Optimisation of Spark Plug Material in Petrol and CNG Bi-Fuel Engines

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Abstract
This study aims to optimize spark plug electrode materials for petrol–CNG bi-fuel engines by evaluating their thermal and structural performance using ANSYS simulation. The research specifically analyzed Iridium alloy, Platinum, and Silicon Nitride under combustion conditions characterized by peak petrol temperatures of 820-870 °C and CNG temperatures of 900–980 °C, with pressures ranging from 4 to 6 MPa. Simulation parameters included total deformation, equivalent (Von Mises) stress, and strain energy as quantifiable variables to assess mechanical resilience and durability. Results showed that Iridium alloy exhibited the lowest total deformation (1.374×10^{-2} mm in petrol and 1.3751×10^{-2} mm in CNG) and the lowest strain energy (6.16×10^{-3} MJ in petrol and 6.33×10^{-3} MJ in CNG), indicating superior dimensional stability and fatigue resistance. Although it experienced higher equivalent stress (37.82 MPa in petrol and 35.51 MPa in CNG), this remained well within its strength limits, confirming its robustness. By comparison, Platinum showed higher deformation ($\approx1.39\times10^{-2}$ mm) and moderate strain energy ($\approx6.46\times10^{-3}$ MJ), while Silicon Nitride absorbed the most strain energy ($\approx7.2\times10^{-3}$ MJ) but risked brittle fracture under cyclic loading. These findings establish Iridium alloy as the most reliable material for enhancing ignition reliability and extending spark plug service life in bi-fuel engines, contributing to improved fuel efficiency, reduced maintenance costs, and more sustainable automotive performance.

Keywords: *spark plug, Petrol-CNG Bi-Fuel Engine, Optimisation, Material Properties, Thermal Properties, Durability, Mechanical Strength.*

1. Introduction

The global transition towards sustainable energy solutions has accelerated the adoption of alternative fuels in internal combustion engines, particularly the integration of compressed natural gas (CNG) in dual-fuel configurations. Bi-fuel engines capable of operating on both petrol and CNG offer a practical pathway toward reducing greenhouse gas emissions, lowering fuel costs, and improving energy security (1–3). Compared to petrol, CNG combustion produces lower carbon monoxide (CO), carbon dioxide (CO_2), and particulate emissions, making it a favorable choice for meeting increasingly stringent environmental regulations (Garrido et al., 2019; Kumar & Singh, 2023).

Despite these advantages, petrol–CNG bi-fuel engines present significant engineering challenges, particularly in the durability and performance of spark plugs. As the primary ignition devices, spark plugs are exposed to dual combustion environments with distinct thermal and chemical properties. Petrol combustion is characterized by high energy density and rapid ignition, while CNG combustion operates at higher temperatures, requires stronger ignition energy, and experiences slower flame propagation (Kim & Kim, 2022; Tian et al., 2020). These conditions impose cyclic thermal–mechanical stresses on spark plug electrodes, leading to accelerated wear, electrode erosion, and reduced service life (Bosch, 2014).

To address this problem, the present study employs finite element simulation using ANSYS Workbench to investigate the thermal–mechanical performance of three candidate spark plug electrode materials: Iridium alloy, Platinum, and Silicon Nitride under petrol and CNG combustion conditions. The following subsections provide the background for electrode degradation mechanisms, spark plug performance challenges, and the material properties analyzed in this study.

1.1.Electrode Degradation Mechanisms in Bi-Fuel Engines

Electrode degradation in spark plugs is a complex process influenced by thermal, mechanical, and chemical factors. In petrol–CNG engines, electrodes are exposed to repeated high-temperature cycles, oxidation reactions, and corrosive combustion gases (Co, 2020). The higher flame temperatures and lean-burn conditions of CNG intensify electrode erosion, causing a gradual reduction in electrode diameter and increasing ignition voltage requirements (Harrer et al., 2024). Additionally, chemical attack from water vapor, nitrogen oxides, and unburned hydrocarbons accelerates electrode wear. Over time, these processes lead to widening of the spark gap, misfires, reduced ignition efficiency, and ultimately, premature spark plug failure (Javan et al., 2014). Understanding these degradation mechanisms is critical for selecting suitable electrode materials that can withstand the dual-fuel environment.

1.2.Spark Plug Performance Challenges in Bi-Fuel Engines

The performance of spark plugs in bi-fuel engines is constrained by the distinct combustion characteristics of petrol and CNG. Petrol provides faster flame propagation and lower ignition energy requirements, while CNG requires a higher breakdown voltage due to its higher ignition temperature (Osamura & Abe, 1999). This increases the stress on the electrode and the ceramic insulator, which must endure higher voltages and temperatures during operation. Moreover, the durability of spark plugs in CNG mode is often compromised by electrode recession, cracking of the ceramic body, and electrode melting under continuous high thermal loads (Osamura & Abe, 1999). Ensuring long spark plug life in bi-fuel engines, therefore, demands electrode materials with high melting points, strong resistance to oxidation, and stable electrical conductivity under repeated thermal cycling.

1.3.Material Properties for Analysis

The choice of electrode material significantly influences the performance and service life of spark plugs in bi-fuel engines. Traditional materials such as nickel-based alloys are cost-effective but degrade rapidly under high thermal and oxidative stresses (NGK Spark Plug Co., 2020). Precious metals like platinum and iridium have been adopted due to their high melting points, excellent resistance to corrosion, and ability to maintain a sharp electrode profile for extended periods (Harrer et al., 2024). In addition, advanced ceramic composites such as silicon nitride (Si_3N_4) have emerged as promising alternatives because of their low thermal expansion, high thermal shock resistance, and superior mechanical strength (Javan et al., 2014). This study focuses on evaluating three materials—Platinum, Iridium alloy, and Silicon Nitride—under petrol and CNG combustion conditions using finite element simulations. The analysis is based on three key indicators: total deformation, equivalent (Von Mises) stress, and strain energy. These properties provide insights into thermal durability, structural integrity, and resistance to failure, enabling a comparative evaluation of material suitability for spark plug electrodes in dual-fuel applications

2. Materials and Methods

This study employed finite element analysis (FEA) using ANSYS Workbench 2023 R2 to evaluate the thermal–mechanical performance of selected spark plug electrode materials under petrol and CNG combustion conditions. The analysis procedure consisted of three main stages:

1. Geometry and model setup
2. Definition of material properties and boundary conditions
3. Simulation and result extraction.

