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Comparative Analysis of Piston Rings Made with Aluminum Titanium Carbide (AlTiC-75-2) and Carbon Cast Steel (AISI 1540) Materials Using Numerical Method

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Authors' contributions

This work was carried out in collaboration among all authors. Author EAD designed the study, performed the statistical analysis and wrote the protocol. Author VH wrote the first draft of the manuscript. Author VH and KWK managed the analyses of the study. Author JNO managed the literature searches. All authors read and approved the final manuscript.

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Original Research Article

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ABSTRACT

Aim: The main purpose of this study is to perform a comparative analysis of piston rings made with aluminum titanium carbide (AlTiC-75-2) and carbon cast steel (AISI 1540) materials using numerical method.
Study Design: Numerical methods.

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Materials and Methods: The 3D piston rings were modelled with SOLIDWORDS version 2019 and imported to ANSYS 2020 RI environment for simulation and analysis.
Results: The study revealed that AISI 1540 and AlTiC-75-2 had maximum deformations of 1.0356 mm and 1.0773 mm, respectively. Also, when the equivalent elastic strains of the piston rings were compared, it was revealed that, the maximum and minimum elastic strain of the AlTiC-75-2 piston was 4.8826e-3 and 2.2581e-5, respectively, whiles the maximum and minimum elastic strain of AISI 1540 was 2.1878e-5 and 2.1878e-5 respectively. Numerical results further showed that AISI 1540 piston suffered the least elastic strain while the AlTiC piston ring endured more elastic strain. Furthermore, results showed that the maximum Von Mises stresses induced in AlTiC-75-2 and AISI 1540 piston rings were 915.2 MPa and 911.27 MPa, respectively, which implies that stresses induced in both rings were beneath the compressive yield strengths of the individual materials, therefore both rings could withstand the load imposed.
Conclusion: Result shows that the AISI 1540 ring has high minimum value than AlTiC which makes it more suitable material in terms of failure as against AlTiC-75-2 with a low minimum safety factor of 0.094187 as against 0.10182 for carbon cast steel. The study therefore recommends that AlTiC-75-2 should be considered as one of the most suitable materials for piston ring design.

Keywords: Deformation; fatigue damage; heat flux; piston ring; simulation.

1. INTRODUCTION

Piston rings are used for the purpose of sealing the combustion chamber gases, thus preventing their leakage through the piston/wall clearance into the crankcase. When fitted into a piston groove, the ring is pressed against the cylinder bore by its own elasticity. Miller introduced modification which allows the steam pressure to act on the inner rim of the ring, thus providing a higher sealing force[1]. Piston rings are key components of engine which directly affect the engine performance and fuel economy[2] . Sealing is the main task of gas rings, namely sealing the gas, to prevent the gas of combustion chamber to flow into the crankcase, and to keep the amount of gas leakage as few as possible [3]. If bad sealing of piston rings occurs, the amount of leakage of gas increase greatly, which leads to the reduction of engine power, this can be avoided by proper piston rings arrangement. At the same time, leakage increase will induce the modification of lubricating oil, affect forces acting on the piston ring, then indirectly induce severe wear of the system[4,5], eventually lead to the sharp decline in the service life of the engine. The study of piston ring pack gas pressure and leakage, does not only provide guidance for the design of piston ring, but also an essential prerequisite to study the lubrication and friction performance of the cylinder piston ring system[6].

Many researchers including [7-9] have investigated and analyzed the gas flow in the system piston-rings-cylinder[10].There are two ways for leakage passage: one way is to generate the relative motion of the piston ring and the ring groove, the gas flowed from the ring body and the ring groove clearance. The gap between the piston ring body and ring groove was very small, thus through this channel, the gas had small amount of leakage. It could be approximately considered as one-dimensional laminar flow, and one-dimensional laminar flow formula could be applied for study [11]. According to the analysis of piston ring pack movement, the piston ring body and the ring groove were attached together for most of the time, which formed a sealed space, so the form of leakage could be negligible. Another way of gas leakage is through the piston ring gap, which is the main form of piston rings blow-by. Piston ring materials and designs have evolved over the years and continue to do so until fuel cells, exotic batteries or something else makes the internal combustion engines obsolete. The main reason of this continuous study and evolution is based on the fact that the piston may be considered the heart of an engine. The piston and piston rings are the most stressed components of an entire vehicle. The piston and piston rings also aid in sealing the cylinder to prevent the escape of combustion gases. It also transmits heat to the cooling oil and the cylinder wall. The main reason is that the mechanical efficiency of an engine is still low and only about 25% of the original energy is used in brake power. Notwithstanding this technological evolution there are still a significant number of damaged piston rings. Damages may have different origins: mechanical stresses; thermal stresses; wear mechanisms; temperature degradation, oxidation mechanisms among others. Fatigue is a source of piston ring damages and traditionally, piston rings damage are attributed to wear and lubrication sources, fatigue is responsible for a significant number of piston ring damages. These damages are attributed to wear and lubrication mechanisms triggering fatigue crack due to excessive load and temperature.

AlTiC is a metal matrix composite consisting of aluminum matrix with titanium carbide particles. It has high thermal conductivity (180–200 W/m K), and its thermal expansion can be adjusted to match other materials [12], silicon and gallium arsenide chips and various ceramics. It is chiefly used in microelectronics as substrate for power semiconductor devices and high-density multi-chip modules, where it aids with removal of waste heat. In this study, the mechanical damages and in particular fatigue damages of the materials were assessed. This study performs a comparative analysis of a three-dimensional internal combustion engine piston rings with two materials (AlTiC and AISI 1540) using numerical method. The operational scenarios of the piston ring and its interactions with the engine cylinder wall were also assessed.

