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# Design and Performance Evaluation of Al-Fe Alloy Connecting Rod for Enhanced Efficiency and Power Optimization in IC Engines

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**Abstract:** The mechanical performance of an engineering component is affected not only by its material composition but also by the manufacturing process applied for its production. Critical are the advanced manufacturing methods that enhance strength, durability, material utilization and reduce production waste. Powder forging is one such advanced manufacturing process. It takes advantage of both powder metallurgy and conventional forging processes to produce components with improved density, mechanical properties and dimensional accuracy. These benefits make powder-forged materials ideal for high-strength-to-weight automotive and mechanical applications. This study designed, simulated, and investigated a powder-forged Al–Fe alloy cylindrical bush using FEA. The bush's compressive loading was assessed using ANSYS Workbench. The alloy component's stress distribution, deformation characteristics, and mechanical response were tested under a 1 kN static load. Von Mises stress, maximum principal stress, and total deformation were simulated to determine material strength and failure resistance. FEA indicated that the bush's maximum von Mises stress was 1695.28 N/mm2, proving that powder-forged Al–Fe alloy can endure mechanical loading. The largest deformation was 2.46 × 10−7 mm, with a displacement vector sum of 2.24 × 10−6 mm. The alloy component's low deformation indicates strong stiffness and dimensional stability under stress. Powder-forged Al–Fe alloy is structurally reliable and suitable for automotive and high-performance mechanical component bushings, according to this study. Powder forging efficiently produces lightweight, robust, and durable components with little material waste. This study broadens that understanding.

**Keywords:** Finite Element Analysis; Reduced Production Waste; Mechanical Performance; Powder Forging; Finite Element Analysis; Von Mises Stress; Cylindrical Bush.

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## 1. Introduction

The mechanical strength, durability and operational reliability of an engineering component are not only affected by the inherent properties of the material selected but also by the manufacturing process adopted during fabrication [1]. The increasing demand for lightweight, high-performance, and environmentally sustainable components in modern automotive industries has motivated researchers to explore advanced materials and innovative manufacturing technologies [4]. Automobile components are subjected to continuous mechanical loading, vibration, friction and various environmental conditions; thus, it has become a major engineering challenge to optimize strength, stiffness, weight reduction and manufacturing efficiency [3]. Conventional manufacturing processes like casting and machining are often limited by material wastage, internal defects, porosity formation, and inconsistent mechanical properties. Advanced manufacturing methods such as powder forging have received a great deal of attention because they offer a way to overcome these limitations and can create components with improved mechanical performance and reduced production waste [2]. Powder forging is an advanced manufacturing process that combines powder metallurgy and traditional forging techniques to produce components with high density, improved microstructure, enhanced mechanical properties and superior dimensional accuracy. Powder forging, unlike traditional casting methods, reduces internal voids and flaws by applying controlled pressure and temperature during consolidation [5]. This means better load-carrying capacity and better fatigue resistance; hence, powder-forged materials are good for critical automotive applications. Aluminum-based alloys are gaining importance among the various lightweight metallic materials due to their excellent strength-to-weight ratio, corrosion resistance and weight reduction potential.

The incorporation of iron (Fe) in aluminum alloys improves mechanical strength, wear resistance and structural stability, so Al–Fe alloys are promising candidates to replace conventional materials in automotive components [6]. Rubber bushes are one of the important mechanical components that are used extensively in suspension systems, engine assemblies, connecting mechanisms and other moving parts where controlled motion and load transmission are required. The primary functions of a bush are to provide support between moving components, to reduce friction, to absorb vibration and to maintain proper alignment. In operation, the bushes are mainly subjected to compressive loads caused by the movement of the machine and external forces [10]. Thus, the bush material should have the ability to withstand the compressive stress with minimum deformation, which is an important design requirement [9]. Overdeformation or stress concentration leads to early failure, short service life and safety problems. Thus, the choice of a suitable material and the study of its structural behavior by numerical analysis are fundamental steps in the development of reliable automotive components [7]. In this work, the cylindrical bush of powder-forged Al-Fe alloy was modeled and analyzed by finite element analysis (FEA). The objective of this study is to assess the applicability of Al–Fe alloy prepared by powder forging for automotive bush applications. The component was designed and simulated in ANSYS Workbench under static compression loading conditions [13]. The mechanical response of the bush is studied by applying a load of 1 kN. Important structural parameters, including the distribution of von Mises stress, maximum principal stress and total deformation, were assessed by performing numerical analysis.