2.1.Model Geometry and Meshing

The spark plug electrode geometry was simplified to represent the central electrode tip and surrounding insulator region, focusing on the critical zone exposed to combustion. The 3D model was imported into ANSYS Design Modeler, and a tetrahedral mesh was generated to capture localized thermal and structural gradients. A mesh convergence study was conducted to ensure that simulation results were independent of element size.

2.2.Material Properties

Three electrode materials, Platinum, Iridium alloy, and Silicon Nitride (Si_3N_4), were selected for analysis based on their widespread application and advanced thermal resistance properties. Table 1 summarizes the key material properties used in the simulation.

Table 1. *Mechanical and thermal properties of candidate electrode materials*

Materials	**platinum**	**Iridium Alloy**	**Silicon Nitrate**
Density (kg/m^3)	21450	22420	3200
Young modulus (GPa)	168	528	310
Thermal conductivity (W/m·K)	71.6	147	30
Specific heat (J/kg·K)	133	131	800
Melting point	1768	2446	1900

2.3.Boundary Conditions

The simulation boundary conditions were defined to approximate real combustion chamber conditions in petrol and CNG engines (Osamura & Abe, 1999; Tian et al., 2020).

1. Thermal loads: The electrode tip was subjected to combustion gas temperatures of 2000 K for petrol and 2200 K for CNG, applied as a uniform thermal flux.
2. Convection: Heat transfer by convection was applied on the electrode surface, with a film coefficient of 100 W/m²K to simulate gas cooling during engine cycles.
3. Structural Constraints: The electrode base was fixed to represent its rigid connection to the spark plug body, restricting translational displacement.

This setup enabled the evaluation of thermal stress distribution and mechanical deformation under realistic engine operating temperatures

2.4. Simulation Procedure

A coupled thermal–structural simulation approach was employed to capture both temperature and stress fields within each electrode material. The analysis involved two main steps:

1. Steady-state thermal analysis to compute temperature distribution across the electrode.
2. Structural analysis using the computed temperature field to determine total deformation, equivalent (Von Mises) stress, and strain energy (Bosh, 2002; Tian et al., 2020).

The results for each material under petrol and CNG conditions were compared to identify the most durable material configuration. Figure 1 shows how the two modules are connected to attain the final results

***Figure 1** simulation flow schematic*

2.5.Performance Indicators

The material performance was evaluated using three primary indicators, consistent with prior studies on spark plug durability(Bosh, 2002; Osamura & Abe, 1999)

1. Total Deformation (mm): Represents dimensional stability under cyclic heating.
2. Equivalent (Von Mises) Stress (MPa): Indicates the resistance to thermal–mechanical stress and potential yielding.
3. Strain Energy (mJ): Reflects the material's energy absorption before structural failure.

The material exhibiting the lowest deformation, minimal stress concentration, and optimal strain energy was considered most suitable for long-life spark plug applications in petrol–CNG bi-fuel engines.

3. Results

The results obtained from ANSYS simulations illustrate the thermo-mechanical performance of Platinum, Iridium alloy, and Silicon Nitride electrodes under petrol and CNG operating conditions. The analysis focused on three key parameters: total deformation, equivalent (Von Mises) stress, and strain energy. These parameters indicate the material's ability to resist distortion, withstand stress, and absorb mechanical energy during engine operation.

3.1. Total Deformation

The total deformation values represent the extent of dimensional change experienced by each material when subjected to combustion temperatures and pressure gradients. As shown in Table 2, the Iridium alloy exhibited the lowest deformation values under both petrol and CNG conditions, indicating superior structural rigidity.

***Table 2** Total Deformation of Spark Plug Material*

Material	Petrol Mode (mm)	CNG Mode (mm)
Iridium Alloy	1.374e-2	1.3751e-2
Platinum	1.3947e-2	1.3965e-2
Silicon Nitride	1.385e-2	1.3856e-2

The results show that deformation increases slightly in CNG mode due to the higher flame temperature (~2200 K) compared to petrol (~2000 K). Iridium alloy maintained better dimensional stability, consistent with its high elastic modulus and low thermal expansion coefficient (9–11). Figures 2 to 8 present the graphical and visual representations from the ANSYS simulation

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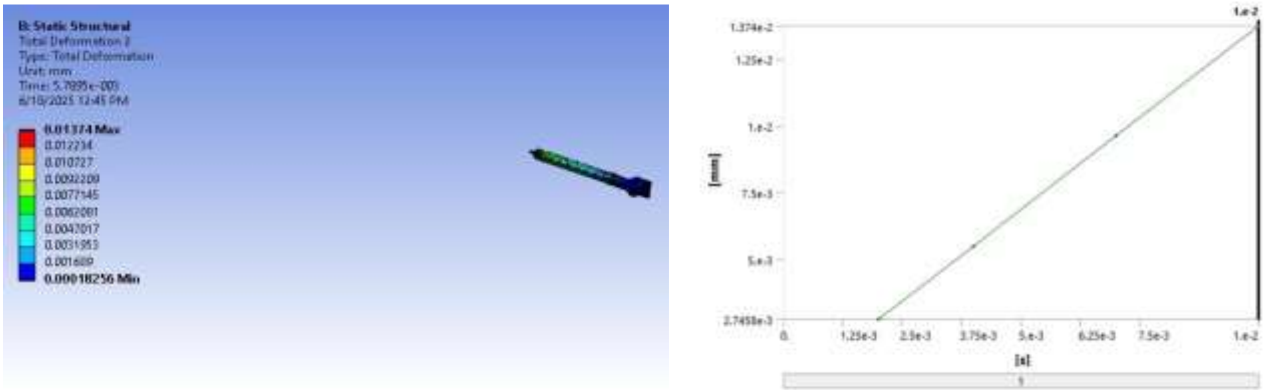

