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Structural and Thermal Analysis of Al 6061-AlN-TiB2 Hybrid Composite Piston Using Ansys and XRD Analysis of Composite Pellets Fabricated by Powder Metallurgy Process

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Abstract: Metal Matrix Composites (MMCs) are advanced materials, which can develop some desirable properties than the matrix material. In this work, Al 6061 alloy reinforced with Aluminium Nitride (AlN) and Titanium Diboride (TiB_2)hybrid composite piston was modelled in solid edge and by using Ansys, structural and thermal properties of the piston was analysed in different compositions. The various compositions are Al 6061 alloy, Al6061-3%AlN-3%TiB_2, Al6061-6%AlN- 6%TiB_2, Al 6061-9%AlN - 9%TiB_2, and Al6061-12%AlN - 12%TiB_2. Equivalent stress, total temperature distribution and total heat flux were analysed in Ansys by providing suitable boundary conditions like upper body temperature 400^0C, force on sides 7.5 MPa, etc. By analysing the results, it was observed that the Al 6061-9%AlN-9%TiB_2 hybrid composite piston has high value of equivalent (von-mises) stress and the high of equivalent (von-mises) stress is 5.4835 GPa. From thermal analysis data, it was observed that the temperature distribution of hybrid composite piston ranges from 40^0C – 400^0C, also the Al 6061-9%AlN-9%TiB_2 hybrid composite piston has high value of total heat flux, and it is 6.8872 MW/m^2. Using powder metallurgy process the fabrication of the hybrid composite was done. The powder mixing was done using pestle and mortar and the mixtures were compacted at 100 psi pressure for 3 minutes in a tungsten carbide die using hydraulic press. Sintering process was done in conventional electric furnace at a temperature of 550^0C. The green and sintered densities of the composite pellets were calculated and also the densification parameter for each composition was calculated. XRD patterns of each specimen shows the presence Al 6061, AlN and TiB_2 in the composite from the observed lattice spacing (d) value with respect to the wavelength and intensity of incident ray.

Keywords: Metal matrix composites, powder metallurgy, Aluminium Nitride, Titanium Diboride, Ansys.

I. INTRODUCTION

Metal Matrix Composite (MMC) are comprise of at least two parts, one is the metal matrix and the subsequent segment is reinforcement. The matrix is characterized as a metal in all cases, but a pure metal is rarely utilized as the matrix. It is commonly an alloy. The matrix and the reinforcements are bonded together in various weight percentages for the fabrication of composite. Metal matrix composites exhibit some attractive characteristics, when compared with organic matrices. It includes (i) higher transverse strength, (ii) higher erosion resistance, (iii) superior thermal conductivity, (iv) better electrical conductivity, (v) strength retention at higher temperatures etc. The ductile matrix allows the blunting of cracks and stress concentrations by plastic deformation and provides a material with improved fracture toughness [1]. The high durability and impact strength of metals and alloys such as magnesium, aluminium, nickel-chromium alloys, and titanium experience plastic deformation under stress. In this aspect, one of the notable goals of MMC is to develop a material with judicious combination of toughness and stiffness. Therefore decreases the sensitivity of cracks and flaws and at the same time increase the static and dynamic properties. When there exists more than one reinforcements present in the composite matrix, it is called a hybrid metal matrix composite. Hybrid MMCs are fabricated by means of dispersing more than one reinforcement materials into a metal matrix in various weight percentages [2].
Ansys is universally useful Finite Element Analysis (FEA) programming package. Finite Element Analysis is a numerical method for analyse a complex framework into extremely little bits called components. The product executes conditions that oversee the conduct of these components and settles them all. These results at that point can be introduced in organized or graphical structures. This sort of investigation is commonly utilized for the structure and streamlining of a framework extremely complex to dissect by hand.
A piston is considered to be the main component of an engine in the automobile industry. The working principle of piston is based on converting the reciprocating motion into rotary motion with the help of a crankshaft via connecting rod. The purpose of the piston is to transfer the force exerted to the crankshaft during the combustion process. In power stroke, piston undergoes a massive amount of thermal and mechanical stress. Due to extreme temperature difference between piston head and cooling galleries, thermal stress is experienced only by the piston. Cyclic gas pressure and inertial forces generated during the piston reciprocation accounts the mechanical load. Thermal and mechanical fatigue load can result in piston side wear, head cracks or other major faults.

Manufacturers are already spending enormous amount of time and resources to overcome these problems. In this paper, the best composition of Aluminium hybrid composite was analysed for engine piston under thermal and structural conditions using Ansys.

A. *Materials*

In this present study Aluminium 6061 alloy powder (PARSWAMANI METALS Ltd., Mumbai, India) was used as matrix material and Aluminium Nitride (AlN) and Titanium Diboride (TiB_2) were used as reinforcing material (COIMBATORE METALS Ltd, Coimbatore, Tamil Nadu). The composition of Al 6061 alloy is shown in table 1.

Table 1. Composition of Al 6061 alloy

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other	Al
0.4-0.8%	0.7%	0.15-0.4%	0.15%	0.8-1.2%	0.04-0.35%	0.25%	0.15%	0.05-0.15%	95.85- 8.56%

Al 6061 alloy containing magnesium and silicon as its major alloying elements and it is a precipitation-hardened aluminium alloy. It has exhibits good weld-ability, and good mechanical properties. Al 6061 alloy is one of the most usual alloys of aluminium used for general purpose [3].Aluminium Nitride (AlN) and Titanium Diboride (TiB_2) were used as reinforcing material. For the fabrication of composites, AlN particles with average size of 10 μm together with TiB_2 particles with average size of 10 μm were used as the reinforcing particles. AlN is a solid nitride of aluminium. It has a high thermal conductivity of up to 285 W/(m•K), and it is an electrical insulator [4]. TiB_2 is an very hard ceramic, which has good oxidation stability, wear resistance and excellent heat conductivity,. TiB_2 can be used as an electrical conductor and as a cathode material in aluminium smelting [5]. It can be shaped by electrical discharge machining. Physical properties of Al 6061, Aluminium Nitride (AlN) and Titanium Diboride (TiB_2) is shown in table 2.

