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Modeling and Analysis of Engine Crankshaft using Polyamide Imide (Torlon) and Acrylonitrile Butadiene Styrene (ABS)

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***Abstract* - The crankshaft is an essential component for the successful and accurate working of the internal combustion engine. Crankshaft is a notably large component in the engine which converts reciprocating displacement motion of the piston to a rotary motion with the aid of four link mechanisms. During the service life of the engine, the crankshaft undergoes a large number of load cycles where its performance and durability play a crucial role. Designers have to keep track and develop new designs regularly based on important parameters such as minimum weight, lasting fatigue strength and lower cost so that improvements may result in lighter engines with better fuel efficiency and higher power output. Also, the crankshaft should be reliably hard enough to withstand excessive bending loads. This work involves evaluating and comparing fatigue and thermal performance of two production materials [Polyamide Imide (Torlon) and Acrylonitrile Butadiene Styrene (ABS)] with conventional Aluminium alloy. A single cylinder crankshaft model is developed using Creo Parametric and analysis of the model is performed using ANSYS Workbench. Static structural and thermal analysis are carried out using three different material properties. The results obtained after comparison analysis results of all three materials show that the 3d printable materials like ABS and Torlon can be used as a potential alternate to the conventionally used Aluminium alloys.**

***Keywords* : ANSYS Modelling*;* Crankshaf*t;* Finite Element Analysi*s;* Material Testing**

1. INTRODUCTION

The internal combustion engine will remain an indispensable part of the automotive and off-road applications in the foreseeable future. However, it must respond to two major challenges: the reduction of pollutant emissions and improvement of fuel efficiency. Electrically driven cars are definitely the future. But until we have cheap, 1000-mile batteries, we still need to run fossil-fuel engines. Potential for improving fuel efficiency is certainly still offered by the internal combustion engine. One such method could be to develop an optimized geometry, material, and manufacturing procedure which will reduce the weight of the engine crankshaft for fuel efficiency and reduce the manufacturing cost due to high volume production of this component**.**

The crankshaft is the most important part of the engine as it transforms the power delivered to the piston by the burning gas of a fuel thereby converting reciprocating motion into a rotary motion. The conventional crankshaft is made from a steel forging or casting and is machined and ground to provide suitable journals for connecting rod and main bearings with suitable lubrication paths for relief from friction. Separate forgings are fitted together as straight as possible during operation as otherwise it could lead to serious damage to the bearings and thence to the engine. The crankshaft experiences a large number of load cycles during its service life, so fatigue performance and durability of this component has to be considered during the design process. Design developments have always been an important issue in the crankshaft production process, as the manufacturing industry always aims to reduce the component cost and weight while improving the fatigue strength and other functional requirements. Vibration and distortion of a crankshaft are main problems which lead to various stresses and defects in the crankshaft. Many of the defects that occur on such units are down to wear in the main bearings causing the crankshaft to change its longitudinal straightness. Crankshaft must be strong enough to take the downward force of the power stroke without excessive bending. So, the reliability and life of an internal combustion engine depend on the strength of the crankshaft. Many authors have discussed about the intensity and stiffness of the crankshaft material influencing the reliability and service life of the engine

Jianxi, et al., [1] has investigated the highly stressed knuckle region of the crank arm and main journal using the finite element method (FEM) and concluded that the crankshaft both reversed and bent when reciprocating and centrifugal inertial force were applied by the piston on the crankshaft.

W.Y Chein, et al., [2] investigated the influence of the residual stresses induced by the fillet rolling process on the fatigue process of a ductile cast iron crankshaft section under bending. The results indicated that the four-bubble failure criterion employed by the author for crack analysis of the crankshaft only determined the crack initiation life for small cracks initiated on the surfaces of fillets. The four-bubble failure criterion did not indicate whether a fatigue crack initiated on the fillet surface can propagate through the compressive residual stress zone induced by the rolling process.

Osman Asi, et al., [3] analyzed the failure of a diesel engine crankshaft used in a truck, which is made from ductile cast iron. The crankshaft was found to break into two pieces at the crankpin portion before completion of warranty period. The author concluded that the absence of the hardened case in the filet region and the presence of free graphite and non-spheroidal graphite in the microstructure of the crankshaft made fatigue strength decrease to lead to fatigue initiation and propagation in the weaker region and premature fracture.

Sun, et al., [4] reviews methods for assessing crankshaft strength to enhance engine durability. Mourelatos, et al., [5] presents a model for studying how crankshaft systems handle dynamic stresses like vibrations during engine operation.

Using FEA in elemental study Bowman, et al., [6] studied the structural behavior of a specific diesel crankshaft which provided a lot of insight onto crankshaft failure conditions.

