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RESEARCH ARTICLE

Structural and thermal analysis of poly (ether ether ketone) / aluminium composites through finite element method of engine piston and compressor valve plate components

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Abstract

Increasing automotive usage drives exploration of polymer matrix composite (PMC) materials rather than conventional metals, such as aluminum (Al), for engine pistons and valve plates, to reduce mass and fuel consumption. The PMC materials generally offer many advantages but have poor thermal properties. Since poly(ether ether ketone) (PEEK) offers superior mechanical properties and thermal stability among thermoplastics, it can be used as a matrix in combination with conventional Al. However, the PEEK-Al composite has not been studied yet, either by simulation or experiment, for these engine parts. In the present study, a novel PEEK-Al composite system was designed, with Al content varying from 10–40 vol%, to identify the composition that yields the optimal mechanical and thermal properties. A structural and thermal analysis was performed using finite element analysis (FEA) in ANSYS. The present results were compared to determine the optimal composite compositions based on their thermomechanical properties. From the entire present FEA results, it is concluded that the PEEK-40%Al has best overall optimum mechanical (i.e., up to 1.056×107 Pa shear stress for Plate and 8.815×107 Pa shear stress for piston) and heat transfer (i.e., up to 2590.3 W/m^2 heat flux for Plate and 74.939 W/m^2 for Piston) characteristics for plate and piston materials. Hence, PEEK-40%Al, which has the best heat-transfer characteristics, can be applied to both engine plates and piston components. Hence, these PEEK-Al composites will enhance engine efficiency and align with automotive sustainability goals.

Keywords: Aluminum, poly (ether ether ketone), finite element analysis, temperature, simulation, composite

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1. Introduction

The automotive industry increasingly investigates polymeric materials to achieve lower weight than traditional metallic aluminum (Al). Conventional materials cannot withstand the high temperatures generated in internal combustion (IC) engines. A piston is a cylindrical component of an engine that undergoes reciprocating motion. The piston is contained within a cylinder, which is airtight owing to the piston rings. As a liquid or gas within the cylinder expands and contracts, the piston moves inside it. With the help of a piston, thermal energy can be converted into mechanical work and vice versa [1]. The circular plates or rings that make up the compressor valve plate are layered between the valve seat and the cover. The rings or plates are drawn towards the area of higher pressure when there is a pressure difference, and they use springs to return to their closed position when the pressure equalizes [2]. Al alloys are widely used in the manufacture of pistons. Al is an excellent conductor of heat and electricity. It is nontoxic, and has low density, excellent, corrosion resistance, and high thermal conductivity, and can be cast, machined and molded quickly [3]. In this context, many researchers have investigated various engine components using different technologies. Sun et al., 2024 [4] described a simulation of hardness plug and thermocouple sensors on an Al-alloy piston-based IC engine and the chamber's heat transmission boundary condi-

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tion. They reported that heat capacity affects fluctuation error and density, and that heat conductivityand time-averaged error are all products of heat capacity. They suggested a method for correcting fluctuation errors. In this context, modification of Al-based materials has been attempted for getting better heat-transfer performance using Al-layered structures as thermal protection system for future flight vehicles [5]. Furthermore, the thermal stresses and heat transfer produced have been tried to investigate numerically where Al, copper (Cu), structural steel, and titanium (Ti) were selected as a solid substrate [6]. Dash et al., 2023 [7] studied structural Al-Si alloy production, structure, and mechanical characteristics for aerospace and automotive usage. Computational modelling and integration of artificial intelligence are key areas for their future research. Additionally, it is non-magnetic and non-sparking in nature.

Al is the sixth most malleable and second-most ductile metal [9]. However, a huge number of Al pistons is damaged due to different reasons including, wear and tear, temperature, and mechanical fatigue [10,11]. In addition, compared to wear and mechanical fatigue damage, the engine pistons or compressor valve plates damaged more due to thermal and mechanical stresses [12]. In this context, composites may be a better option for improving thermomechanical properties. Du et al., 2024 [8] explored to improvise the diesel engine performance by applying ‘thermal swing’ via plasma electrolytic oxidation (PEO) technique. However, it has some drawbacks, such as a slow response to temperature changes and elevated surface temperatures.

In this context, poly(ether ether ketone) (PEEK) could be a great potential option due to its high melting temperature (345 °C) lesser weight with high mechanical properties [13]. The chemical formula of PEEK is $[-C_6H_4-O-C_6H_4-O-C_6H_4-CO-]_n$. It is a colourless organic thermo-plastic polymer belongs to the poly(aryl ether ketone) (PAEK)family and used in many engineering applications. The PEEK polymer was first developed in November 1978 [14]. It exhibits high volume resistivity and high surface resistivity. This rigid opaque (grey) material offers a unique combination of mechanical properties, resistance to chemicals, wear, fatigue and creep as well as exceptionally high temperature resistance, up to 260 °C (working temperature) [15,16]. PEEK is a tough, semi-crystalline, high-performance thermoplastic polymer, and has good biocompatibility, thermal and mechanical properties [13,17–19]. Therefore, recently, the PEEK-based composites are being explored for different engineering applications and biomedical applications [20–22]. Researchers are thus taking interest on its thermal and mechanical studies for different engine parts in automobile sector [23,24].

Yan et al., 2025 [25] examined a piston failure at extreme heat and pressure conditions. The distribution of stress fields and temperatures within an Al-Si alloy piston was simulated using finite element analysis(FEA).Fatigue failure most likely occurred in the throat region. Cracks in the Al matrixcaused by the hard particlesaccelerated thermal fatigue. This research lays the groundwork for a model to predict the experimentally determined lifetimes of Al-Si alloy pistons. To optimize the thermal properties of the piston design while keeping costs down, it helped to investigate thermal stress distribution using finite element method (FEM) before developing prototypes [26]. Vaidya et al., 2023 [27] optimised the design requirements of composite connecting rods using engineering carbon fibre thermoplastics to meet the 14,000 N load and 1 mm maximum deflection. Iterative optimisations were performed on the rods to improve their geometry, wall thickness, and load-bearing surfaces. The optimized composite connecting rod was projected to be 78% lighter than the incumbent steel component, and material and shape optimization enabled the design to exceed the 14,000 N requirement.