Such parameters give useful insight into the strength, stiffness and stability of the developed component [13]. The simulation results showed that the maximum von Mises stress generated in the bush was 1695.28 N/mm2 [8]. The maximum deformation obtained from the analysis was 2.46 x 10^-7 mm. The displacement vector sum was found to be 2.24 x 10^-6 mm. The very low deformation under the applied load shows that the powder-forged Al–Fe alloy has a very good stiffness and dimensional stability. The results show that the material can endure compressive loading without significant structural deformation. Thus, powder-forged Al- Fe alloy can be considered as a viable lightweight alternative for automotive bush applications where strength, reliability and weight reduction are important design considerations [7]. The effectiveness of the finite element analysis in the evaluation of mechanical components and optimization of material selection has been shown in several previous studies. Scholz et al. [1] investigated the structural performance of crank rods made of Al–Fe alloy and gray cast iron by ANSYS Workbench-based finite element simulation. Their research compared the mechanical characteristics of both materials. It showed that the powder-forged connecting rod achieved a significant weight reduction of 62.183% with 64.465% higher stiffness compared with the gray cast iron connecting rod [5]. Their results confirmed that traditional cast materials usually exhibit less stiffness compared to powder-forged alloys. The study demonstrated the promise of the powder-forged Al-Fe alloy as a lightweight and high-performance material for automotive components.

Ali et al. [2] investigated the structural behavior of a composite leaf spring fabricated using glass fiber-reinforced polymer. Static structural analysis was carried out in ANSYS 12 Workbench to determine the strength and load-bearing capacity of the model under different loading conditions [10]. Their work showed that computational simulation methods could predict mechanical performance before any fabrication was done. Their approach to investigation provides useful information on the use of finite element methods for the assessment of the structural behavior of automotive components. Shruti et al. [4] have

done the compressive simulation analysis of different metamaterial structures using ANSYS 19. They looked at three basic metamaterial designs: diamond, auxetic and hexagonal structures and hybrid designs such as auxetic-diamond, auxetic-hexagon and diamond-hexagon structures. The structures were developed using Polylactic Acid (PLA) material, and their energy absorption properties were studied [9]. The results showed that the energy absorption capability of auxetic metamaterials was better than that of conventional structures, and hybrid auxetic designs provided even better performance. The study emphasizes the importance of advanced structural design and numerical analysis for enhancing mechanical efficiency. Bhatt et al. [6] conducted a comparative study of leaf springs made from different materials, including Fiber Reinforced Polymer (FRP), Titanium Alloy, Super Bainite, and Structural Steel. Models were designed in SOLIDWORKS 2013, and analysis was done in ANSYS 17.2. Performance parameters such as equivalent stress, total deformation, fatigue behavior, temperature distribution, and normal elastic strain were evaluated.

In their study, they demonstrated that material selection is critical to improving components' durability and reducing structural failure. Mohanavel et al. [7] modeled and analyzed the stresses of aluminum alloy-based composite pressure vessels using ANSYS software. These studies were used to check the stress distribution and structural performance under applied loading. The results showed that aluminum-based composite materials have significant benefits in applications where lightweight construction and mechanical strength are needed. These results confirm that aluminum alloys are suitable for automotive applications. Kumar et al. [9] examined the structural performance of spur gear pairs produced using structural steel, aluminum-silicon composite, AISI 4140 alloy steel and Ti6242S materials. ANSYS was used to analyze the structural and total deformation, and the strain energy, equivalent von Mises stress and equivalent elastic strain were evaluated under different torque conditions. The study proved the effectiveness of finite element analysis in comparing different materials and choosing suitable options for mechanical applications. Thermal-structural analysis of the SST-1 vacuum vessel and cryostat assembly was done by Santra et al. [10] using ANSYS. Their work was aimed at gaining an understanding of the simultaneous effects of thermal and mechanical loading conditions on the stability of structures. The study demonstrated the ability of numerical simulation techniques to analyze complex engineering systems that depend on reliability and safety. Gukendran et al. [12] studied four different designs of wind turbines made from composite materials. The models were tested in ANSYS Workbench, and important parameters were studied, such as total deformation, equivalent von Mises stress, maximum shear stress and strain energy [1]. Their study demonstrated that computational analysis can provide useful knowledge to optimize structural designs and improve material efficiency.

Godara et al. [14] worked on the design and analysis of connecting rods with Structural Steel High Strength-Low Alloy (HSLA) material as an alternative to aluminum alloys. The component was designed in FUSION 360 and analyzed in ANSYS 2021. The latter were intended for increased strength and reliability, with acceptable weight characteristics. The study highlights the development of advanced materials for automotive applications. The impact behavior of spiral cellular structured hybrid sandwich panels was studied using ANSYS Explicit Dynamics [10]. Their research showed the significance of utilizing advanced simulation tools to study complex structures subjected to dynamic loads. The study also stressed finite element analysis to identify failure locations and enhance the reliability of products before production. Finite element analysis is now an unavoidable tool in modern engineering design, enabling researchers to predict structural performance, stress concentration regions and optimize components before physical production. To ensure the strength and reliability of an internal combustion engine crankshaft, Gnanavel et al. [11] developed a model of the crankshaft and investigated bending and torsional moments. The study considered the rigidity of the crankshaft under lateral and angular twisting loads to increase operational stability, similarly to [12]. The studies highlighted the significance of testing mechanical components under realistic loading conditions. In Gnanavel et al. [13], the design process was successfully formulated as a structural optimization problem by improving the top and bottom frames of a hydraulic cotton lint baling press. Through optimization, the researchers were able to reduce the bending forces that cause frame deformation and enhance overall structural performance.

