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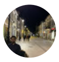
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Increasing heat transfer in 4-stroke SI engine fins by nanocoating

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ABSTRACT

A large amount of heat is produced in the IC engine during the combustion process, which directly affects the performance, fuel efficiency, and life of the engine. Extended surfaces are extensively uised in many engineering applications as they are simple to design, consume less space, weigh less. Implementation of high emissivity nanoparticles increases the heat transfer by increasing the surface area of the component. In this research, a plasma coating technique was used to provide a coating of silicon carbide (SiC) nanoparticles on 4-stroke IC engine fins. Furthermore, a Finite Element model identical to the test rig was generated and a numerical simulation was carried out using the FEA technique to investigate the heat dissipation, total heat flux and directional heat flux under applied temperature conditions. The emissivity and heat transfer results obtained from the test rig showed improvement in emissivity and enhancement in heat transfer through the fins.

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Heat flux; nanoparticles; EDAX; finite element analysis; surface modification

1. Introduction

After the 1950s, various versions of internal combustion engines were introduced and tested. The introduced engines functioned through different techniques and reliable with sources of mechanical energy and engine cycles. The main form of the engine was designed and developed by J.J.E. Lenoir, which was introduced in early 1860. With continuous research and development in those engines, more effective engines were then presented in ten years from the time the first engine was developed. The new engines had more operational power of about 4.5 kW and improved efficiency by up to 5%.

In 1867, an atmospheric engine named Otto-Langen engine was introduced to provide an enhanced efficiency of by around 11%, power of 0.3 kW and a rotational speed of 80 RPM. This engine designed by Eugen Langen used to propel the shaft by transmitting the power stroke to the shaft with the rack and pinion mechanism. The Otto-Langen engine proposed by Eugen Langen provided an efficient expansion ratio than the previous versions of engines, thereby providing the greater efficiency than other kinds of engines.

During the era of Eugen Langan and Nicolaus Otto, the modern development in the engine and introduction of efficient engine designs proposed engine's functioning on four stroke cycles. The surface coating of the engines is one of the primary factors that influence the performance of the engine. In recent years there have been multiple developments, innovations being carried out to enhance the quality of contact surfaces. The availibile resources and methodologies have fulfilled the product efficiency and other requirements of the modern era. The components used in the adverse environments lead to their early failure and thereby reduction in their life. These failures are mainly due to the harsh working conditions, relative high friction between the mating parts, excessive heat generation at the mating contacts and corrosion of the surfaces (Meikandan, Malarmohan, and Hemachandran 2017; Devaraja 2021; Okawa 2021; Premkartikkumar 2021).

To improve the deficiency of the component of the engines, the material must sustain in hostile working conditions. The material of the components should provide maximum resistance to the surface degradation, corrosion and failure. The various surface treatments and modification processes are being adopted to overcome the difficulties as discussed above. Several methods are adopted to provide the materials coated with suitable medium to show its mechanical properties, physical properties and chemical properties. The surface coating works as the intermediate medium between the surrounding and the material, thereby preventing the direct contact of the affecting element with the material (Benko 2014).

Anodising, electroplating, cladding, diffusion coating, shot peening, polymer film, flame hardening, induction hardening, thermal hardening and lubrication are some of the techniques adapted for surface treatment. First, the anodising process is used to add up the thickness over the surface of the metal by an electronic process. The material surface to be processed is suspended with an electrolytic solution where the metal act as an electrode anode (Minagar et al. 2012; Nagarani, Mayilsamy, and Venkataramana Murthy 2016). Second, electroplating is another process of formation of metallic coating over the surface of the secondary metal. The process is carried out by means of an electric charge wherein the metal surface to be treated is provided

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with negative electric charge, thereby performing as a cathode. The metal is deposited in the solution primary containing its salts. The salts of the metal exhibit positive ions, which get deposited on the surface of the metal, thereby forming a protective layer (Chandran, Panda, and Mallik 2018; Augustyn et al. 2021). Furthermore, it is lubricated to form a thin layer separating the metal surface and surrounding aspects (Gropper, Wang, and Harvey 2016). In the thermal spraying process, the metal is melted into droplets and is imposed on the surface of the metal to be processed. The impinging process is performed continuously to form a layer of metal, forming a protective coating (Budinski 1998).

The object of the proposed work is to perform a surface coating of nanoparticles of silicon carbide (SiC) on the fins of 4-stroke IC engine by the plasma coating technique, and to investigate the emissivity and heat transfer from the test rig. Moreover, numerical investigation was carried out with the finite element analysis to study the heat dissipation, total heat flux and directional heat flux through the wall of the FEA model. The study provides the experimental and numeric results for the improvement in emissivity and heat transfer of the fins after coating with the nanoparticles of SiC.