Table 2.Physical properties of Al 6061, Aluminium Nitride (AlN) and Titanium Diboride (TiB_2)

Sl.No.	Properties	Al 6061 alloy	Aluminium Nitride (AlN)	Titanium Diboride (TiB_2)
1	Density (g/cm^3)	2.7	2.92	4.52
2	Young‟s Modulus (GPa)	68.9	302	534
3	Poissons Ratio	0.33	0.23	0.13
4	Thermal Conductivity (W/m.K)	178	60	25

II. LITERATURE SURVEY

G Gopal et al stated the Static, Dynamic and Thermal analyses of assembly of piston, connecting rod and crankshaft [6]. The materials considered for piston are Aluminium alloy 6061 and Aluminium alloy 2618, for connecting rod are Aluminium alloy 6061 and Titanium and for crankshaft are EN308 and High Alloy steel. By observing the static analysis results, the stresses are increased and the displacements are less when Al 2618 Piston, Titanium Connecting rod and High Alloy Steel Crankshaft are taken. By observing the thermal analysis results, the heat transfer rate is more when the materials for Al 6061 Piston, Al 6061 Connecting rod and for EN308 Crankshaft are considered. By observing the dynamic analysis results, the stress values are less when Al 2618 Piston, Titanium Connecting rod and High Alloy steel Crankshaft are considered. Sachit T S et. al stated that the coating region on the surface of piston, cause an increase in the temperature as compared to uncoated [7]. So that due to increase in temperature the combustion in the combustion chamber increases. Also due to increase in heat flux in coated piston that maintains the required temperature near the chamber and reduces the thermal fatigue in other regions of piston.K.Satyanarayana explained the Quasi dynamic stress analysis of the piston at compression ratios of 16.5, 17.5 and 18.5 with the experimental observations obtained from a computerized diesel engine test rig [8]. Ideally the stress analysis has to be carried out at all angles of crankshaft rotation. It was observed that maximum temperature occur on the piston crown and minimum temperature at piston skirt for all compression ratios.I.J.IsaacPremkumar et al explained that the Hemispherical Existing Piston (HEP) and Deep Cylindrical Piston (DCP) had maximum stress values compared to Shallow Re-Entrant Piston (SRP) due to piston geometry bowl [9]. The maximum equivalent stress value of 8.2473 MPa for HEP was decreased to 7.9803 Mpa for SRP due to its well-structured piston design with appropriate compression ratio. The total deformation rate was changed from 0.0015612mm of HEP to 0.001448 mm of SRP because of enough stiffness in SRP.

Y. Pazhouhanfaret. al explained the Microstructural characterization and mechanical properties of Al 6061 reinforced with TiB_2MMC [10]. By using stir casting methodAl-TiB_2 composites with different amounts of reinforcement (3, 6 and 9 wt%) were fabricated. In this paper Microstructure, mechanical properties and the fracture surfaces of tensile specimens were studied. It is observed that the tensile strength was increases with increase of weight percentage of TiB_2 without significant decrease of elongation to failure. Increase in themechanical properties is due to decreasing matrix grain size, interaction of dislocations with reinforcement particles and high load bearing capacity of reinforcement particles. A. Chidambaram et. al fabricated AA6061–5wt.% TiB_2 and mechanical properties were identified [11]. It is observed that the strength and hardness of the composite increases with increase in weight percentage of reinforcement. The increase of Vickers hardness of composite compared matrix alloy is ~57 ± 1 HV to ~69 ± 1 HV and the yield strength improvement is ~113 Mpa (annealed) to~167 Mpa, also the ultimate tensile strength increased from ~146 Mpa to ~177 Mpa.S. Suresh et. al explained the mechanical behaviour of stir cast Al–TiB_2 composites using response surface methodology [12] and the wear prediction. The fabrication of composite was done by stir casting technique. It is observed that the

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mechanical properties like hardness, tensile strength etc are increases with increase in amount of reinforcement. Wear test was done in pin on disc apparatus and it is observed that wear rate decreases with increase in amount of reinforcement.

III. THERMAL AND STRUCTURAL ANALYSIS USING ANSYS

FEA is a computer model, of a material or design either new design or existing product refinement, that is stressed and analysed for specific results. It is used to represent the numerous algorithms (functions) in linear and non-linear systems. Linear systems do not take into account plastic deformation and non-linear systems consider the plastic deformation and are capable of testing a material up to fracture. Numerous FEA programs additionally are outfitted with the capacity to utilize various materials inside the structure. Methodology followed for the analysis of hybrid composite piston is shown in figure 1.

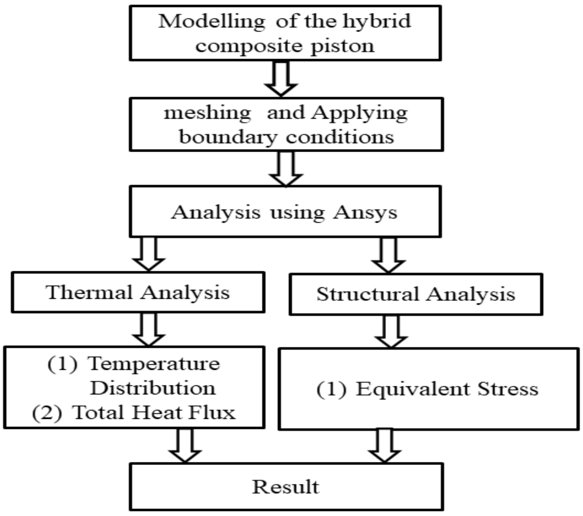

Figure 1. Methodology followed for the analysis of hybrid composite piston

A. *Modelling of piston geometry*

The piston was designed in solid works software and it is imported to Ansys for the analysis of thermal and structural properties like equivalent stress, temperature distribution and total heat flux. The modelling of composite was done in Cartesian coordinate system and matric unit system was followed. The modelled composite piston is shown in figure 2.

