iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: VI Month of publication: June 2025

DOI: https://doi.org/10.22214/ijraset.2025.72243

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

Casting Defect Analysis and Optimization of an Internal Combustion Engine Piston using FEA

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Abstract: This research investigates the impact of casting defects—particularly shrinkage and porosity—on the thermal and structural performance of aluminum pistons used in internal combustion engines. The study integrates CAD modeling via CATIA V5 with Finite Element Analysis (FEA) through ANSYS to evaluate piston behavior under high thermal stress. Three design iterations were examined: one without shrinkage, one with uniform shrinkage, and one with varying shrinkage. Results highlight that casting defects significantly raise stress concentrations, reduce fatigue life, and threaten component integrity. The study concludes with optimization recommendations and proposes advanced defect-mitigation strategies using future digital manufacturing technologies.
Keywords: Casting defects, piston, shrinkage, finite element analysis, thermal stress, CATIA, ANSYS, porosity, fatigue analysis.

I. INTRODUCTION

Pistons are subjected to intense thermal and mechanical loading, making them critical components in engine durability and performance. Casting remains a common manufacturing process for pistons, but it frequently introduces defects such as porosity, shrinkage cavities, and cold shuts. This study aims to investigate how these casting defects affect piston integrity using a combination of design, simulation, and material evaluation.

II. LITERATURE REVIEW

Numerous studies have highlighted the correlation between casting defects and mechanical failure in engine components. Shrinkage has been identified as a dominant factor, influencing dimensional stability and stress concentrations. Literature also emphasizes simulation tools like FEA and CFD for defect prediction. Materials such as aluminum alloys (e.g., A356) offer weight reduction and thermal benefits but are sensitive to porosity and cracks if improperly cast.

III. PROBLEM STATEMENT AND OBJECTIVES

Casting-induced defects jeopardize piston durability by weakening structural integrity under cyclic thermal loads. The goal of this study is to model and simulate a piston under real-world conditions with and without such defects, and to provide recommendations for minimizing defect impact via process optimization.

IV. METHODOLOGY

The piston was designed using CATIA V5 in three iterations: a baseline model, a model with uniform shrinkage, and a model with localized shrinkage. These models were exported to ANSYS for structural and thermal simulations. Thermal simulations involved a casting temperature of 750°C and evaluated heat flux and temperature distribution. Structural simulations included static stress and fatigue analysis under combustion pressure and temperature loads.

V. FEA SETUP AND BOUNDARY CONDITIONS

Material: A356 Aluminum Alloy
Thermal Conductivity: 167 W/m·K
Young's Modulus: 70 GPa
Poisson's Ratio: 0.33
Yield Strength: 250 MPa
Thermal Expansion Coefficient: 23×10^{-6}/°C
Boundary Conditions: Fixed supports at piston pin location, thermal loading at crown (750°C), ambient surroundings at 25°C.

VI. RESULTS AND DISCUSSION

The baseline piston without defects showed a maximum stress of 494.92 MPa and minimal deformation. In contrast, the defected model reached peak stress values of 1098 MPa, nearly double, due to localized concentration near cracks and pores. Fatigue life analysis revealed a reduced safety factor and life span in the presence of casting defects. These results confirm that even minor shrinkage or porosity can significantly compromise component life.

VII. CONCLUSION

This study concludes that casting defects critically affect piston performance. Simulation results validate the need for defect mitigation during casting. Implementing better mold design, controlled cooling, and defect-detection techniques can significantly enhance component reliability. The integration of simulation in early design phases helps in optimizing designs before physical manufacturing.

VIII. FUTURE SCOPE

Future work can explore transient thermal cycles, crack propagation models, microstructure evolution, and the use of AI-driven defect prediction. Advanced methods like ultrasonic-assisted casting and 3D-printed molds can further reduce defect formation. Multi-physics simulations integrating vibration, combustion, and thermal loads can yield even more accurate performance insights.