In this context, polymers are lighter, whereas metals or alloys are heavier. Although some polymers, including PEEK, have excellent mechanical properties, they are not as good as metals, such as aluminium, in terms of thermal properties. Indeed, the compressor valve plate and piston, made of PEEK-Al composites, have not yet been examined experimentally or by simulation. To investigate the effectiveness of PEEK-Al composites in engine pistons and compressor valve plates, this study aims, for the first time, to develop a model of these composites with varying quantities of aluminium-particle reinforcement. It is expected that the PEEK-Al would have better heat transfer characteristics whether used as a piston or a plate since a recent study provided empirical evidence of this composite’s feasibility [28]. Few finite element modelling studies of compressor valve plates have been reported to date. For this reason, appropriate simulation work may enable improvements in engine component design through finite element analysis (FEA) of the engine plate and piston, potentially facilitating their application in internal combustion engines, thereby achieving improved reliability and efficiency.

Therefore, in the present modeling study, PEEK is selected to be used for making of an engine piston and a compressor valve plate owing to its desirable mechanical properties and higher melting temperature beside lightweight [15,22]. The low density of PEEK composites can significantly reduce fuel consumption. However, because of its semi-crystalline nature, blending this polymer with other thermoplastics and thermosetting polymers(resins)is challenging. Although PEEK has good mechanical properties, it exhibits poorer thermal properties than Al. Thus, the present study aims to model PEEK-based composites with variable amounts of Al-particle reinforcement to investigate the performance of PEEK/Al composite-based engine pistons and compressor valve plates. Compared with conventional metals, PEEK/aluminium composites reduce component mass, thereby lowering emissions and fuel consumption in IC engines. The study further maps various Sustainable Development Goals(SDGs)related to energy efficiency and sustainability in the automotive sector. Specifically, this present study will (i) emphasize improved thermal management in engine components, leading to reduced energy use for SDG 7 (Affordable and Clean Energy), (ii) include the innovation fostered by advanced PEEK/Al composites, which will enhance manufacturing resilience and sustainability for SDG 9 (Industry, Innovation, and Infrastructure), (iii) focus on decreasing material usage and promoting energy-saving production methods through the use of lighter composites for SDG 12 (Responsible Consumption, and Production), and finally, (iv) produce the environmental benefits of weight reduction in parts, translating to lower fuel demand and significant carbon dioxide (CO2) savings for SDG 13 (Climate Action).

Therefore, for the first time, a novel composite system consisting of PEEK and Al was designed, with Al content varying from 10–40% by volume, to determine the optimal mechanical and thermal properties of the PEEK-Al composites. Hence, this study may be particularly useful for the design and development of engine parts based on composite materials, such as pistons and plates. In the present study, 'Al' denotes 'pure Al' and 'PEEK-Al' denotes 'composites.'

2. Material and method

2.1. Materials

In the present study, PEEK was combined with different volume percentages of Al to produce composites with compositions of 90% PEEK and 10% Al (denoted PEEK-10%Al), 80% PEEK and 20% Al (denoted PEEK-20%Al), 70% PEEK and 30% Al (denoted PEEK-30%Al), and 60% PEEK and 40% Al (denoted PEEK-40%Al) for use in an IC engine piston (named 'piston') and a compressor valve plate (named 'plate'). This composite is feasible in practice since we recently developed PEEK/Al composites in which Al content varied from 10 to 40 % [28]. The input properties of the composites were evaluated using the rule of mixtures and used as input for the FEA performed in ANSYS software v.18. ANSYS was used to perform structural and thermal analyses; subsequently, samples exhibiting favorable properties were identified and compared. The total deformation, equivalent elastic strain, shear stress, temperature, and total heat flux of the two modeled components for all designed PEEK/Al composites were simulated. The physical and mechanical properties of aluminum and PEEK obtained from the literatures [29,30] are illustrated in Table 1.

Table 1. Physical, mechanical, and thermal properties of pristine aluminum and pure PEEK materials

Materials	Materials	
	Al	PEEK
Density (kg/m^3)	2770	1300
Young's modulus (MPa)	69000	3600
Poisson's Ratio	0.33	0.37
Tensile yield strength (MPa)	90	100
Compressive yield strength (MPa)	130	118
Tensile ultimate strength (MPa)	110	100
Isotropic thermal conductivity (W/mK)	237	0.25
Specific heat (J/kg K)	903	1340

2.2. Components design in solidworks

2.2.1. Compressor valve plate model

A model of the compressor valve plate (hereafter referred to as the 'plate'), drawn in SolidWorks v.17, is shown in Figure 1.

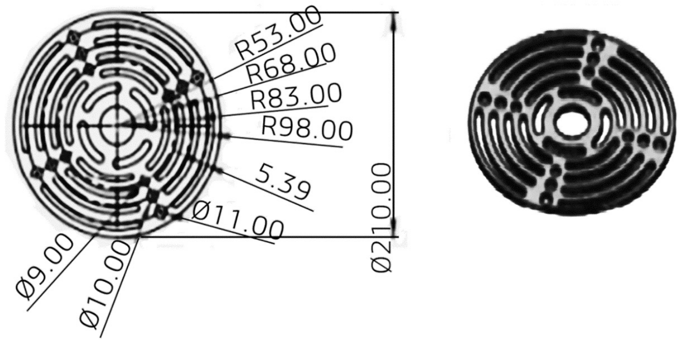


Figure 1. Compressor valve plate (i.e., shortly named as 'plate') drawn in SolidWorks

2.2.2. Engine piston model

A model of an engine piston (hereafter referred to as 'piston'), drawn in SolidWorks v.17, is shown in Figure 2.

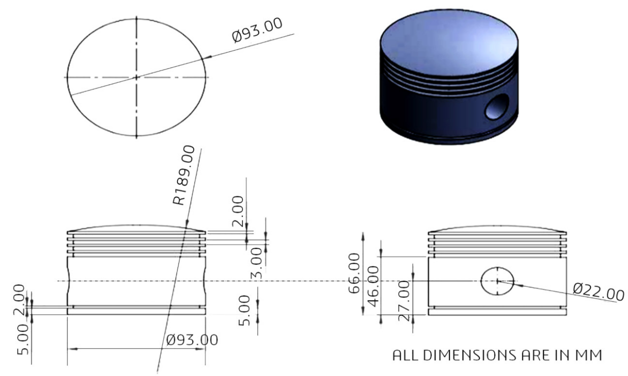


Figure 2. Engine piston (i.e., shortly named as 'piston') drawn in SolidWorks

2.3. Thermal analysis for compressor valve plate and engine piston

2.3.1. Temperature

Temperature distributions of the Al-based plate and PEEK-based piston are depicted in Figures 3 and 4, respectively. In pure Al or PEEK, the highest temperature occurred at the center of the plate, and the lowest occurred at the periphery. On the other hand, in pure Al or PEEK, the highest temperature was obtained at the top of the piston, and the lowest at the piston bottom (piston skirt). The maximum (MAX) and minimum (MIN) temperature distributions for the Al- and PEEK-based plate and piston are illustrated in Table 2.

