Computer Aided Design and Investigation of Impact Characteristics of Heavy-Duty Aluminium alloy 6082-T6 Wheel

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ABSTRACT

Continuous improvements in wheel design has taken centre stage of the interests in the automobile industry. Material innovations and discoveries by metallurgists have helped tremendously in this regard as varieties of structural materials are made available to help structural engineers and industrialists. Alloy 60682-T6 impact properties were investigated in this research; Solidworks CAD software was employed in the modeling of the impact form of the wheel. Ansys was utilized in carrying out the finite element analysis of the impact model using non-linear dynamics due to anisotropic considerations of the material composition and wheel failure mode. The change in momentum technique was used in correlating the force-deflection method of probing the impact response of structural member.

Total deformation of 0.07m was observed around the drop centre of the wheel with an estimated plastic work (critical strain energy density of wheel) of 160.1Nmm/mm^3. Equivalent strain at fracture was 0.0897 and maximum momentum of the wheel on impact is 1.17×10^7Ns.

Index Terms – Al 6082, Ansys, Anisotropy, Design, Drop centre, Finite element analysis, force-deflection, Total deflection, Wheel.

1 INTRODUCTION

The wheel is a critical part of the vehicle suspension and power-train system. It provides balance and comfort to both payload (s) and humans in the vehicle by absorbing shock and readily overcoming motion impeding obstacles on the road. Wheels could be manufactured for; racing, passenger car or light weight purposes, as well as heavy-duty requirements [1] and [2]. Irrespective of which purpose a wheel is intended to be used, the wheel is manufactured with consideration to styling appearance, safety and engineering requirements because the wheel tours through very rough and hazardous environments especially those of heavy-duty vehicles [3].

Newly manufactured wheels are mandated to pass three standard tests: radial fatigue test; cornering/bending test and impact test.
The radial fatigue test simulates radial induced load on the rim and investigates the wheel's response to such loading condition;

the cornering/bending test simulates the event of the wheel undergoing a bend as a result of the torsional load or bending moment induced at the hub through the axle; while the impact test simulates the circumstance where a sudden load comes upon it or the wheel suddenly hits a bump on the road [4], [5] and [6]. For each of these tests the wheel is expected to conform to some experimentally verifiable results; whereby it does not, the wheel is said have failed.

The impact behaviour of a wheel is dependent on the wheel design, wheel material, manufacturing process and impact condition.

Contemporary research on wheels make use of a number of modern software for its modeling and simulations of the three standard tests. The application of these software have proven to be very effect and reliable not only in the area of wheel design but also in the economics surrounding general wheel manufacturing as they afford a prototype of the wheel model where all required tests are carried out, modifications are made where necessary before a final manufacturing process of a standard wheel is initiated, thereby saving a great deal of cost and time [3], [4] and [5].
The design of a wheel should be based on some basic theories which relate the tyre inflation pressure to relevant linear dimensions of the intended wheel geometry for optimal performance.

Wheel material selection is also very key because the basic goal is to ensure that materials with lighter weight, yet with excellent mechanical properties are continuously enhanced in the wheel manufacturing business without compromising the safety and engineering requirements. The combination of wheel mechanical properties is key to its response to various induced load conditions. Regardless, materials intended for this purpose should be fairly economical and easily machinable in order to compete with existing wheel models in the market [7].

Wheel manufacturing processes are dependent on the wheel material and are largely responsible for the final properties and behaviour of the wheel under test conditions. Hence, the most suitable and safe methods with respect to material consideration and vehicle class [8].

Some researchers investigated the effect of design variability in styling appearance and wheel manufacturing materials by altering the original design of a Volkswagen polo 1.0 TSI wheel rim and sketched the new models using CREO 2.0 software and conducted a FEA using Ansys software. It was discovered that all three designs were safe and within standard limits. Among the three designs, it was reported that ‘simple rim design’ was more promising than the ‘centrifugal and pentagonal’ rim. In terms of wheel materials; steel alloy wheels give better results, followed by aluminium and magnesium wheels. Hence, magnesium wheel is limited to racing cars. The revealed that Aluminium wheels gave the best fatigue response amongst the three materials. In any case it was discovered that the maximum displacement occurred at the location of the bead seat [1].

Ganesh and Periyasamy [4] designed a spiral four-wheeler of aluminium alloy using Catia and analyzed same using Ansys by subjecting the wheel to; bending, pressure, centrifugal, vertical and combined loading conditions, and proposed a new wheel that is 10.34% lighter than existing wheel with guaranteed design safety.

The response of forged steel and aluminium alloy wheels were investigated for the same rim design using Catia software and analyzed using Ansys revealed that; aluminium wheel rim suffers more stress compared to forged steel. Both wheels demonstrated Von-mises stresses lesser than their ultimate strengths, hence, with respect to deflection considerations, forged steel wheel is preferred to aluminium wheel on the bases of this particular design. Modal analysis revealed that the first and second mode frequencies are safe for both wheels [7].