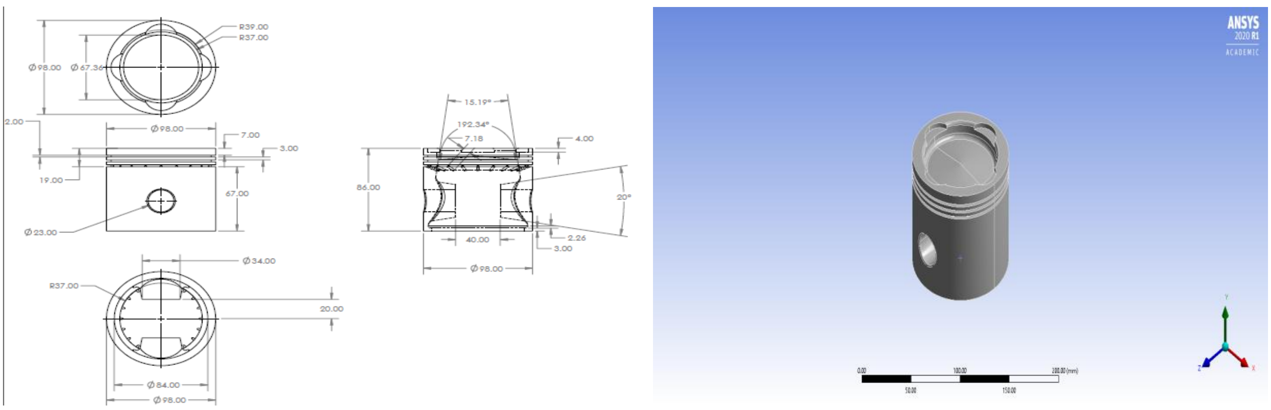

Figure 2. Geometry of the piston

B. *Meshing of hybrid composite piston*

The model is made into number of elements and nodes at the elements. The nodes make a grid called a mesh. This mesh is programmed to contain the material structural and thermal properties which define how the structure will react to certain boundary conditions, depending upon the stresses, the node density is assigned. Solid mass element Solid- Brick 20 node 186 is selected for meshing of hybrid composite piston for structural analysis. Thermal mass element Solid 20 node 90 is selected for meshing the hybrid composite piston for thermal analysis. Figure 3. shows the meshed part of the piston. After meshing, the solution was found out for the thermal and structural properties of composite piston. Meshing details include the following factors.Element size - 1.8, Number of element – 52077, Number of nodes – 13353, Type of element – Tetrahedral

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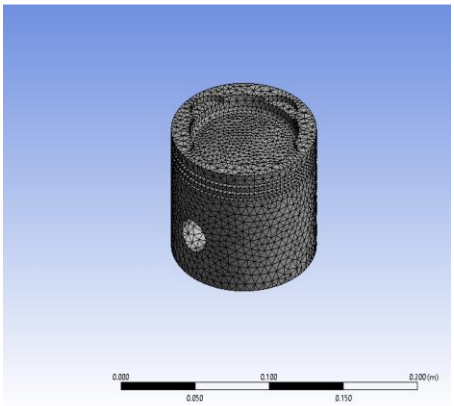

Figure 3. Meshed view of hybrid composite piston

C. *Appling boundary conditions*

After meshing the hybrid composite piston, the properties of the material is to be assigned for geometry. Then the boundary conditions must be applied to the hybrid composite piston for further analysis. The temperature at the top of composite piston was 400^0C and it is a fixed temperature for analysing the composite. The one side of the composite piston was fixed and it can rotate around the fixed side. The applied boundary conditions are shown in figure 4..

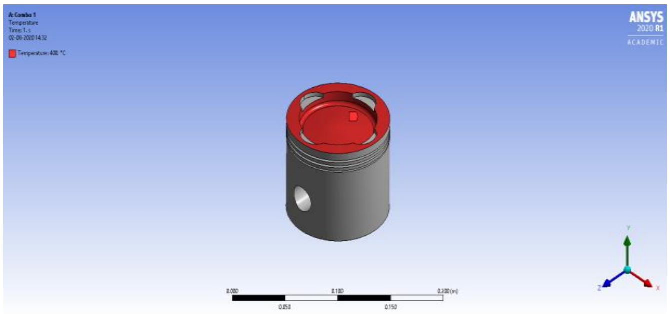

Figure 4. Applied boundary conditions

IV. FABRICATION OF HYBRID COMPOSITE PELLETS USING POWDER METALLURGY

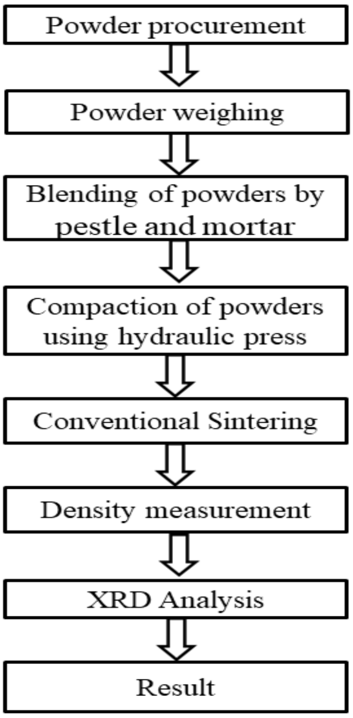

Figure 5. Flow chart of work plan for the experiments

The hybrid composite pellets with varying weight percentage of reinforcements like 0%, 3%, 6%, 9% and 12% were fabricated by powder metallurgy process. The powder metallurgy process include following stages. The fabrication process start with weighing the powdered matrix (Al 6061) and reinforcement (AlN and TiB_2) materials using an electronic weighing machine with an accuracy of 0.001g for each composition, followed by blending of powders using pestle and mortar for 15 minutes. Then compaction of powders in a tungsten carbide die using a hydraulic press with a pressure of 100 psi. Finally, sintering of the compacted specimen using a conventional electric furnace was done at a temperature of 550^0C for 1 hour. Thus a specimen with 10 mm diameter and 5-7 mm height hybrid composite pellets were fabricated. The schematic representation of work plan for this experiment is shown in figure 5.

Figure 6. shows the temperature profile for the conventional electric furnace. Initial temperature is set as 27 ^{0}C and it reaches about 550^0C for sintering process at a rate of 3.33^0C / min.

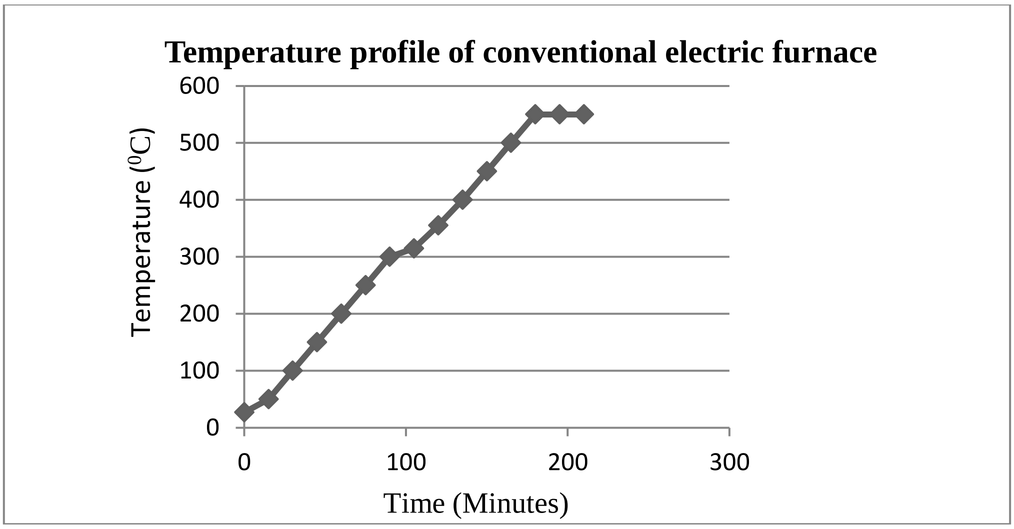

Figure 6.Temperature profile for conventional electric furnace

A. *Density measurement*
The green and sintered densities of the hybrid composite pellets were calculated using the formula density=mass/volume. For calculating densities, the mass and volume of the pellets should be known. The mass of the green and sintered pellets were measured using an electronic weighing machine and the volume of pellets can be found by the equation, volume = area*height = $\pi * r^2 * h$. Here 'r' is the radius of pellets and 'h' is the height of pellet. The radius and height of pellets can be measured using a verniercaliper. Thus the volume of the pellets can be found out. Thus using the formula, the green and sintered densities can be found out. The densification parameter gives an idea about the degree of densification occurred during sintering process. It be found using the formula