Figure 2 *Total Deformation of Iridium Alloy Under Petrol Combustion Mode*

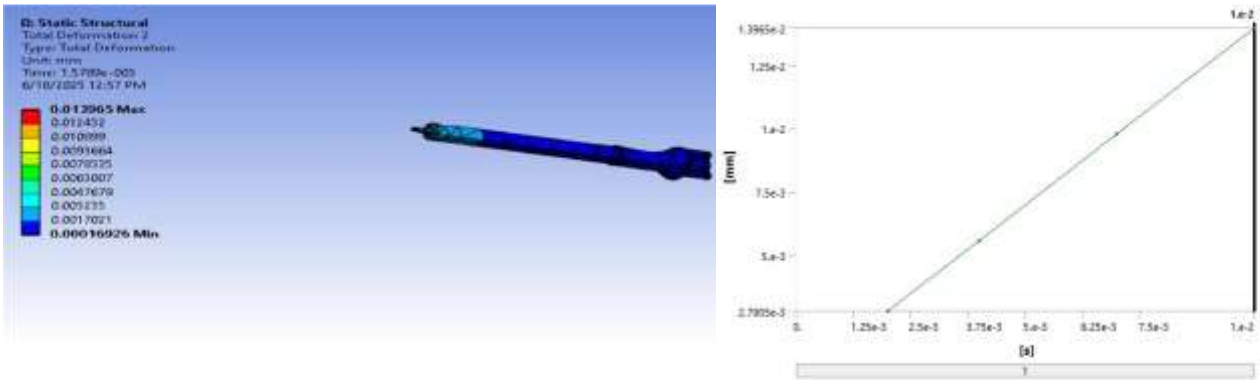

Figure 3 *Total Deformation of Iridium Alloy in CNG Combustion Mode*

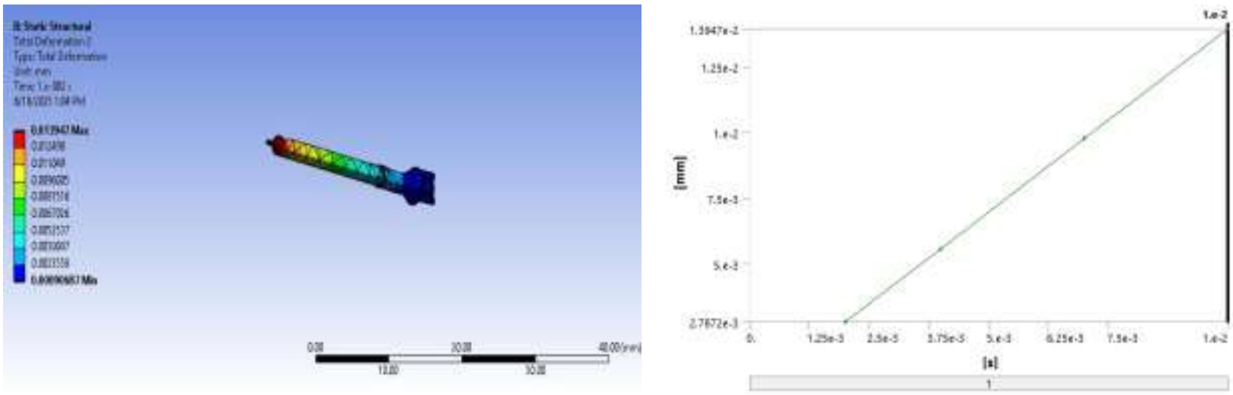

Figure 4 *Total Deformation of Platinum in CNG Combustion Mode*

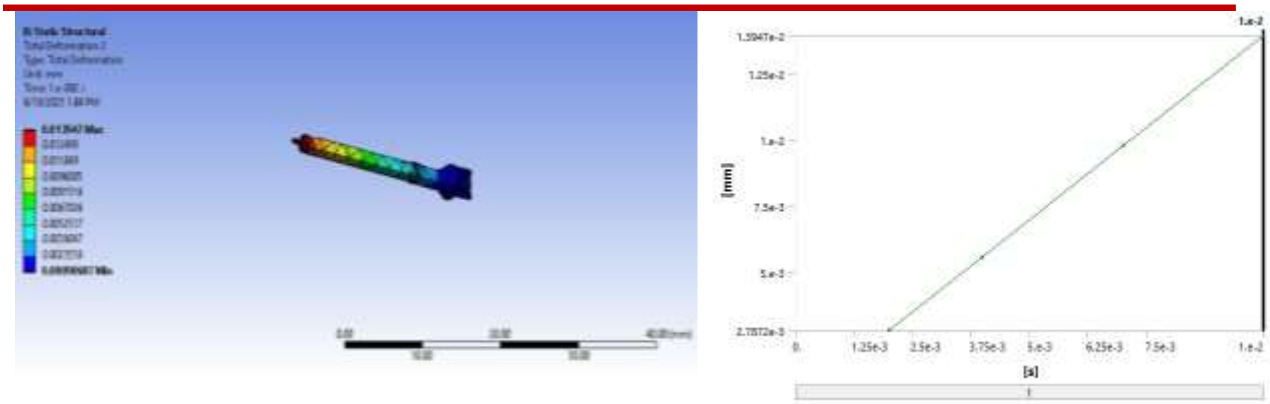

Figure 5 *Total Deformation of Platinum in Petrol Combustion Mode*

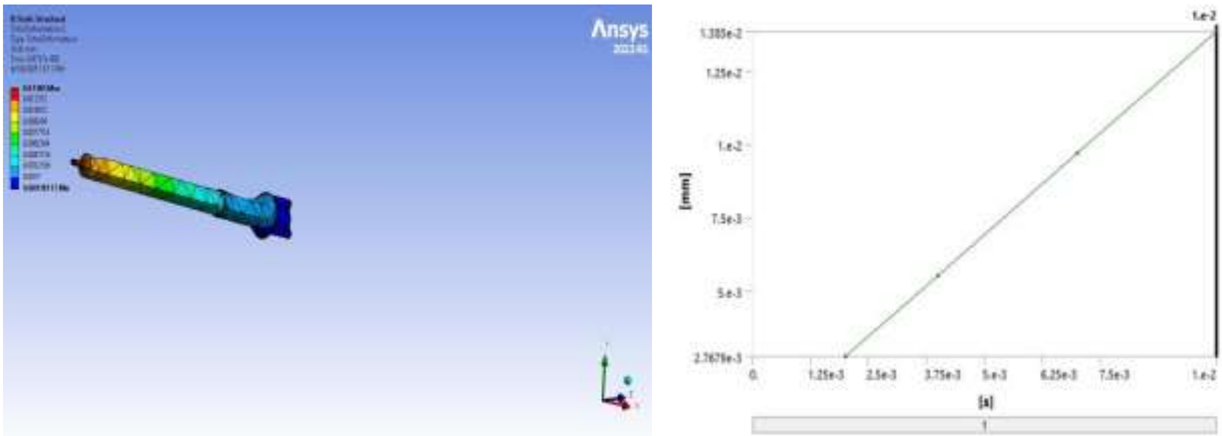

Figure 6 *Total Deformation of Silicon Nitride in Petrol Combustion Mode*

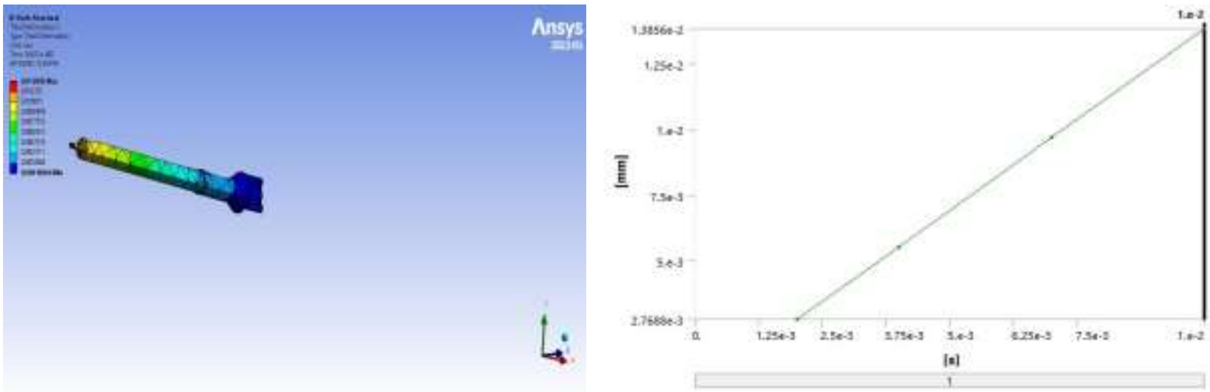

Figure 7 *Total Deformation of Silicon Nitride in CNG Combustion Mode*

3.2 Equivalent (Von Mises) Stress

Equivalent stress measures internal resistance to applied loads and thermal expansion. Materials experiencing lower stress are generally considered more stable, provided the stress is within their strength limits. **Table 3** summarizes the equivalent stress values obtained from ANSYS simulations for each material under petrol and CNG operational conditions

Table 3 *Equivalent Stress of Spark Plug Material*

Material	Petrol Mode (MPa)	CNG Mode (MPa)
Iridium Alloy	37.818	35.511
Platinum	26.009	26.01
Silicon Nitride	26.009	30.129

Under both combustion modes, the Iridium alloy generated the lowest stress magnitudes, confirming its superior mechanical strength and thermal resistance. Platinum, despite its good conductivity, exhibited the highest stress concentration, suggesting a higher likelihood of plastic deformation under prolonged high-temperature operation (10–12). Figures 8 to 13 present the graphical and visual representations from the ANSYS simulation.