2. Mechanism of coating formation in the plasma spraying process

The plasma spraying is widely used for generating a thin layer of metallic and non-metallic material. This adaptability with metals and nonmetals makes it suitable for a wide range of applications such as cermet and ceramics (Fauchais et al. 1996; Satpathy et al. 2007). The metallic or non-metallic material is heated up to to reach it molten form and follow impingement on the surface of the metal (Selvan et al. 2011). The plasma spraying requires a temperature difference of 310 K between the melting temperature and disintegration temperature (Fauchais, Vardelle, and Vardelle 1991). The plasma spraying surface technique is advantageous because of its flexibility in decomposition materials and excellent engineering properties. Additionally, the cost-effective spraying technique is suitable for on-site applications without component's size limitations (Sidhu and Prakash 2006). The plasma spraying technique is most efficient among all spraying techniques. This is mainly used for high temperature sustaining and corrosion affecting components such as engines and turbines (Niranatlumpong, Ponton, and Evans 2000).

The plasma spray includes the formation of high velocity particles leaving the nozzle and impinges on the surface of the metal. The rate of flow of particles from the nozzle, size of the striking particles and temperature of the impinging particles are the primary aspects that affect the metal's surface (Figure 1).

The particles in the fully molten state impinge from the nozzle and get deposited on the surface, whereas the particles in an unmolten state spring back, thereby decreasing the effectiveness of the spraying process. While the semi-melted particles are integrated with the completely molten particles, thereby altering the material properties and their fine structures. The molten, semi-molten and un-molten particles are deposited (Figure 2).

The molten metal particles leaving the nozzle at a relatively lower velocity get flatten over the metal surface, thereby forming splat after its impact. These molten particles become spiracle equilibrium due to surface tension (Figure 3). The molten particles striking at higher velocities get collapsed at the age, thereby forming multiple precipitations. The cooling rate ranges 100–110 K sec on account of the adverse heat transfer from the impacting particles to the metal surface.

3. Heat transfer through nanoparticles

The requirement of the engineering property of a metal varies with the application and its working conditions. Various techniques are used to improve the mechanical, physical, chemical, thermal and electrical properties of the material in accordance with the requirement of the material for the specific application. The nanoparticle technology has been widely used because of effective reduction in the structure dimensions wherein the scattering energy can be effectively controlled (Ragothaman, Gokulakrishnan, and Arjun 2014). The thermal properties of each nanoparticle can be used and changes to a degree, which substantially differ from bulk material properties (Warzoha and Fleischer 2014). Moreover, prior studies showd that the transfer of heat mainly depends upon the nanolevel material properties. The rate of heat flow within these nanoparticles can be reduced by enhancing the internal boundary and the scattering of photons. For this purpose, scientists further developed the grain boundaries of the nanoparticles. Nanoparticle generally exhibits low or high thermal properties; therefore, their combination with other expedients becomes stimulating (He et al. 2015).

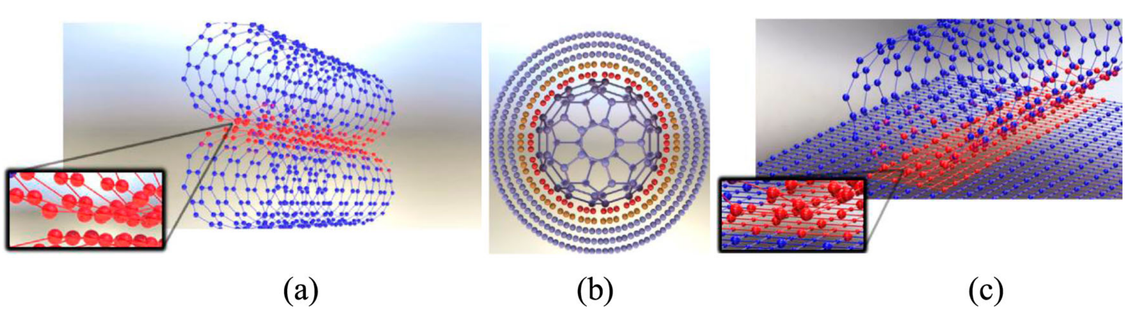


Figure 1. Heat transfer through the nanoparticle coating (a) nanoparticle–nanoparticle, (b) nanoparticle-matrix material and (c) a nanoparticle in contact with a substrate (Warzoha and Fleischer 2014).

