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A GENETIC ALGORITHM APPROACH TO PISTON COATING THICKNESS OPTIMIZATION IN INTERNAL COMBUSTION ENGINES

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Abstract: Increasing demands for improved efficiency and durability in internal combustion engines drive the development of thermal barrier coatings (TBCs) on aluminum-silicon (Al-Si) alloy components, mitigating heat damage and enhancing combustion performance. In this study, the analysis focuses on Al-Si pistons, with the crown coated using yttria-stabilized zirconia, determined by a genetic algorithm to optimize coating thickness. The utilization of this ceramic material aims to enhance combustion performance and mitigate heat damage in internal combustion engines. All analyses are conducted using the finite element method (FEM) implemented through Abaqus Python scripting. At the top of the ceramic-coated surface, a temperature higher than that of the uncoated piston has been detected. Thermal readings show the coated piston reached 769.682℃, whereas the uncoated one hit 585.894℃. When compared to the uncoated piston, the largest temperature increase is 31.45%.

Key words - Genetic Algorithm, Abaqus Python scripting, TBC Coatings, Finite element method

I. INTRODUCTION

Pistons serve as the mechanical heart of internal combustion engines, reciprocating compressors, and a myriad of industrial applications. However, this critical component is not without its challenges, as it operates under extreme conditions characterized by elevated temperatures and intense mechanical stresses. These conditions inevitably lead to significant thermal losses, a phenomenon that not only diminishes engine efficiency but also poses a threat to the longevity of engine components. To combat this issue, according to author S. Caputo, coatings unequivocally enhance both the longevity and performance of pistons. Among the diverse array of coating materials available, Thermal Barrier Coatings (TBCs) have emerged as a promising avenue for improving the performance and durability of pistons in ICEs [1]. Among the myriad materials employed in TBC applications, the authors K. Hu and Z. Yao[2] concluded that the yttria-stabilized zirconia [3] emerges as a standout contender, offering exceptional thermal resistance and mechanical robustness. Finding the perfect thickness is a tricky puzzle that requires using sophisticated computer methods and optimization algorithms. According to the author S. J. Patel [4], genetic algorithms (GAs) have emerged as a powerful tool for tackling complex optimization problems in engineering design. GAs, inspired by the principles of natural selection and evolution, offer a robust framework for exploring a diverse range of design alternatives and iteratively refining solutions to meet specified performance criteria. the finite element technique (FEM), which offers a stable framework for modelling the complex interactions between forces in internal combustion engine parts. The authors L. Luo and M. Zhao[5] said that Abaqus is a complex software program that is at the forefront of FEM-based analysis. It is well-known for its user-friendly interface and strong simulation capabilities. Abaqus' extensive feature set enables academics to address a wide range of engineering problems, from Multiphysics simulations to structural analysis. By harnessing the computational power of Abaqus, coupled with the flexibility of Python scripting, we conduct sophisticated analyses to optimize coating thickness, enhance heat transfer efficiency, and minimize thermal losses. In the context of IC engine analysis, the fitness of each solution is evaluated using Finite Element Method (FEM) simulations, with metrics such as heat flux serving as surrogate measures of performance. Through successive generations, the GA converges towards optimal solutions, effectively navigating the complex landscape of coating thickness optimization [6] to achieve desired objectives such as minimizing thermal losses and maximizing engine efficiency.

II. METHODOLOGY

The analysis follows a series of steps outlined below:

- First, Developed the piston model in Abaqus software, utilizing Abaqus Python scripting.

Table 1. Thermal and mechanical properties of the piston and coating materials[2], [7], [8].

Material	Density [kg/m^3]	Specific Heat [J/kg °C]	Thermal conductivity [W/m °C]	Thermal expansion 10^{-6}[1/°C]	Modulus of elasticity [GPA]	Poisson's ratio [m/m]
Piston material (Aluminum alloy)	2700	910	155	21	90	0.33
Coating material (YSZ)	6010	450	2.12	11.5	205	0.25

- Next, employing a Genetic Algorithm (GA), we systematically vary the thickness of the piston. Each iteration through the GA is accompanied by a thermal analysis, where the performance of the piston under different thickness configurations is assessed.
- This iterative process continues until the GA converges on the best solution, optimizing the piston thickness for maximum efficiency and performance. All steps are shown in Fig. 1.