In this FEA study, a 1 s step size was used, as noted in Figures 3 to 6, for the following purposes: (i) improving accuracy in capturing transient effects, (ii) stabilizing the solution, and (iii) tracking sensitive responses. The time step of 1 s indicates the increment used for the applied parameters. The 1-s time step permits the simulation to record rapid changes in temperature, displacement, or stress more accurately, predictably, and precisely, especially during transient thermal events or thermal shocks. A finer time step also helps maintain numerical stability by reducing the risk of missing critical changes or introducing errors caused by an excessively large time step. When the time step was increased from 1.0 to 2.0 s, the maximum temperature changed significantly. As the time step decreases from 1.0 s to 0.5 s and 0.1 s, the maximum temperature converges, exhibiting an insignificant percentage change. This supports the use of a 1 s time step as accurate and computationally efficient, with an inaccuracy of less than 1.5%. Structural materials are sensitive to temperature gradients or rapid thermal loading, and a finer time step, i.e., 1 s, can more effectively resolve the evolution of thermal strains and stresses. However, using a fine time step of less than one second may increase computational cost, so the time step has been optimized to balance the desired accuracy with available computational resources.

The piston temperatures may vary from 100 °C to 300 °C or above [32,33]. Although 100°C is not extremely high, heat transfer and material stresses begin to play significant roles in IC engine design. In this study, we started from the lowest temperature range of the polymer matrix composites.

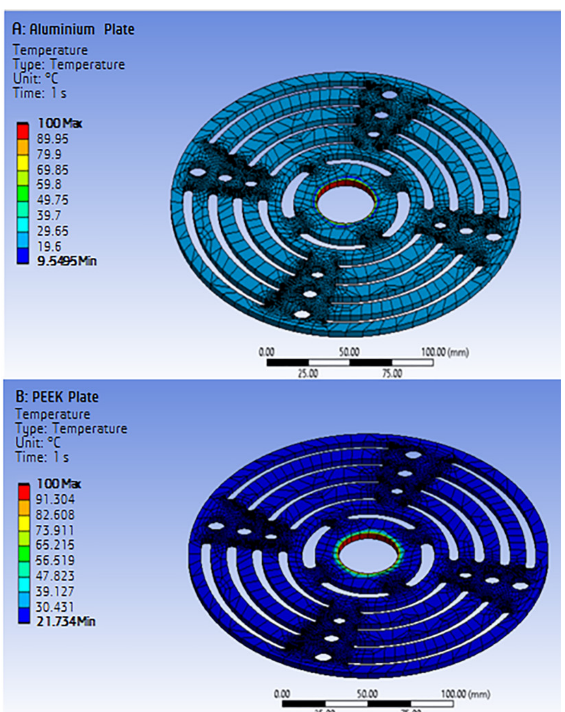


Figure 3. A temperature distribution for aluminium **(A)** and PEEK **(B)** materials-based plate

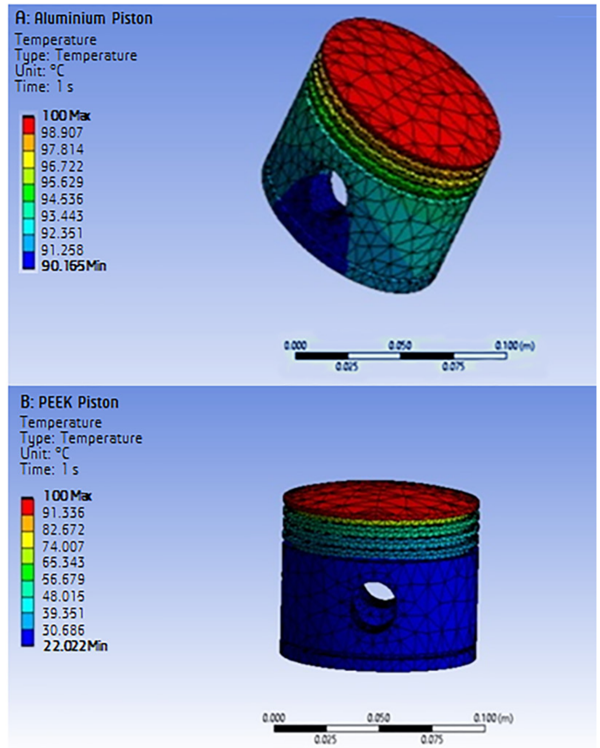


Figure 4. A temperature distribution for aluminium **(A)** and PEEK **(B)** materials-based piston

Table 2. Temperature distribution for aluminium and PEEK materials-based plate and piston

Component	Output	MIN Temperature (°C)	MAX Temperature (°C)
Compressor Valve Plate or Plate	Temperature of aluminum	9.5495	100
	Temperature of PEEK material	21.734	100
Engine Piston or Piston	Temperature of aluminum	90.165	100
	Temperature of PEEK material	22.022	100

2.3.2. Total heat flux

Total heat flux results for the aluminium- and PEEK-based plate and piston are depicted in Figures 5 and 6, respectively. In pure Al or PEEK, the heat flux distribution was also obtained and, similar to the temperature distribution, was highest at the center and lowest at the periphery of the plate. On the other hand, in pure Al or PEEK, the highest heat flux was obtained at the top of the piston, and the lowest at the piston's bottom or skirt. Total heat flux values of pristine Al-based and pure PEEK-based plate and piston are illustrated in Table 3. Heat flux results indicate that Al exhibits a higher heat flux than PEEK, because Al has a higher thermal conductivity. It also indicates that the heat-flux range of the plate is much higher than that of the piston. Furthermore, the overall heat flux of the plate is substantially higher than that of the piston.