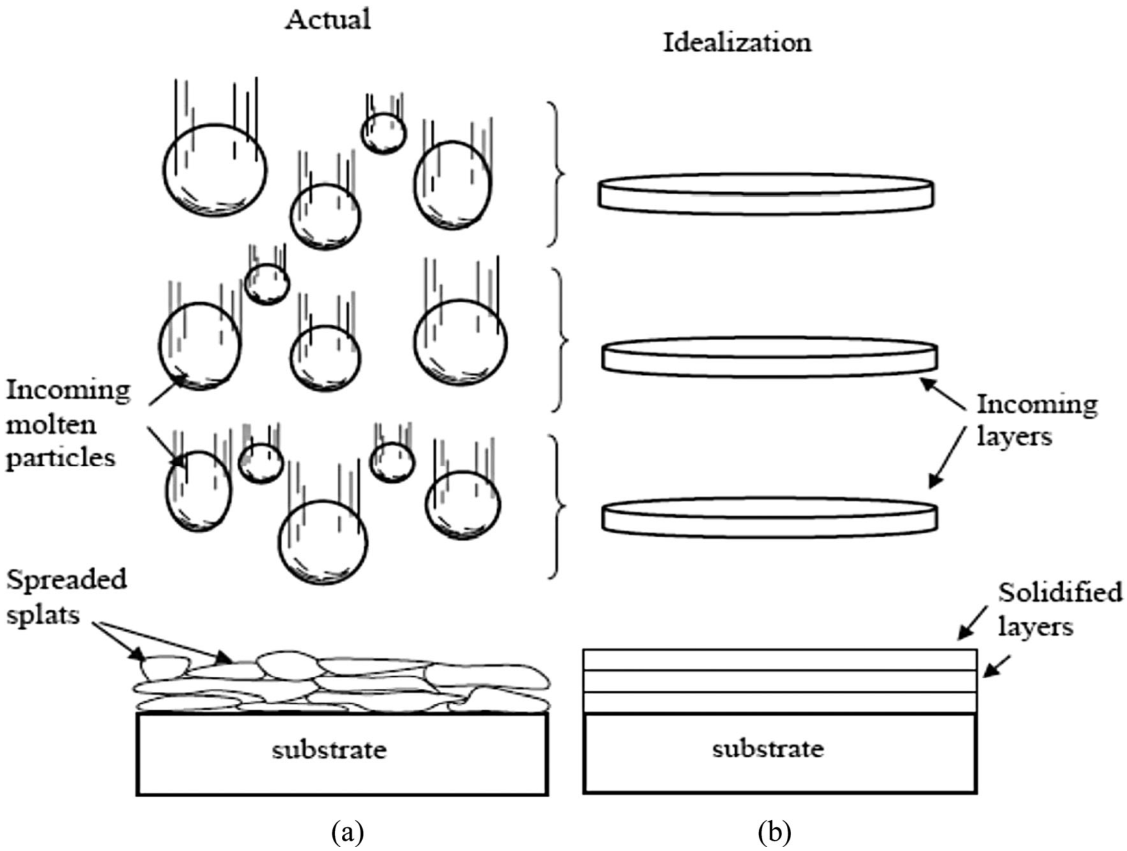


Figure 2. Schematic of the (a) physical plasma spray process and (b) its idealisation for modelling (Ng and Gan 2005).

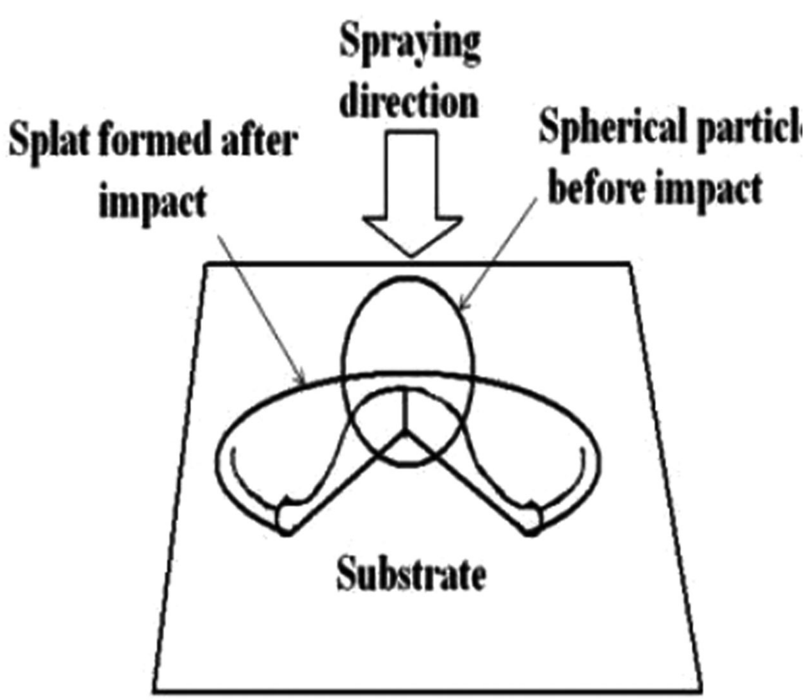


Figure 3. Splat formations after the impact of the spherical powder during spraying (Ng and Gan 2005).

Figure 4. IC engine cylinder bore used for the study.

Table 1. Chemical composition of cylindrical bore material by wt. %.

C	Si	Mn	P	S	Cr	Cu	Mg	Ni	Fe
3.85	2.15	0.845	0.061	0.110	0.183	0.65	0.005	0.11	Bal.

4. Experimental set-up and testing

Two-cylinder bores (Figure 4) of a Hero Honda Splendor engine are taken for testing. One bore is non-coated and the other bore is nano-coated with silicon carbide nanopowder (Size $<$ 100 nm). Chemical composition was checked by optical emission spectro-analysis % by weight.