$$\text{Densification parameter} = \frac{Sintered\ density - green\ density}{theoretical\ density - green\ density}$$

B. *XRD analysis*
X-ray diffraction is very common technique for the study of crystal structures and atomic spacing of materials. X-ray diffraction works on the basics of constructive interference of monochromatic X-rays in a crystalline sample. These X-rays are generated by a cathode ray tube. Then it is filtered to produce a monochromatic radiation, which is collimated to concentrate the work sample. The work samples produce useful interference of the incident rays and a diffracted ray when conditions satisfy the Bragg"s Law ($n\lambda=2d \sin\theta$). The wavelength of electromagnetic radiation to the diffraction angle and the lattice spacing in crystalline samples is related using this law. These diffracted X-rays from the work samples are then detected, processed and counted simultaneously. All potential diffraction directions of the lattice should be reached due to the random orientation of the powdered material by scanning the sample through a range of 2θ angles. Conversion of the diffraction peaks to d-spacing makes identification of the mineral because of the unique d-spacing in the each mineral. The assessment of d-spacing with standard reference patterns and the deflected rays are collected. Angle between the incident and diffracted rays is the key component of all diffraction.

V. RESULTS AND DISCUSSION

A. *Structural analysis of hybrid composite piston using Ansys*
The Combustion of gases in the combustion chamber exerts pressure on piston head during power stroke. The Ansys workbench was used to inspect the structural characteristics of piston geometries by applying the boundary condition as pressure force. Consequently whatever the load was applied on piston the result of power stroke which causes damage to piston pin and also induces

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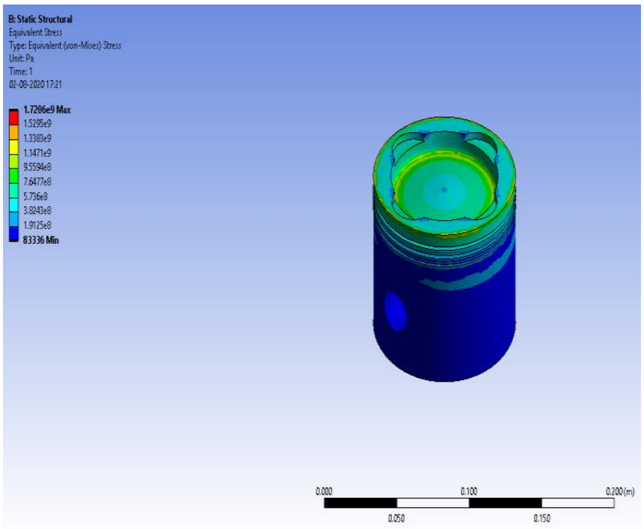
bending stress. The stress analysis of piston geometries was done under structural boundary conditions which were applied to the finite element model of the pistons.

(a) Analysis of Equivalent (von-mises) stress of hybrid composite piston



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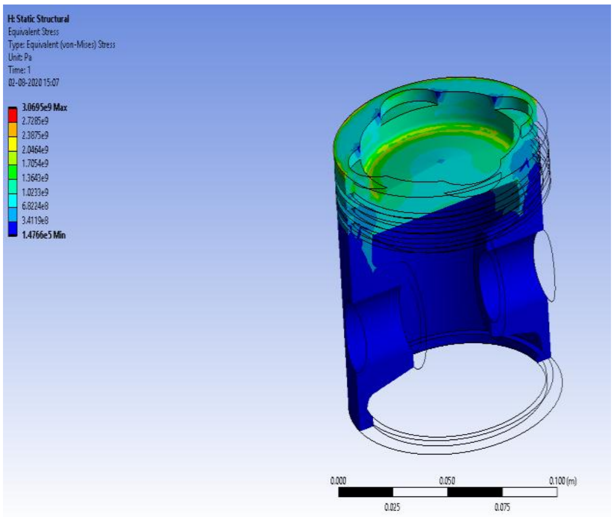

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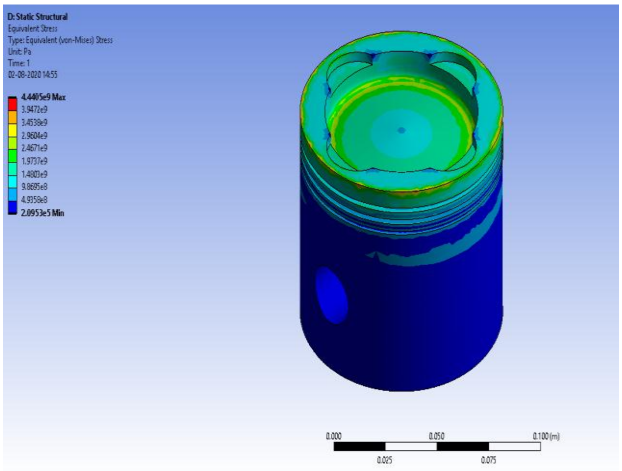

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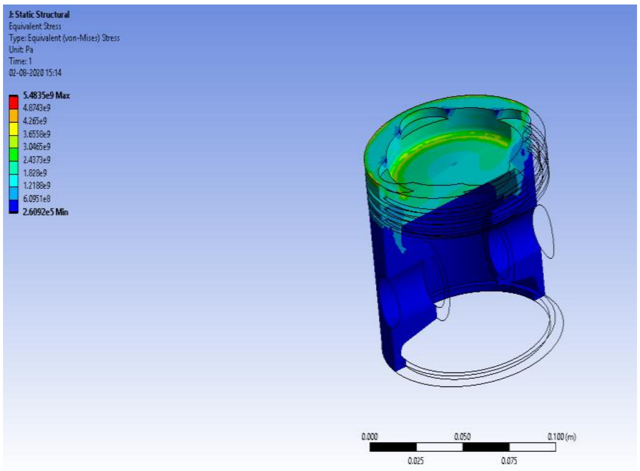