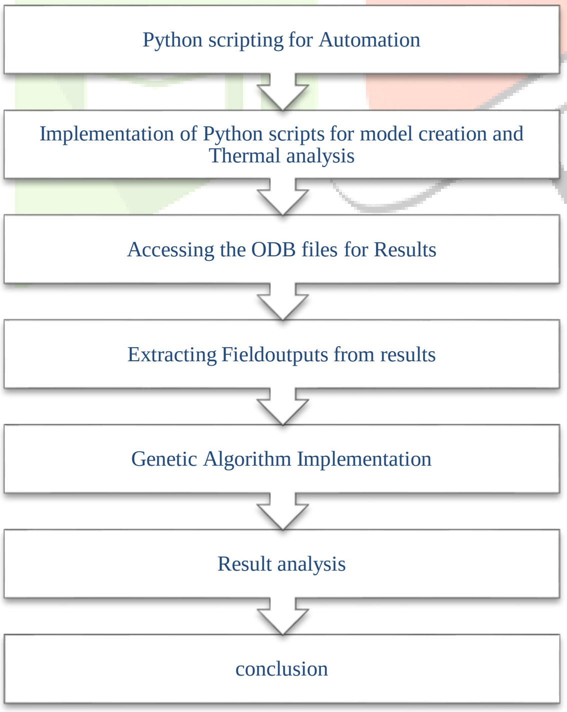

Fig. 1. Methodology used for this analysis.

III. THERMAL BARRIER COATING MATERIAL

Thermal barrier coating (TBC) materials are particularly suitable for applications subjected to high temperatures [1]. These materials exhibit exceptional thermal resistance properties, capable of withstanding temperatures of up to 1000C. In this study, we employ a genetic algorithm (GA) procedure to optimize the thickness of the thermal barrier coating, followed by a steady-state thermal analysis. Yttria-stabilized zirconia (YSZ) stands out as one of the most renowned TBC materials due to its outstanding properties [2], [9]. Aluminum is chosen as the piston material for this analysis. The thickness range considered for optimization via the GA spans from 0.0135 to 1.4mm. All the properties of Yttria-stabilized zirconia (YSZ) are shown in Table 1.

IV. GENETIC ALGORITHMS

Genetic Algorithm's (Gas) simulate natural selection and evolutionary processes, offering a reliable method for handling complex optimization problem Fig. 2 . They include iteratively reducing a population of feasible solutions under the direction of fitness functions that evaluate measures related to engine performance [6]. Through the application of evolutionary principles of adaptation and selection modeling, GAs may be used to methodically investigate and refine different configurations of coating thickness in order to optimize engine longevity and performance. This approach should provide a methodical and efficient way to attain the ideal coating thicknesses for a certain engine, which will ultimately lead to increase longevity and performance. GAs iteratively alter parameters across multiple iterations, eventually convergent towards an ideal solution. Through the process of iterative refinement, a large solution space may be explored and insights into the intricate relationships between coating thickness and engine performance can be gained. Furthermore, by facilitating the examination of trade-offs between conflicting goals, GA enable engineers to decide on coating thickness with a comprehensive grasp of performance requirements. Therefore, by utilizing GAs, engineers can optimize overall operational efficiency and dependability by methodically improving engine performance while guaranteeing lifetime.

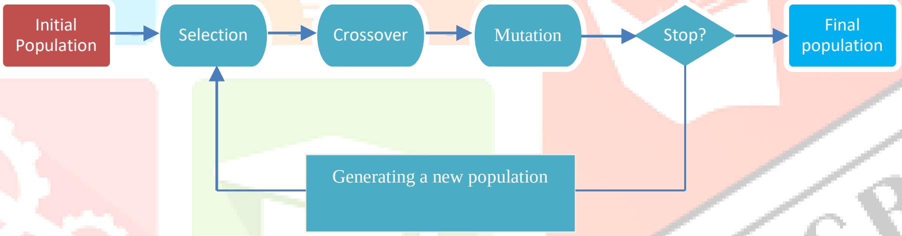

Fig. 2. Genetic algorithm principle

V. FINITE ELEMENT MODELLING OF PISTON

This current study involves conducting steady-state heat transfer analyses on a coated piston within a specified thickness range of 0.0135 to 1.4mm. These analyses are carried out iteratively using Abaqus Python scripting capabilities. The piston design is created within the Abaqus software platform using Python scripting. The dimensions of the piston, sourced from the references [10] [11] [12], are as follows:

- The piston diameter = 50mm
- Piston pin hole diameter = 18mm
- Overall piston height = 58mm
- Distance between piston rings = 2mm

These parameters serve as the foundation for the piston model within the simulation environment, ensuring accuracy and consistency in the computational analysis. The geometric configuration of the piston is generated within the Abaqus software environment through Python scripting, ensuring a tailored and precise representation. Utilizing Abaqus's meshing capabilities, the geometry is discretized into smaller elements, enabling accurate computational predictions. The temperature distribution across the piston surfaces is carefully studied, and the results are explained in detail in later parts of the paper. For the heat transfer analyses the material properties of Yttria Stabilized zirconia and coated piston is taken from Table 1.

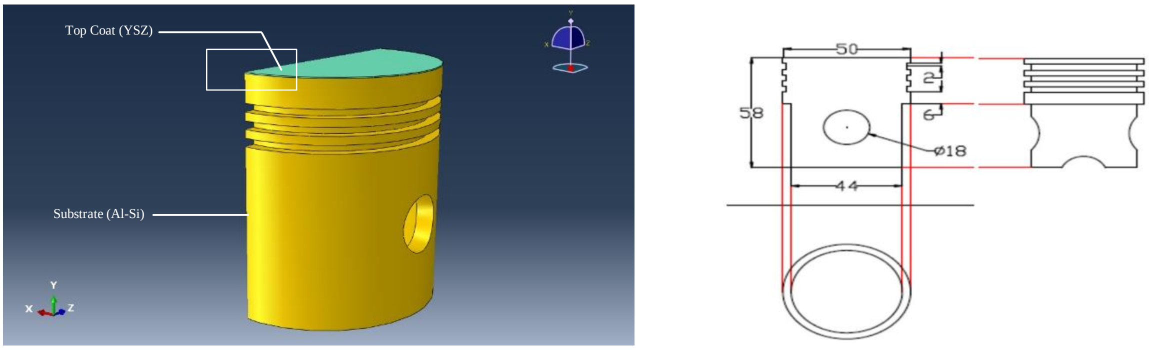

Fig. 3. Piston model with coating

The temperature distribution is shown at different surfaces and their results are discussed further.

VI. STEADY STATE THERMAL ANALYSIS OF PISTON

Steady state thermal analysis is a computational technique used to study the thermal behavior of a system under steady state conditions, where the temperature distribution remains constant with time [7]. This analysis is particularly useful for understanding how heat is transferred within a structure or component when subjected to steady thermal loads.

In the context of analyzing a piston, heat transfer primarily occurs through convection, a process where heat is transferred between the piston and its surrounding fluid (usually air or coolant) due to the fluid's motion. The Hohenberg equation, a mathematical expression derived from fluid dynamics principles, is often employed to model this convective heat transfer

$$h_{gas}(t) = \alpha V_c(t)^{-0.06} P(t)^{0.8} T(t)^{-0.4} (Sp + b)^{0.8}$$

Where $h_{gas}(t)$ is represented in watts per square meter kelvin (W/m^{2}K). It depends on various instantaneous parameters: $V_c(t)$, $P(t)$, and $T(t)$, denoting the volume (in cubic meters), pressure (in 10^5 pascals), and temperature (in kelvin) of the cylinder, respectively. Additionally, S_P represents the mean piston speed, expressed in meters piston speed, expressed in meters per second (m/s). The piston surface is coated with YSZ (Yttria-Stabilized-Zirconia) material, as illustrated in Fig. 3, The finite element model comprises a total of 3,40,107 elements, with 1,80,053 nodes strategically positioned for comprehensive analysis. The boundary conditions are specified to represent the thermal environment surrounding the piston, where the surface heat flux load is applied on top surface of the piston is 300w/m2 and the boundary conditions are applied to the piston are Ambient temperature $T_{\infty} = 28$°C across the piston. The analysis begins by discretizing the piston geometry into finite elements, each representing a small portion of the piston structure. These elements are interconnected at nodes to form a mesh. The thermal properties of the piston material, such as conductivity and specific heat, are assigned to the elements based on material properties Table 1.