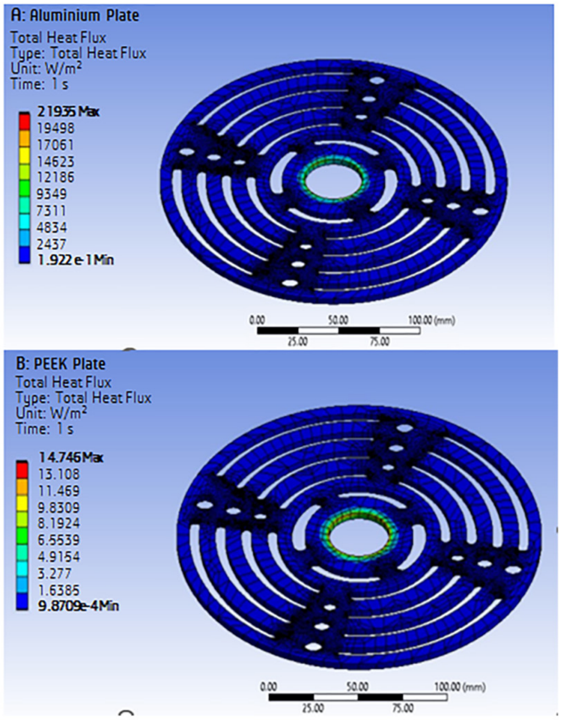


Figure 5. Total heat flux results for aluminium **(A)** and PEEK **(B)** materials-based plate

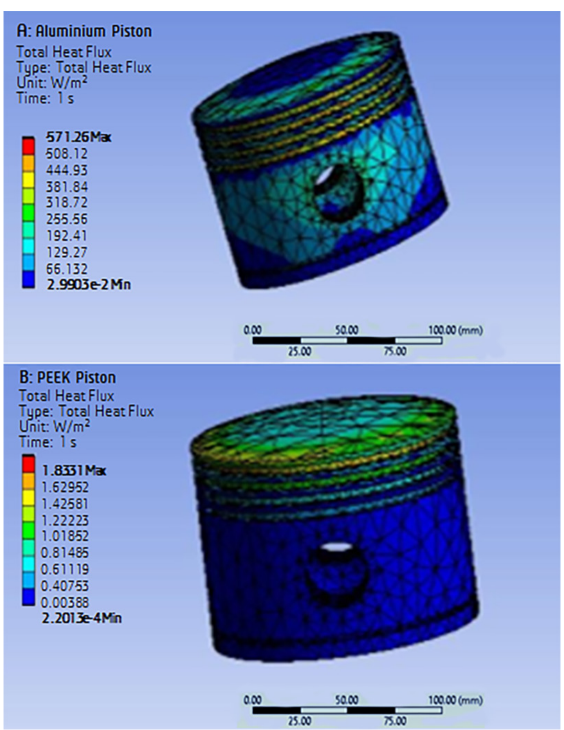


Figure 6. Total heat flux results for aluminium **(A)** and PEEK **(B)** materials-based piston

Table 3. Overall values for total heat flux for plate and piston of pristine Al and pure PEEK

Component	Output	MIN Total Heat Flux (W/m²) $\times 10^{-3}$	MAX Total Heat Flux (W/m²)
Plate	Total heat flux of Al	192.2000	21935.0000
	Total heat flux of PEEK material	0.9871	14.7460
Piston	Total heat flux of Al	29.9030	571.2600
	Total heat flux of PEEK material	0.2201	1.8331

2.4. Properties evaluated by rule of mixtures

The rule of mixtures is a technique for approximately estimating the properties of composite materials, assuming that all composites are homogeneous. It predicts the composite property based on the volume-weighted average of the properties of the phases (matrix and dispersed phase) [33]. The rule-of-mixtures equations are widely used to determine the properties of an unknown composite. Here, rule-of-mixture equations are presented in Eqs.1 – 3, which were used to determine the mechanical properties of the composites, where X_{uc} is a property of the composite, X_{uf} is a property of the filler, X_m is a property of matrix at the failure strain of the fiber, V_m and V_f are the matrix volume fraction and the filler volume fraction, respectively. Eq. 1 represents a general equation for all composites, whereas Eqs. 2-8 represent specific formulae for different properties. Eqs.9-11 were used to calculate the specific heat capacity of composite ($C_{p,mix}$) [34]. The mechanical and thermal properties of all composites are presented in Table 4.

$$X_{uc} = X_m V_m + X_{uf} V_f \tag{1}$$

Density:

$$\rho = \rho_{Al} V_{Al} + \rho_P V_P \tag{2}$$

where, ρ - density of composite, ρ_{Al} - density of aluminium, V_{Al} - volume fraction of Al, ρ_P - density of PEEK and V_p - volume fraction of PEEK.

Poisson's ratio:

$$\mu = \mu_{Al} V_{Al} + \mu_P V_P \tag{3}$$

where, μ - Poisson's ratio of composite, μ_{Al} - Poisson's ratio of Al and μ_p - Poisson's ratio of PEEK.

Young's modulus:

$$E = E_{Al} V_{Al} + E_p V_p \tag{4}$$

where, E - Young's modulus of composite, E_{Al} - Young's modulus of Al and E_p - Young's modulus of PEEK.

Tensile yield strength:

$$\sigma_{yt} = \sigma_{Al} V_{Al} + \sigma_P V_P \quad (5)$$

where, σ_{yt} - tensile yield strength of composite, σ_{Al} - tensile yield strength of Al and σ_p - tensile yield strength of PEEK.

Compressive yield strength:

$$\sigma_{yc} = \sigma_{cAl} V_{Al} + \sigma_{cP} V_{cP} \quad (6)$$

where, σ_{yc} - compressive yield strength, σ_{cAl} - compressive yield strength of Al and σ_{cp}- compressive yield strength of PEEK.

Tensile ultimate strength:

$$\sigma_{uc} = \sigma_{uAl} V_{Al} + \sigma_{uP} V_P \quad (7)$$

where, σu_c - tensile ultimate strength of composite, σu_{Al} - tensile ultimate strength of Al and σu_p - tensile ultimate strength of PEEK.

Isotropic thermal conductivity:

Isotropic thermal conductivity, $K = K_{Al} V_{Al} + K_p V_p$ (8)

where, K - isotropic thermal conductivity of composite, K_{Al} - isotropic thermal conductivity of Al and K_p - isotropic thermal conductivity of PEEK.

Specific heat:

The rule of mixtures presented in Eq.9 for determining the specific heat ($C_{p,mix}$) of a two-phase composite is computed by weighted average based on the mass fractions of each phase, assuming that the total energy is conserved and the temperature change is uniform. This Eq.9 is converted from mass fraction to volume fraction and density in Eq.10, where r_{mix} represents the density of the composite, which is expressed in terms of volume fraction and density of individual phases in Eq.11 [35].

$$C_{p,mix} = (m_{Al} \times C_{p,Al}) + (m_p \times C_{p,p}) \quad (9)$$

$$C_{p,mix} = \frac{(V_{Al} \times \rho_{Al} \times C_{p,Al}) + (V_p \times \rho_p \times C_{p,p})}{\rho_{mix}} \quad (10)$$

$$C_{p,mix} = \frac{(V_{Al} \times \rho_{Al} \times C_{p,Al}) + (V_p \times \rho_p \times C_{p,p})}{(V_{Al} \times \rho_{Al}) + (V_p \times \rho_p)} \quad (11)$$

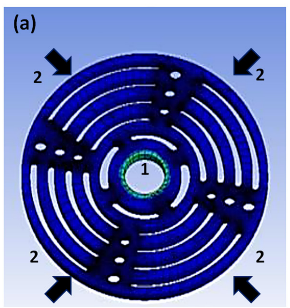
where, m_i = mass fraction of component i, $C_{p,mix}$ = specific heat capacity of composite (J/kg·K), V_i = volume fraction of component i, ρ_i = density of component i (kg/m³), $C_{p,i}$ = specific heat capacity of component i (J/kg·K).