While the majority of authors focused on model analysis and validation Wang, et al., [7] and Henry, et al., [8] focused on modeling crankshaft vibrations for design optimization and introduced a new 3-D approach to predicting crankshaft durability.

Although other researchers [9, 10] delved into material research for crankshaft production, they failed to explore the potential of 3D printable materials

In the current study, finite element analysis of crankshaft is carried out using the FME software ANSYS to simulate the static analysis of a single cylinder crankshaft model developed using Creo Parametric (Fig.1). The results of stress and deformation distributions of the crankshaft are obtained. The results could be regarded as a theory basis to optimize the design of crankshaft and to analyze the structure dynamics of crankshaft. Here study is conducted based on a single cylinder engine crank shaft shown below. This work involves evaluating and comparing fatigue and thermal performance of two thermoplastics [Polyamide Imide (Torlon) and Acrylonitrile Butadiene Styrene (ABS)] with conventional aluminum alloy.

Fig.1. Single Cylinder Crankshaft to be Modeled using Creo Parametric

2. MATERIAL CHARACTERISTICS

2.1. TORLON POLYMER

Torlon has exceptional mechanical and thermal properties. It is a brand name for a family of polyamide-imide (PAI) resins developed by Solvay Specialty Polymers. Torlon resins are known for their outstanding combination of high-temperature resistance, chemical resistance, and mechanical strength

For reliable performance at extremely high temperature and stress, TORLON polymers are used. Parts made of TORLON Engineering polymers perform under conditions generally considered too severe for thermoplastics such as parts for the space shuttle or the engine of a world-class race car. Across a wide range of industries-electrical and electronics; business equipment; aerospace; transportation; process and heavy equipment — TORLON parts meet design challenges. Some other engineering resins may perform at 500°F, but TORLON polymers maintain superior strength at this extreme temperature. Of the high-temperature plastics, TORLON polymers have the advantage of being injection-moldable, through which exact replication and low unit costs can be achieved making TORLON polymers the cost-effective solution to difficult design problems. TORLON high performance polymer is a poly (amide imide), with the general structure in (Fig. 2)

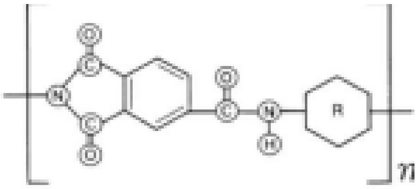

Fig. 2 Torlon Polymer Structure

The variety of applications requiring high temperature resistance, high strength, and the economies of injection-molding has led to the commercialization of several TORLON grades with different mechanical properties (Fig. 3), which can be divided into two categories; the high strength grades and the wear resistant grades. The high strength grades perform more like metals at elevated temperature, even under considerable stress.

These grades are ideally suited for repetitively-used precision mechanical and load bearing parts. The inherent lubricity TORLON poly (amide-imide) is enhanced with additives in the wear resistant grades. Moving parts made of TORLON polymers provide dependable service in lubricated and non-lubricated environments. The engineering properties of Torlon are shown in Table 1.

Table 1 TORLON Polymer categories

TORLON ENGINEERING POLYMERS	
HIGH STRENGTH	**WEAR RESISTANT**
4203L	**4347**
5303	**4301**
7130	**4275**

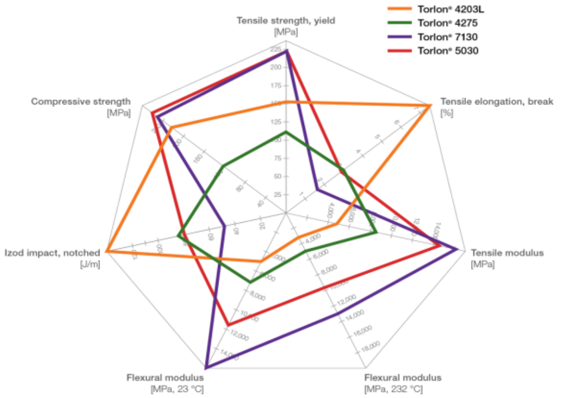

Fig.3. Mechanical Properties comparison between TORLON Grades

High impact strength, exceptional mechanical strength, and excellent retention of these properties in high temperature environments characterize all TORLON resins.

TORLON poly (amide-imide) can be used in applications previously considered too demanding for many other engineering plastics because of its outstanding tensile and flexural strength combined with retention of these properties in continuous service at temperatures in excess of 450°F (232°C).

