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A Comprehensive Review of Stress and Strain Analysis in Pistons Utilizing Composite Materials via ANSYS Software

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Abstract - A piston is a crucial component of reciprocating engines, reciprocating pumps, compressors, and pneumatic cylinders, among other similar mechanisms. Enclosed within a cylinder, it seals gases via piston rings and converts the energy of expanding gases into mechanical energy. The piston operates within the cylinder liner or sleeve and is typically made of aluminium or cast-iron alloys. This study focuses on designing a piston for a bike's petrol engine, analysing stress and strain using composite materials through computational simulations via ANSYS software. Pistons endure significant mechanical loads and thermal stresses, emphasising their importance in various mechanical systems. Integrating composite materials in piston design offers benefits like improved strength-to-weight ratios and tailored mechanical properties. ANSYS software enables detailed finite element analysis (FEA), allowing engineers to accurately simulate and assess composite piston performance under diverse conditions. This paper delves into methodologies for composite modelling, material characterisation, and setting up boundary conditions within ANSYS to predict stress and strain accurately. Furthermore, recent advancements and challenges in composite piston analysis are discussed, covering fatigue analysis, thermal effects, optimisation techniques, and failure criteria assessment. Insights from this review contribute to a comprehensive understanding of composite piston mechanics, guiding future research towards optimising their performance and durability in engineering applications.

Keywords- Internal Combustion (IC) Engines, Performance, ANSYS Software Composite Modelling, Boundary Conditions, Load Conditions, Meshing

1. INTRODUCTION

The term "internal combustion engine" typically denotes an engine characterised by intermittent combustion, encompassing well-known variants like the four-stroke and two-stroke piston engines alongside innovations such as the six-stroke piston engine and the Wankel rotary engine. Another category of internal combustion engine operates through continuous combustion, including gas turbines, jet engines, and most rocket engines, all functioning on the same principle as previously outlined. Additionally, firearms represent another form of internal combustion engine.

1.1 Working of Petrol Engine

The working principle of a petrol engine involves several key stages that enable fuel conversion into mechanical energy.

Intake Stroke: The process begins with the intake stroke, where the piston moves downward within the cylinder. As it does so, the intake valve opens, allowing a mixture of air and fuel (petrol) to enter the combustion chamber.

Compression Stroke: Following the intake stroke, the piston moves upward, compressing the air-fuel mixture within the combustion chamber. This compression increases the pressure and temperature of the mixture, preparing it for combustion.

Combustion (Power) Stroke: The spark plug ignites the mixture when the air-fuel mixture is most compressed at the top of the compression stroke. The ignited fuel rapidly burns, generating a high-pressure explosion. This explosion forces the piston downward, providing the engine's power output.

Exhaust Stroke: The piston moves upward again once the power stroke is complete. As it does, the exhaust valve opens, allowing the burned fuel gases to exit the combustion chamber and enter the exhaust system. This prepares the cylinder for the next cycle.

Repeating the Cycle: The engine continues this four-stroke cycle – intake, compression, power, and exhaust – in rapid succession as long as fuel is supplied and ignition occurs. This continuous cycle generates the mechanical energy needed to power the vehicle.

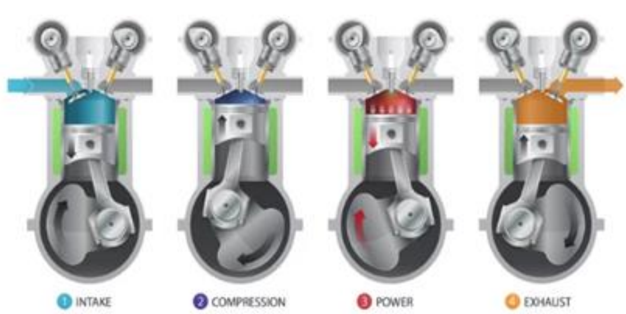

Figure 1. Four-Stroke Cycle of Engine

A petrol engine operates by intaking a mixture of air and fuel, compressing it, igniting it to produce combustion, and then expelling the resulting exhaust gases. This process repeats continuously to generate the mechanical energy required for propulsion. A typical combustion reaction involves the reaction between methane (CH_4) and oxygen (O_2) to produce carbon dioxide (CO_2) and water vapour (H_2O) as follows:

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

In this reaction, methane combines with oxygen in the presence of heat or a spark to yield carbon dioxide and water vapour. This combustion process releases energy in the form of heat and light. All combustion reactions are exothermic, releasing energy into the surrounding environment. This energy is crucial for converting into useful mechanical energy in reciprocating engines. The modern reciprocating engine follows a four-stroke cycle, completing four-piston movements before the combustion process concludes. These four strokes enable the completion of a thermodynamic cycle. A four-stroke engine, also known as a four-cycle engine, is an internal combustion engine where the piston undergoes four distinct strokes while driving a crankshaft. Each stroke represents the full travel of the piston along the cylinder in either direction. These four strokes are:

1. Intake: Also called induction or suction, this stroke begins at the top dead centre (T.D.C.) and ends at the bottom dead centre (B.D.C.). The intake valve remains open as the piston draws an air-fuel mixture into the cylinder by creating a vacuum pressure during its downward motion.

2. Compression: Starting from B.D.C. or the end of the intake stroke, this stroke ends at T.D.C. The piston compresses the air-fuel mixture in readiness for ignition during the power stroke. Both intake and exhaust valves are closed during this stage.
3. Combustion: Also known as power or ignition, this marks the start of the second revolution in the four-stroke cycle. At this stage, with the crankshaft completing a full 360-degree revolution, the compressed air-fuel mixture at T.D.C. is ignited by a spark plug (in gasoline engines) or by heat generated through high compression (in diesel engines). This ignition forcefully drives the piston back to B.D.C., producing mechanical work to turn the crankshaft.
4. Exhaust: Also known as the outlet stroke, during this phase, the piston returns from B.D.C. to T.D.C. while the exhaust valve remains open. This movement expels the spent air-fuel mixture through the exhaust valve.

An internal combustion engine is distinguished by the release of chemical energy from the fuel inside the engine, which is directly utilised for mechanical work, contrasting with external combustion engines, where a separate combustor is employed to burn the fuel. The internal combustion engine originated and evolved in the late 1800s, profoundly impacting society and standing as one of the most significant inventions of that era. The internal combustion engine has been the foundation for the successful development of many commercial technologies. For example, consider how this engine has transformed the transportation industry, allowing the invention and improvement of automobiles, trucks, aeroplanes and trains.

1.2 Stress-Strain analysis of piston (Petrol Engine)

Stress-strain analysis of pistons in petrol engines involves assessing the mechanical behaviour of the piston under various operating conditions. This analysis ensures the piston's structural integrity, performance, and durability.

Material Selection: Choosing the appropriate material for the piston is essential. Common materials include aluminium alloys, cast iron, and sometimes advanced composite materials. The material's mechanical properties, such as Young's modulus, yield strength, and thermal expansion coefficient, significantly influence the stress-strain behaviour of the piston.

Finite Element Analysis (FEA): FEA is a powerful computational tool used to simulate and analyse the behaviour of complex structures like pistons under different loads and boundary conditions. In the stress-strain analysis context, FEA helps predict the distribution of stresses and strains throughout the piston structure.

Loading Conditions: Various loading conditions must be considered during the analysis, including combustion pressure, inertial forces due to piston acceleration, thermal expansion, and mechanical loads from connecting rods and crankshafts. These loads induce stresses and strains in different regions of the piston.

Boundary Conditions: Properly defining boundary conditions is essential for accurate analysis results. This includes constraints applied to the piston, such as fixing certain degrees of freedom or applying prescribed displacements or loads at specific locations.

Thermal Analysis: Since pistons are subjected to high temperatures during combustion, thermal analysis is crucial for understanding thermal stresses and deformations. Thermal loads from combustion and heat transfer must be coupled with structural analysis to predict the piston's response accurately.

Post-Processing: Post-processing techniques are used to interpret the results after analysis. This includes visualising stress and strain distributions, identifying critical regions prone to failure, and evaluating safety margins based on material properties and design criteria.

Optimisation: Based on the results of the analysis, iterative optimisation techniques can be employed to improve the piston design. This may involve modifying the geometry, material selection, or manufacturing process to enhance performance while ensuring structural integrity.