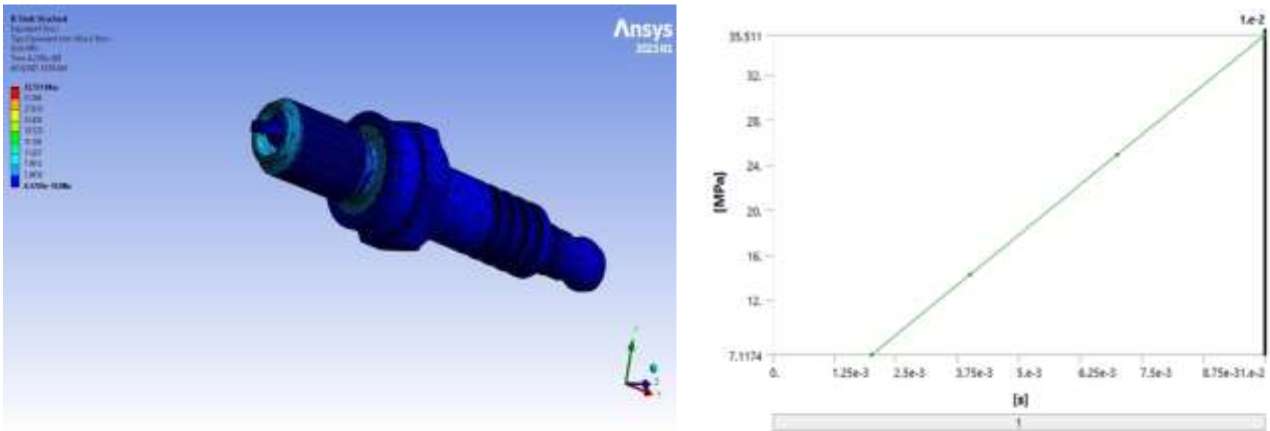

Figure 8 *Equivalent Stress of Iridium in GNG Combustion Mode*

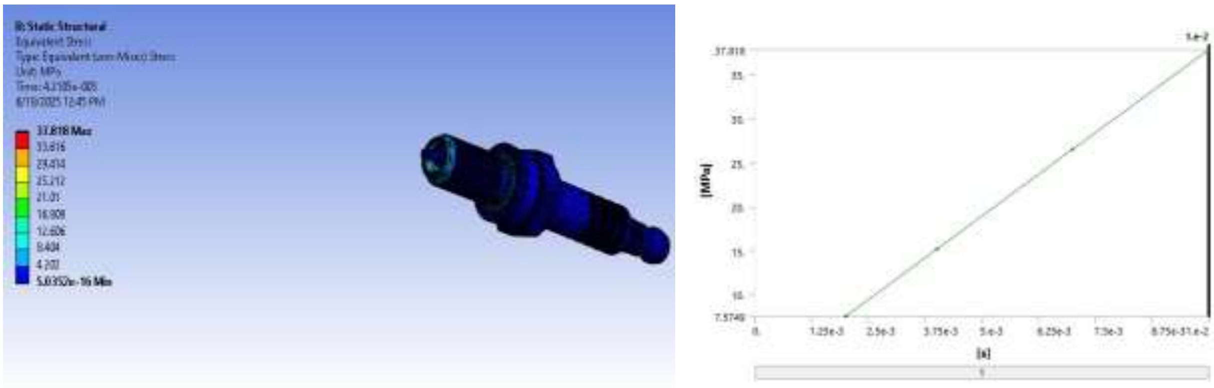

Figure 9 *Equivalent Stress of Iridium in Petrol Combustion Mode*

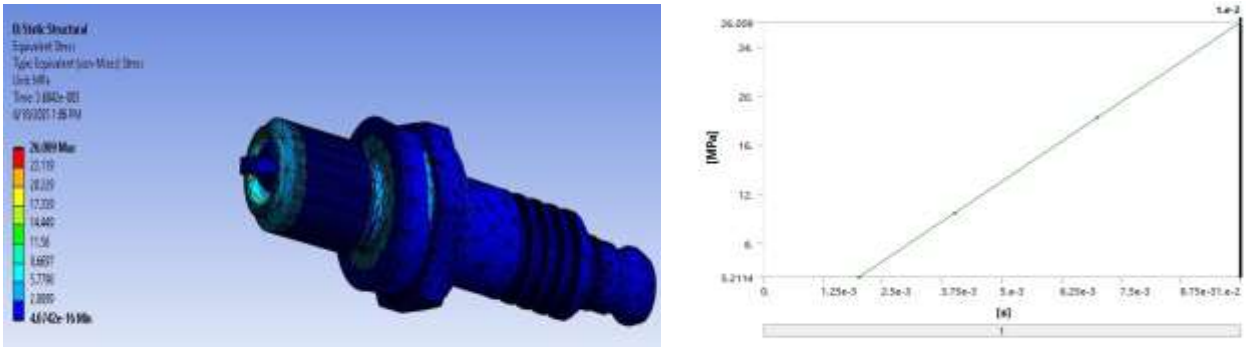

***Figure 10** Equivalent Stress of Platinum in CNG Combustion Mode*

***Figure 11** Equivalent Stress of Platinum in Petrol combustion Mode*

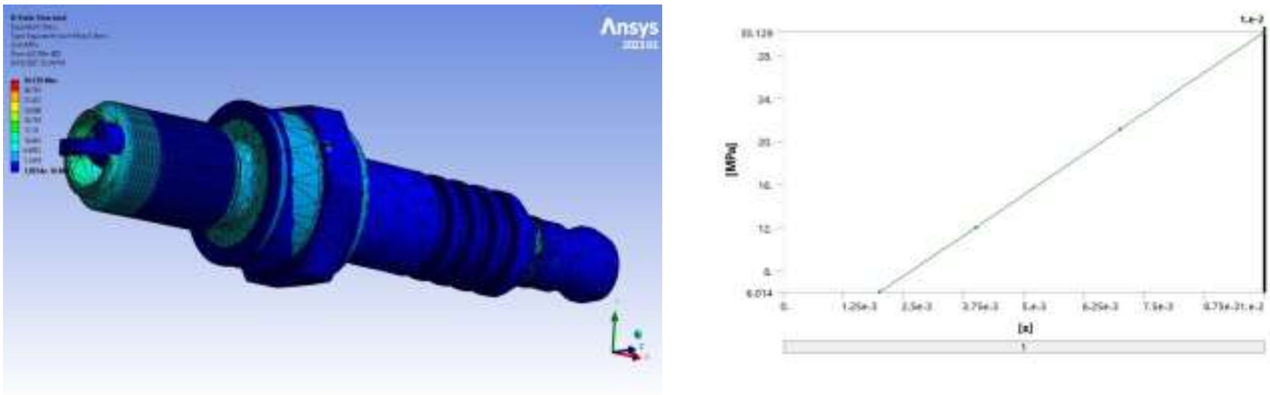

***Figure 12** Equivalent Stress of Silicon Nitride in CNG Combustion Mode*

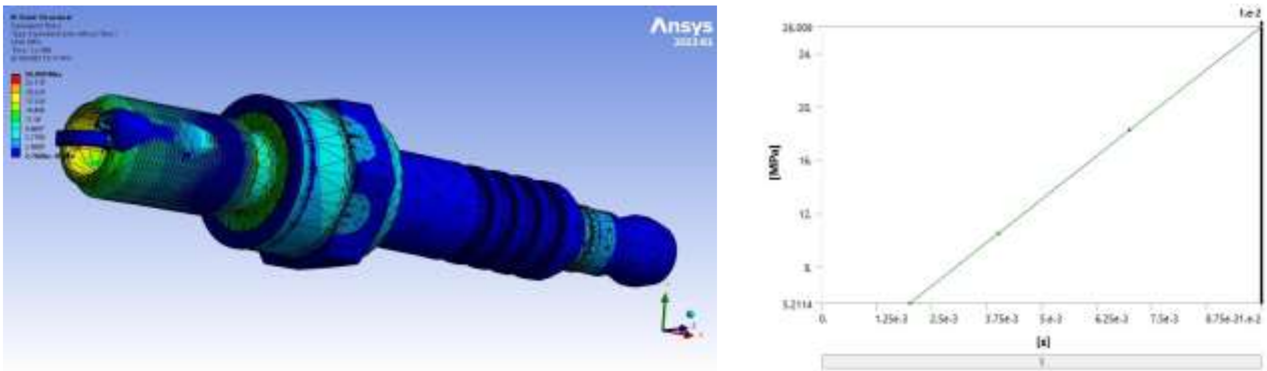

***Figure 13** Equivalent Stress of Silicon Nitride in Petrol Combustion Mode*

3.3.Strain Energy

Strain energy indicates the amount of energy absorbed elastically during loading. While higher energy absorption may reflect improved shock resistance, it may also suggest potential vulnerability to fatigue in brittle materials. The ANSYS simulation results for strain energy under petrol and CNG operating modes are summarized in Table 4

***Table 4** Strain Energy of Spark Plug Materials*

Material	Petrol Mode (MJ)	CNG Mode (MJ)
Iridium Alloy	6.1603e-3	6.3317e-3
Platinum	6.4586e-3	6.45515e-3
Silicon Nitride	7.0165e-3	7.208e-3