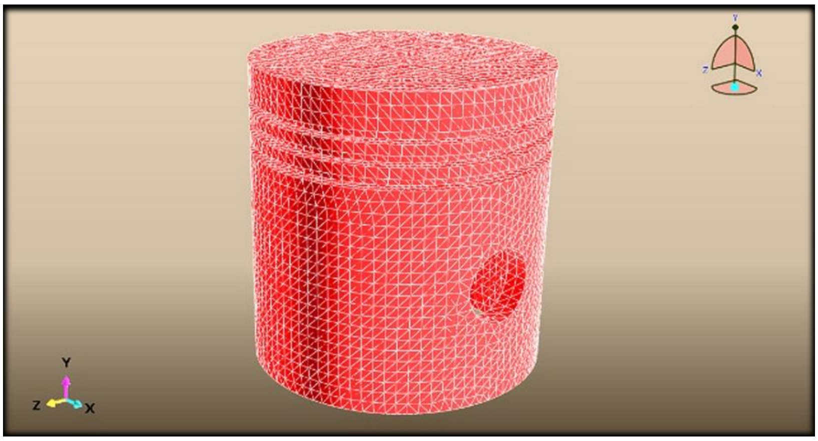

Fig. 4. Mesh model of piston

Using numerical methods like the finite element method (FEM) [13], the system's thermal behavior is simulated by solving the governing equations iteratively. The solver calculates the temperature distribution within the piston and its surrounding fluid, considering both conduction and convection. Once the solver converges to a solution, the results of the analysis provide insights into the temperature distribution across the piston, heat fluxes, and other relevant thermal parameters. We can then evaluate the piston's thermal performance under steady state conditions, identify areas of potential overheating or thermal stress, and optimize the design to meet thermal requirements.

VII. RESULT AND DISCUSSIONS

The thermal analysis results, depicted in **Error! Reference source not found.**, reveal notable differences between the coated and uncoated pistons. Specifically, the coated piston exhibits a significantly higher temperature compared to its uncoated counterpart.

The thermal readings indicate that the coated piston reached a temperature of 769.682℃, while the uncoated piston registered a temperature of 585.894℃. This substrate temperature differential of approximately 180℃ underscores the impact of piston coating on heat retention within the combustion chamber during the combustion process. Moreover, these findings corroborate the effectiveness of the coating in enhancing thermal insulation properties. By retaining higher temperatures within the combustion chamber, the coated piston facilitates more efficient combustion, leading to improved engine performance and fuel efficiency. Additionally, the observed temperature disparity underscores the potential for mitigating heat loss and optimizing thermal management strategies in internal combustion engines. Furthermore, these results highlight the significance of ongoing research and development efforts aimed at refining piston coatings for enhanced thermal performance[14]. Further investigations may delve deeper into the specific mechanisms underlying the observed temperature differentials and explore innovative coating materials and application techniques to further enhance engine efficiency and durability. Overall, the findings presented here contribute valuable insights to the ongoing discourse surroundings thermal management in internal combustion engines, offering avenues for continued optimization and innovation in automotive engineering.