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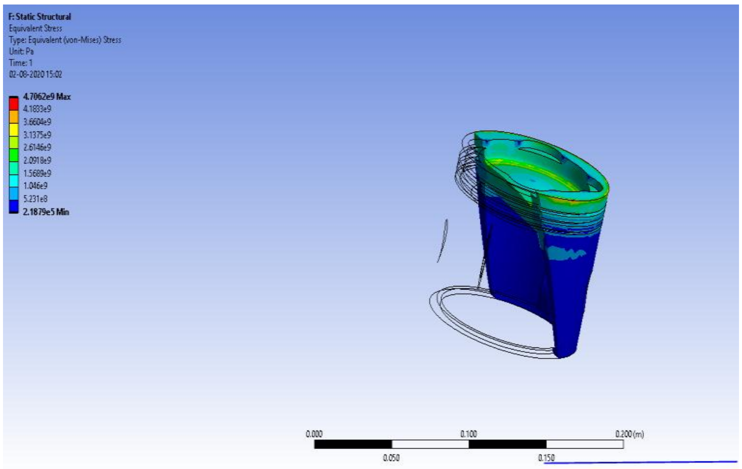

(e)

Figure 7. Equivalent (Von- mises) stress of (a) Al 6061 alloy, (b) Al 6061 - 3% AlN - 3% TiB_2, (c) Al 6061- 6% AlN - 6% TiB_2, (d) Al 6061-9%AlN-9%TiB_2, (e) Al 6061-12%AlN-12%TiB_2 hybrid composite piston

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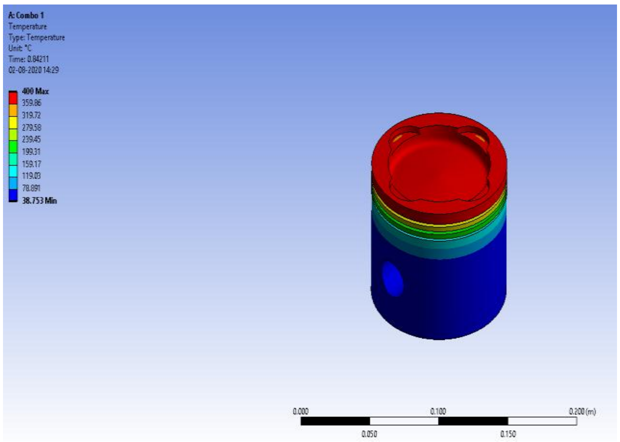
The observation from plots of Equivalent (von-mises) stress is given. The Equivalent (von-mises) stress is maximum at the top of all hybrid composite pistons. The observed values are: for Al 6061 alloy, its maximum value is 1.7206Gpa, for Al 6061-3%AlN-3%TiB_2, its maximum value is 3.0695 Gpa, for Al 6061-6%AlN-6%TiB_2, its maximum value is 4.405 Gpa, for Al 6061-9%AlN-9%TiB_2, its maximum value is 5.4835 GPa, for Al 6061-12%AlN-12%TiB_2, its maximum value is 4.7835 GPa. It was observed that Al 6061-9%AlN-9%TiB_2 composite piston has high value of Equivalent (von-mises) stress when compared to other hybrid composite pistons. The value for high Equivalent (von-mises) stress is 5.4835GPa

B. *Thermal analysis of hybrid composite piston*

For the thermal analysis of hybrid composite piston in Ansys, the convection boundary conditions are needed to be considered as the surface load, which is inflicted on the outside surface due to the direct contact of the combusted charge on the piston head; therefore temperature of 400^0C is provided to the upper surface of the piston.

(a) Analysis of temperature distribution of hybrid composite piston



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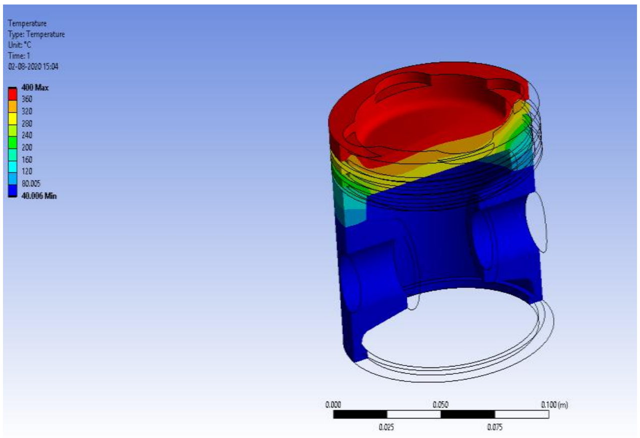

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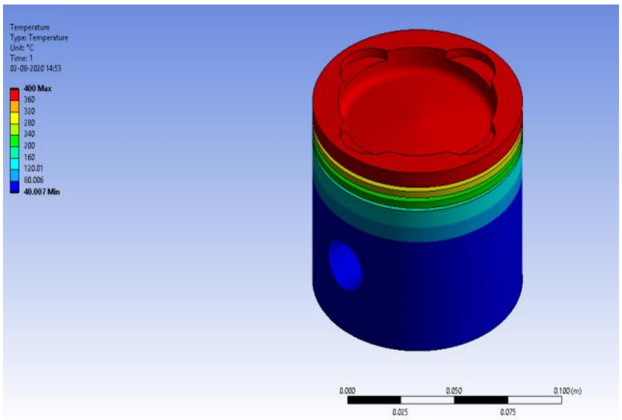

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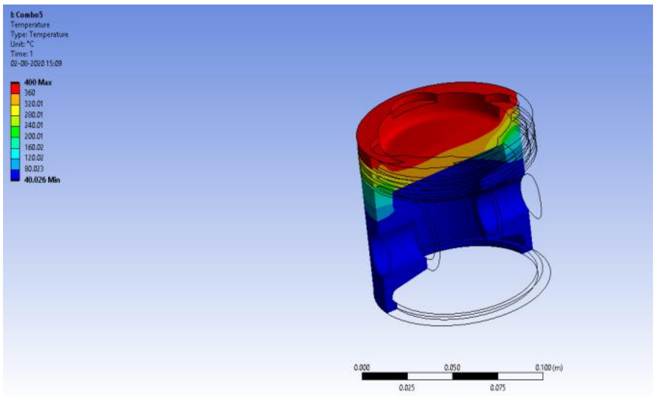