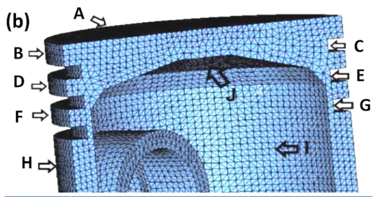
Table 4. Mechanical and thermal properties of all the composites

Composites Properties	Composition of Composites			
	PEEK-10%Al	PEEK-20%Al	PEEK-30%Al	PEEK-40%Al
Density (kg/m^3)	1447	1594	1741	1888
Young's modulus (Pa)	10.14×10^9	16.70×10^9	23.40×10^9	30.00×10^9
Poisson's Ratio	0.366	0.362	0.358	0.354
Tensile yield strength (MPa)	99	98	97	96
Compressive yield strength (MPa)	119.0	120.4	121.6	122.8
Tensile ultimate strength (MPa)	101	102	103	104
Isotropic thermal conductivity (W/mK)	23.93	47.60	71.28	94.95
Specific heat (J/kgK)	1256.3	1188.1	1131.4	1083.5

2.5. Boundary conditions

For structural analysis, the boundary conditions were determined by finite element analysis (FEA) using Eqs. 1 and 7. For steady-state thermal analysis, the initial and boundary conditions were determined using Eqs.8 and 9 prior to conducting the FEA. We also assumed steady-state, isotropic conditions in this study and neglected creep and fatigue. The environment was assumed to be constant across the different parts of the plate and the piston. The boundary conditions were applied as per the reported works [1,2,23,24,36], where for the compressor valve plate, the center (point 1) was fixed and a uniformly distributed pressure was applied at the periphery (point 2) as depicted in Figure 7a. In the present study, a pressure of 6 MPa was applied to both the plate and the piston. The meshed model characteristics of the piston in the present study were: element size, 1.8 mm; number of elements, 52077; number of nodes, 13353; and element type, tetrahedral. Because many elements (more than 52000) were used, the selected element size of 1.8 mm is sufficient to accurately capture the geometry and stress distribution of the piston. The tetrahedral elements ensure geometric accuracy and $C_{p,mix} = (m_{Al} \times C_{p,Al}) + (m_p \times C_{p,p})$ are ideal for intricate geometries, such as pistons. In fact, the findings would be largely consistent with those obtained using a 1.8 mm mesh size if the mesh size were further refined to 1.5 mm or 1.2 mm. Less than 0.15% of the total elements exceeded the upper limit for the aspect ratio. Hence, the current mesh yields mesh-independent results because further refinement would only increase computational cost without appreciably altering the physical predictions. Mesh independence is used to ensure that the mechanical and thermal results of the simulation reflect the underlying physics of the problem rather than depend on mesh density. Mesh independence is achieved when further increasing mesh density (i.e., smaller elements and more nodes) results in changes of less than 4% in the maximum deformation, stress concentration, or thermal behaviour. Consistency between the medium and fine meshes implies mesh independence. This confirms that the simulation setup is robust. Figure 7b depicts the convective boundary conditions applied to the piston at surfaces A–I for the thermal analysis.





Region	Heat Transfer Coefficient (W/m² °C)	Bulk Temperature (°C)
A	698	650
B, C	470	500
D, E	470	180
F, G	470	170
H	470	110
I	240	95
J	900	95

Figure 7. The convective boundary conditions of the **(a)** compressor valve plate and **(b)** engine piston.

3. Results and discussion

3.1. Structural analysis for compressor valve plate

The distributions of total deformation, equivalent elastic strain, and von Mises shear stress for the plate and piston of all PEEK-Al composites, as well as for pristine Al and pure PEEK-based materials, have been evaluated. The MAX values of the total deformation, equivalent elastic strain, and von Mises shear stress distributions for the plate and the piston of all the PEEK-Al composites, along with pristine Al and pure PEEK-based materials are plotted in Figures 8 to 10, respectively. The deformation values are very low, measuring approximately 0.0084 m for the PEEK-20%Al plate component and 0.0012 m for the pure PEEK piston component. The plate exhibited higher deformation and strain than the piston because the plate was thinner. The pristine Al and PEEK samples exhibit minimal deformation. The deformation increases with Al content up to 20%Al in PEEK-Al compositesbut decreases significantly with greater Al particle reinforcement. The composite deforms most at 20%Al, which may reflect a balance between stiffness and ductility. Greater Al-particle reinforcement increases rigidity and reduces deformation. Conversely, the pure PEEK component exhibits the greatest deformation, demonstrating the dominance of the polymer under piston loading, whereas the pure Al piston exhibits minimal deformation. In PEEK-Al composites, deformation decreases steadily as Al particle reinforcement increases. The inclusion of Al particle reinforcement increases piston stiffness and minimizes deformation. These findings inform the design of composites with optimized mechanical properties for engine components, thereby enhancing performance and durability.

For instance, the MAX and MIN values obtained from the total deformation, equivalent elastic strain, and von Mises shear stress distributions for a specific composite (i.e., a PEEK-40%Al plate) are shown in Figures 11 to 13. In the composite, the highest deformation and strain were observed at the plate periphery and the lowest at the plate center. In a similar way, the MAX values were obtained from the distribution images of total deformation, equivalent elastic strain, and von Mises shear stress for other material-based plate and piston components and plotted in Figures 8 to 10. Figure 8 shows that plate deformation is lower in PEEK-30%Al and PEEK-40%Al, whereas it is highest in PEEK-20%Al. Figures 8 and 9 show that the magnitudes of deformation and strain in all piston materials are significantly lower than those in plate materials. The total strain behavior of the plate materials differs from that of the piston materials. On the other hand, Figure 10 shows that the lowest maximum (MAX) shear stress is exhibited by PEEK-10%Al. In contrast, shear stress values were higher for the PEEK-30%Al and PEEK-40%Al composites. As Al vol% in PEEK increased, the MAX value of the total deformation of the PEEK-Al composites in the piston decreased; interestingly, the MAX values of the von Mises shear stress distributions for all PEEK-Al composite materials in the piston increased with Al concentration. Nevertheless, the MAX shear stress was highest for the PEEK-40%Al composite-material-based piston, which closely resembles the Al-based automotive components designed by other researchers [29].