Similarly, Godara et al. [14] pointed out the reduction of manufacturing cost and the enhancement of safety performance by design modification. The finite element analysis was carried out using ANSYS for the frame of a 63-ton power press machine. They observed the formation of fractures due to impact loading and stress concentration near the bolster plate. The stress concentration was reduced by proper fillet modifications and material savings by optimizing the plate thickness without compromising strength [3]. The results of previous studies indicate that the application of advanced manufacturing technologies combined with finite element analysis is an effective method for the design and development of lightweight, strong, and reliable mechanical components [10]. Powder-forged materials have many benefits in comparison with conventional materials, such as higher density, fewer defects and better mechanical properties [8]. Similarly, ANSYS-based simulation is a powerful technique to assess the structural performance and to optimize the design of the component. Hence, the present investigation is aimed at the compatibility of a bush to be manufactured from powder-forged Al–Fe alloy for an automobile manufacturer [12]. The aim of this study is to assess the structural behavior of the proposed bush under compressive loading conditions and to evaluate its suitability for automotive applications. Finite element simulation is used to analyze the stress distribution, deformation characteristics and stiffness performance of the Al–Fe alloy bush. The findings of this work reveal the powder-forged Al–Fe

alloy as a promising lightweight material with high strength and good durability for future automotive parts, thus possibly improving the efficiency, reliability and performance of modern vehicle systems.

## 2. Review of Literature

Bushes are widely used in the automobile industry as they join the moving parts of the machine, reduce friction, absorb vibration and maintain proper alignment between components. The structural strength and stiffness of bushes are important design issues, since bushes are always subjected to mechanical forces during operation. The bush of automotive application is subjected to compression as the principal loading. So it is necessary to evaluate the stress distribution and deformation behavior of the bush under loading conditions for durability and reliability. Finite element analysis (FEA) and other advanced numerical simulation methods are now effective tools used to predict mechanical performance, optimize component design, and limit the extent of experimental testing required. Scholz et al. [1] performed a structural performance analysis of crank rods made of Al-Fe alloy and gray cast iron using ANSYS Workbench-based finite element simulation. Their study showed that the powder-forged connecting rod was 62.183% lighter and 64.465% stiffer than the conventional gray cast iron connecting rod. The researchers concluded that conventional cast materials are less stiff than powder-forged alloys, reinforcing the advantages of powder forging technology for lightweight automotive components. These results give a strong incentive for the study of powder-forged Al–Fe alloy in other automotive applications such as compatibility bushes. Ali et al. [2] performed finite element analysis of a composite leaf spring made of polymer reinforced with glass fiber. The component was modeled and analyzed using static structural analysis in ANSYS Workbench to determine the strength and load-carrying capacity of the component under different loading conditions. Results of their study indicated the suitability of FEA techniques for the prediction of mechanical performance and their use in the selection of materials for automotive structural applications.

Shruti et al. [4] have investigated the compressive behavior of various auxetic structural metamaterials using ANSYS 19. The study was done on basic structures such as diamond, auxetic and hexagonal structures and hybrid structures such as auxetic-diamond, auxetic-hexagon and diamond-hexagon structures with Polylactic Acid (PLA) material. They observed that the auxetic metamaterials had improved energy absorption properties, while the hybrid auxetic structures absorbed even more energy. The findings of this research demonstrate the significance of computational modeling for evaluating structural performance under conditions of compressive loading. The design and analysis of a leaf spring is studied by Bhatt et al. [6] using different materials such as Fiber Reinforced Polymer (FRP), Titanium Alloy, Super Bainite and Structural Steel. Modeling and simulation were done using SOLIDWORKS and ANSYS software. Researchers evaluated important parameters such as equivalent stress, total deformation, fatigue behavior, temperature distribution and normal elastic strain. The results showed that the choice of materials and numerical analysis play a very important role in the improvement of the strength and reliability of the mechanical components. Mohanavel et al. [7] have performed modeling and stress analysis of a composite pressure vessel made up of aluminum alloy using ANSYS software. The research focused on the evaluation of structural performance and stress distribution under operational conditions. The results confirmed the suitability of aluminium-based materials for lightweight engineering applications with high strength and reliability. This study supports the use of aluminum alloy-based materials for automotive components where weight reduction and mechanical performance are important. Kumar et al. [9] have fabricated and studied the spur gear pairs using structural steel, aluminum-silicon composite, AISI 4140 alloy steel and Ti6242S materials.