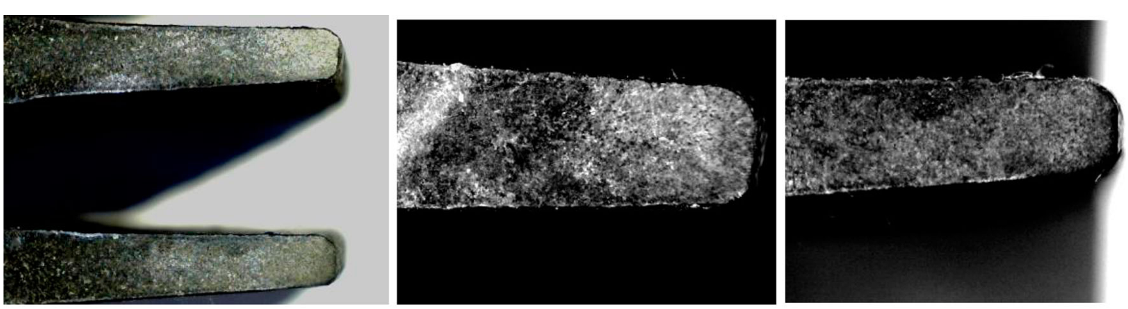
The chemical composition corresponds to the high-grade grey iron with mottling effect at the cylindrical bore (see Table 1). The chemical composition could give 300–350 Mpa tensile strength on casting in sand moulds.

Figure 5(a) shows the sectioned fins of I.C. Engine with two successive fins. The photo-macro-graph shows two distinctive zones. One along the boundary of fins and the other is the metal matrix of grey iron from which the casting was made. The magnification is 10X which shows the thin layer of coated material along the edges of the fins. Figure 5(b) shows the photo-macro-graph of one fin with coated material along the edge of the fin. The magnification of 20X resolved the edge further to observe the coating given on the fins. As can be seen in Figure 5(c), more resolution of the coating is observed in another fin. The white layer reflected by the light at the edge shows the coated silicate coating.

Two thermocouples on the inner and the tip of the fin through which the in and out temperatures are recorded (Figure 6). Non-coated bore is tested and heated with a blow torch up to an optimum engine temperature. In and out temperatures are recorded. Now this bore is again heated to the inlet temperature on non-coated bore and the out temperature is recorded.

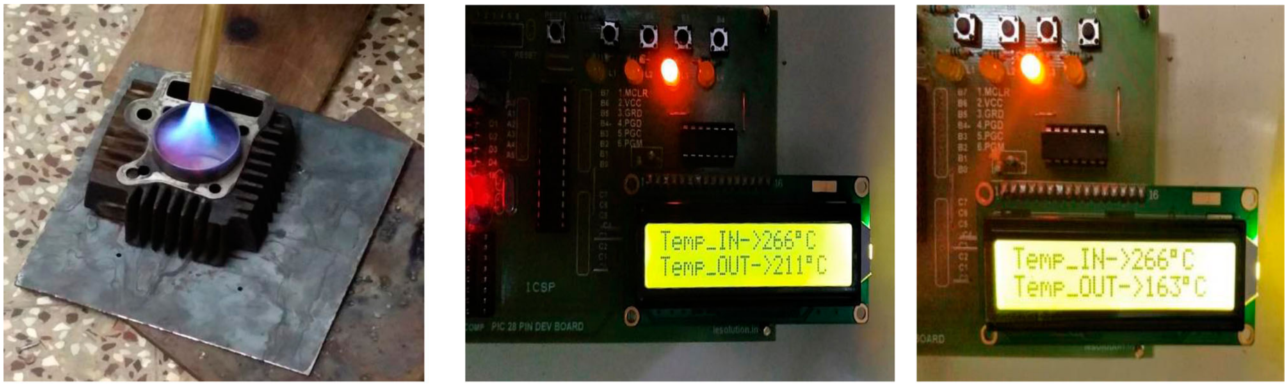
5. Results and discussion

The Hero Honda splendor fin is designed and analysed by coating layers of silicon carbide (SiC). Analysis is done for 0.25, 0.35, and 0.45 microns. An identical solid model of cylinder bore was designed in PTC Creo 2.0, whereas the numerical simulation of the fins was carried out in ANSYS Workbench academic version. Furthermore, the solid model of the engine bore was imported in the ANSYS design modeller through the step interface. The faces of the fins undergoing heat dissipation were selected through