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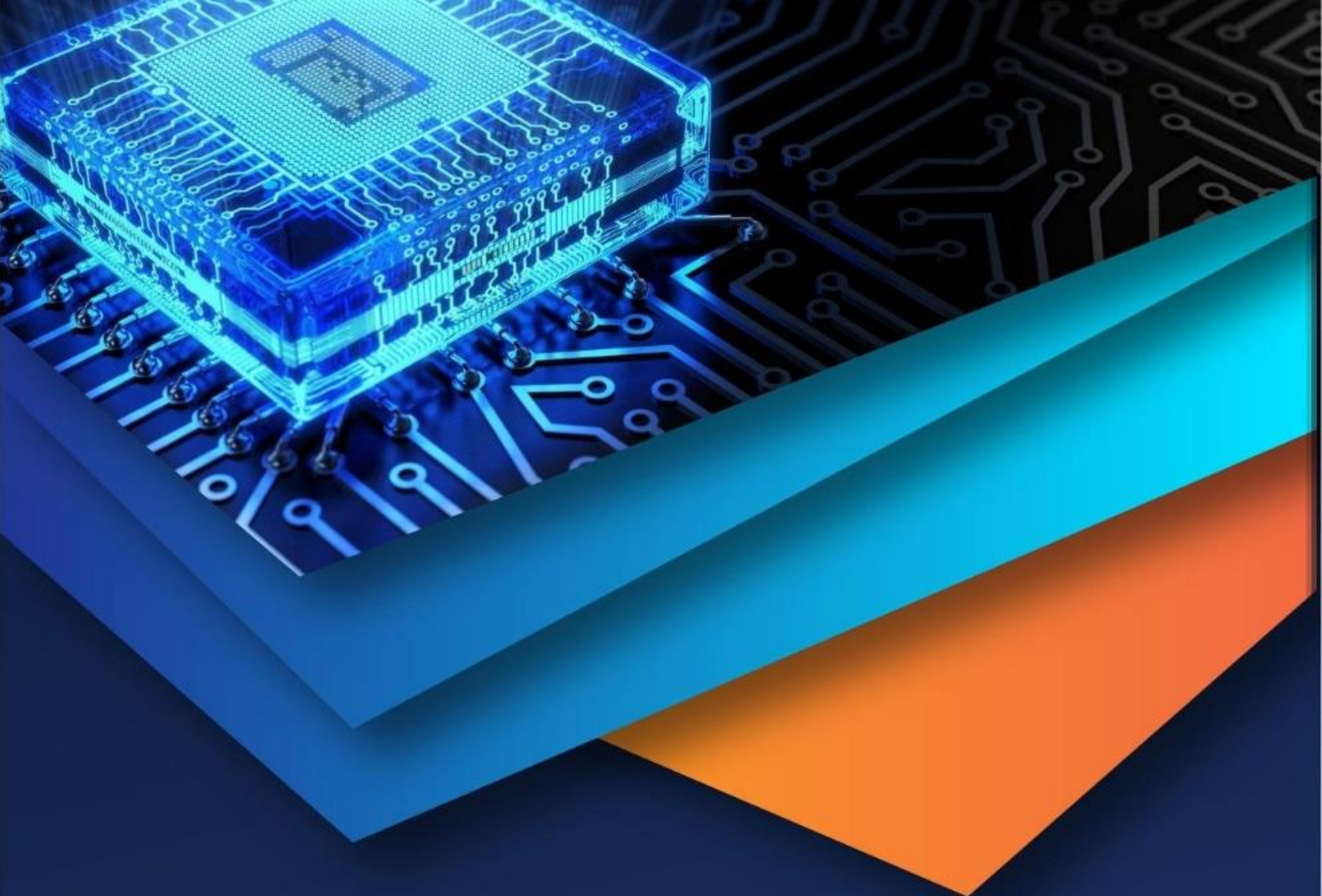

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