Finite Element Analysis of the impact behaviour a nonlinear elasto-plastic model of an A356 cast aluminium alloy wheel tyre assemble under the action of a standard drop load using Ansys software revealed that; major deformations up to 50.21mm occurred at the tyre portion, while a maximum displacement of 16.3mm occurred at the rim flange. However, the wheel does not fracture under the given load and stress conditions [9].

A CAD using UNIGRAPHICS and FEA simulation of a passenger car aluminium alloy wheel with tyre assembly for; radial fatigue, cornering and impact tests gave results at variance with standard wheel requirements as stresses observed according to the finite element software (Ansys) where much higher than expected results. Initial results for radial fatigue test gave; 66.4MPa, cornering test gave; 119MPa and impact test gave; 873.1MPa stress values at the spokes. The wheel was predicted to have failed in each case with respect to wheel-life consideration as revealed by S-N curve for the combination. Critical values for the model for each functionality test were; 60MPa, 90MPa and 750MPa respectively. The wheel was redesigned by removing material at back of the wheel and all tests reconducted, new results predicted a wheel that would pass all tests as the functionality test values of the redesigned model; 58.8MPa, 86.9MPa and 738MPa respectively are now below the critical values [5]. They further suggested that natural frequency of the wheel should be above 350MPa to avoid NVH and the redesigned wheel was tested to have a value of 392.45Hz. Minimum wheel stiffness by standard requirement is 45N/m, redesigned wheel's stiffness was 85N/m.

Shwetabh et al, [10]. Probed the impact response of; Al-12%Si alloy, Aluminium alloy 5052, Aluminium alloy 6061, Ti-5 Al-2.5Sn alloy, Ti-13 V-11 Cr-3 Al alloy and Mg-AZ31B alloy wheels with common design model using CATIA and FEA software ANSYS. The investigation showed that alloy wheel materials suffered similar deformation and within the range of 0.22561mm – 0.28335mm with Al-12%Si at the lower limit and Ti-13 at the upper limit of deformation. However, equivalent Von mises stresses were observed to be approximately 16.6N/m^2, for all three aluminium alloy wheels, whereas the titanium alloys have the higher values of 20.4 and 21.25N/m^2 respectively. Mg-AZ31B alloy wheel accumulated the least stress value of 14.7N/m^2. Modal analysis revealed that the least frequencies are obtained from Ti-13. Thus, the Ti-13 wheel will be more durable compared to others. Finally, they proposed that based on the test results, a Mg-AZ31B is a better wheel material owing to its less deformation tendency, equivalent stress and almost equal frequency for all modes.

Finite element analysis simulation of vibration response for a particular wheel design for conventional aluminium 6061-T6, SPFH540 Steel and AZ91 magnesium alloy materials, showed that magnesium alloy wheels demonstrated better damping performance advantages over the other wheels with a weight reduction of about 32.3% over aluminium 6061-T6. however, the dynamic impact performance was reduced at the expense of lighter weight implication. Since it is desired that dynamic impact performance of the magnesium alloy wheel competes favourably with the other wheels, structural optimization of the magnesium alloy wheel was carried out by defining the structural parameters of the wheel and using the acceleration and shock response of the wheel as the output; the optimal dynamic impact performance and weight reduction targets were achieved by reducing the acceleration by

13.9% and the velocity by 11.8% thereby improving the passenger ride comfort [11].

Computer Aided Design and optimization by FEA was applied to an existing wheel of 26kg by removing excess material from the design area of the wheel. Famous Aluminium alloy A356 was used and radial, lateral and bending loads of ; 8976N, 4044N and 4488N respectively. The corresponding response of the optimized wheel under these load actions were respectively; 94, 64 and 35MPa, whereas the yield stress of the wheel material was 185MPa. The weight was reduced to 12.15kg by topology optimization. Wheel geometry was modified for easy manufacturing and better stress distribution on the rim [12].

Emmanuel and Ebuhgni [13]; generated a CAD of a passenger car steel wheel using SOLIDWORK and conducted fatigue analysis using finite element analysis software Ansys. They reported that stress distribution in a wheel is cyclic and is due the design radial load and inflation tyre pressure. It was observed that the maximum Von mises stress occurred at the wheel forks and ventilation holes at 163.6MPa where fatigue failure occurs.

Chang and Yang [14]; conducted finite element simulation of impact response of an elasto-plastic and isotropic aluminium 6061-T6 alloy wheel-tyre assembly. A striker of 475kg, 375mm length, 125mm width and 126.94mm height was made to strike the wheel-tyre assembly which were located at 13^o to the horizontal plane from a height of 230 ± 2mm above the highest point of the test piece. The wheel fracture was observed to be plastic and the plastic work done by the wheel on impact was estimated to be 41.21Nmm/mm^3. The critical strain energy density was measured to be 28.46Nmm/mm^3 which is lower than the estimated plastic work. Hence, the wheel is predicted to pass the impact test.

The research sets out to probe the behaviour of an AL EN 60682 wheel on impact with respect to: internal energy, momentum history and strain energy of the wheel.