While many competitive resins can claim "excursions" up to 500°F (260°C), TORLON polymers function with integrity at extremely high temperatures, which demonstrate the exceptional retention of tensile and flexural strength of TORLON resins at elevated temperatures. As shown in Fig. 4 TORLON resins have outstanding tensile and flexural strengths across a broad temperature range. From the above grades TORLON 7130 has been selected in this study due to its exceptional tensile and flexural strengths.

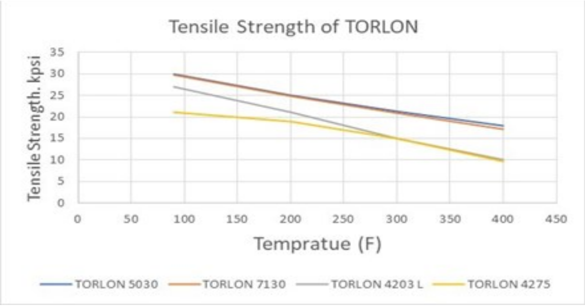

Fig. 4.1 Tensile Strength of TORLON resins at different temperatures

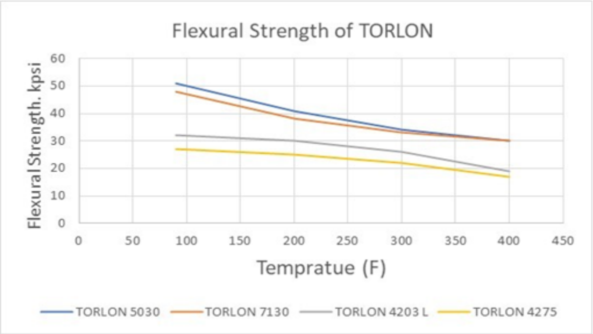

Fig. 4.2 Flexural Strength of TORLON resins at different temperatures

2.2 ABS POLYMER

Acrylonitrile butadiene styrene (ABS) is a thermoplastic polymer used for injection molding applications. The most important mechanical properties of ABS are impact resistance and toughness. A variety of modifications can be made to improve impact resistance, toughness, and heat resistance. The impact resistance can be amplified by increasing the proportions of polybutadiene in relation to styrene and also acrylonitrile, although this causes changes in other properties. Impact resistance does not fall off rapidly at lower temperatures. Stability under load is excellent with limited loads. Thus, by changing the proportions of its components, ABS can be prepared in different grades. Two major categories could be ABS for extrusion and ABS for injection molding, then high and medium impact resistance. Generally, ABS has better characteristics within a temperature range from −20 to 80 °C (−4 to 176 °F). The General structure of ABS is given in (Fig.5)

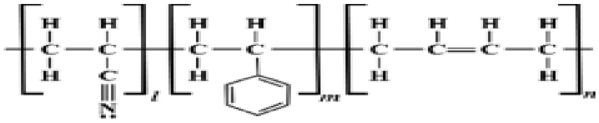

Figure. 5 ABS Polymer Structure

2.3. ALUMINIUM ALLOY

The aluminum alloy selected here for comparison is the 6061 graded annealed aluminum alloy. The chemical composition of the said alloy is given below in Table 2 and the mechanical composition is given in Table 3.

Table 2 Chemical Composition of Aluminium 6061 alloy

Element	Specified
Si	0.40 to 0.80
Fe	0.70 Max
Cu	0.15 to 0.40
Mn	0.15 Max
Mg	0.80 to 1.20
Zn	0.25 Max
Cr	0.04 to 0.35
Al	Reminder

Table 3 Mechanical and Electrical Properties of Aluminum 6061 alloy

Ultimate Tensile Strength	27kg/mm^2
% Elong	8 %
Hardness in BHM	80

3. DESIGN AND EXPERIMENTAL ANALYSIS

3.1. DESIGN MODEL

The model of single cylinder crankshaft is created using CREO PARAMETRIC 3.0. Finite element analysis will be performed on the crankshaft in order to optimize the weight and manufacturing cost. The design and specification of crankshaft are obtained from the Ducati Desmoquattro engine.

After modeling, the static structural, thermal and thermo-structural analysis is carried out for three different material properties. Torlon and ABS polymers are compared with commercially used aluminum alloy crankshafts.

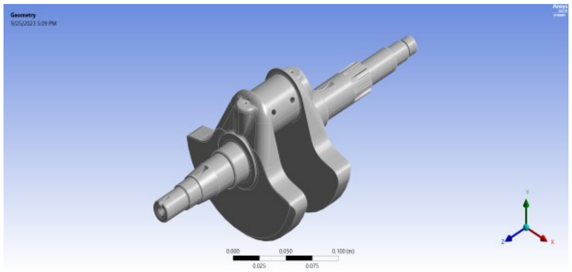

Fig .6. Crankshaft Model

3.2. ENGINEERING DATA (MATERIAL SELECTION)

Material addition in engineering data is done on ANSYS WORKBENCH by adding the new material and its properties. The Mechanical and Thermal properties of the materials added in the material library are shown below in Table 4.