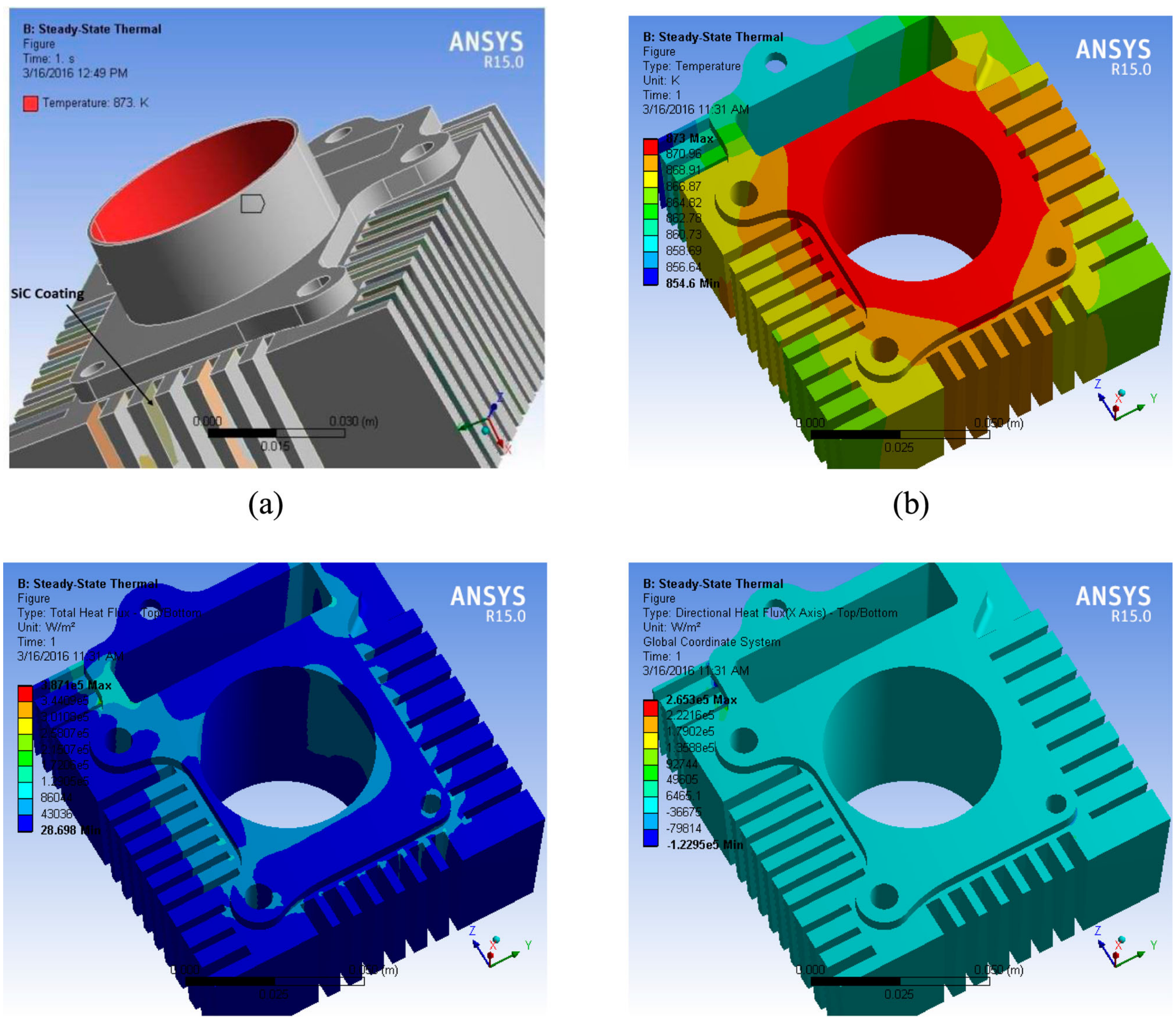
(a) (b) (c)

Figure 5. IC engine sectioned fins – micro-images.



(a) (b) (c)

Figure 6. (a) Heating of bore before coating, (b) T_{in} and T_{out} before coating, and (c) T_{in} and T_{out} after coating.



(a) (b)

(c) (d)

Figure 7. (a) Temperature, (b) heat dissipation, (c) total heat flux and (d) directional heat flux results at 35 microns.

the selection filters, and surfaces were generated for further analysis. As can be seen in Figure 7(a), the generated surfaces over the fin area represent the SiC coating, which is identical to the experimental testing. In the pre-processing of the numerical simulation, the thickness of the surface over the fin area was altered to perform numerical simulation for 35 and 45 microns. The boundary conditions are applied, which included the thermal conditions, and numerical calculations were carried out in the post-processing part of the analysis. The simulation results were obtained for heat dissipation, total heat flux and directional heat flux at 35 and 45 microns (Figures 7 and 8).

Being the most heated part of the engine, the wall of the inner bore was applied with a temperature of 873 K at a steady state (Figure 7(a)). An automated mesh was generated to convert the FE model into finite elements, while a fine mesh was developed at the fin area for superior numerical results. The analysis was carried out for a single step, and the results were obtained in the post-processing part of the simulation.