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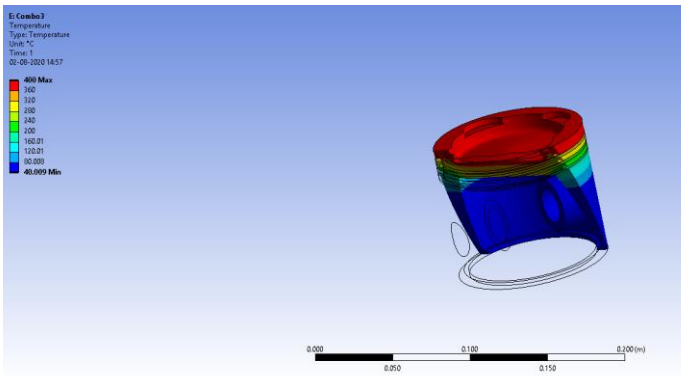

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Figure 8. Total temperature distribution of (a) Al 6061 alloy, (b) Al 6061 - 3% AlN - 3% TiB_2, (c) Al 6061- 6% AlN - 6% TiB_2, (d) Al 6061-9%AlN-9%TiB_2, (e) Al 6061-12%AlN-12%TiB_2 hybrid composite piston

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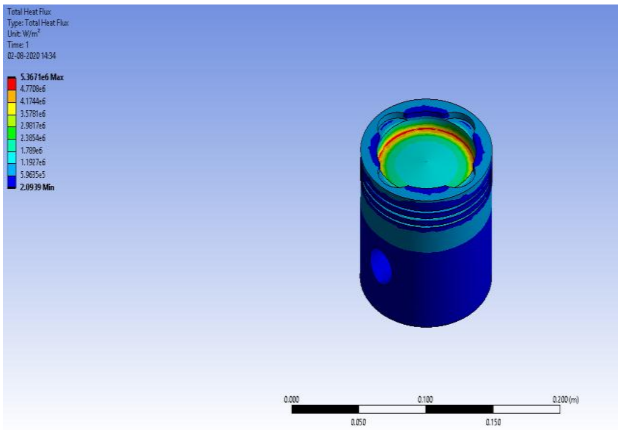
From the analysis, it is observed that the temperature distribution of hybrid composite piston ranges from 40^0C – 400^0C.Also it is observed that, there is a negligible change in the range of temperature distribution over various compositions.

(b)Analysis of total heat flux of hybrid composite piston



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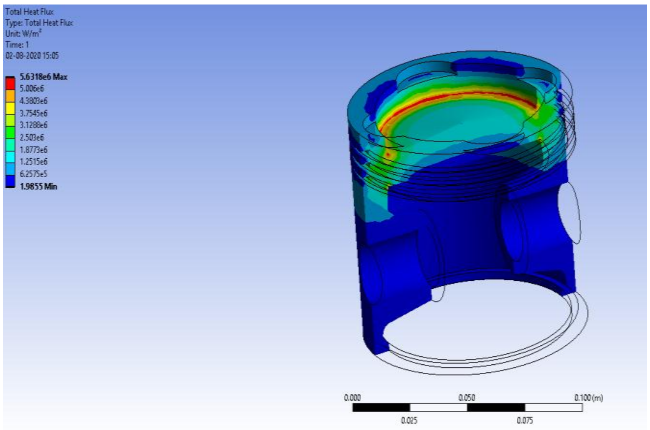

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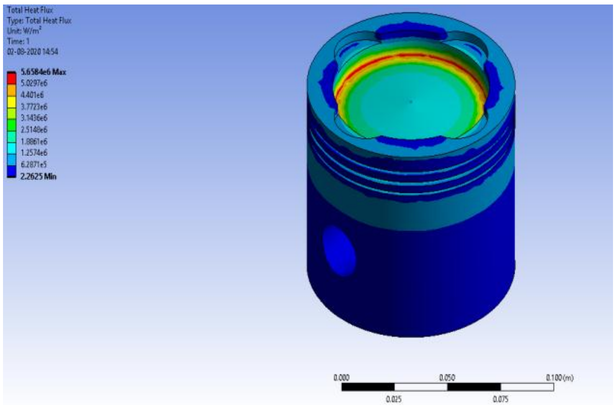

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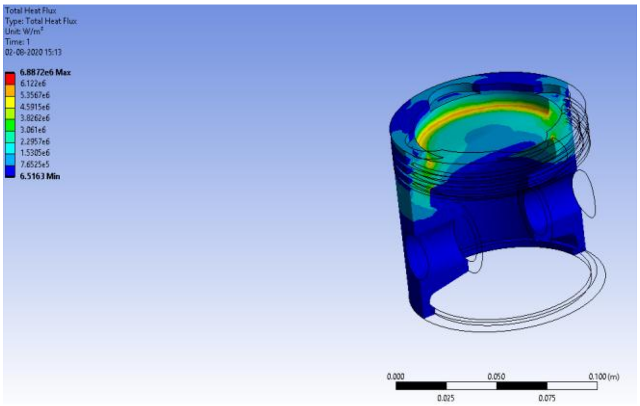

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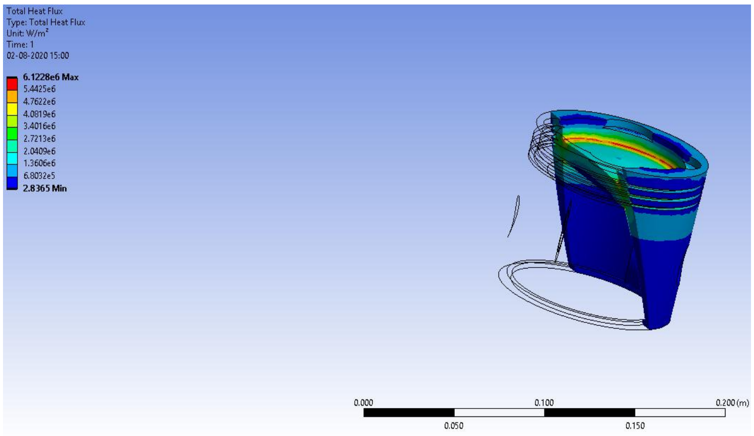


(e)

Figure 9. Total heat flux of (a) Al 6061 alloy, (b) Al 6061 - 3% AlN - 3% TiB_2,(c) Al 6061- 6% AlN - 6% TiB_2, (d) Al 6061-9%AlN-9%TiB_2, (e) Al 6061-12%AlN-12%TiB_2 hybrid composite piston