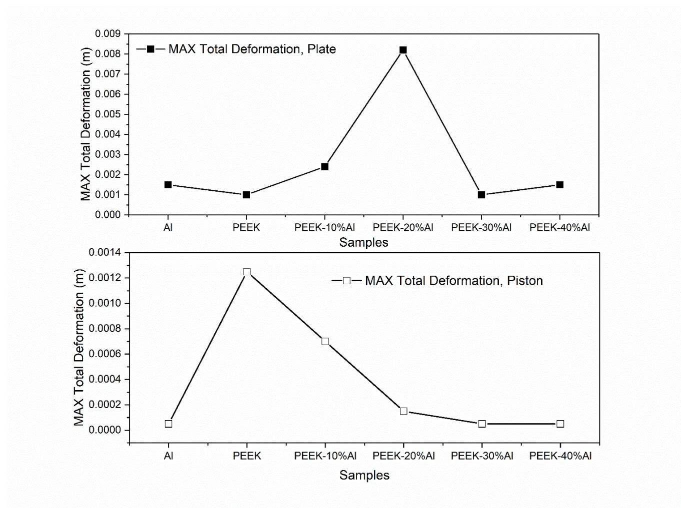


Figure 8. Maximum (MAX) values of the Total deformation of all the PEEK-Al composites along with pristine Al and pure PEEK-based materials for plate and piston

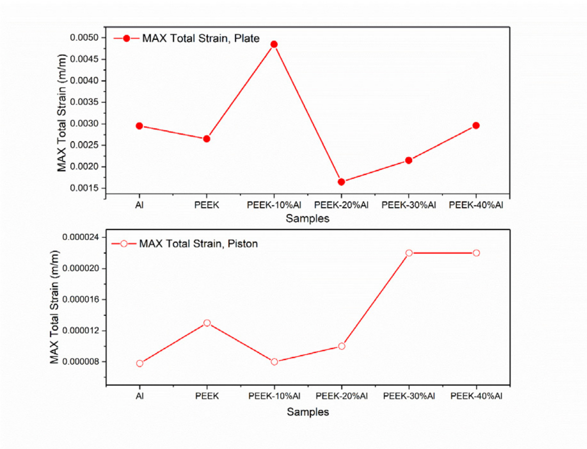


Figure 9. Maximum (MAX) values of the Equivalent elastic strain of all the PEEK-Al composites along with pristine Al and pure PEEK-based materials for plate and piston

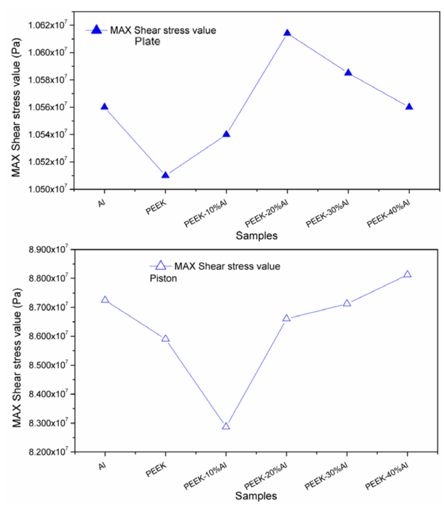


Figure 10. Maximum (MAX) values of the von Mises Shear stress distributions of all the PEEK-Al composites along with pristine Al and pure PEEK-based materials for plate and piston

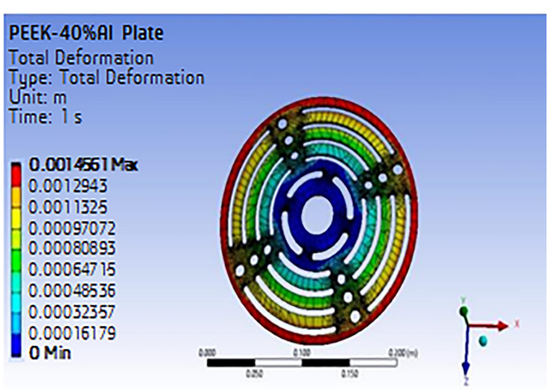


Figure 11. Total deformation of PEEK-40%Al composite for plate

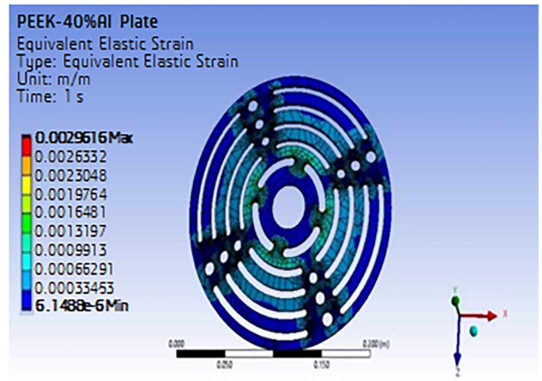


Figure 12. Equivalent elastic strain of PEEK-40%Al composite for plate

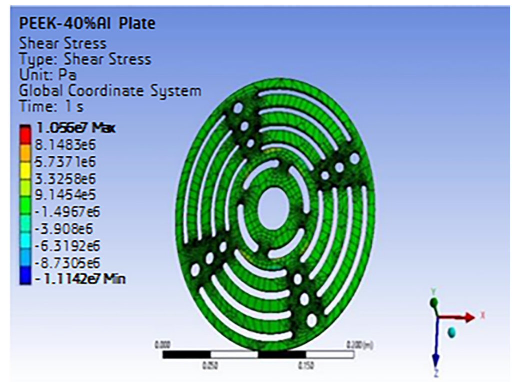


Figure 13. Shear stress of PEEK-40%Al composite for plate

3.2. Thermal analysis for compressor valve plate

In the thermal analysis, the temperature and heat-flux distribution results of all the PEEK-Al composite material-based plates and pistons have been analyzed. For instance, the temperature and heat-flux distribution images of a specific PEEK-Al composite, i.e., a PEEK-40%Al plate and piston, are shown in Figures 14–17. The highest temperature and heat flux were obtained at the center of the plate, while the lowest values were obtained at its periphery. The MIN values of temperature and the MAX values of heat flux, obtained from the temperature and heat-flux distribution images of all PEEK-Al composite-based plates and pistons, are shown in Figures 18 and 19. The highest temperature and heat flux were obtained at the top surface of the piston, and the lowest temperature and heat flux were obtained at the bottom surface of the piston. The corresponding MAX and MIN temperature distribution data for the plate and piston based on PEEK-Al composite material are illustrated in Table 5. Similarly, the corresponding MAX and MIN total heat flux values for the PEEK-Al composite-material-based plate and piston are shown in Table 6. It is to be mentioned that the heat transfer rate of the plate and piston was determined by analyzing the heat flux of the materials [37]. In addition, Figure 18 for the piston shows that pure Al has the highest temperature, while the PEEK-40%Al composite shows the lowest temperature. Thus, PEEK-40%Al exhibited the best thermal properties as a piston material. However, in Figure

19, for both the plate and the piston, the PEEK-40%Al composite showed the heat flux. Therefore, PEEK-40%Al exhibited the best heat-transfer characteristics as both plate and piston materials.