1.1 Wheel Nomenclature

The wheel is characterized by a number of parts: the rim, rim flange, beads and bead seats, drop centre, disc, hub, bolt and ventilation holes etc. dimensional nomenclature include: offset, rim diameter, centre line, bolt and ventilation diameters, centre bore etc. However, modern wheels for passenger vehicles are trending towards poke wheels while disc wheels have become typical of heavy-duty application.

- **Rim:** the rim is the entire cylindrical cross section accommodates the tyre, the weight of the vehicle, passenger and payload.
- **Rim flange:** this is the curved circumference of the rim. It is traditionally curved outwards to secure the tyre in position.
- **Beads and bead seats:** beads are the circular humps that are patterned round the body of the rim while the bead seats are the low areas or grooves between neighbouring beads. The beads and bead seats together, gives a firm grip to the typre and provide the necessary contact between the rim and the tyre.
- **Drop centre:** this is the central groove or rail round the rim that bear the radial load and provides the base upon which the tyre seats properly.
- **Disc:** this is the central part of the wheel that houses the bolt holes, ventilation holes and the hub. It is an essential part of the wheel or at least its replica.
- **Hub:** this is located at the centre of the disc and it provides the connection between the front axle and the steering.
  Fig 1.0 shows some of the features and dimensions of a typical wheel.

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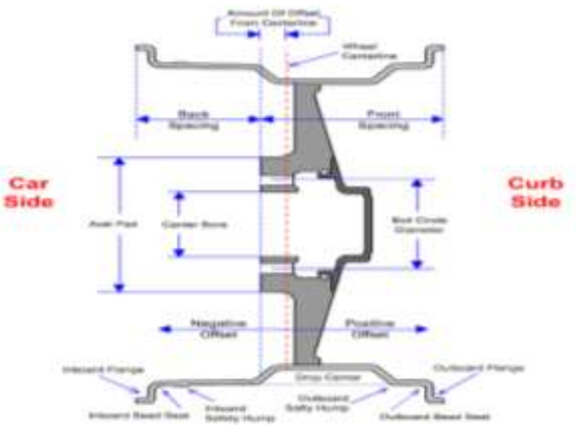

Fig 1.0. wheel features and dimensions of a typical wheel Source: [15]

1.2 WHEELMANUFACTURING PROCESSES

There are quite a number of methods for wheel manufacturing in contemporary industrial activities. The type of method adopted depends on the wheel material as well as the desired terminal conditions such as; thermal and corrosion resistivity, impact strength, ductility, toughness, etc. desired for the wheel Kalpesh and Shailes [8].

The wheel manufacturing processes are primarily:

- Casting
- Forging.

- **Casting:** generally known as "Die Casting", is a manufacturing process where solid metals are melted and heated to a desired temperature after which, it is poured into a cavity mold with proper shape. The melting and heating process may require different furnace heating temperatures; different chemical substances maybe added to modify chemical composition of metals [16].
  It is reported that three main types of 'Die Casting' exist; *pressure die casting, gravity die casting and vacuum die casting* [16].

Pressure Die Casting: In this process, the molten metal is made to distribute itself within cast mold by action of natural air pressure. It uses different types of die casting machines that ay range between 80 – 100 tons, depending on the ultimate pressure one wishes to achieve. It is has two main subdivision; "High pressure die casting and Low pressure die casting" depending on the amount of pressure used in the process. This process is usually faster and gives high quality products. High pressure die casting has wider range of applications compared to low pressure die casting and produces parts with superior mechanical properties [16].

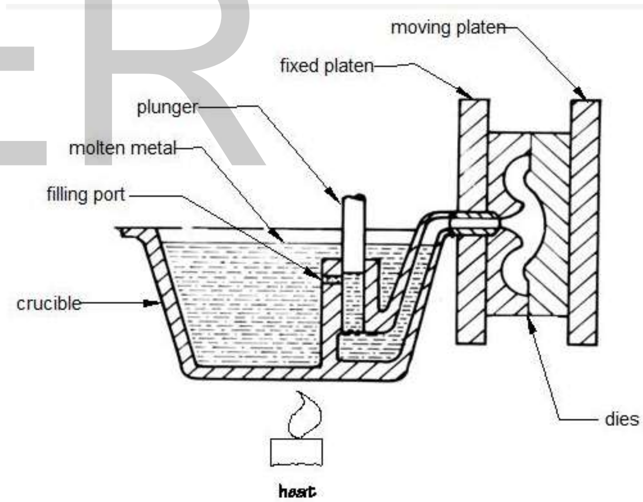

Fig 2.0 A hot chamber pressure die casting.

Gravity casting: This casting technique solely relies on the action of gravity for the spread of the metal within the mold. This process is popularly used for medium and high-volume production processes. Its capability varies from one manufacturer to another in the sense that some firms use automated type and others use the manual type. The technique uses permanent mould, thus, it is easier to achieve a near net shape product [16]. The operation is generally more economical compared with general die casting operation. Small batches of production can be achieved with this method, as well as flexibility in design, short development time and desirable mechanical properties such as high tensile strength on the metal component [8].