Table 4 Mechanical and Thermal Properties

MATERIAL TYPE	ALUMINIUM ALLOY	TORLON	ABS
TENSILE STRENGTH	310 MPa	113 MPa	70 MPa
YIELD STRENGTH	276 MPa	103 MPa	48 MPa
POISSON'S RATIO	0.33	0.39	0.35
YOUNG'S MODULUS	68.9 GPa	6.2 GPa	2.28 GPa
DENSITY	2.7 g/cc	1.46 g/cc	1.04 g/cc
THERMAL CONDUCTIVITY	210 W/m-k	0.370 W/m-k	0.171 W/m-k
SPECIFIC HEAT CAPACITY	0.900 J/g-C	1.26 J/g-C	1.85 J/g-C
MELTING POINT	660.37 C	260 C	250 C

3.3. BOUNDARY CONDITIONS

3.3.1. Static Structural

The Crankshaft is fixed on both sides allowing no displacement but only rotation because the crankpin has contact only with the journal bearing so no lateral movement takes place except rotation around the journal which means both the ends of the crankshaft are constrained for all degrees of freedom. The pressure is applied to the crank pin bearing on the outer surface as a torsional moment. It is because there is a tangential force and radial force acting on many contact points which is extremely difficult to predict. The fixed constraint of the crankshaft and the moment applied to it are shown in the figure below. The moment is calculated from a standard engine data of 97mm bore and 128mm stroke and a gas pressure of 55.7 Pa. A moment of 604.78 N-m is applied as shown in Figure 7.

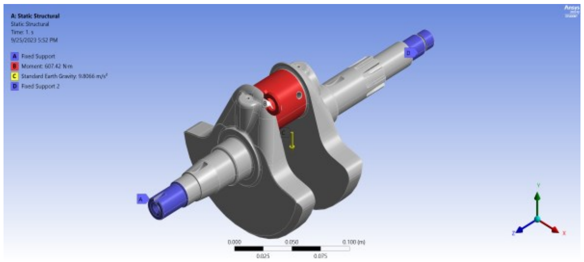

Fig.7 Fixed support and Moment applied

3.3.2. Thermal

During rotational motion, heat is generated on the crankpin, excess heat flux may be generated leading to the reduction of quality. A temperature value is given to the crankpin along with a corresponding convection value to the outer surface of the bearings. A nominal temperature value of 200 C is assumed for conduction with 22 C convection by the outer surface of the journal. The thermal conditions are shown in Fig 8.

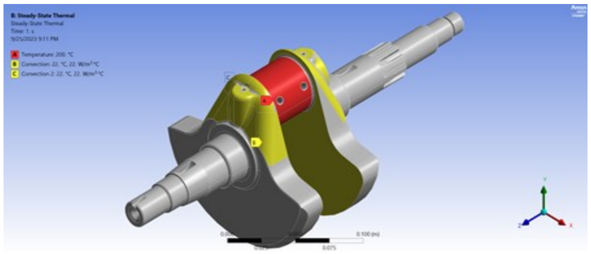

Fig.8. Thermal boundary conditions

The heat flux values along with the overall temperature distribution were recorded and results obtained are explained below.

4. RESULTS AND DISCUSSION

4.1 Static Structural

4.1.1 Maximum Deformation

The investigation concerns the deformation of the crankshaft under specified loading conditions across various material compositions. Presented in Table 5 are the corresponding values, while Figures 9, 10, and 11 depict the deformed models utilizing Aluminum, Torlon, and ABS materials, respectively.

