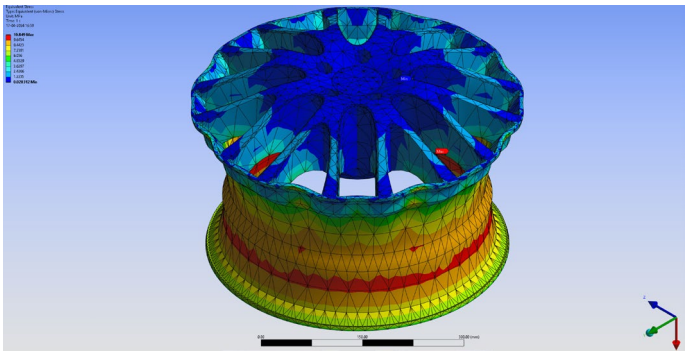

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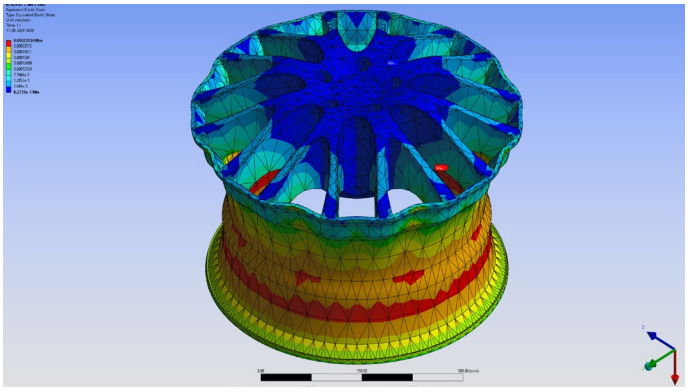

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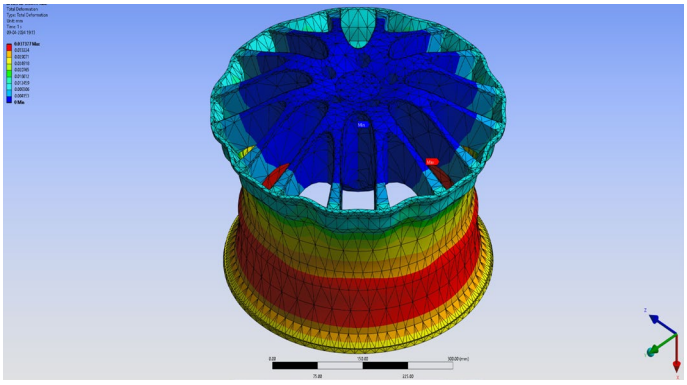
Fig. 5. FEA output for the AZ91D/1.5 wt.% TiB_2 composite under the given load: (a) Total deformation (mm), (b) Von mises stress distribution (MPa), and (c) Elastic strain distribution (mm/mm).



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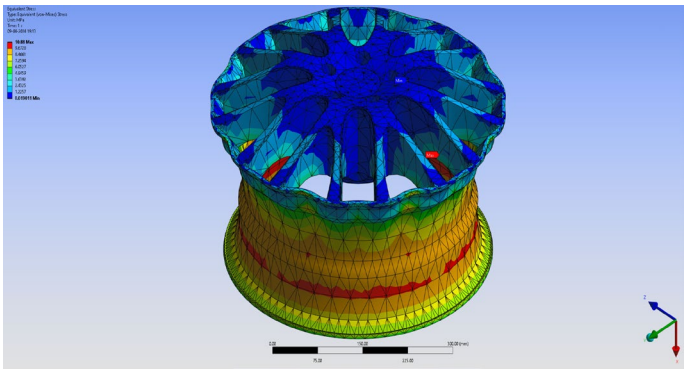

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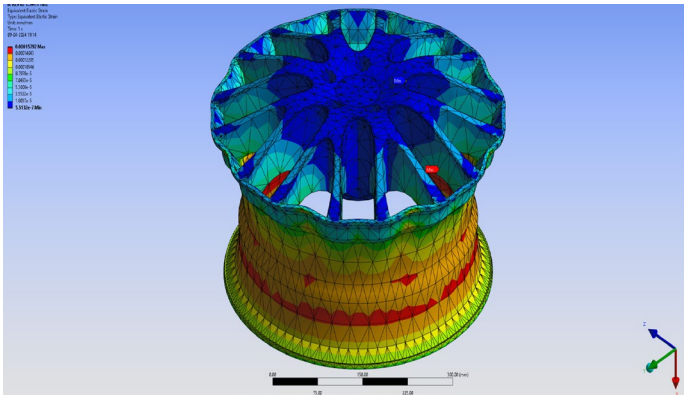

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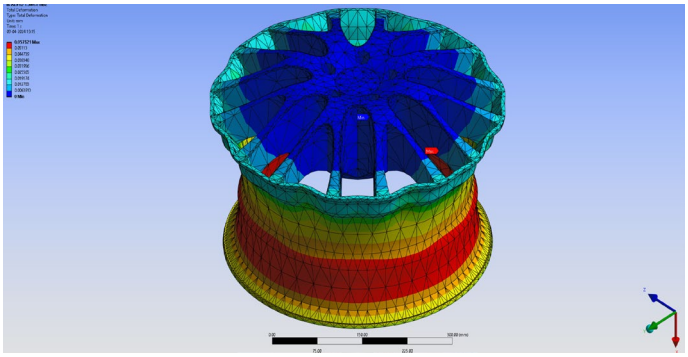
Fig. 6. Results for Al6061 with the same loading and constraint: (a) Total deformation (mm), (b) Von Mises stress pattern (MPa), and (c) Elastic strain (mm/mm).