Vacuum die casting: In this method, the molten metal flows into the die made of steel in an airtight bell-housing due to a pressure difference which is controlled by the vacuum between the molten metal and cavity. It comprises of two receivers; outlet top and sprue through which the molten metal enters the die and the vacuum. As the molten metal flows due to pressure difference, it does so through the sprue, then, to the die where the metal solidifies and the cycle of operation repeats itself for a couple of time. The automotive industries greatly utilize this method for the production of a couple of parts [16].

- **Forging:** This is a process that shapes a solid piece of metal with force or compression. High pressure machines will change the shape after the aluminum is heat treated. A wheel frame is forged multiple times to achieve the final shape. When the final shape is made, machining smooths and buffs the wheel. A special type of forging is ‘Roll forging’; it is similar to the basic forging technique except that the metal is run between heavy stamps or wheels. The pressure form the roll forces the raw material into the shape and thickness needed [13]. Both of these methods produce high performance wheels that are commonly used for competitive racing. Most high-quality sport cars like Porsche and Lamborghini use forged aluminium wheels [13].

1.3 Properties of Aluminium Alloy EN 6082AW-T6

Aluminium alloy 6082 is medium strength alloy with excellent corrosion resistance. It has the highest strength of the 6000 series alloys and widely known as a structural alloy and is manufactured in different shapes and sizes. It is a relatively new alloy in the aluminium 6000 series and has successfully replaced alloy 6061 in many applications. It is difficult to produce thin walled complicated extrusion shapes with this alloy. The extruded surface finish is not as smooth as other similar strength alloys in the 6000 series. In the T6 and T651 temper, alloy 6082 machines better and produces tight coils of swarf when chip breakers are used [17].

Although alloy 6082 is highest in strength of the entire aluminium 6000 series, it is generally known to be a medium strength structural alloy. It can be produced in form of; Bar, plate, sheet, tube and extrusions [18].

Applications: The alloy in its various forms can be applied in; highly stressed members, Trusses Bridges, Cranes, Transportation vessels, Ore skips, Beer barrels and Milk chums.

It has been reported that mechanical properties of ductile materials are normally determined by tensile test but when plastic deformation is the aim of the study, then the compression test is most suitable as it allows large deformations without the fracture of the specimen under probe [19]. Similar studies conducted independently by [20] and

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[21] give the anisotropic values of various members of the aluminum 6000 series according to Tables 1.3. The chemical and mechanical properties of the design alloy are given in Tables 1.1 and 1.2 respectively.

Table 1.1 Chemical composition of EN AW-6082

Element	**Composition (%)**
Manganese (Mn)	0.46
Iron (Fe)	0.21
Magnesium (Mg)	0.24
Silicon (Si)	1.12
Copper (Cu)	0.017
Zinc (Zn)	0.002
Titanium (Ti)	0.023
Chromium (Cr)	0.005
Lead (Pb)	0.001
Aluminium (Al)	97.89

***Source:** (Alco, 2019)

Table 1.2. Mechanical properties of EN AW-6082

Structural	
Young's Modulus	68.9GPa
Poisson's Ratio	0.33
Density	2.7g/cm^3
Thermal Expansion	0.0000252/^{o}C
Tensile Yield Strength	276MPa
Compressive Yield Strength	-
Tensile Ultimate Strength	310MPa
Elongation at break	12%
Fatigue Strength	96.5
Thermal	
Thermal conductivity	167 W/mK
Specific Heat Capacity	896J/kg^{o}C
Electromagnetics	
Relative Permeability	-
Resistivity	3.99e-006Ohm cm

*Source: (Aalco, 2019)

Table 1.3. Anisotropic values of various aluminium alloys.

Aluminium alloy	K[MPa]	n	Ultimate stress σ_u[MPa]
AA6082 T6	588.7	0.205	290
AA2024 T4^a	806	0.200	476
AA6111^b	504	0.270	272

*****Source: Dowling [8] and [9]

Some other researchers [22], carried out investigation on the "Stress-Strain behaviour of aluminium alloys at a wide range of strain rates". Uniaxial tensile tests at stain rates between 10^{-3} and $10^3 s^{-1}$ were performed at room temperature to determine the mechanical behaviour of the extruded aluminium profiles. The anisotropy of the materials were tensile teste in three directions; 0^o, 45^o, 90^o, with respect to the extrusion direction (ED) and the results displayed in Table 1.4a to Table 1.4c

Alloy	r_0	r_{45}	r_{90}
AA6060-T6	1.0	0.988	1.079
AA6082-T6	1.0	0.919	0.975
AA7003-T6	1.0	0.814	0.923
AA7108-T6	1.0	0.870	0.954

*Source: (Chen et al, 2009)

Table 1.4b. Average logarithmic strain at fracture from SHTB tests with strain between 100 and 1000s^{-1} for each alloy an tensile direction. The standard deviation is given in parenthesis.