During the normal operation of the engine, as the fuel mixture is being compressed, an electric arc is created to ignite the fuel. This occurs close to TDC (Top Dead Centre) at low RPM. As engine rpm rises, the spark point is moved earlier in the cycle to ignite the fuel charge while it is still being compressed. We can see this advantage reflected in the various Otto engine designs. The atmospheric (non-compression) engine operated at 14% efficiency. The compressed charge engine had an operating efficiency of 32%. The heat flow through the piston ring to the cylinder liner is complex to model analytically due to a large number of circumstances that occur under a four-stroke cycle, all of which can affect the heat flow. A number of these circumstances are presented below.

1. Varying oil film thickness affects the oil's thermal conductivity and causes surface-to-surface contact between the piston rings and the cylinder liner.
2. The rings may twist during a stroke and change the contact geometry.
3. Piston ring manufacture tolerances can vary and affect the clearance between the ring and the liner.
4. Surface-to-surface or hydrodynamic friction may arise in the ring-liner interaction, raising the oil and surface temperatures.
5. Tilting of the piston circumferentially varies the contact between the piston rings.
6. Combustion gases may penetrate the top land crevice and locally increase the heat flux input to the piston top land.
7. Thermal expansion of the piston and the piston ring changes the piston- and the piston ring geometry.
8. Combustion gas blow-by will affect the heat transfer by adding convective heat transfer to the piston and the cylinder liner.

2. FINITE ELEMENT METHOD

The finite element method is a commercially used numerical technique to find an approximate solution to partial differential and integral equations. In some partial differential equations, the first problem is creating an equation approximating the studied equation. This means that errors should not accumulate during calculations, thereby causing the output to be meaningless. The finite element method can be utilised to perform a multidimensional heat transfer analysis. This type of solution method uses elements representing the object's body. Each element expresses the physical, geometrical and material properties of the structure. The elements consist of nodes; a shape function describes the node value changes along the elements. The number of nodes of an element can vary, but generally, three or four-node elements are used in a 2D analysis.

In contrast, for 3D analysis, four or eight-node elements are commonly used. Each node has a certain number of degrees of freedom depending on the analysis type. The finite element analysis consists of a computer model of a material or designs that are stressed and analysed for specific results. It is often used to refine existing products or for any new design. Modifying existing design, product, or structure is utilised to qualify the product for a new service condition. Sometimes, in structural failure, FEA may help determine design modifications to meet new conditions. Generally, two types of analysis are used in the manufacturing industry: 2D modelling and 3D modelling. In 2D modelling, the analysis runs on a normal computer, leading to less accurate results.

On the other hand, 3D modelling gives more accurate results by sacrificing the ability to run on all but the fastest computers effectively. The complex nature of linear systems is less complex than non-linear systems. Non-linear systems account for plastic deformation; many test a material to its fracture. The advantages of the finite element method are given below.

1. Solving non-linear problems can be easily performed.
2. The formulation is easy in FEM and allows solving of different problems.
3. Domains having more than one material are easily analysed.
4. Selecting an approximation of a higher degree polynomial can improve the accuracy of results.
5. The method can be used for any irregularly shaped domain.
6. It can be used in all types of boundary conditions.
7. The generation of algebraic equations can be easily done and solved.
8. A generalised code can be developed for analysis if required for a large class of problems.