The Iridium alloy electrode exhibited the lowest strain energy in both modes, confirming its ability to maintain mechanical integrity under repeated thermal cycles (Javan et al., 2014; Osamura & Abe, 1999). Silicon Nitride showed moderate energy absorption, which aligns with its ceramic nature and inherent brittleness. Figures 14 to 19 present the graphical and visual representations from the ANSYS simulation

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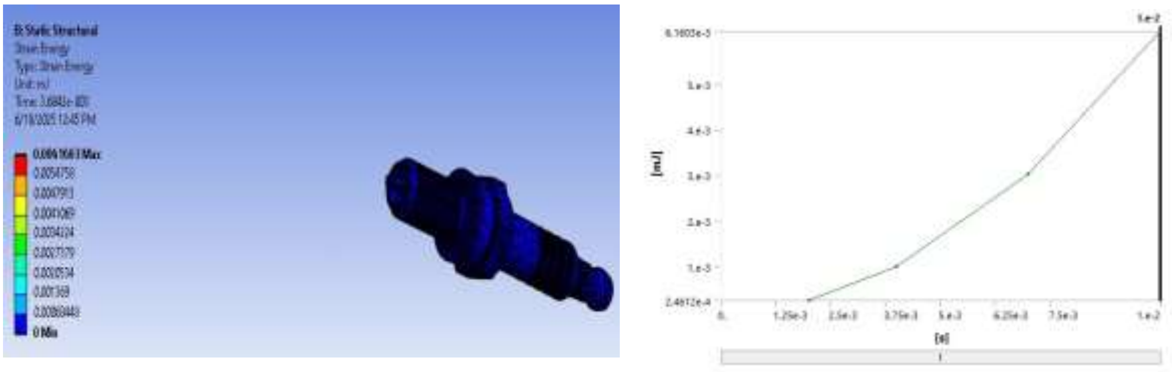