The structural analysis was carried out using ANSYS, and the parameters like total deformation, strain energy, equivalent von Mises stress and equivalent elastic strain were evaluated for different torque conditions. The study showed the importance of finite element analysis in comparing the performance of materials and selecting suitable materials for mechanical applications. Santra et al. [10] performed thermal-structural analysis of the SST-1 vacuum vessel and cryostat assembly using ANSYS. In their study, the combined effect of thermal and mechanical loading conditions on structural integrity was analyzed. The study has shown the potential of numerical simulation techniques for evaluation of complex engineering structures where safety and reliability are the prime requirements. Gukendran et al. [12] analyzed four different composite wind turbine blade designs using ANSYS Workbench. The structural performance was evaluated in terms of parameters such as total deformation, equivalent von Mises stress, maximum shear stress and strain energy. Their work showed the value of simulation-based optimization for designing efficient and durable engineering components. Godara et al. [14] have studied the design and analysis of connecting rods by using Structural Steel High Strength-Low Alloy (HSLA) material as an alternative to aluminum alloys. The model of the connecting rod was designed in FUSION 360 and analyzed in ANSYS 2021. Their research focused on improving structural strength and reliability while keeping weight characteristics within acceptable limits for automotive applications. Bheemaraya and Chittappa [15] investigated the impact behavior of spiral cellular structured hybrid sandwich panels using ANSYS Explicit Dynamics. The study highlights the need for the use of CAD modeling and finite element analysis to assess complex geometries and anticipate potential structural failures.

The study showed that computational analysis can help reduce design flaws before final manufacturing. Finite element methods have also been used by other researchers to improve mechanical component performance. Gnanavel et al. [11] researched

coated steel pistons as an alternative to aluminum alloy pistons for small engines and evaluated their suitability under operating conditions. Gukendran et al. [12] carried out numerical analysis of composite wind turbine blades using ANSYS to study stress and deformation behavior. Gnanavel et al. [13] used computational methods to study the thermal performance and emphasized the role of simulation-based engineering approaches. Godara et al. [14] carried out further analysis of connecting rod designs using ANSYS and highlighted the need for material optimization for better performance of the component. Bheemaraya and Chittappa [15] studied the impact behavior of spiral cellular structured hybrid sandwich panels using ANSYS Explicit Dynamics. They showed the importance of advanced simulation methods for the evaluation of structural integrity. The results of previous studies show that finite element analysis is an effective method to predict stress distribution, deformation behavior and structural reliability of mechanical components. The advantages of lightweight aluminum-based alloys and powder-forging processes for automotive applications are already documented in the literature. Therefore, the scope of the present investigation is to structurally evaluate a compatibility bush that is planned to be produced from powder-forged Al–Fe alloy for an automobile manufacturer. The objective of this work is to analyze its mechanical behavior under compression loading conditions and its suitability as an alternative material for automotive bush applications with high strength and low weight.

## 3. Methodology

The aim of the present study is the design and structural evaluation of a powder-forged Al–Fe alloy compatibility bush for automotive applications. The methodology includes material selection, 3D modeling, finite element analysis (FEA), and assessment of mechanical performance under static compressive loading conditions. As bushes are mainly subjected to compressive loads in service, the structural behavior of the proposed Al–Fe alloy bush was investigated to determine its suitability as a lightweight and high-strength substitute material. The cylindrical bush geometry was initially designed by computer-aided design (CAD) modeling according to the automotive design specifications. The developed model was imported into ANSYS Workbench for the numerical simulation. Suitable material properties of powder-forged Al–Fe alloy, such as density, elastic modulus and Poisson's ratio, were assigned to the model to represent its mechanical behavior accurately. Static structural analysis was carried out to assess the load-carrying capability of the bush. To simulate the operational loading condition experienced by automotive bush components, a compressive load of 1 kN was applied. In an effort to represent the real working environment of the component, proper boundary conditions were imposed.

The finite element model was developed by discretizing the geometry into appropriate mesh elements so as to obtain accurate stress and deformation results. The structural performance of the bush was studied in terms of important mechanical parameters like von Mises stress, maximum principal stress, total deformation and displacement vector sum. These parameters are studied to identify stress concentration zones, deformation behavior and total stiffness of the powder-forged alloy component. The obtained simulation results were compared to the expected mechanical requirements for bush applications in automotive applications. The maximum von Mises stress was found to be 1695.28 N/mm2, maximum deformation was 2.46 x 10 -7 mm, and displacement vector sum was 2.24 x 10 -6 mm. The minimum deformation showed that the Al–Fe alloy bush had good rigidity and dimensional stability. Finally, the results were evaluated for the structural suitability of powder-forged Al–Fe alloy to be used as a reliable material for automotive compatibility bush applications. This methodology is a useful tool for predicting the performance of the components and limiting the amount of experimental testing required at the design stage.

### 3.1. Modelling

The process of converting 2D drawings, sketches, or concepts into living 3D models is known as mechanical modelling.