Table 5 Deformation Values

Material	Maximum Deformation (mm)
Aluminum	0.0016
Torlon	0.019
ABS	0.043

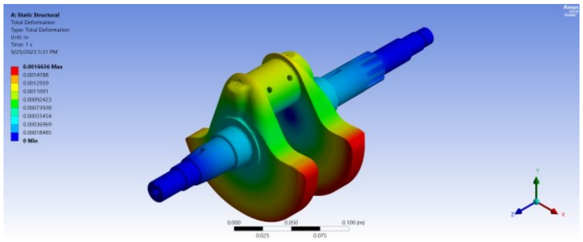

Fig 9. Aluminum Alloy Deformation

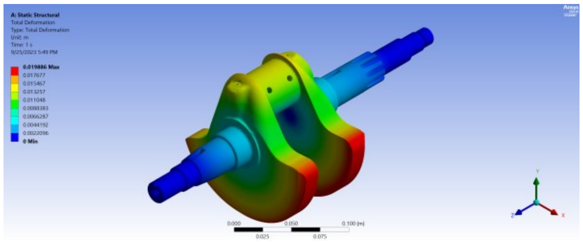

Fig 10. Torlon Deformation

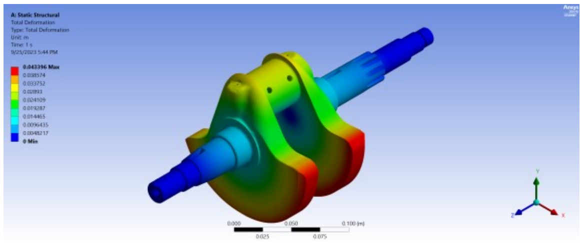

Fig 11. ABS Deformation

It can be seen that maximum deformation is taking place on the base of the crankshaft. Aluminum alloy shown in Figure 9 has the least deformation as it has better ductility when compared with Torlon and ABS materials. The deformation of Torlon and ABS shown in Figure 10 and 11 respectively are still within strain limits of their respective materials to allow for functioning without the risk of failure.

4.1.2 Equivalent Stress Distribution

The maximum von-Mises stress values of the crankshaft under specified loading conditions across various material compositions are presented in Table 6, while Figures 12, 13, and 14 depict the deformed models utilizing Aluminium, Torlon, and ABS materials, respectively.

Table 6 Maximum Stress Values

Material	Maximum Stress (N/mm^2)	Material Yield (N/mm^2)
Aluminum	37.84	276
Torlon	37.849	103
ABS	37.86	48

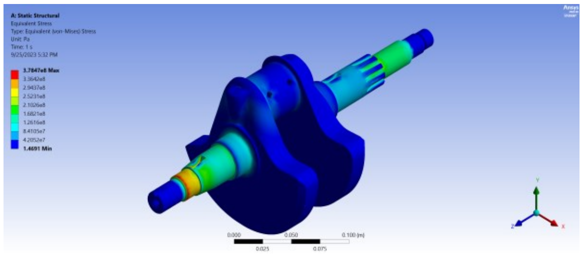

Fig 12. Aluminum Equivalent Stress

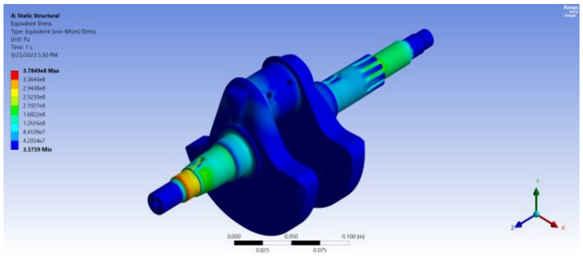

Fig 13. Torlon Equivalent Stress

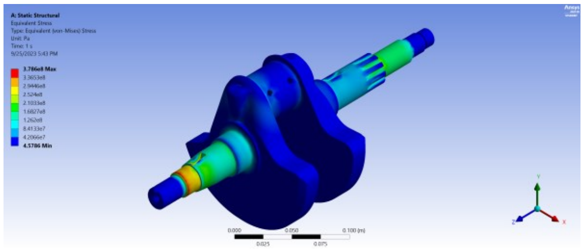

Fig 14. ABS Equivalent Stress

Testing under static conditions revealed that the maximum stress developed on the crankshaft is in the same range for all 3 materials. On assessing Figure12, Figure 13 and Figure 14, it is evident that maximum stress is developed on the arms of the crankshaft. The stress values obtained for all 3 materials are below the material yield point. This makes the component safe to use in static conditions.

4.2 Thermal

4.2.1 Temperature Distribution

The temperature distribution of the crankshaft under specified thermal loading conditions across various material compositions are presented in Table 7, while Figures 15, 16, and 17 depict the thermal distribution in the crankshaft utilizing Aluminium, Torlon, and ABS materials, respectively.