The observation from plots of total heat flux is given. It was observed that the maximum heat flux occurs at the top of all hybrid composite pistons. The observed values are; for Al 6061 alloy, its maximum value is $5.3671*10^6$ W/m^2, for Al 6061-3%AlN-3%TiB_2, its maximum value is $5.6318*10^6$ W/m^2, for Al 6061-6%AlN-6%TiB_2, its maximum value is $5.658*10^6$ W/m^2, for Al 6061-9%AlN-9%TiB_2, its maximum value is $6.8872*10^6$ W/m^2,for Al 6061-12%AlN-12%TiB_2, its maximum value is $6.1228*10^6$ W/m^2.It was observed that Al 6061-9%AlN-9%TiB_2 composite piston has high value of total heat flux, and it is $6.8872*10^6$ W/m^2

C.*Density measurement*

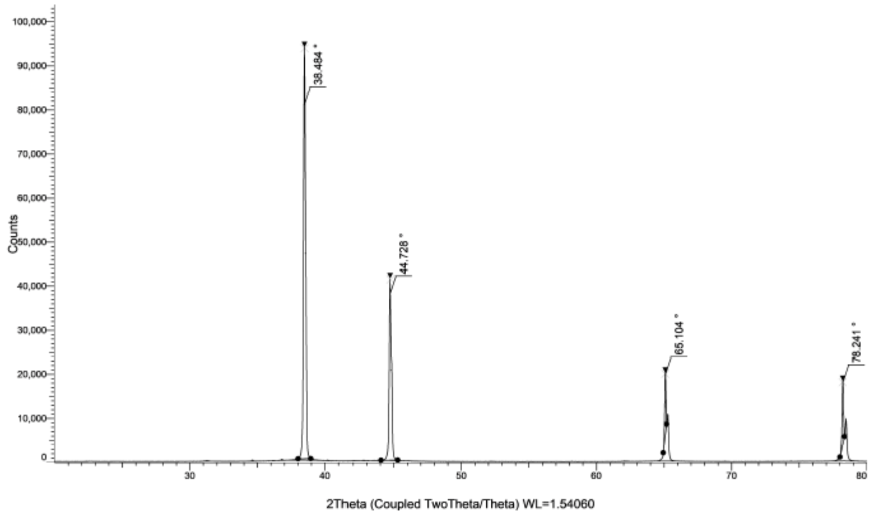
The Green and sintered densities of Al 6061 - AlN - TiB_2 hybrid composite pellets were identified. It was observed that the density of hybrid composite pellets were higher than that of the matrix material. The green and the sintered densities of Al 6061- AlN TiB_2 composites increases with weight percentage of AlN and TiB_2 reinforcements present in the composites. The reason for the increase in the densities of the composites is due to the presence of AlN and TiB_2 in the matrix material and the presence of porosity. However, the porosity can be reduced with increasing the compacting pressure leading to decrease in green density of Al 6061-AlN-TiB_2 composite. The densification parameter for various weight percentages of composite were also calculated using the formula. The calculated green and sintered densities of hybrid composite pellets and densification parameter were shown in the table3.

Table 3. Green and sintered density of hybrid composite pellets

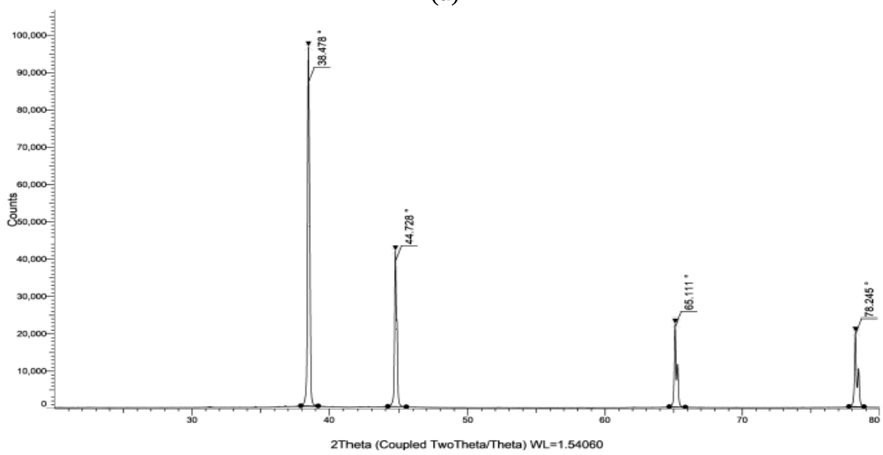
Composition	Green density (g/cm^3)	Sintered density (g/cm^3)	Densification parameter
Al 6061 alloy	2.64	2.68	0.667
Al 6061 alloy – 3%AlN-3%TiB_2	2.69	2.74	0.614
Al 6061 alloy – 6%AlN-6%TiB_2	2.75	2.82	0.754
Al 6061 alloy – 9%AlN-9%TiB_2	2.79	2.86	0.564
Al 6061 alloy – 12%AlN-12%TiB_2	2.87	2.93	0.519

D. *XRD Analysis*

XRD studies are carried out using Philips PW1710 model. The 2θ angle is varied from 10-80^0 with the composite pellet as the target material having a wavelength of 1.5418 Å. The results of XRD studies of Al 6061 alloy – AlN-TiB_2 composite in various compositions are presented in Figure 5.4. It is witnessed from figure 5.4 that all peaks are corresponds to Al 6061 alloy, AlN and TiB_2. It is clearly witnessed that as the percentage of Al 6061, AlN and TiB_2 content is increased with increasing weight percentage of reinforcement. No additional peaks are observed suggesting no reaction produced. The XRD results is shown in figure 10.



(a)



(b)