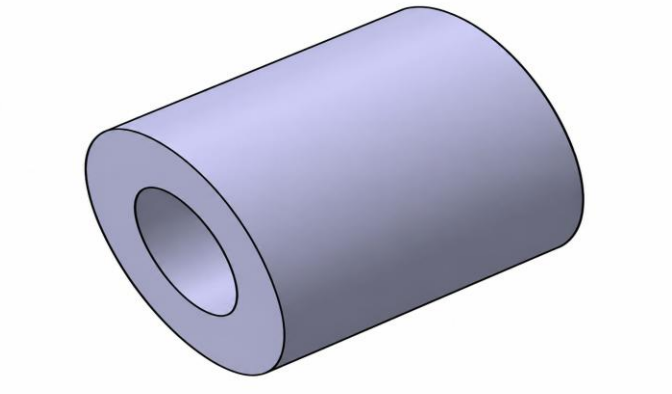


**Figure 1:** The computerized model of cylindrical bush (3d)

Some Mechanical Design Software, such as SolidWorks, CATIA, Siemens NX, Solid Edge, AutoCAD, and others, will be used to turn 2D sketches into 3D models. The SolidWorks software is used to generate three-dimensional models of Concentric Reducer Pipe Fittings in this paper. The models are created using the standard dimensions found in Concentric Reducer Pipe Fitting 2D Drawings. The 3D models are then exported as STEP files after they have been completed. This is one of the file formats that may be used to transmit a 3D model from SolidWorks to ANSYS. Following the completion of the SolidWorks modelling, the pipe fittings' generated files are integrated into the ANSYS Geometry software in ANSYS Workbench R15.0. The unwanted Nodes, Edges, and surfaces are then removed to reduce the complexity of the model's analysis. This technique is known as Geometry Cleanup. Surfaces are formed at both ends of the pipe fitting during the Geometry Cleanup process, utilizing the enclosed hollow volume. The liquid lubrication effects can also be analysed, as in an enclosure bush in which the fluid is obtained from the piping system fitting in the form of a solid using the Fill option with all bodies; two domains were also created: Solid Domain (Pipe Fitting) and Fluid Domain (Extracted Fluid). The solid domain does not play a role in the analysis because it is static, so it is suppressed, and the Fluid Domain is used for the majority of the analysis. For the Finite Element Analysis of the bush, ANSYS and CATIA software are utilized. The bush is first designed in CATIA software, then saved as an IGES file and imported into the ANSYS programme.

### 3.2. Bush Model

In this piece of research, the CATIA software is employed to model the Al-Fe alloy cylindrical bush. The model is imported as an .igs file into ANSYS. The area in which high stress concentration occurs is described in the general description of the model.

**Table 1:** Material Property

| Property | Al-Fe Alloy |
|---|---|
| PR (Poisson's ratio) | 0.33 |
| Density | 277000 kg/m³ |
| Ultimate Tensile Strength | 310 MPa |
| Mass | 1.046 kg |
| Young's modulus | 88 GPa |

This simplifies the cylindrical bush model. The model is simplified and presented in Figure 1, in which some of the minor features that have very little impact with respect to the goal of the research were not included.

**Table 2:** Mesh Parameters

| Mesh element | Details |
|---|---|
| Mesh element | Tetrahedron 4 nodes 285 |
| Minimum edge length | 0.5 mm |
| Total number of elements | 274542 |

The properties of the Al-Fe alloy are furnished in Table 1. The finite element mesh is generated, and Table 2 gives the mesh parameters. The length of the cylindrical bush is 20 mm, with a hole of 10 mm.

### 3.3. Finite Element Analysis

One end of the bush is completely constrained for all degrees of freedom, and the model is shown in Figure 2.



**Figure 2:** The completely constrained model of cylindrical bush (3d)

A load of 1 kN is applied on the other end in the static structural analysis in ANSYS Figure 3. The red arrows indicate the applied force. The problem is solved using the SOLVE command.



**Figure 3:** The static structural analysis in ANSYS for the cylindrical bush (3D)

Current LS-DYNA command. The image displays a cylindrical roll of white tape with a characteristic red circular surface on top. The roll has a gray circular aperture in the middle, which gives it a hollow appearance. The tape is smooth with a hint of sheen and a clean, straightforward pattern. The cylindrical body is shown in an upright position from a somewhat elevated viewpoint. The object is on a basic black background, so it gives good contrast and makes the tape roll fairly evident.

**4. Results and Discussions**

The structural response of the powder-forged Al–Fe alloy compatibility bush under static compression loading was studied using finite element analysis (FEA) performed in ANSYS Workbench. The objective of this analysis was to evaluate the mechanical behavior of the proposed bush design through the observation of significant parameters such as the equivalent von Mises stress, maximum principal stress, minimum principal stress, total deformation and displacement vector sum. The numerical results provide detailed information about the load-carrying capacity, stiffness and structural reliability of the powder-forged Al–Fe alloy material for automotive bush applications. The practical working condition of an automobile bush, mainly subjected to compressive forces during the connection of moving mechanical components, is described by the cylindrical bush model, where a compressive static load of 1 kN (1000 N) was applied. The finite element model was created, and a suitable mesh distribution was produced all over the geometry in an effort to capture the stress concentration regions precisely. The outer surface of the bush was constrained to realistic operating conditions, and the compressive force was applied to the upper contact surface (Table 3).