	Logarithmic strain at fracture, ε_f		
Alloy	0^o	45^o	90^o

AA6060 − T	1.530(0.10	0.856(0.09	1.422(0.10
AA6082 − T	0.707(0.14	0.901(0.05	0.638(0.12
AA7003 − T	0.592(0.04	0.928(0.09	0.785(0.05
AA7108 − T	0.579(0.05	0.949(0.07	0.606(0.05

*Source: (Chen et al, 2009)

Table 1.4c. Material parameters for four alloys

	σ_0(MP	Q_R(MP	C_R	$\varepsilon_0(s^-$	C_v	M
AA6060 -	196.1	51.2	24.7	0.001	0.003	1.0
AA6082 -	310.2	62.7	24.3	0.001	0.001	1.0
AA7003 -	344.2	115.7	15.1	0.095	0.011	1.0
AA7108 -	354.4	101.1	19.9	0.001	0.009	1.0

*Source: (Chen et al, 2009)

3.0 MATERIALS AND METHOD

The wheel material under investigation is Aluminium alloy 6082-T6. Famous CAD software Solidworks was employed to generate the design model of the wheel. Same was imported to the Finite Element package, Ansys. Where impact analysis was conducted. Most of the wheel dimensions were obtained through manual measurement with the aid of various measuring instruments, while others were obtain from basic material properties and geometric relations as postulated by the 'thin-wall theory' given by [23]. Wheel mechanical properties were obtained from table 1.2 according to [17]. The design inflation tyre pressure used was the minimum allowed pressure 1MPa according to [24]. The impact simulation was made possible through the use of a rectangular block of standard mass which was attached to the wheel flange at 13^o to simulate wheel-road hub/bumper obstacle collision. Wheel offset could be; positive, negative or zero. Hence, a zero offset was used in the design model. Ultimately, the wheel was designed with respect to anisotropic consideration since predicted fracture mode is a function of the plastic work of the wheel material at the point of the failure. Table 1.3 gives the design wheel dimensions.

Table 1.5. Design wheel dimensions

Specification	Value
Rim width	264mm
Wheel diameter	570.2mm
Pitch circle diameter	340mm
Centre bore diameter	494mm
Bolt diameter	26.4mm
Ventilation hole diameter	69.25mm
Rim thickness	7mm
Disc thickness	14mm
Number of bolt holes	10
Number of ventilation holes	10
Material	Steel
Manufacturing process	Die Casting

The design tyre pressure for heavy-duty purpose is set at $p = 4$MPa

$$\sigma_c = 0.8 \times \sigma_y \qquad (1)$$

Where; σ_c and σ_y are the circumferential and yield stress of the wheel

Also $\sigma_c = \frac{p \times d}{2t_r}$ (2)

Where: p is the design inflation tyre pressure; d is the rim diameter and t_r is the rim thickness.

From (3.1 and 3.2); $\sigma_c = 220.8MPa$ and $t_r = 5.16mm$

Thin-wall theory requires that; $t < \frac{1}{10} of d$ and $\frac{1}{10} of d = \frac{1}{10} \times 570 = 57mm$

Since $t_r < 57mm$; hence, thin-wall theory is applied.

Design number of bolt holes; $n = 7$. With respect to rim width and number of design bolts holes, the distance between a pair of semi-opposite bolts/studs, $Q = 302mm$ (solidworks gave similar value)

The pitch circle diameter is given by (3)

$$\text{PCD} = \frac{Q}{Cos(90/n)} \qquad (3)$$

$\therefore$ PCD $= 310mm$

3.1 Generating The CAD Model of The Wheel

With the evaluated dimensions, the mathematical model of the wheel was generated by means of solidworks software. First of all, a J-shape 2D profile of the wheel is created in the front plane with respect to a horizontal reference construction line. Various features such as; revolve, extrude boss, sweep, extrude cut, circular pattern were utilized in generating and finishing the 3D design model as shown in Fig 3.1. The rectangular block to depict the road hub/bumper was generated in solidworks in a similar fashion.