As can be seen in Figure 7(b), the temperature results obtained for 35-micron-thick FE model showed the dissipation of heat, maximum at the cylindrical bore and then gradually decreased from the bore, wherein the minimum temperature, 854.6 K, was recorded at the outer edge of the fin. Furthermore, the total heat flux observed at the cylindrical part of the engine was 3.87e5 W/m^2, while no significant flux could be witnessed at the fins. Moving on to directional heat flux, the engine block seemed to have constant directional heat flux at around 6465.1 W/m^2.

Another similar analysis was carried out while altering the FE model with another nanocoating of 45 microns (Figure 8(a)).

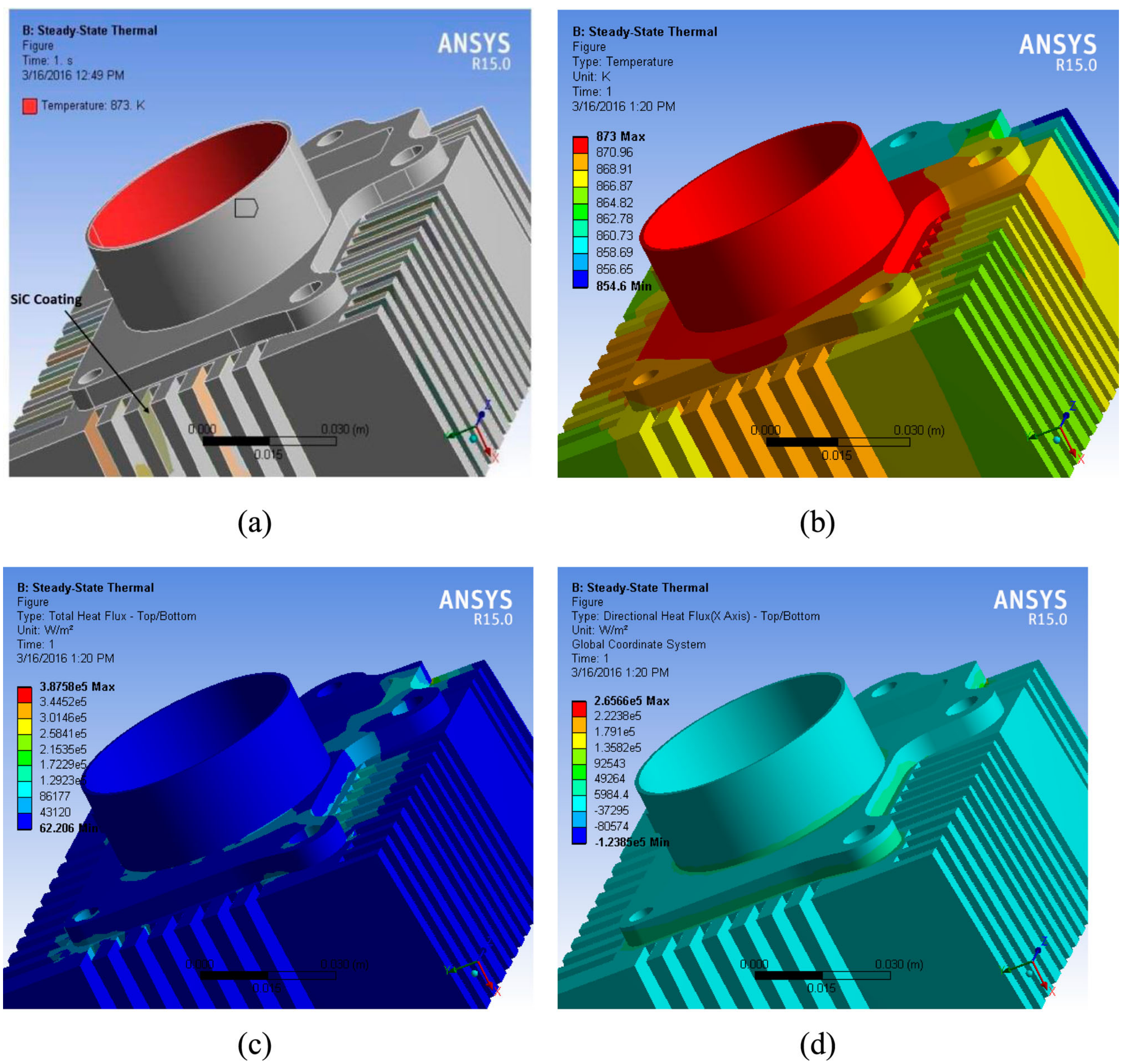


Figure 8. (a) Temperature, (b) heat dissipation, (c) total heat flux and (d) directional heat flux results at 45 microns.