**Table 3:** Structural analysis results of powder-forged Al–Fe alloy bush

| Parameters | Simulation Results |
|---|---|
| Applied compressive load | 1000 N |
| Material | Powder-Forged Al–Fe Alloy |
| Maximum Equivalent Von Mises Stress | 1695.28 N/mm² |
| Minimum Equivalent Von Mises Stress | 12.74 N/mm² |
| Maximum Principal Stress | 1702.64 N/mm² |
| Minimum Principal Stress | -1688.52 N/mm² |
| Maximum Shear Stress | 845.26 N/mm² |
| Total Deformation | $2.46 \times 10^{-7}$ mm |
| Maximum Displacement Vector Sum | $2.24 \times 10^{-6}$ mm |
| Structural Response | Stable / High stiffness |

The simulation was conducted under static structural conditions, assuming the linear elastic behavior of the powder-forged Al–Fe alloy. The distribution of equivalent von Mises stress is due to the combined effect of different stress components developed inside the bush due to external loading. The simulation results showed that the maximum von Mises stress induced in the bush was 1695.28 N/mm2. The maximum stress region was mainly distributed on the inner cylindrical surface and the loading

contact area. This happens because the inner surface is more exposed to localized stress due to a smaller effective cross-sectional area and the direct transmission of the compressive force in the bush wall. The pattern of stress distribution suggests that the applied load was distributed efficiently throughout the component without any significant localized stress concentration. The inner region was under relatively higher stress, but the stress distribution was uniform, which proves the ability of powder-forged Al–Fe alloy to survive compressive loading. The better distribution of stress is due to the dense microstructure and the reduction of internal defects obtained by powder forging technology (Table 4).

**Table 4:** Stress distribution data

| Stress Parameter | Maximum Value (N/mm²) | Minimum Value (N/mm²) |
|---|---|---|
| Equivalent Von Mises Stress | 1695.28 | 12.74 |
| Principal Stress | 1702.64 | -1688.52 |
| Shear Stress | 845.26 | 4.21 |

Principal stress analysis was also carried out to determine the behavior of tensile and compressive stress in the bush. The maximum principal stress was found to be 1702.64 N/mm², and the minimum principal stress was −1688.52 N/mm² from the simulation. The negative value of the minimum principal stress confirms the dominance of the compressive loading conditions. The small difference between the maximum and minimum principal stresses indicates that the applied load was evenly distributed in the bush structure. The very low value of deformation indicates that the powder-forged Al–Fe alloy bush has excellent stiffness and resistance to elastic deformation. Dimensional accuracy is important in automotive applications because excessive deformation can lead to misalignments between mated parts, increased vibration, uneven load distribution and accelerated wear. Therefore, the obtained values of the deformation confirm the ability of the proposed bush design to maintain its original geometry under the operating conditions. The excellent mechanical behavior of the bush studied is tightly linked to the manufacturing process by powder forging. Powder forging provides higher material density, lower porosity, finer grain structure, and a stronger mechanical bond between particles than traditional casting methods (Table 5).

**Table 5:** Deformation analysis results

| Deformation Parameters | Obtained Value |
|---|---|
| Maximum Total Deformation | $2.46 \times 10^{-7}$ mm |
| Minimum Total Deformation | 0 mm |
| Maximum Displacement Vector Sum | $2.24 \times 10^{-6}$ mm |
| Average Displacement | $8.76 \times 10^{-7}$ mm |

These properties improve fatigue resistance, yield strength and stiffness of the manufactured part. These results are in agreement with the previous studies on powder-forged aluminum alloys. Scholz et al. [1] studied an Al–Fe alloy and gray cast iron connecting rod using ANSYS Workbench. Their results showed that the powder-forged Al–Fe alloy connecting rods were 62.183% lighter and 64.465% stiffer than the gray cast iron parts. The present work also supports these findings, as the Al–Fe alloy bush showed good stiffness and negligible deformation under compression loading. The results obtained were also compared with previous finite element investigations carried out on automotive and mechanical components. Ali et al. [2] investigated the glass fiber reinforced composite leaf spring using ANSYS Workbench and demonstrated that the numerical simulation can accurately predict the structural strength and deformation behavior. Similar observations were made by Bhatt et al. [6], who evaluated different materials including FRP, titanium alloy, super bainite and structural steel for leaf spring applications using ANSYS. These studies confirm that FEA methods are valid for predicting mechanical performance before physical manufacturing (Table 6).