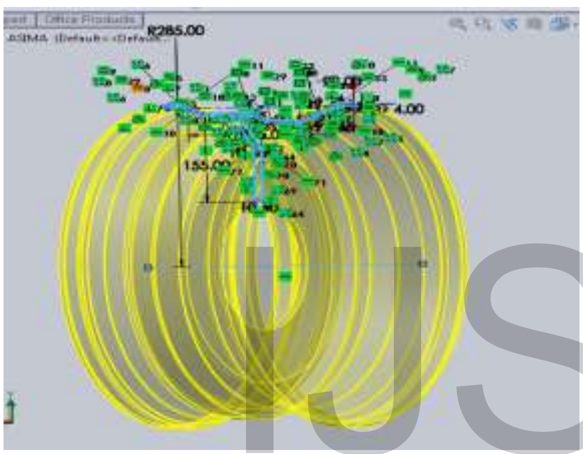


Fig 3.0. A revolved 3D preview of the design wheel in solidworks

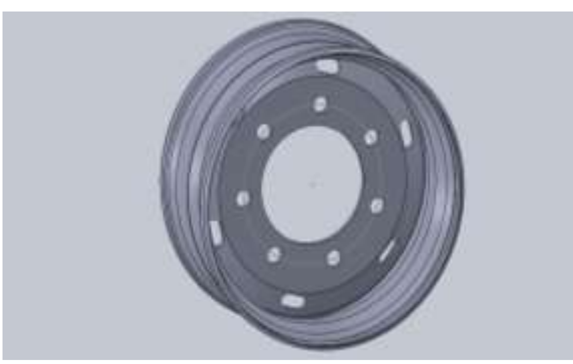


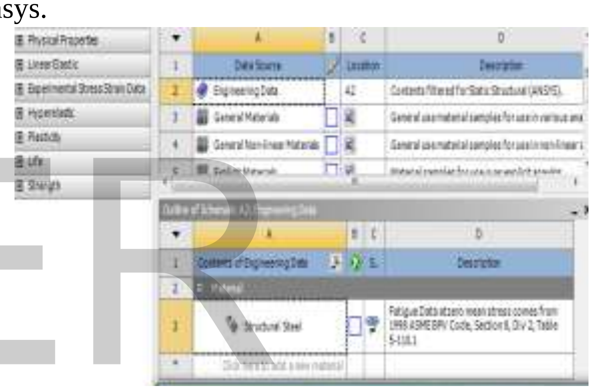
Fig 4.0 A fully developed 3D model of the design wheel.

3.2 Finite Element Analysis (FEA) Of Wheel

The finite element analysis of the design wheel was processed in the finite element package (Ansys). Generally, there are three phases of processing any component under investigation.

a. **Pre-processing Phase:** this phase involves the inputting of the mechanical properties of the wheel material in the Ansys Engineering Data dialog box. This enables the software to recognize the material in use and carry out all tasks with respect to these properties. Usually, there is default structural steel material properties therein, but these material properties are edited and the desired ones entered.

Table 1.6 inputting the mechanical properties of Aluminium alloy 6082 in Ansys.



b. **Processing Phase:** This phase involves importing the 3D model of the wheel-hub assembly from solidworks, through the Internal Graphics Exchange Scheme (IGES) into Ansys workbench, setting all necessary boundary conditions as appropriate for the in-service condition of the wheel on the road, discretizing (meshing) the wheel-hub assembly into very small elements (finite elements).

c. **Post-processing Phase:** this phase involves applying the necessary loads and displaying of results in the Ansys workbench.

3.3 Impact Model of The Wheel

The wheel-hub impact model is displayed in fig 5.0 where the obstacle (rectangular block) is seen attached to the rim flange of the wheel.

The Autodyn in Ansys is used for providing the necessary connection between both bodies. It presents the obstacle and the wheel as two different rigid bodies. The connection is defined to be trajectory and penalty based. This is to enable for simulation of the wheel under motion condition as a multibody. The penalty is dependent on the material properties as well as the impacting energy.

One of the most important development is the force-deflection characteristic of the vehicle. The force- deflection characteristic is correlated to change of momentum or the change of velocity during the impact. In this work, the change in momentum during impact has been observed and presented in the result section of this report.

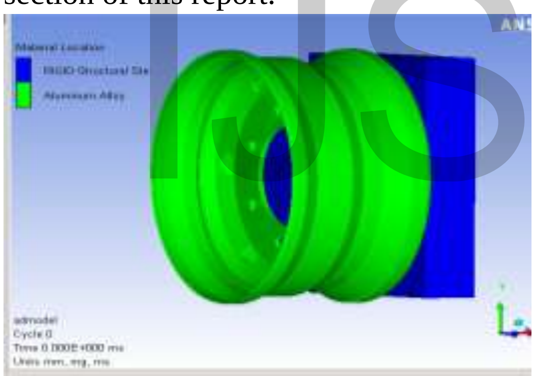


Fig 5.0 Impact model of wheel.

Fig 6.0 Connections and Interaction of Impact Model

3.4 Boundary Condition

The assumption used in defining the boundary condition is such that the crash happens between 0 to 1 second and the vehicle cruise for a distance between 0 to 1 meter intermittently as shown in Fig 7.0 and Fig 8.0. Time is also taken to be the time taken to impact. The displacement is defined as a ramp distance in a specified direction at some time interval.