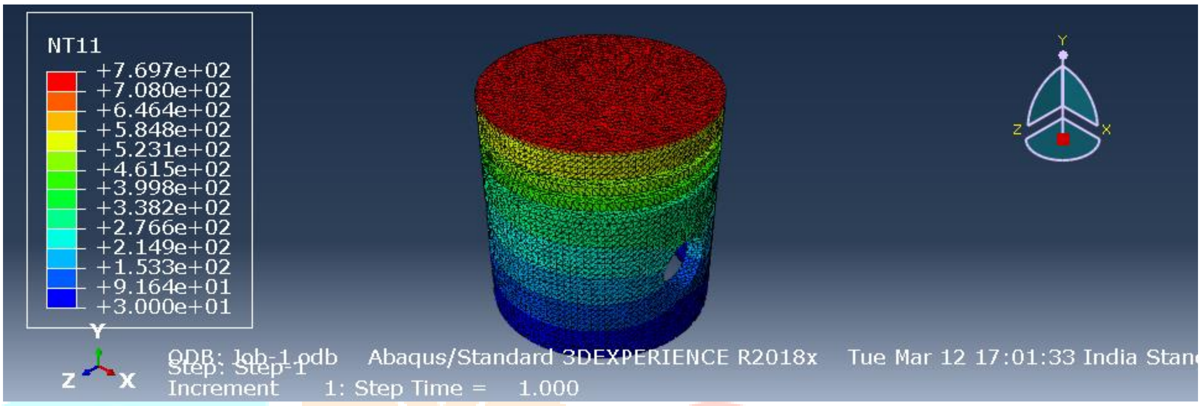

Fig. 5. Distribution of temperature on top surface with 1.384mm coating thickness.

The presented graphs illustrate the relationship between Genetic Algorithm (GA) iterations and fitness values (temperatures), as well as the correlation between thickness and temperature in a particular context. The GA iterations and corresponding fitness values [℃] from the obtained results are depicted in a graph Fig. 7. It's evident that as the GA iterations increase, the fitness values also increase, indicating a trend towards achieving the optimum solution. This observation underscores the iterative nature of genetic algorithms, where successive generations tend to improve upon the previous ones, converging towards an optimal outcome.

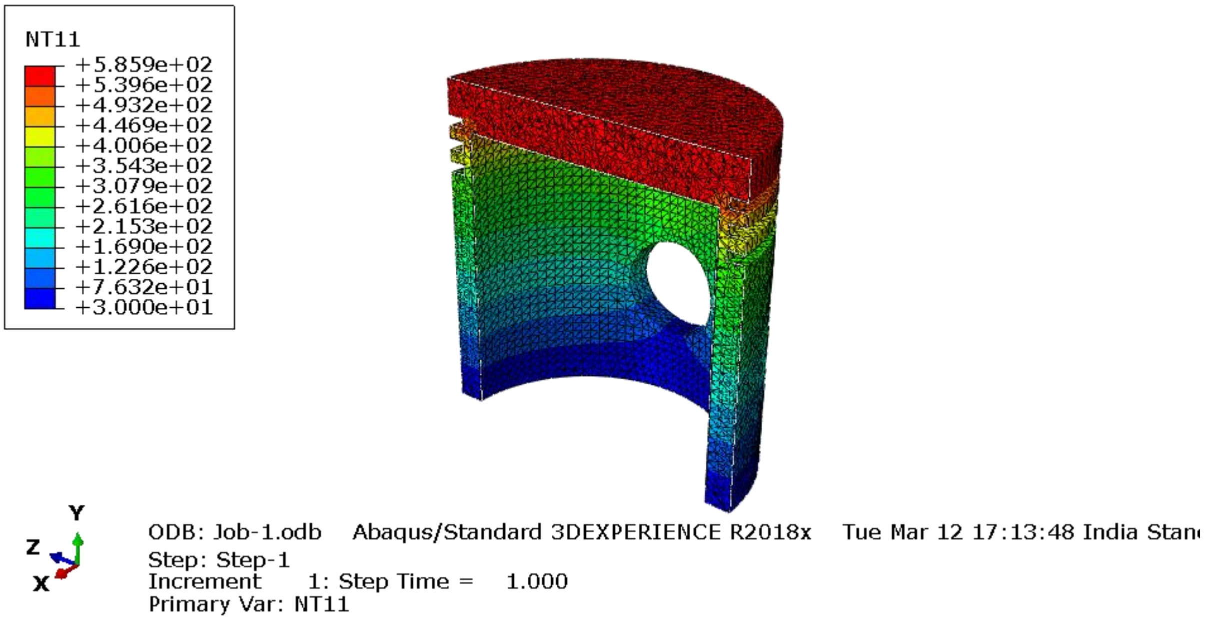

Fig. 6. Temperature [℃] distribution plot of a section view of the uncoated piston.