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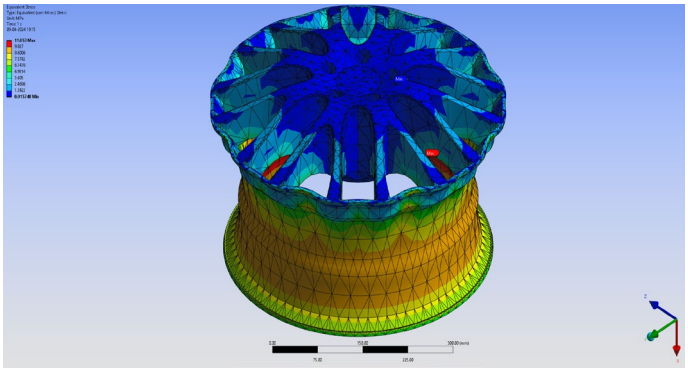

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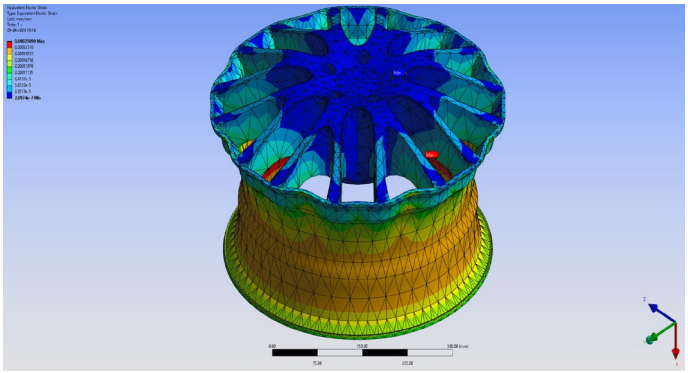

(c)

Fig. 7. FEA plots for the A356 alloy: (a) Total deformation (mm), (b) Von mises stress levels (MPa), and (c) Elastic strain (mm/mm) under identical constraints.

Table 4. Consolidated mechanical properties and FEA outcomes for AZ91D/1.5 wt.% TiB_2 composite, Al6061 and A356 alloys, including modulus, strength, density and deformation responses under identical loading.

Parameters	**Materials**		
	AZ91D/1.5 wt.% TiB_2	**Al6061**	**A356**
Young's Modulus (GPa)	46.9	68.9	44.0
Yield Strength (MPa)	171.1	276.0	99.0
Ultimate Tensile Strength (MPa)	253.1	310.0	228.0
Density (g/cm^3)	1.85	2.70	2.67
Total Deformation (mm)	0.055	0.0374	0.0575
Von Mises Stress (MPa)	10.85	10.88	11.053
Elastic Strain (mm/mm)	2.31×10^{-4}	1.58×10^{-4}	2.51×10^{-4}

While these results confirm the suitability of AZ91D/1.5 wt.% TiB_2 for lightweight wheel rims, it should be noted that they are based solely on finite element simulations. Experimental validation through mechanical testing and full-scale wheel trials will be necessary, as real-world conditions involve variable loading, fatigue and environmental effects that cannot be fully replicated in static FEA. This aligns with recent work by Zanchini et al. (2023) [15], who combined experiments and numerical simulations on automotive wheel rims to show that FEA alone cannot capture all fatigue and failure modes.

4 Conclusion

In this work, we used computer simulation (FEA) to study how AZ91D magnesium alloy reinforced with 1.5 wt.% TiB_2 behaves when used for a wheel rim and compares it with two aluminium alloys, Al6061 and A356. The results showed that the reinforced AZ91D alloy bends only 0.055 mm under load, which is slightly better than A356 and only a little more

than Al6061, even though it is much lighter than both. All three materials stayed well within their safe limits because the stresses were far below their yield strength. The strain in the composite was also lower than A356, mainly because the TiB_2 particles helped strengthen the magnesium by refining the grains and sharing the load.

When both stiffness and weight are considered together, the AZ91D-TiB_2 composite shows a strong advantage. Being much lighter than aluminium alloys, it can help reduce the weight of the wheel and suspension, which often leads to better braking, quicker acceleration and smoother handling. Its deformation value also sits comfortably within the commonly accepted safe range for performance rims (0.04-0.06 mm), suggesting that it can handle real-world loads without losing stability.

However, this study is based only on simulation. In real driving, wheels face changing loads, bumps, potholes, corrosion, humidity and long-term fatigue, which cannot be fully captured by static FEA. For this reason, further work is needed. Future studies should include fatigue tests, impact tests and durability checks in different environments. It would also be useful to study corrosion, wear and long-term performance in wet or humid conditions. Optimising the casting process and performing crash or impact simulations may also help prepare the material for commercial use. Most importantly, laboratory tests and actual wheel trials are required to validate and expand the results seen in simulation.

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