Table 7 Minimum Temperature Values

Material	Minimum Temperature(C)
Aluminum	191.25
Torlon	22
ABS	23.15

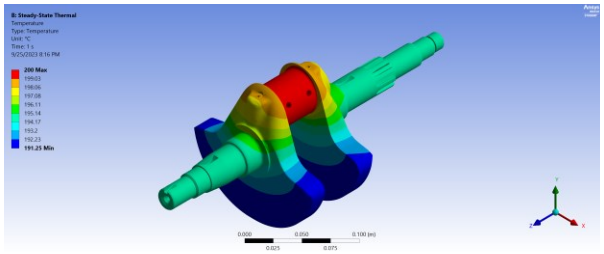

Fig 15. Aluminum Temperature Distribution

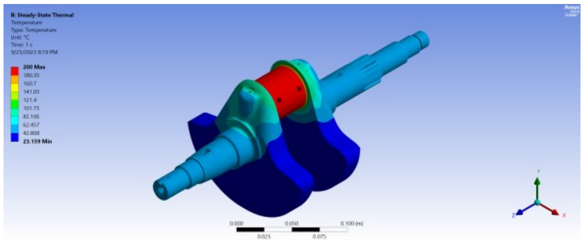

Fig 16. Torlon Temperature Distribution

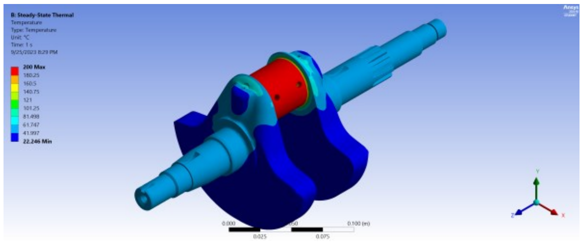

Fig 17. ABS Temperature Distribution

From Figure 16 and Figure 17 it is understood that heat convection happens in a much higher rate in Torlon and ABS. The convection in crankshaft using Aluminium alloy is very minimal as shown in Figure 15. The higher melting point of Aluminium when compared to the other 2 materials make up for the minimal heat convection values. These values provide evidence that all 3 materials are suitable for working in engine conditions without reaching their melting point.

4.2.2 Heat flux

The heat flux within the crankshaft under specified thermal loading conditions across various material compositions are presented in Table 9, while Figures 18, 19, and 20 depict the heat flux distribution within the crankshaft utilizing Aluminum, Torlon, and ABS materials, respectively.

Table 8 Maximum Heat Flux Values

Material	Max Heat Flux (W/m^2)
Aluminum	190000
Torlon	13998
ABS	8107

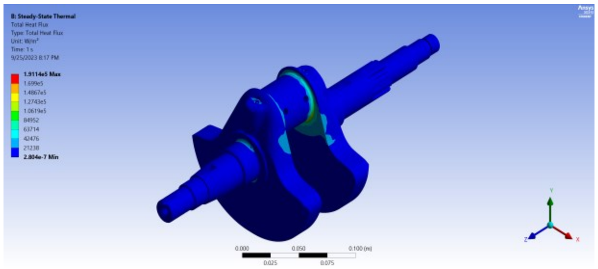

Fig 18. Aluminum Heat Flux

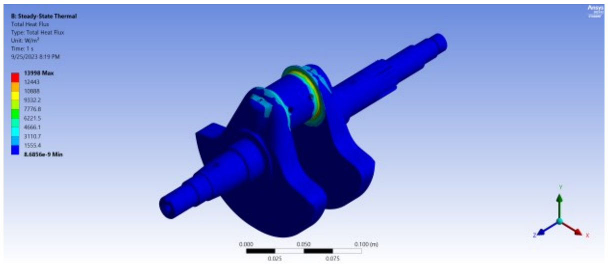

Fig 19 Torlon Heat Flux

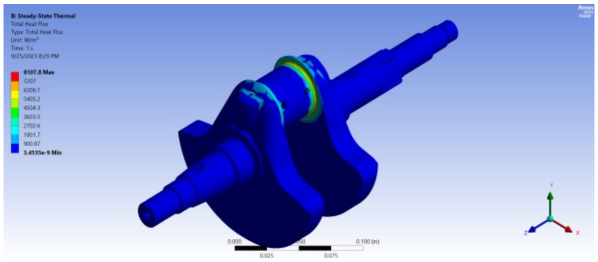

Fig 20. ABS Heat Flux

From figures 18, 19, and 20 it is evident that maximum heat flux is generated along the joining points of the crank pin. The heat flux of aluminum is higher than Torlon and ABS. This indicates that heat transfer takes place at a quicker rate in Aluminum when compared to Torlon and ABS. The heat flux of ABS and Torlon are stable enough for heat transfer to proceed even though it is lower than Aluminum.

4.2.3 Discussion

The difference in values for the thermal analysis is mostly due to the variations in the thermal conductance values. This variation could be a result of the following factors

I) Atomic Structure: In metals like aluminum, there are free electrons that can move through the lattice of metal atoms, carrying heat energy efficiently. These free electrons allow for the rapid transmission of heat. Plastics, on the other hand, do not have such free electrons, and the heat transfer in plastics occurs primarily through the vibration of the molecules.

II) Density: Metals like aluminum have a high density and a closely packed atomic structure, which facilitates efficient heat conduction. Plastics typically have lower densities and a more open molecular structure, which hinders heat transfer.