When the Al volume fraction exceeds 0.4 (40% Al), heat transfer properties may increase due to a higher density of conductive Al particles, but the binding properties of the PEEK matrix may be reduced, thereby diminishing the mechanical integration between the PEEK matrix and Al particles. Hence, they are not included in either engine-plate materials or piston materials.

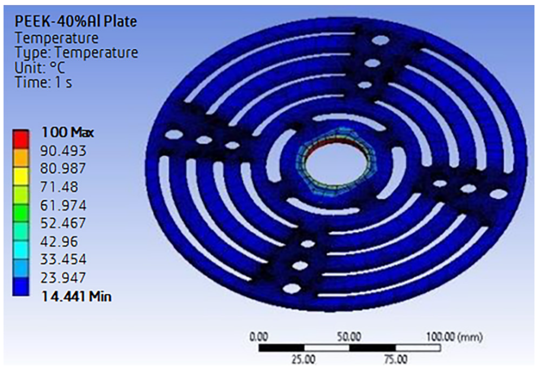


Figure 14. Temperature distribution of PEEK-40%Al composite material-based plate

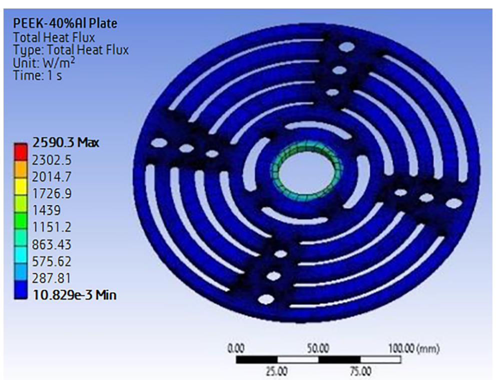


Figure 15. Total heat flux distribution of PEEK-40%Al composite material-based plate

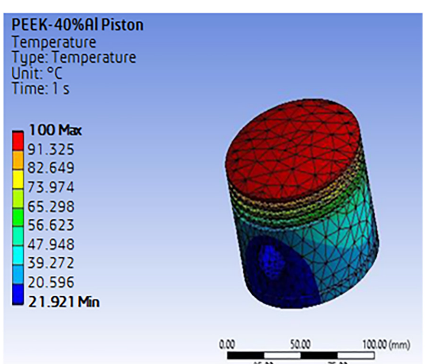


Figure 16. Temperature distribution of PEEK-40%Al composite material-based piston

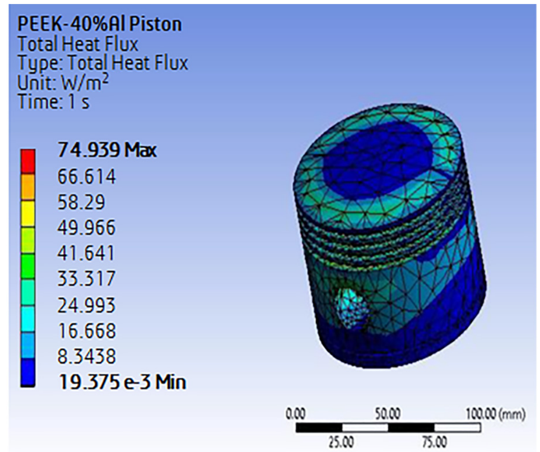


Figure 17. Total heat flux distribution of PEEK-40%Al composite material-based piston

Table 5. Temperature distribution for PEEK-Al composites-based plate and piston

Component	OUTPUT	MIN Temperature (°C)	MAX Temperature (°C)
Plate	PEEK-10%Al	13.151	100
	PEEK-20%Al	13.646	100
	PEEK-30%Al	14.060	100
	PEEK-40%Al	14.441	100
Piston	PEEK-10%Al	23.735	100
	PEEK-20%Al	21.240	100
	PEEK-30%Al	19.430	100
	PEEK-40%Al	17.320	100

Table 6. Overall values for total heat flux for plate and piston of PEEK-Al composites

Component	OUTPUT	MIN Heat flux (W/m2) $\times 10^{-3}$	MAX Heat flux (W/m2)
Plate	PEEK-10%Al	4.9327	1465.1000
	PEEK-20%Al	5.5031	1909.7000
	PEEK-30%Al	7.7944	2268.8000
	PEEK-40%Al	10.8290	2590.3000
Piston	PEEK-10%Al	9.9961	38.9500
	PEEK-20%Al	13.5720	52.5320
	PEEK-30%Al	16.5665	64.1080
	PEEK-40%Al	19.3750	74.9390

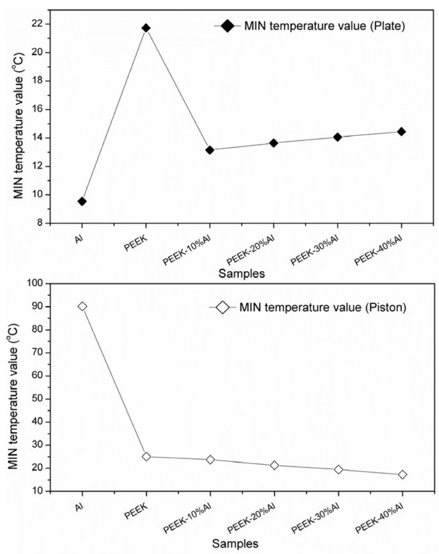


Figure 18. Minimum (MIN) temperature distributions of all the PEEK-Al composites along with pristine Al and pure PEEK-based materials for plate and piston