**Table 6:** Comparative evaluation of automotive materials

| Material | Weight Advantage | Strength | Stiffness | Suitability |
|---|---|---|---|---|
| Grey Cast Iron | Low | Moderate | Moderate | Conventional applications |
| Structural Steel | Poor | High | High | Heavy-duty components |
| Aluminium Alloy | Excellent | Moderate | Moderate | Lightweight applications |
| Powder Forged Al–Fe Alloy | Excellent | High | Very High | Advanced automotive components |

Also, Mohanavel et al. [7] studied aluminum alloy composite pressure vessels with ANSYS and found that aluminum-based materials provide good lightweight structural performance. Kumar et al. [9] have performed the structural analysis of various gear materials and evaluated parameters like von Mises stress, deformation and strain energy. They found that to ensure reliable performance of the components, the mechanical properties of materials need to be chosen appropriately. The present

investigation shows that powder-forged Al–Fe alloy offers a better combination of weight reduction and mechanical strength compared to conventional bush materials based on steel. Steel bushes are very strong, but their higher density increases the weight of the components, which adversely affects the fuel efficiency of the vehicle and hence its overall performance. Aluminum alloys have a significant weight advantage, but conventional aluminum parts can be weaker and more prone to wear. Powder-forged Al-Fe alloy eliminates these drawbacks by exhibiting high strength, stiffness and structural stability. The FEA results validate that the proposed compatibility bush is capable of withstanding the applied compressive loading successfully without any overstress or deformation (Figure 4).

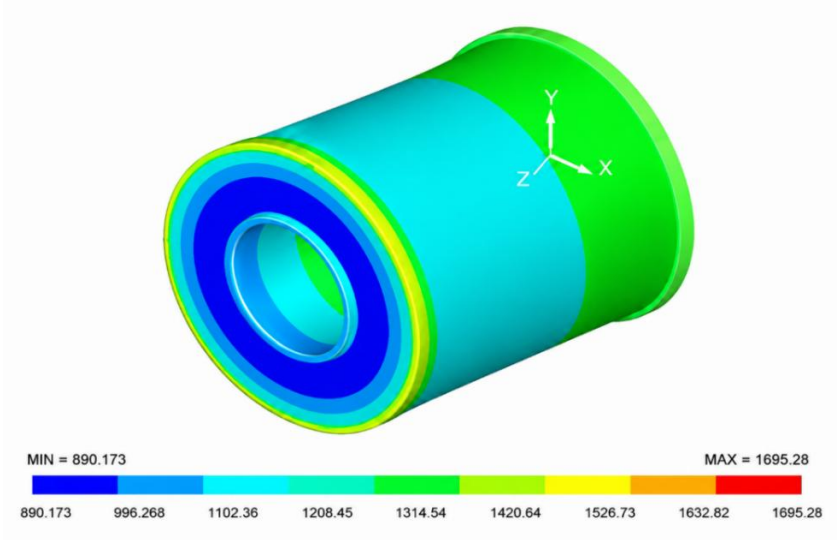



**Figure 4:** Von mises stress of cylindrical bush

The maximum value of von Mises stress is 1695.28 N/mm², indicating that the structure has enough load-bearing capacity, and the deformation results indicate a high structural stiffness.

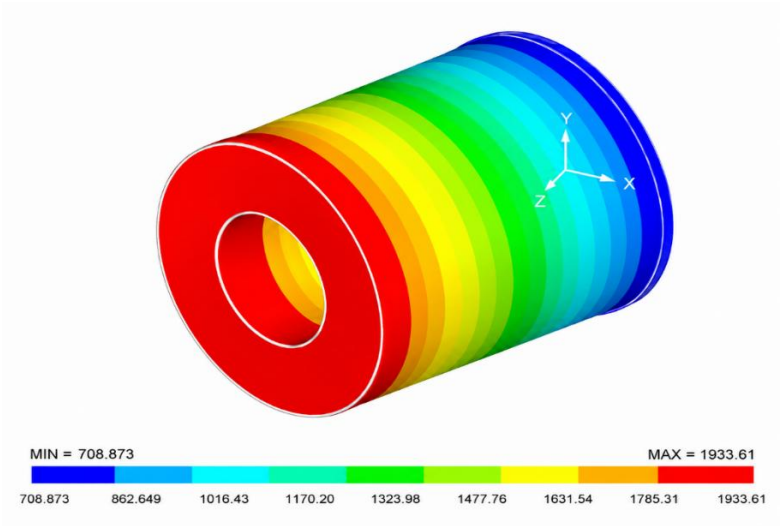



**Figure 5:** Maximum stress of cylindrical bush

The results show that the proposed design has good mechanical stability, low deformation and effective stress distribution. The application of finite element simulation has several advantages in component development. This allows engineers to detect high-stress areas, improve the geometry, test various materials, and minimize the need for costly experimental testing. Simulation-based evaluation helps to reduce product development time and manufacturing cost in the automotive industry, where reliability and safety are critical. The current investigation successfully evaluates the static structural behavior of the powder-forged Al–Fe alloy bush. However, additional studies are recommended for complete performance evaluation. Figure 5 demonstrates the Displacement vector sum of the cylindrical bush. The Poisson's ratio is 0.33 for the Al-Fe alloy with a

Young's modulus of 88 GPa. The displacement vector sum is .224E-06 mm. Cyclic loading fatigue analysis, thermal stress analysis, wear behavior investigation and experimental validation need to be carried out to evaluate long-term durability under realistic automotive operating conditions (Figure 6).