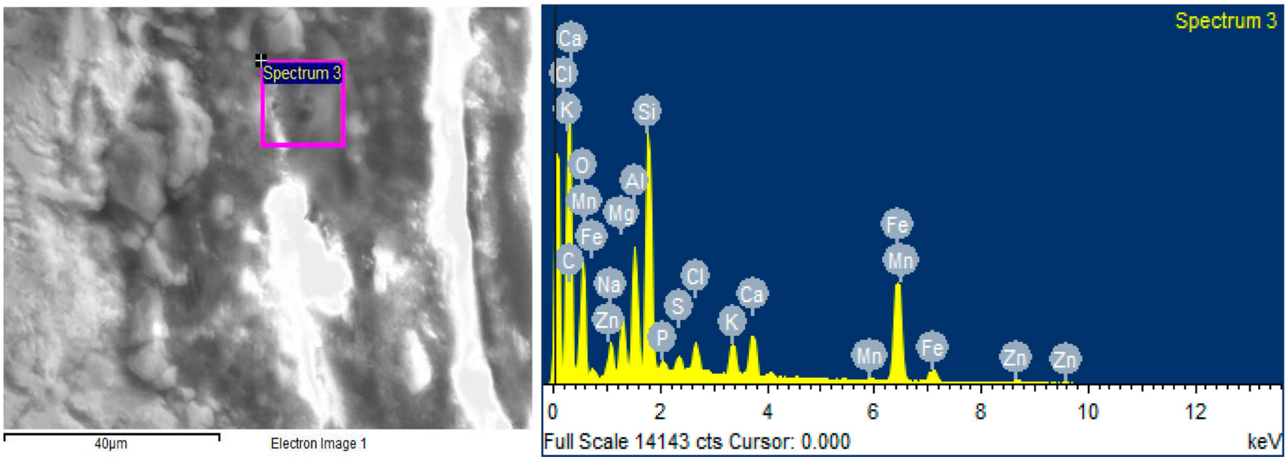


Figure 9. EDAX analysis of IC engine fins.

The identical simulation was followed to obtain the numerical results wherein the temperature of 873 K was applied to the bore of the engine block (Figure 8(b)) The numerical results showed no significant variation between the 35 and 45 microns' FE model, having the same heat dissipation outputs, maximum at 873 K and minimum at 854.6 K. Also, the directional heat flux increased with thicker nanocoating, at 62.206 W/m^2 at overall block, including the majority of the fin area. Also, it can be seen from Figure 8(d) that the maximum directional heat flux was concentrated at the joint connecting the fins to the bore, with 49,264 W/m^2 being the mean heat flux.

The EDAX analysis was performed, the results of which can be seen in Figure 9 and Table 2. The SEM photomicrograph is taken at the edge of the cylinder. The Edax analysis at the Fins edge of the cylinder showed high silicon content more than the original base metal silicon, which is only 2.15% by weight. The high oxygen content with silicon-forming silicate with SiO3 ion shows the coating of silicate on the edge. The other elements being impurities as the cylinder is a used one and rusted. Note the iron content is lower as the coating has masked the base metal and its value is reduced. Had it been from base metal the iron content would be more than 85% by weight.

Figure 10(a) shows the photomicrograph of the I.C. engine cylinder fins edge. Being coating of inorganic material as silicate, it shows a distinct layer. The thickness of the coating varies between 25 microns and 40 microns in thickness. The base material being sand cast grey iron shows the uneven surface. The magnification is 1000X. Figure 10(b) is the SEM photo-micrograph magnified at 1300X exhibits another edge of the fins of the cylinder and shows the silicate coating on the surface of the grey iron cylinder fins. The coating outer surface is more uniform than the inner surface. As can be seen in Figure 10(c), SEM photo-micro-graph shows one edge of the cylinder rusted the cylindrical surface due to the porosities in the coated material. The magnification is 1050X. The magnified view of the fin at 1200X as in Figure 10(d) shows another edge of the fins of the cylinder. Moreover, the observation displays the silicate coating on the surface of the grey iron cylinder fins. Also, the coating at the outer surface is more uniform than that at the inner surface. Furthermore, the fins are highly magnified at 2500X to get a detailed view of the coated surface. The SEM photo-micrograph, as displayed in Figure 10(e), shows the advanced magnification, which resolved the two material matrixes, namely the base metal cast iron at the right side and the coating of silicate at the left side. This image is taken at the surface of the fins and it resolved the coated surface. As a final point, Figure 10(f) shows the base metal grey iron micrograph at 750X. The presence of temper carbon graphite flakes is as type 'B' rosette grouping with preferred orientation in the pearlite matrix.

Table 2. EDAX analysis report.

Element	Weight (%)	Atomic (%)	Compound (%)	Formula
C K	18.93	26.39	69.37	CO_2
Na K	0.81	0.59	1.09	Na_2O
Mg K	1.07	0.74	1.78	MgO
Al K	2.25	1.40	4.25	Al_2O_3
Si K	4.20	2.50	8.98	SiO_2
P K	0.23	0.13	0.53	P_2O_5
S K	0.32	0.17	0.80	SO_3
Cl K	0.63	0.30	0.00	
K K	0.73	0.31	0.88	K_2O
Ca K	1.07	0.45	1.50	CaO
Mn K	0.12	0.04	0.15	MnO
Fe K	7.35	2.20	9.46	FeO
Zn K	0.47	0.12	0.59	ZnO
O	61.82	64.68		
Total	100.00			