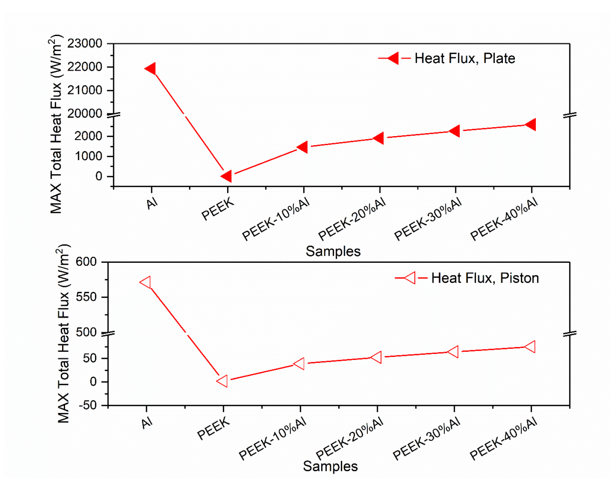


Figure 19. Total heat flux distributions of all the PEEK-Al composites along with pristine Al and pure PEEK-based materials for plate and piston

3.3. Comparison and prediction

It is to be mentioned that the present simulation predicts MAX von Mises equivalent stresses and heat flux values in piston areas, aligning with previous Al-Si alloy piston studies' MAX heat flux ($5.5562 ´10^6$ W/m^2) based on coatings [38], MAX deformation (0.039441 mm), and peak stresses (22.885 - 41.17 MPa) [39]. Researchers also reported that the standard piston model used in diesel engine FEA showed that maximum stress varied from 228 MPa to 89 MPa [39,40]. Their approach provided granular regional analysis and maintained stresses below the alloy's yield strength, thereby ensuring design safety. According to the literature, enhanced thermal barrier coatings and improved long-term fatigue resistance can improve the performance of Al-Si pistons.

In addition, the density of the standard Al piston was estimated to be reduced by 21-31% when using these PEEK-Al composites. According to current industry studies, a 21–31% decrease in engine or vehicle mass is often associated with a 13–25% increase in fuel efficiency. These benefits arise because every 10% reduction in mass results in approximately a 6–8% improvement in fuel economy. This gain occurs because a lighter vehicle requires less energy to move, thereby immediately reducing fuel consumption for the same increase in engine performance. Therefore, if the mass of the engine or vehicle is reduced by 21-31%, we may anticipate a gain in fuel economy of approximately 13–17%, given that the performance and other characteristics of the system remain the same.

Furthermore, for Al material, other researchers showed maximum heat flux value of 24838 W/m^2 [41], which is slightly lower than our obtained value for Al-based compressor valve plate material (21935 W/m^2). The structural mechanical properties, including deformation and shear-stress values in the present study were significantly better than those reported in the other study [42], in which eutectic aluminum (Al + 11-13% silicon) alloys were used for the piston, resulting in very high MAX total deformation of 1.2518 mm, MAX equivalent elastic strain of 0.052884 mm/mm, MAX elastic shear stress of 0.071391 MPa, MAX shear stress of 1905.5 MPa, and MAX equivalent stress of 3756.6 MPa. It is to be noted that the feasibility of this composite has been experimentally developed by a recent study [28]. Hence, internal combustion engines could be made more efficient and dependable with the help of this simulation work's contribution to better engine part design using finite element analysis of the plate and piston [43].

4. Conclusion

In the present study, FEA was used to analyse the compressor valve plate and engine piston made of Al, PEEK, and their composites with varying Al volume percentages 10%, 20%, 30%, and 40%. Structural and thermal FEA results indicate that PEEK-40%Al demonstrates heat transfer characteristics when used as both plate and piston material. The PEEK-40%Al material would exhibit the best heat transfer (up to 2590.3 W/m^2 heat flux for compressor valve plate and 74.939 W/m^2 for engine piston) and overall optimal mechanical properties (up to 1.056×10^7 Pa or 10. 56 MPa shear stress for compressor valve plate and 8.815×10^7 Pa or 88.15 MPa shear stress for engine piston) for both the plate and piston components.

The present composite piston simulation study lacks experimental validation, employs steady-state conditions, and omits fatigue and wear analyses. Real engine operation and long-term durability depend on cyclic loading and material deterioration, both of which are ignored by most models. For a thorough evaluation of piston design, experimental testing and transient analysis are required because such restrictions may affect life projections and performance assessments.

The method for preparing the plate and piston from composite materials is not included in the present study. In the future, this study may be evaluated experimentally and compared with these simulated results. Future directions in piston and valve plate research may involve transient heat transfer to simulate operating conditions, cyclic loading to understand fatigue behaviour, and hybrid reinforcements to enhance mechanical and thermal performance. Next-generation lightweight, high-performance engine components will benefit from these improvements in design accuracy, durability forecasts, and material optimization.

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Appendices

IC	internal combustion
Al	aluminium
ICE	internal combustion engine
Cu	copper
PEEK	poly(ether ether ketone)
PAEK	poly(aryl ether ketone)
PEEK-10%Al	composite having 90 vol% PEEK and 10 vol% Al
PEEK-20%Al	composite having 80 vol% PEEK and 20 vol% Al
PEEK-30%Al	composite having 70 vol% PEEK and 30 vol% Al
PEEK-40%Al	composite having 60 vol% PEEK and 40 vol% Al
PEO	Plasma electrolytic oxidation
Piston	engine piston
Plate	compressor valve plate
FEA	finite element analysis
MIN	minimum
MAX	maximum
X_{uc}	property of the composite
X_{uf}	property of the filler
X_m	property of matrix
ρ	density of composite
ρ_{Al}	density of aluminium
ρ_P	density of PEEK
V_{Al}	volume fraction of Al
V_p	volume fraction of PEEK
μ	Poisson's ratio of composite
μ_{Al}	Poisson's ratio of Al
μ_P	Poisson's ratio of PEEK
E	Young's modulus of composite
E_{Al}	Young's modulus of Al
E_P	Young's modulus of PEEK
σ_{yt}	tensile yield strength of composite
σ_{Al}	tensile yield strength of Al
σ_P	tensile yield strength of PEEK
σ_{yc}	compressive yield strength
sc_{Al}	compressive yield strength of Al
sc_P	compressive yield strength of PEEK
su_c	tensile ultimate strength of composite
s_{uAl}	tensile ultimate strength of Al
s_{uP}	tensile ultimate strength of PEEK
K	isotropic thermal conductivity of composite
K_{Al}	isotropic thermal conductivity of Al
K_P	isotropic thermal conductivity of PEEK
C	specific heat of composite
C_P	specific heat of PEEK
C_{Al}	specific heat of Al

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