III) Molecular Structure: The molecular structure of plastics is often composed of long polymer chains with weaker intermolecular forces compared to the metallic bonds in metals.

4.3 Coupled Thermal - Structural Analysis

In real-time conditions, coupled thermal-structural analysis are carried out together so that engineers can better understand how these systems will behave in actual operating conditions. By coupling thermal and structural analyses, engineers can accurately predict the effects of temperature on the structural integrity of a system. The thermal output is coupled with the static structural module and the structural stability of the crankshaft is checked.

*4.3.*1 Total Deformation

Under the coupled condition, the deformation of the crankshaft under specified loading conditions across various material compositions are analysed and the maximum values are presented in Table 10, while Figures 21, 22, and 23 depict the deformed models of the crankshaft utilizing Aluminium, Torlon, and ABS materials, respectively.

Table 9 Maximum Deformation Values

Material	Maximum Deformation Values (mm)
Aluminum	0.0028
Torlon	0.020
ABS	0.046

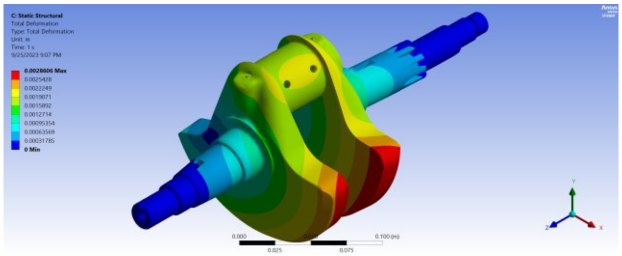

Fig 21. Aluminum Coupled Deformation

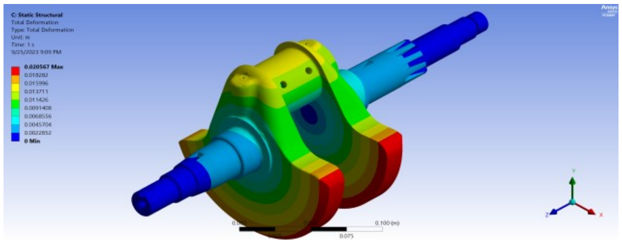

Fig 22. Torlon Coupled Deformation

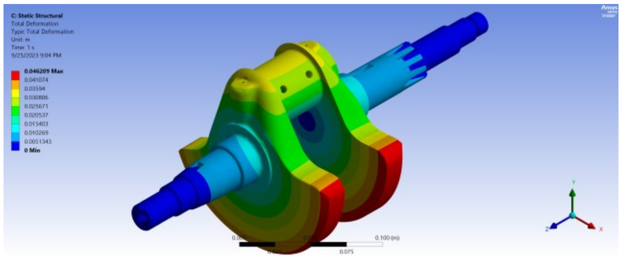

Fig 23. ABS Coupled Deformation

When coupled with the thermal results, the static deformation values tend to increase slightly. Aluminium still has the highest deformation value. ABS and Torlon have not had a very significant rise in deformation values when compared in static conditions. The values obtained are within allowable stain limit of their respective materials to allow for the proper functioning of crankshaft without the danger of sudden failure or tearing.

4.3.2 Equivalent Stress

Examining the stress distribution of the crankshaft under specified loading conditions across various material compositions revealed the maximum equivalent stress, material yield and factor of safety values for all three materials. The corresponding values are presented in Table 10, while Figures 24, 25, and 26 depict the stress distribution models of the crankshaft utilizing Aluminium, Torlon, and ABS materials, respectively.

Table 10 Maximum Stress Values

Material	Max Equivalent stress(N/M M^2)	Material Yield(N/M M^2)	Factor of Safety
Aluminum	119	276	2.31
Torlon	47.39	103	2.19
ABS	46.8	48	1.02