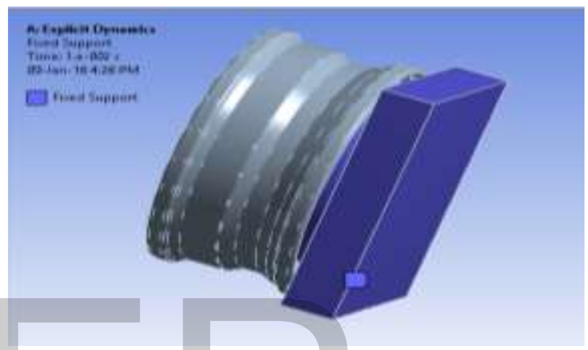


Fig 7.0. Boundary CSonditions

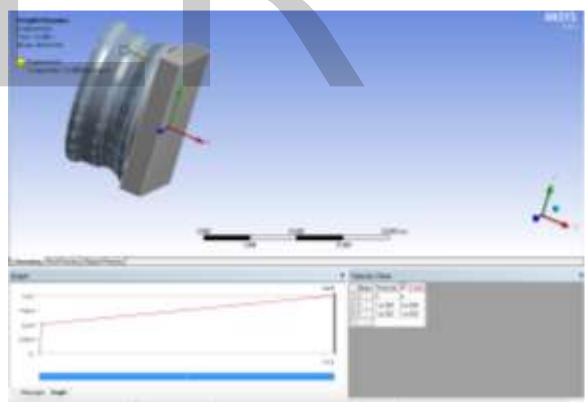


Fig 8.0. Displacement Boundary Condition

3.5 Model Discretization

The impact model of the wheel was discretized into finite elements in Ansys work bench. A mesh size of 0.01m was used. Solid 187 10 node tetrahedral is employed for the analysis. The impact model was allowed three degrees of freedom at each node as shown in fig 9.0

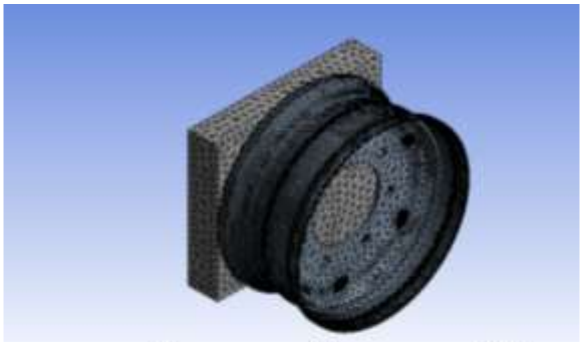


Fig 9.0. Meshing of Impact Model

4.0 Impact Test Results

The Total Deformation, Equivalent Elastic Strain, Momentum and Internal Energy curves results in Ansys are demonstrated in fig 10.0 through 13.0.

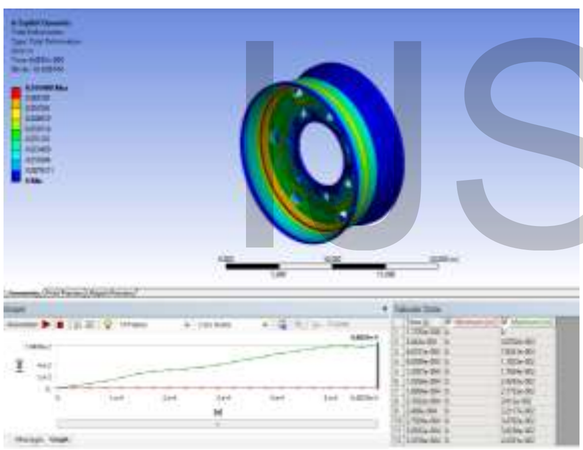


Fig 10.0. Total Deformation On Impact

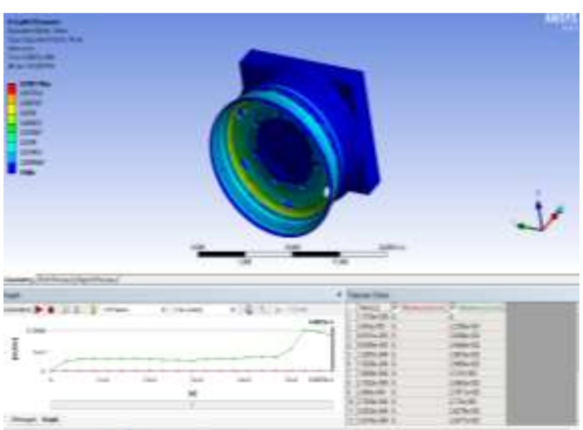


Fig 11.0. Total Elastic Strain On Impact

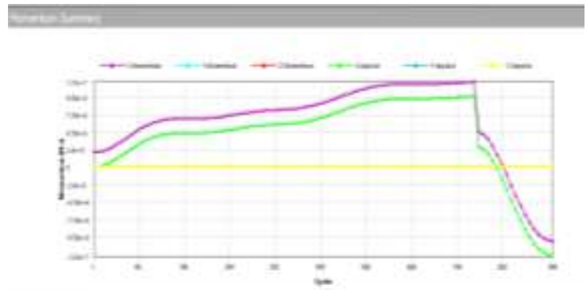


Fig 12.0. Momentum History On Impact

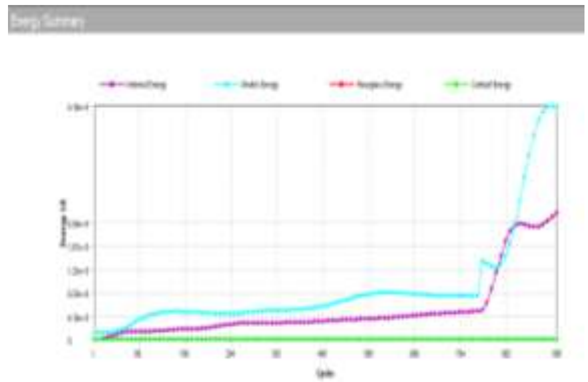


Fig 13.0. Energy History On Impact

Table 1.7. Summary of Impact Test Results

Analysis Parameters	Values
Total deformation	$0.07m$
Max. Momentum in x – direction	1.17×10^7N.s
Impulse in x – direction	$9.58 \times 10^6 \mathrm{N.s}$
Max. Kinetic Energy	$4.18 \times 10^9 \mathrm{J}$
Internal Energy	$2.09 \times 10^9 \mathrm{J}$

4.6 Evaluating The Impact Energy Of The Wheel

It has been reported by [20] that aluminium alloy wheels fails in ductile manner and that wheel failure occurs when the strain energy density of the test wheel exceeds the plastic work (W_p) at fracture.