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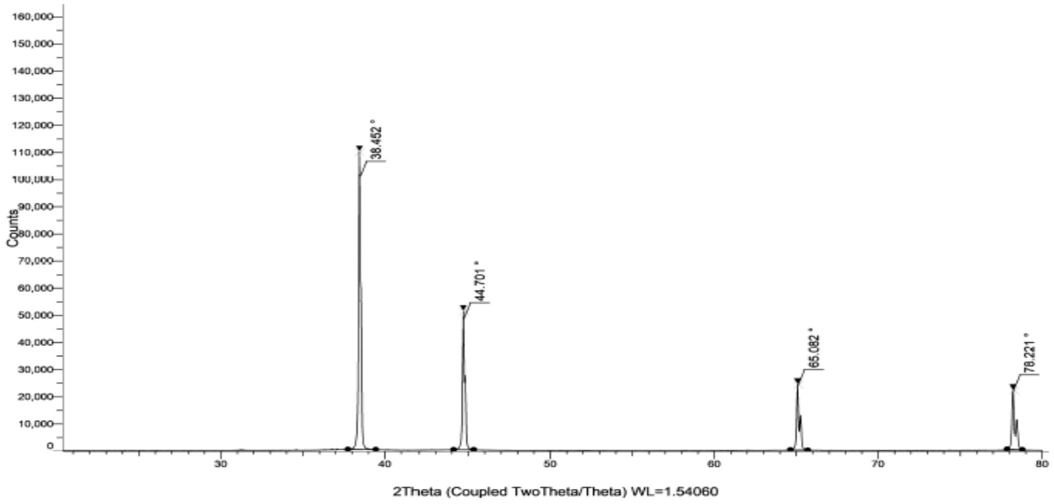
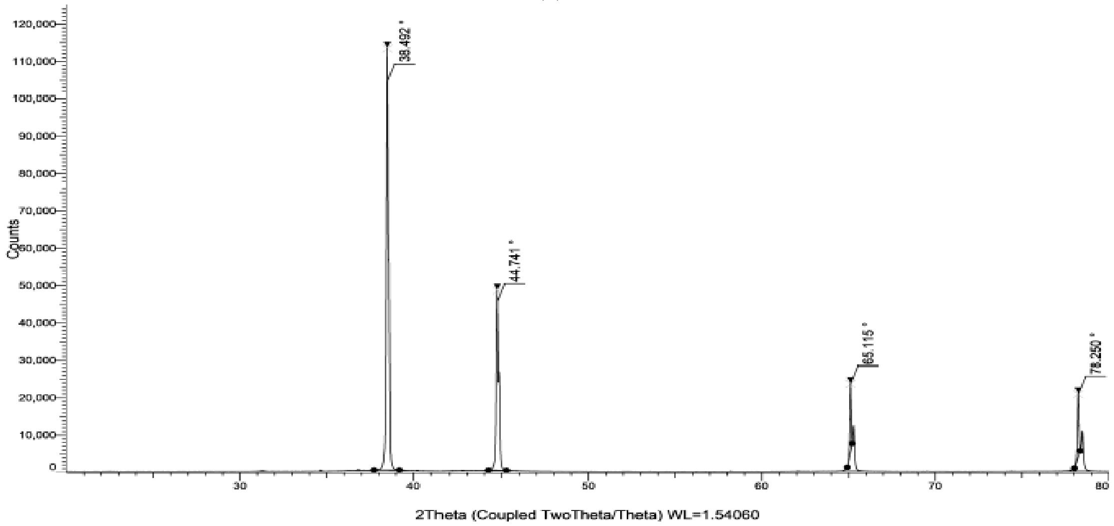
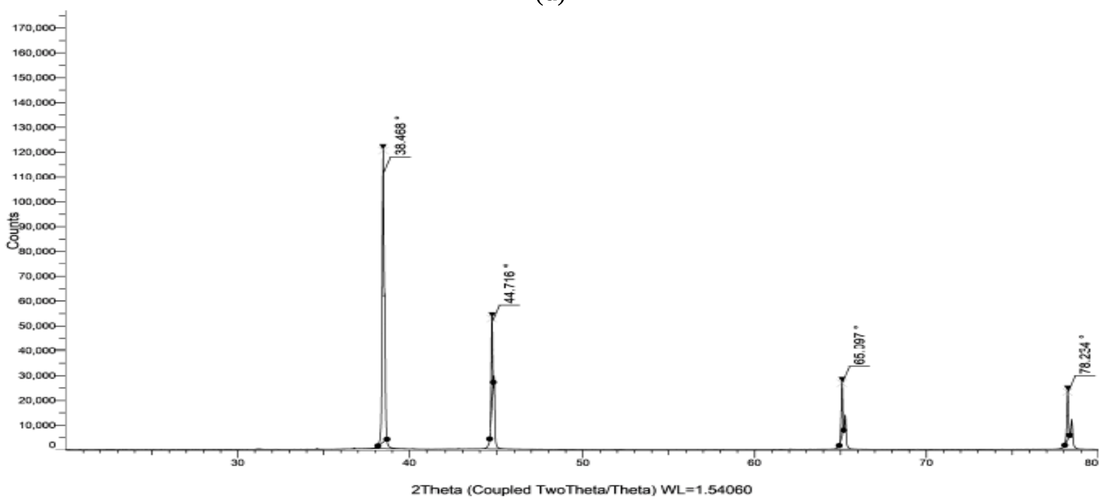


(c)



(d)



(e)

Figure 10 XRD results of (a) Al 6061 alloy, (b) Al 6061-3%AlN 3%TiB_2, (c) Al 6061-6%AlN 6%TiB_2, (d) Al 6061-9%AlN 9%TiB_2, (e) Al 6061-12%AlN 12%TiB_2 hybrid composite

From the XRD results, it is observed the lattice spacing (d) value of elements in the composite. The lattice spacing (d) value is shown in the table 4.

Table 4. Observed d (Lattice spacing) value of hybrid composites from XRD analysis

Composition No.	d- value in Å			
	Angle			
	78	65	44	38
1	1.22094	1.4317	2.02441	2.3371
2	1.22081	1.4231	2.02438	2.3375
3	1.22076	1.4345	2.0389	2.3368
4	1.2211	1.4320	2.025	2.3392
5	1.2209	1.4336	2.0235	2.3382

VI. CONCLUSIONS

In this present research work, structural and thermal analysis of hybrid composite piston was carried outin Ansys. Equivalent stresses, temperature distribution and total heat flux of hybrid composite piston was analysed using Ansys. Al6061alloy based hybrid composites was prepared using powder metallurgy technique with different TiB_2&AlN content. The XRD characterization was performed and observed the lattice spacing (d) value of the hybrid composite. The green density and sintered density of hybrid composite was calculated. From the present study following conclusion are made;

From structural analysis, it is observed that Al 6061-9%AlN-9%TiB_2 hybrid composite piston has high value of Equivalent (von-mises) stress and the value is 5.4835 Gpa

It is observed that the temperature distribution of hybrid composite piston ranges from 40^0C – 400^0C. And there is a negligible change in the range of temperature distribution over various compositions

Also observed that, Al 6061-9%AlN-9%TiB_2 composite piston has high value of total heat flux, the value is $6.8872*10^6$ W/m^2

From density measurement, it was observed that the densities of hybrid composite pellets were higher than that of the matrix material. The green and the sintered densities of Al 6061- AlN-TiB_2 composites increases with increase in weight percentage of AlN and TiB_2 reinforcements

From XRD analysis observed the value of lattice spacing for the materials. Also find that, all composite consist of same type of material such as Al 6061, AlN and TiB_2

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