6. Conclusion

In the present study, the plasma coating technique was used to provide a coating of silicon carbide (SiC) nanoparticles on 4-stroke IC engine fins. The high emissivity coating of silicon carbide could enhance heat transfer, thereby increasing the rate of cooling of the engine. The numerical simulation could obtain precise results for the applied boundary conditions, which opened up the ways to study the temperature gradient, heat dissipation, total heat flux and directional heat flux for three coatings thickness of 25 microns, 35 and 45 microns. The thin layer coating of silicon carbide nanopowder with 45 microns thickness was provided on the cylinder bore while adopting the suitable surface treatment methodology. The prototype comprising a nano-coated engine fins was tested to obtain the inlet and outlet temperature values at the cylinder bore, which

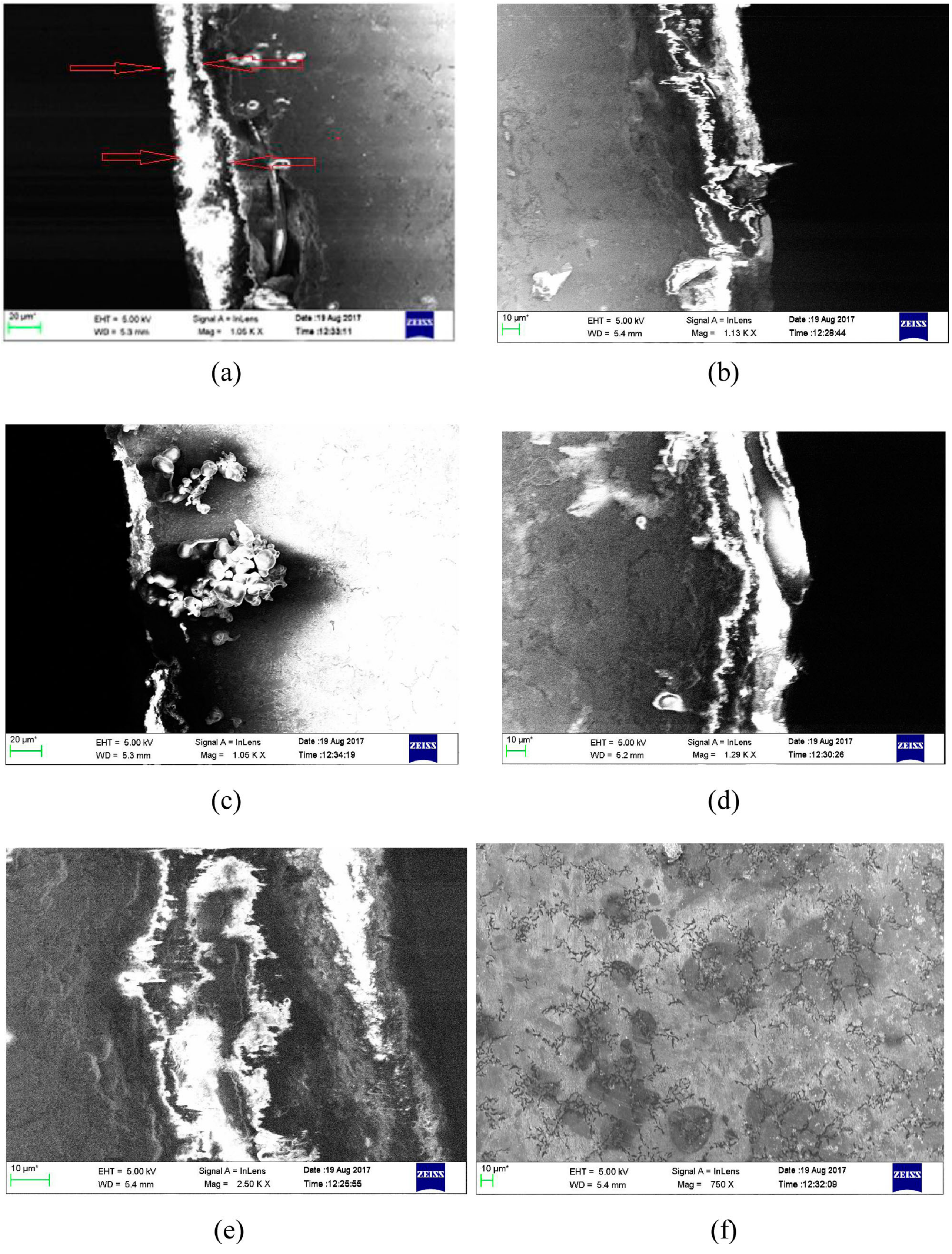


Figure 10. SEM images at the edge of the cylinder.

showed 120% more emissivity for the practical bore than the non-coated fin. It can be concluded from the finite element results obtained from the numerical analysis and the practical observations that the emissivity enhances the rate of air cooling of the engine bore. Also, the use of silicon carbide (SiC) powder as coating material is found to have higher rate of the heat transfer.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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