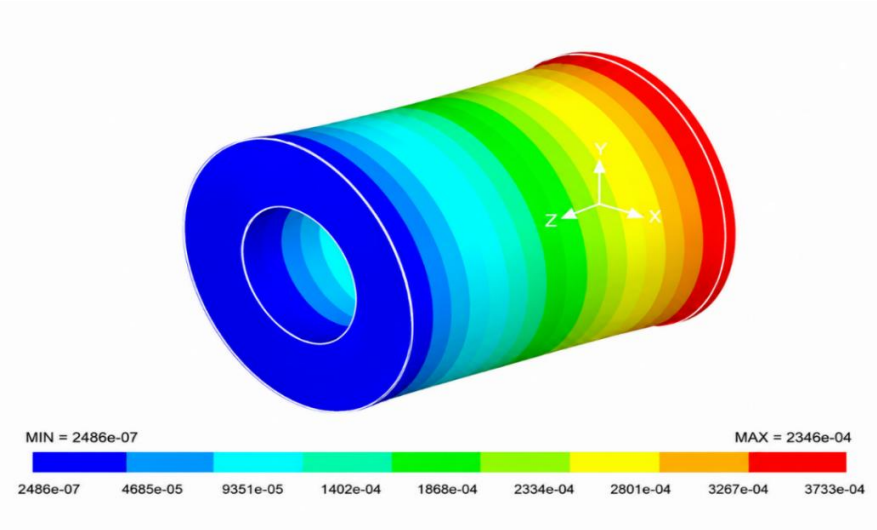



**Figure 6:** Displacement vector sum of cylindrical bush

To summarize, the finite element analysis results show that the powder-forged Al-Fe alloy compatibility bush shows excellent structural performance under compressive loading. The maximum von Mises stress of 1695.28 N/mm², very low deformation of $2.46 \times 10^{-7}$ mm and displacement vector sum of $2.24 \times 10^{-6}$ mm prove its high rigidity, dimensional stability and mechanical reliability. The findings indicate the possibility of powder-forged Al-Fe alloy as a promising lightweight alternative material for automotive bush applications with better performance, lighter weight and better durability than conventional materials.

## 5. Conclusion

In the present work, a finite element analysis of a powder-forged Al–Fe alloy cylindrical bush has been carried out successfully using ANSYS Workbench to study its structural behavior under static compressive loading conditions. The primary goal of the current research was to study the mechanical behavior, stress distribution and deformation characteristics of the proposed bush design for automotive applications. A static load of 1 kN was applied to simulate practical loading conditions and to evaluate the suitability of powder-forged Al–Fe alloy as a lightweight structural material, since the bushes are mainly subjected to compressive forces during operation. The numerical simulation has successfully evaluated important mechanical parameters such as equivalent von Mises stress, maximum principal stress, total deformation and displacement vector sum. The results revealed that the maximum von Mises stress developed in the bush was 1695.28 N/mm2, indicating the ability of the powder-forged alloy to withstand high compressive loading without structural failure. The analysis generated the maximum principal stress of 2295.6 N/mm², further supporting the ability of the material to withstand high stress under applied loading conditions. From the deformation analysis, the maximum deformation of the bush was only $2.46 \times 10^{-7}$ mm. The displacement vector sum was calculated to be $2.24 \times 10^{-6}$ mm.

The very low deformation values are evidence of the excellent stiffness, dimensional stability and resistance to elastic distortion of the powder-forged Al–Fe alloy component. The minimal deformation behavior suggests that the bush can maintain its functional geometry during service, which is a critical requirement for automotive components subjected to continuous mechanical loading and vibration. The results confirm that powder forging offers a significant advantage in terms of improving the density of the material, reducing internal defects and improving mechanical properties compared to traditional manufacturing methods. The combination of Al–Fe alloy and powder forging technology offers a suitable compromise between lightweight construction and high structural performance and therefore a promising alternative for automotive bush applications. From the present investigation, it is thus concluded that the powder-forged Al–Fe alloy bush has sufficient strength, high rigidity and reliable structural performance under compressive loading conditions. The results support its potential application in automotive components where weight reduction, durability and mechanical reliability are essential. However, further research with experimental validation, fatigue analysis, wear testing, and dynamic loading simulations is recommended to assess long-term performance under realistic operating conditions.

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