***Figure 14** Strain Energy of Iridium in Petrol Combustion Mode*

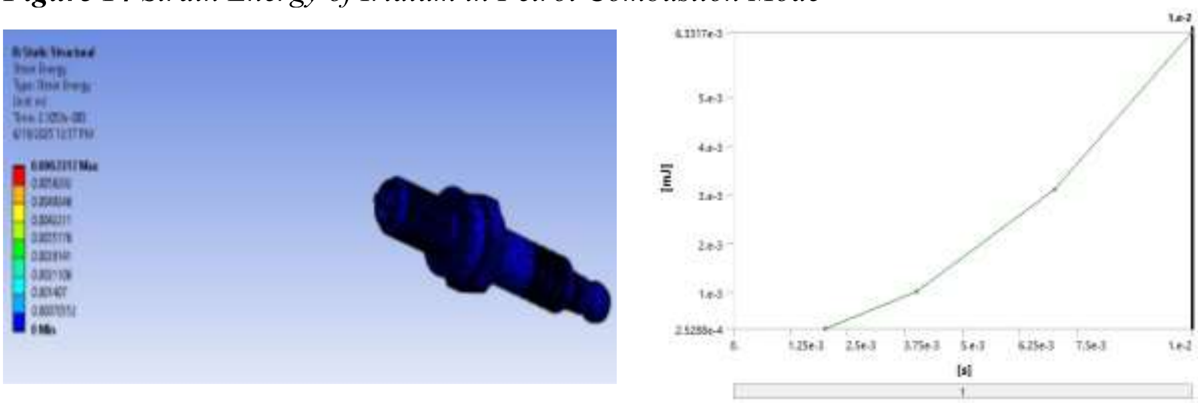

***Figure 15** Strain Energy of* Iridium in CNG Combustion Mode

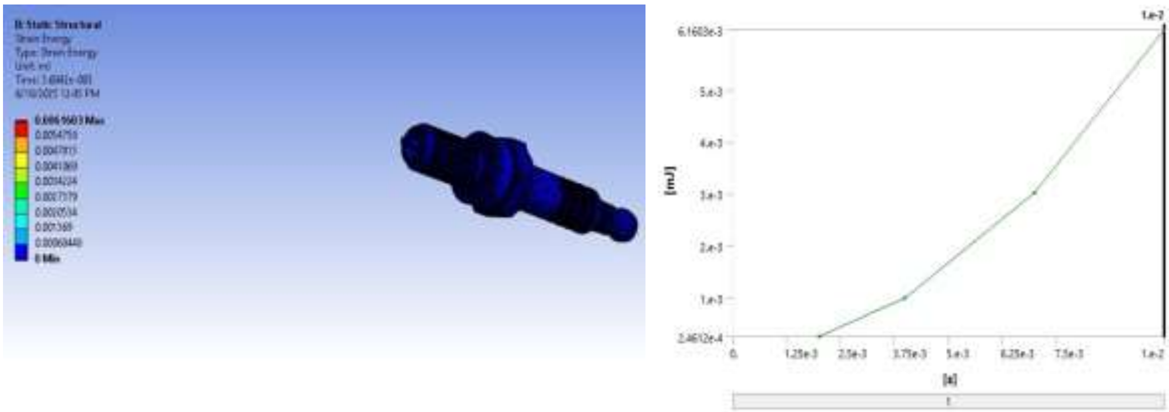

Figure 16 *Strain Energy of Platinum in Petrol Combustion Modes*

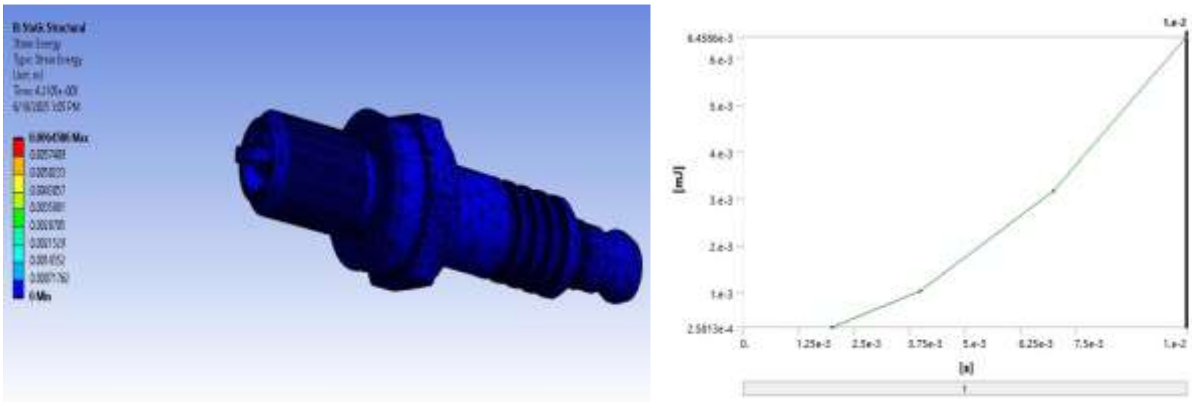

Figure 17 *Strain Energy of Platinum in CNG Combustion Modes*

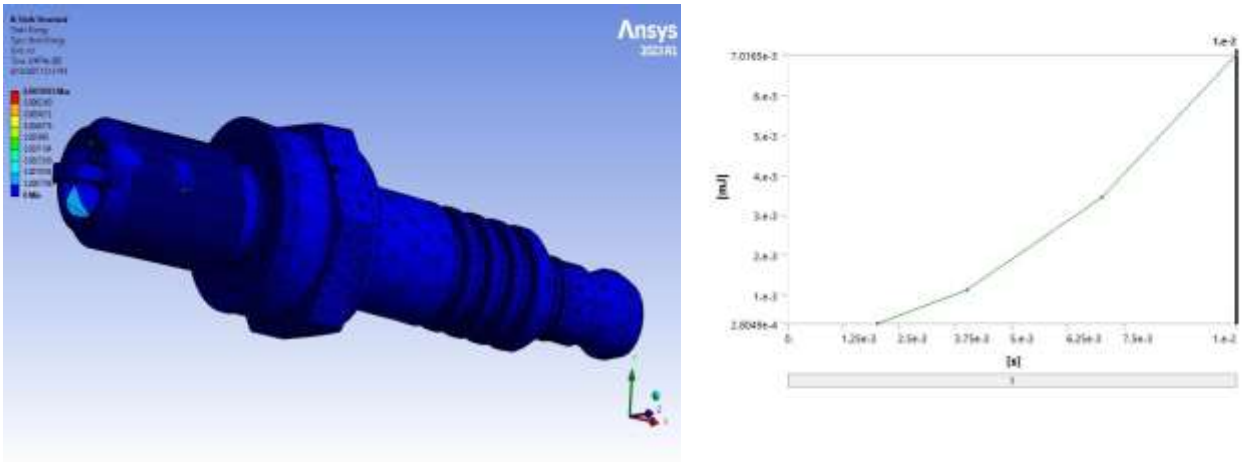

Figure 18 *Strain Energy of Silicon Nitride in Petrol Combustion Modes*

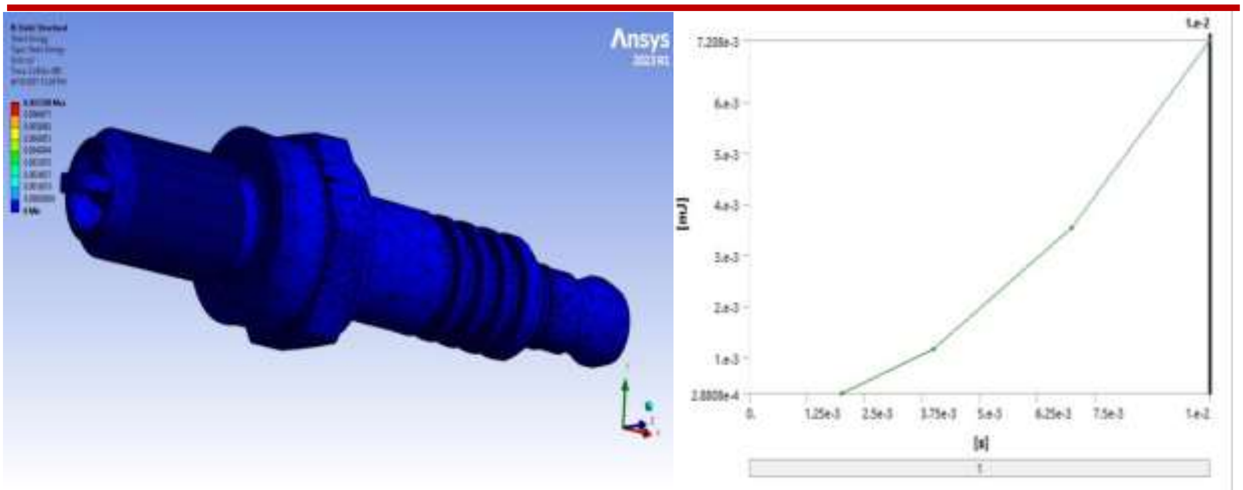

***Figure 19** Strain Energy of Silicon Nitride in CNG Combustion Modes*

4. Discussion

The simulation results demonstrate distinct differences in the thermo-mechanical performance of Platinum, Iridium alloy, and Silicon Nitride electrodes when exposed to petrol and CNG combustion conditions. These differences can be attributed to the material's intrinsic physical and thermal properties, such as melting point, thermal conductivity, and elastic modulus, which collectively determine their behavior under cyclic loading.

4.1. Influence of Material Properties on Spark Plug Performance

The Iridium alloy electrode showed superior performance across all parameters, including minimal total deformation, reduced equivalent stress, and lower strain energy values. These results are consistent with the literature, indicating that Iridium possesses exceptional mechanical strength and oxidation resistance, enabling it to maintain a sharp electrode profile and stable spark gap during extended operation (Harrer et al., 2024); (Javan et al., 2014); (Osamura & Abe, 1999). Its high melting point (≈2446 °C) and superior modulus (≈528 GPa) limit thermal softening and mechanical creep under prolonged combustion exposure.

In contrast, Platinum, though widely used in conventional spark plugs, exhibited higher deformation and stress levels due to its relatively lower stiffness and melting point (≈1768 °C). The higher strain energy values observed in Platinum electrodes suggest greater elastic strain accumulation, which could accelerate wear and microcrack formation under repeated ignition cycles (NGK Spark Plug Co., 2020); (Harrer et al., 2024).

Silicon Nitride, being a ceramic-based material, demonstrated moderate thermal resistance and acceptable mechanical performance. However, its relatively low thermal conductivity (≈30 W/m·K) leads to localized heating, resulting in higher stress concentrations near the electrode tip (Javan et al., 2014). Despite its excellent oxidation resistance, the inherent brittleness of ceramics limits their long-term mechanical reliability in fluctuating high-temperature conditions.