It's evident that as the GA iterations increase, the fitness values also increase, indicating a trend towards achieving the optimum solution. This observation underscores the iterative nature of genetic algorithms, where successive generations tend to improve upon the previous ones, converging towards an optimal outcome. The graph provides a visual representation of this iterative refinement process, demonstrating how the algorithm iteratively adjusts parameters to enhance performance and reach the desired solution. Moreover, the Fig. 8 reveals a significant relationship between thickness and temperature, showcasing that as the thickness increases, there is a corresponding enhancement in fitness values. The fitness values obtained in the iterations are 585.894℃, 597.328℃, 611.369℃, 626.961℃, 644.512℃, 681.134℃, 746.589℃, 759.602℃, 769.682℃ corresponding to the coating thickness values 0mm, 0.0224mm, 0.2822mm, 0.3915mm, 0.5145mm, 0.771mm, 1.2288mm, 1.3195mm, 1.3841mm. This correlation suggests that increasing thickness holds promise for augmenting temperature, thereby enhancing the overall efficiency of performance. Such findings underscore the importance of thickness as a critical factor influencing temperature, and consequently, the efficacy of the system under consideration.

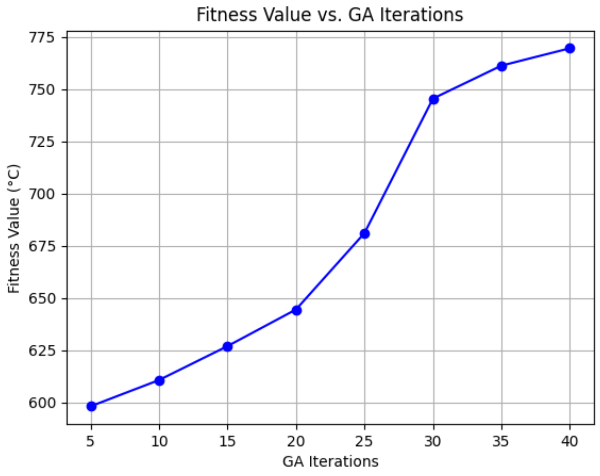

Fig. 7. GA Iterations and Fitness value [℃] from obtained results

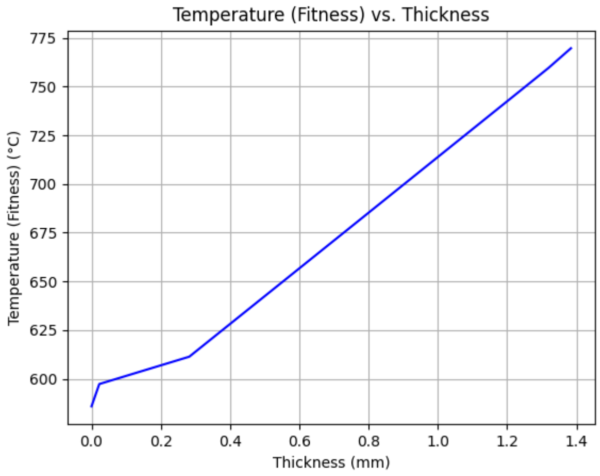

Fig. 8. Thickness (mm) and Temperature [℃] from obtained results

In summary, the graphical representations highlight the interplay between GA iterations, thickness, and temperatures, elucidating how iterative optimization processes and physical parameters contribute to the performance and efficiency of the system.

VIII. CONCLUSIONS

From the finite element analysis of yttria stabilized zirconia, it is clear that YSZ help to increase the temperature of the piston. It is evident from the finite element modeling that the thickness of the coating affects the piston's temperature. For every coating thickness taken into consideration, the piston crown surface showed the highest temperature. A temperature greater than that of the uncoated piston has been observed at the top of the ceramic-coated surface. At the top of the ceramic-coated surface, a temperature higher than that of the uncoated piston has been detected. Thermal readings show the coated piston reached 769.682℃, whereas the uncoated one hit 585.894℃. The greatest temperature increase is 31.45% as compared to the uncoated piston. It is therefore determined that the use of TBC raises the engine's combustion chamber temperature and increases thermal efficiency. There is a decrease in temperature at the piston's substrate surface, which improves engine performance and efficiency.

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