3. LITERATURE REVIEW

Shubham Shrivastava and Shikar Upadhyay (2016) conducted a study where the cylinder block was designed using Solidworks software, incorporating perpendicular fins to enhance heat dissipation. Modifications were made to reduce the fin thickness, and the material selection focused on aluminium alloy 1050 for improved heat transfer efficiency. The analysis revealed significant weight reduction without compromising strength. K. Venkatareddy and V. Chandrashekar Goud (Year not provided) utilised Solidworks and ANSYS Workbench software to design and analyse pistons with various materials. They conducted structural and thermal analyses on pistons made of grey cast iron, aluminium alloy, and composite materials. Their findings favoured aluminium silicon carbide graphite (Al-SiC Graphite) due to its superior performance. K. Sundaram and N. Palanikumar (Year not provided) explored the deposition of SiC composites on aluminium for piston applications. They used Pro-E modelling and ANSYS simulation software to analyse pistons made of different materials. Their results highlighted aluminium with 10% SiC as the most suitable option. Abino John and Jenson T Mathew (2015) studied composite aluminium silicon carbide (AlSiC) pistons. Compared to aluminium, AlSiC pistons exhibited reduced deformation and stress and better temperature distribution, overcoming limitations faced by traditional aluminium pistons. Using computational tools, S. Bhattacharya et al. (2014) conducted a thermo-mechanical analysis on natural gas engine cylinder heads. Their study evaluated overheating damage and mechanical stress distribution in critical areas, showcasing agreement between computed and experimental data. J. Barriga et al. discussed the advancements of concentrated solar power (CSP) technology, particularly in parabolic trough solar collectors. These collectors aim to increase operating temperatures to improve productivity and efficiency, emphasising the importance of selective absorber coatings. Li Wanyou and Guo Yibin (Year not provided) presented an in-depth analysis of interring gas dynamics and temperature distribution in internal combustion engines that contain piston ring packs. Their study utilised inverse heat conduction concepts and regression analysis to investigate the impact of groove parameters on blow-by gas flow. Isam Jasim Jaber and Ajeet Kumar Rai analysed pistons made of different materials using CATIA and ANSYS software. Their structural analysis revealed stress concentrations on the piston crown, with aluminium alloy pistons deemed most suitable under given loading conditions. A. J. Helmisyah and M. J. Ghazali explored the application of ceramic thermal barrier coatings on compressed natural gas direct injection (CNGDI) piston crowns to reduce thermal stresses. Their study highlighted the effectiveness of partially stabilised zirconia coatings in mitigating thermal stress concentrations. Petkovic et al. (2011) empirically validated a mathematical model for heat transfer in exhaust systems. Their study focused on unsteady heating and temperature measurements in exhaust pipes, demonstrating good agreement between modelling and experimental results. Triwiyanto et al. investigated thermochemical treatments to enhance the surface properties of AISI 316L stainless steel. Their study utilised fluidised bed furnace treatments to produce expanded austenite layers, improving hardness and wear resistance. Ming et al. discussed the Royal Automotive Club of Victoria's Energy Breakthrough event, emphasising the significance of aerodynamic design in human-powered vehicles. A. Moridi et al. simulated stress distribution in A356.0 cast aluminium-silicon alloy with thermal barrier coatings using ABAQUS software. Their study focused on optimising coating thickness and interface roughness to improve fatigue life. B.M. Krishna and J.M. Mallikarjuna investigated in-cylinder flow patterns around intake valves in internal combustion engines using Particle Image Velocimetry (PIV). Their study revealed consistent airflow direction irrespective of intake valve opening conditions. F.S. Silva discussed the complexity of engine pistons and the continuous evolution of their design, materials, and manufacturing techniques. The study highlighted common damage mechanisms in pistons, including wearing, temperature, and fatigue-related issues.

4. METHODOLOGY

The methodology encompasses several key steps to comprehensively analyse composite pistons' stress and strain behaviour using ANSYS software. Firstly, selecting composite materials involves evaluating various options, such as strength-to-weight ratio, thermal conductivity, and manufacturing feasibility. Following material selection, accurate 3D models of the composite piston are created within ANSYS, incorporating material properties obtained through experimental characterisation or literature review. Next, boundary conditions are defined to simulate realistic operating conditions, including constraints and applied loads such as combustion pressure, inertial forces, thermal expansion, and mechanical loads from connecting rods and crankshafts. The finite element analysis (FEA) phase begins with mesh generation, ensuring adequate refinement to accurately capture localised stress and strain variations. Structural analysis using ANSYS predicts stress and strain distributions throughout the piston structure under different loading conditions.

In contrast, thermal analysis evaluates the effects of high temperatures during combustion, considering thermal loads from combustion and heat transfer. Post-processing techniques within ANSYS are then utilised to visualise stress and strain distributions, identify critical regions prone to failure, and evaluate safety margins based on material properties and design criteria. Additionally, appropriate failure criteria are applied to assess the likelihood of failure in the composite piston under different operating conditions. Iterative optimisation techniques are employed based on analysis results to improve the composite piston design, considering modifications to geometry, material selection, and manufacturing processes. Performance evaluation of the optimised piston design focuses on metrics such as reduced weight, improved strength, and increased durability.