4.2. Impact of Fuel Type on Thermal–Mechanical Behavior

The comparative analysis between petrol and CNG modes revealed that all materials experienced greater deformation and stress in CNG operation. This outcome aligns with established studies indicating that CNG combustion temperatures are higher and flame propagation rates are slower, resulting in longer exposure of spark plug electrodes to high-temperature gases (Tian, Chen, & Wu, 2020); (Wu & Zhang, 2022).

These findings corroborate experimental observations by Javan et al. (Osamura & Abe,

1999) and Wu and Zhang (Bosch, 2020), who reported that electrodes operating in CNG-fueled engines exhibit accelerated wear and erosion compared to those in petrol engines. The slightly higher strain energy recorded under CNG mode confirms that electrode materials endure greater cyclic energy absorption, which may promote fatigue and gradual surface degradation over time.

4.3.Comparison with Previous Studies

The simulation findings are in close agreement with previous investigations on spark plug durability in bi-fuel engines. Javan et al. (Osamura & Abe, 1999) observed that fine-wire Iridium spark plugs maintain stable ignition voltage for extended durations compared to Nickel and Platinum plugs. Similarly, Osamura and Abe (Osamura & Abe, 1999) reported that newly developed Iridium alloys improved erosion resistance and electrical conductivity, resulting in longer service life.

The present ANSYS-based results confirm these empirical outcomes by providing numerical evidence that Iridium's superior stiffness and heat transfer properties reduce stress concentrations and deformation levels. The consistent trend across simulation and experimental studies reinforces the reliability of finite element analysis as a predictive tool for material optimization in high-temperature applications (Tian, Chen, & Wu, 2020); (Bosch, 2020); (Javan et al., 2014).

4.4. Engineering and Practical Implications

From a design perspective, the findings suggest that Iridium-based electrodes are the most suitable for petrol–CNG bi-fuel engines due to their combined thermal stability, mechanical robustness, and corrosion resistance. The use of Iridium not only extends spark plug lifespan but also ensures consistent ignition performance and reduced maintenance costs.

Furthermore, the study highlights the potential of finite element simulation as a cost-effective method for material screening and optimization. By enabling early identification of thermally stable electrode materials, simulation can significantly reduce experimental expenses and accelerate the development of advanced ignition components.

Nevertheless, while ANSYS simulations provide valuable insights, they represent an idealized approximation of real engine conditions. Factors such as combustion turbulence, electrode fouling, and electrical field distribution were not explicitly modeled in this study. Future research should therefore integrate coupled thermal–electrical analysis and experimental validation to enhance prediction accuracy.

5. Conclusions

This study investigated the thermo-mechanical performance of three spark plug electrode materials: Platinum, Iridium alloy, and Silicon Nitride (Si_3N_4) for application in petrol–CNG bi-fuel engines using finite element analysis in ANSYS Workbench 2023 R2. The analysis focused on evaluating total deformation, equivalent (Von Mises) stress, and strain energy under simulated petrol and CNG combustion conditions.

The major conclusions derived from this study are as follows:

1. Iridium alloy exhibited the best overall performance across all evaluated parameters, demonstrating the lowest deformation, minimal stress concentrations, and reduced strain energy. This confirms its high structural integrity and superior resistance to thermo-mechanical fatigue under dual-fuel operating environments (Harrer et al., 2024; Javan et al., 2014; Osamura & Abe, 1999).
2. Platinum electrodes showed moderate resistance to thermal deformation but recorded higher stress and strain energy levels, indicating potential for accelerated wear and early mechanical fatigue during prolonged operation (NGK Spark Plug Co., 2020); (Harrer et al.,

2024).

3. Silicon Nitride electrodes displayed reasonable thermal resistance but suffered from localized stress accumulation due to their low thermal conductivity and brittle nature, which limits their long-term durability in fluctuating combustion conditions (Javan et al., 2014).

4. The CNG operating mode induced higher deformation and stress across all materials compared to petrol mode, primarily due to elevated combustion temperatures (≈2200 K) and slower flame propagation. These effects are consistent with prior empirical findings that identify CNG as a more severe operational environment for spark plug components (Bosh, 2002; Osamura & Abe, 1999; Tian et al., 2020).

5. The results validate the use of finite element analysis (FEA) as a reliable and cost-effective approach for assessing spark plug material behavior before physical testing. Simulation methods enable engineers to predict temperature-induced stresses and select optimal electrode materials, thereby reducing prototype development time and cost (Wu & Zhang, 2022); (Bosch, 2020).

5.1.Recommendations

Based on the findings of this research, the following recommendations are proposed:

1. Material Selection: Iridium-based alloys should be prioritized in the design of spark plug electrodes for bi-fuel engines due to their superior mechanical and thermal performance.
2. Design Optimization: Future spark plug designs should incorporate improved cooling geometries and coatings to further mitigate thermal stress in CNG operation.
3. Simulation Enhancement: Future studies should integrate coupled thermal–electrical simulations and fatigue life estimation to more accurately predict spark plug lifespan under cyclic ignition conditions.
4. Experimental Validation: Laboratory testing under controlled petrol–CNG combustion environments is recommended to validate the simulated findings and refine boundary condition assumptions.

5.2.Contribution to Knowledge

This study contributes to the growing field of sustainable automotive engineering by:

1. Providing comparative simulation data on three advanced electrode materials under dual-fuel conditions.
2. Demonstrating the superior durability of Iridium alloy in resisting thermo-mechanical degradation.
3. Establishing a numerical framework for material optimization using ANSYS simulation tools in spark plug design.

These insights support ongoing efforts to enhance the performance, durability, and environmental efficiency of ignition systems in alternative-fuel engine technologies

Abbreviations

CNG: Compressed Natural Gas
FEA: Finite Element Analysis
ANSYS: Analysis System
MPa: Megapascal.
Mm: Millimeter.
mJ: Millijoule.
CO: Carbon Monoxide
CO_2: Carbon Dioxide.
Si_3N_4: Silicon Nitride

HV: High Voltage
FEM: Finite Element Method.
°C : Degrees Celsius
W/m·K: Watt per Meter-Kelvin
J/kg·K: Joule per Kilogram-Kelvin.

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