From anisotropic studies we know that;

$$W_p = \int_0^{\varepsilon_f} \sigma_t d\varepsilon_p \quad (4)$$

Where; ε_f the fracture strain in tensile test; σ_t is the true stress and ε_p is the plastic strain but;

$$\sigma_t = k[\varepsilon_p]^n \quad (5)$$

k is the strength coefficient and n is the strain hardening index for the tempered condition.

$$\therefore W_p = \int_0^{\varepsilon_f} k[\varepsilon_p]^n d\varepsilon_p = \frac{\sigma_f \varepsilon_f}{1+n} \quad (6)$$

σ_f is the true stress at fracture from the physical tensile test.

The flow stress ratio r_α is defined as the ratio between the flow stress σ_f^α in a tensile test in direction α σ_f^0 in a reference test in the ED for the same amount of plastic work. According to The flow stress ratio is given by;

$$r_\alpha = \frac{\sigma_f^\alpha}{\sigma_f^0} \quad (7)$$

Using the empirically determined anisotropic values for the design material at $\alpha = 90^o$ according tables 1.3 and 1.4a – 1.4c; $r_\alpha = 0.975$, $\sigma_f^0 = 310.2\text{MPa}$, $\varepsilon_f = 0.638$, $n = 0.205$

Hence form (7); $\sigma_f^\alpha = (0.975)(310.2) = 302.4\text{MPa}$

Similarly, from (6); $W_p = \frac{\sigma_f \varepsilon_f}{1+n} = \frac{(302.4)(0.638)}{1+0.205} =$ 160.1Nmm/mm^3 (critical value). This is equivalent to the maximum strain energy density the design wheel is expected to have at fracture. Hence, for the wheel to survive the impact test, the strain energy density is expected to be lower than its estimated critical value.

5. Results and Discussion

From the foregoing results of wheel response; the total deformation on impact is observed to be 0.07m and it occurs around the drop centre of the wheel according to figure 10.0. This is a large dent on the wheel and therefore, a poor impact response compared to the works of [16], [14] and [20]. This may be due to design choice of wheel critical parameters such as *offset* because in this design, a zero offset is used which means the disc is centrally fixed round the inner face of the drop centre which sustain some amount of residual static stress before impact. Therefore, on impact, the wheel's drop centre is subjected to great compression stress half-way to the side of the obstacle hence, the relatively humongous deformity. Also from fig 10.0, the deformation curve shows that the growth of the deformation was rapids and attained its maximum value in about 6.0×10^{-4}s from the time of impact.

From fig 11.0, the strain suffered by the wheel was fairly steady between 0 and 0.05 until it suddenly sprouts to a maximum value of; $\varepsilon_f =$ 0.0897 at fracture and then nose dived as the wheel undergo retardation after impact.

From summary of the momentum history of the wheel on impact as shown in fig 13.0, the change in momentum as a result of impact while the wheel was on cruise increased steadily and reached a maximum of 1.17×10^7 N.s at a wheel life of about 833 cycles and dropped to -1.23×10^7Ns at a wheel life of 990 cycles.

The kinetic energy of the wheel gradually increased from about 1.33×10^8J and attained a peak value of 4.18×10^9J at a wheel life of 990 cycles after impact. Correspondingly, the internal energy of the wheel was revealed to be 2.09×10^9J.

Based on available empirical data by [7] and [10] in line with work done by [20], the maximum strain energy density of the wheel is expected not to exceed the plastic work at fracture estimated to be 160.1Nmm/mm^3.

6. Conclusion

The impact test for the design wheel uses numerical algorithm to simulate the impact behaviour of the wheel on a rigid hub/bumper. This simulation helps in determining the crashworthiness of the wheel. The design used in this research has proven to have poor crashworthiness characteristics. However, crashworthiness characteristics of a vehicle wheel has long been explored to large extent. Improvement of the safety and crashworthiness features is a continuous in the automotive industry. One of the most important development is the force-deflection characteristics of the vehicle wheel. The force-deflection characteristic is correlated to change of momentum or change of velocity during the impact which has been duplicated in this work.

It is strongly believed that the choice of wheel design offset is a key factor to the wheel impact performance therefore it is recommended that the designed be modified with a different offset choice especially a positive offset for better performance since this alloy under investigation has been reported to be a structural material and the one with highest strength amongst members of the aluminium 6000 series.

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