Furthermore, recent advancements and challenges in fatigue analysis, thermal effects, optimisation techniques, and failure criteria assessment are discussed. Future research directions are proposed to enhance the performance and durability of composite pistons, considering emerging materials and advanced computational methods. Integration with engine systems and the importance of experimental validation to corroborate computational findings and refine simulation models for real-world applications are also emphasised. Overall, this methodology aims to provide valuable insights into composite piston analysis, contributing to the advancement of piston design and engineering practices in internal combustion engines.

5. RESULTS AND DISCUSSION

A comprehensive exploration of stress and strain analysis in pistons utilising composite materials with ANSYS software, shedding light on prevailing trends, challenges, advancements, and constraints within the field. Numerous studies delve into the intricacies of designing and scrutinising pistons, particularly those destined for internal combustion engines, with a specific focus on petrol engines, to decipher their mechanical behaviour across varied operational scenarios. One pivotal aspect highlighted in the literature is the criticality of material selection in piston design, weighing factors such as mechanical properties and thermal conductivities. Materials under scrutiny encompass aluminium alloys, cast iron, and composite blends like aluminium silicon carbide (AlSiC). Concurrently, Finite Element Analysis (FEA) emerges as a potent computational tool, enabling the simulation and scrutiny of piston dynamics, thereby facilitating precise predictions of stress and strain distributions under diverse loading circumstances.

Furthermore, the literature underscores the necessity of considering a gamut of loading conditions during analysis, encompassing combustion pressure, inertial forces, thermal expansion, and mechanical loads stemming from connecting rods and crankshafts. Defining boundary conditions accurately emerges as pivotal to ensuring the fidelity of analysis outcomes, thereby enabling realistic simulations of piston behaviour. Given the extreme temperatures experienced by pistons during combustion, thermal analysis emerges as a linchpin in accurately comprehending thermal stresses and deformations. Engineers can precisely predict piston responses by coupling thermal loads from combustion and heat transfer with structural analysis. Subsequent post-processing techniques allow for the interpretation of analysis results, facilitating the visualisation of stress and strain distributions while pinpointing critical regions prone to failure.

Moreover, studies delve into iterative optimisation techniques to refine piston designs, contemplating alterations to geometry, material selection, and manufacturing processes. Recent advancements in composite piston analysis span a spectrum of domains, encompassing fatigue analysis, thermal effects, optimisation methodologies, and failure criteria assessment. These strides underscore an ongoing commitment to augmenting the performance and durability of pistons across engineering applications.

6. CHALLENGES AND FUTURE DIRECTIONS

Challenges in piston analysis include the complex nature of thermal effects, the need for accurate material characterisation, and the optimisation of composite piston designs. Future research directions focus on further optimising piston performance and durability, integrating composite materials with other engine components, and emphasising the importance of experimental validation to refine simulation models for real-world applications. Overall, the literature review provides a comprehensive understanding of stress and strain analysis of pistons using composite materials with ANSYS software, offering valuable insights to guide future research and development in this field.

7. CONCLUSIONS

After reviewing literature from various authors, it is evident that Al-Si-based alloys have been extensively utilised in automotive pistons and other thermal applications due to their commendable mechanical and thermal properties, lightweight structures, and environmentally friendly characteristics. However, basic Al-Si alloys may prove inadequate for manufacturing automotive pistons, potentially developing unwanted stresses during production. Controlling exhaust gas temperature can enhance the lifespan of catalytic converters. Moreover, the heat transfer within the exhaust system directly impacts internal combustion engines' performance and emission characteristics. Therefore, regulating temperature within the automotive exhaust system enhances engine performance. The mechanical and thermal properties of aluminium-based piston alloys, including eutectic and hypereutectic alloys, primarily rely on heat treatment. Research indicates that a two-step solution treatment of Al-Si alloy yields superior mechanical properties compared to a single-step solution treatment. The pursuit of higher efficiencies, reduced specific fuel consumption, and minimised emissions in modern internal combustion engines has been a focal point for engine researchers and manufacturers over the past few decades. With global concerns regarding the dwindling supply of fossil fuels and increasingly stringent emissions regulations, the engine industry faces the challenge of developing practical, cost-effective, and environmentally conscious solutions to power vehicles. In calculating the temperature effect and heat transfer to the engine piston crown, it was concluded that employing spatial and time-averaged combustion side boundary conditions proves to be the most favourable and suitable treatment method within engineering approximations.

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