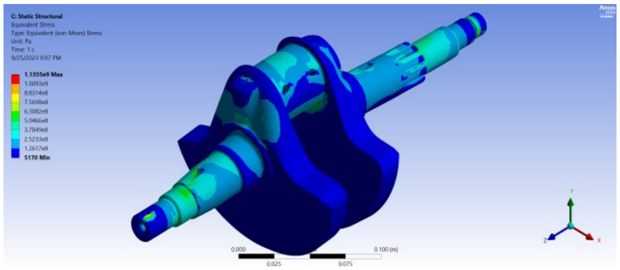

Fig 24. Aluminum Coupled Equivalent Stress

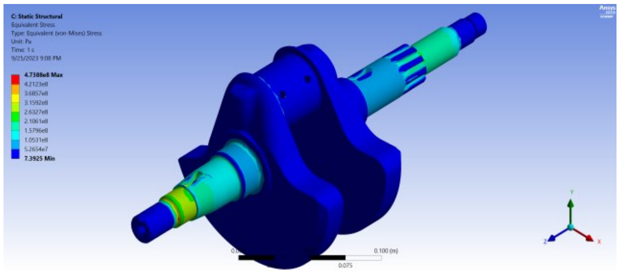

Fig 25. Torlon Coupled Equivalent Stress

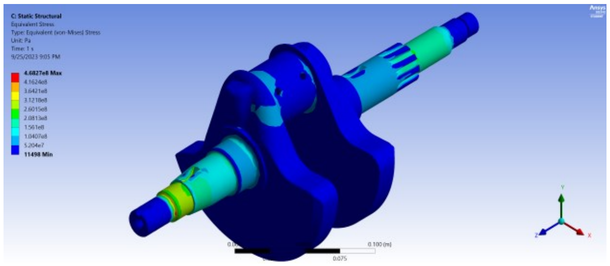

Fig 26.ABS Coupled Equivalent Stress

When coupled with the thermal results, the equivalent stress value varies for each material. Maximum stress value is obtained in Aluminum and the stress distribution for the same is shown in Figure 24. There is a slight increase in the stress values obtained for ABS and Torlon when compared to static conditions. The stress distribution images for Torlon and ABS are shown in Figures 25 and 26 respectively. The Factor of Safety value is greater than 1 for both ABS and Torlon in this coupled condition. This proves that all 3 materials are safe to be used.

4.3.3 DISCUSSION

While the static and thermal analysis are performed to study the behavior of the crankshaft under different operating conditions. The values obtained from the coupled thermo-structural are ultimately used to validate the model as a whole considering the maximum deformation and von-mises values.

On doing this, the maximum deformation value for all 3 materials is confirmed to be well within the elastic limit and the Factor of safety calculated from considering the material yield strength and maximum von-mises stresses is above 1.

This makes the design safe for all 3 material conditions and suggests that ABS and Torlon could be a potential alternative to Aluminum.

5. CONCLUSION

The crankshaft is studied under 3 material conditions and simulations are carried out under static, thermal and coupled thermo-structural conditions. The results indicate the following

- The Deformation values of Aluminum, ABS and Torlon during static loading are 0.0016 mm,0.019 mm,0.043 mm respectively. This is within the allowable strain limit of these materials which make it suitable to use.
- The maximum Von Misses stress values of Aluminum, ABS and Torlon during static loading are around 37.84 N/mm^2 for all 3 materials. The material yield of all 3 materials is more than the maximum stress value. This makes all 3 materials safe to use.
- The thermal analysis carried out analyses the heat convection behavior of Aluminum, ABS and Torlon. Starting with a working temperature of 200 C, Aluminum, ABS and Torlon obtained minimum temperature values of 191.25 C, 22 C, 23.15 C respectively, indicating that heat convection is higher in the plastic materials when compared to aluminum. All 3 materials have enough convectional behavior to avoid reaching the melting point during thermal loading.
- The maximum heat flux values of ABS and Torlon are 13998 W/m^2 and 8170 W/m^2 respectively which is very low when compared to the maximum heat flux value of Aluminum which is 190000 W/m^2. Hence, even though heat might not get dissipated easily throughout the crankshaft in the plastic materials, as the material melting point is not reached during working conditions it wouldn't have a significant effect on the overall crankshaft performance.
- While the Stress value for all materials shows little to no variation in static loading conditions, when coupled with thermal conditions major changes are found. The Deformation values for Aluminum, ABS and Torlon are 0.0028 mm,0.020 mm and 0.046 mm respective while the maximum Von Misses stress values are 119 N/mm^2, 47.39 N/mm^2 and 46.8 N/mm^2 respectively. The deformation values obtained is within stain limit and stress value is within material yield point making the design safe to use for all 3 materials.

- The change in values during thermo-structural analysis indicate that as temperature is induced in the crankshaft, it becomes more vulnerable to deformation as it is subjected to high intensity of stress than normal conditions as both static and thermal stress act on it. This suggests that importance should be given to make sure that crankshaft is such a way that it is structurally stable at higher operating temperatures.
- Introducing Torlon and ABS in 3D printing could potentially reduce engine component production costs and enhance efficiency due to its lightweight nature, lower expansion coefficient than aluminum, and recyclability, thereby reducing the use of expensive metals like Aluminum. Since ABS and Torlon are lighter in weight when compared to Aluminum, the overall engine efficiency can also be increased.
- From the results obtained from this research, Torlon and ABS can be recommended as one alternate and cost-efficient choice of material for the production of crankshaft.

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