2. MATERIALS AND METHODS

The 3-D piston rings were modelled using the engine specification (Table 1) with SOLIDWORDS version 2019 as shown in Fig. 1; and imported to ANSYS 2020 RI environment for simulation and analysis. Aluminium Titanium Carbide (AlTiC-75-2) and carbon cast steel (AISI 1540) were used for the study. Tables 2 and 3 present the mechanical properties of the propose materials. In this model, the famous Johnson and Cook constitutive model as in [13] was adopted and modified to stimulate the mechanical behavior of the piston ring. The equivalent yield stress of the model is therefore expressed as;

$$\sigma = \left(\sigma_0 + B\varepsilon_p^n\right)\left(1 + CIn\frac{\varepsilon}{\varepsilon_0}\right) \tag{1}$$

In Equation (1), σ_0 is the static yield strength, ε_p denotes the effective plastic strain, ε and ε_0 are the effective and reference strain rates, respectively; B, C and n are the material constants. The fracture criterion is based on the damage progression where damage of the material is expected to occur when the damage parameter, (ω) exceeds unity as in Eq. (2).

$$\omega = \sum\left(\frac{\Delta\varepsilon^{pl}}{\varepsilon_f^{pl}}\right) \tag{2}$$

Here ε^{pl} represents increment of the equivalent plastic strain, ε_f^{pl} denotes strain at failure.

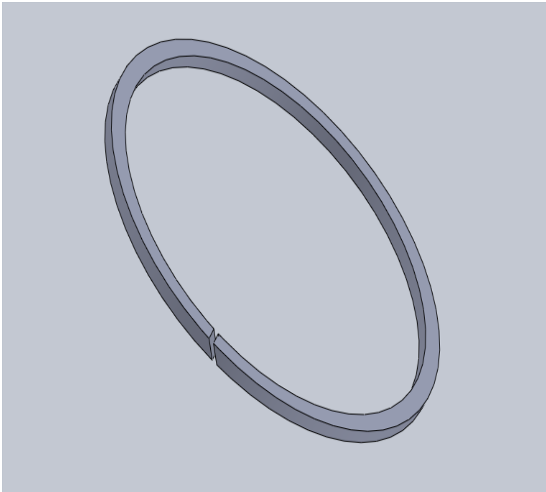

Fig. 1. Model of 3D piston ring

Table 1. Engine specifications

Engine Type	4-Stroke
Bore × Stroke (mm)	57×58.6
Displacement	149.5 cc
Maximum Power	17.7 bhp at 9400 rpm
Maximum Torque	19.3 Nm at 59200 rpm
Compression Ratio	10.65/1

Table 2. Mechanical properties of aluminium titanium carbide (AlTiC-75-2)

Properties	Value
Density	2890 kg/m^3
Ultimate streng	34760448.52 kJ/m^2
Yield strength	43527018.25 kJ/m^2
Shear strength	29255861.37 kJ/m^2
Fatigue strength	14373088.68 kJ/m^2
Elastic modulus	17023445.46 kJ/m^2
Poisson's ratio	0.25
Elongation	5.4 %
Flexural strength	45871559.63 kJ/m^2

Table 3. Mechanical properties of carbon cast steel (AISI 1540)

Parameters	Values
Density	7850 kg/m^3
Ultimate tensile strength	40774719.67 kJ/m^2
Tensile yield strength	55045871.55 kJ/m^2
Compressive yield strength	27522935.78 kJ/m^2
Poisson’s Ratio	0.25
Youngs Modulus	21406727.82 kJ/m^2
Shear Modulus	8154943.93 kJ/m^2
Shear Strength	21712538.22 kJ/m^2
Thermal conductivity	128 kJ/m^2
Fatigue Strength	7645259.93 kJ/m^2

3. RESULTS AND DISCUSSION

The piston ring materials were subjected to structural pressure of 15 MPa and thermal condition of 1000ºC for analysis. Temperature distribution, total heat flux, directional heat flux, deformation, equivalent elastic strain, von Mises stress, strain energy, life prediction, fatigue damage and factor of safety of the two piston rings materials are presented for analysis.

3.1 Thermal Analysis of the Piston Rings

The temperature, directional heat flux and total heat flux of the piston ring are important because these parameters can influence the ring’s integrity. The AISI 1540 rings maximum inner and outer surface temperatures were 350°C and 312.71°C, respectively. However, the AlTiC-75-2 minimum surface temperatures was lower than that of cast steel with temperature value of 115.15°C in the piston ring material selection. For the rings outer area, the maximum heat flux was 2.9927 W/mm^2, which was located all-round the sliding surfaces of the rings. For the outer ring area, the maximum directional heat flux was scattered and was 0.57812W/mm^2.

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Fig. 3 displays simulated results of existing piston ring material which has the maximum of 1.8334W/m^2 and minimum of 0.0044779W/m^2 for carbon cast steel whiles AlTiC recorded 2.9927W/m^2 maximum and 0,000455045506Wm^2 as minimum. It is clear that the AiTiC can perform better and also have longer lifespan. The AlTiC can give a longer life in operating conditions under normal temperature conditions, in comparison to the carbon cast steel. However, the AlTiC result is in disagreement since it curbs the modification of the ring size caused by heat [14,15].

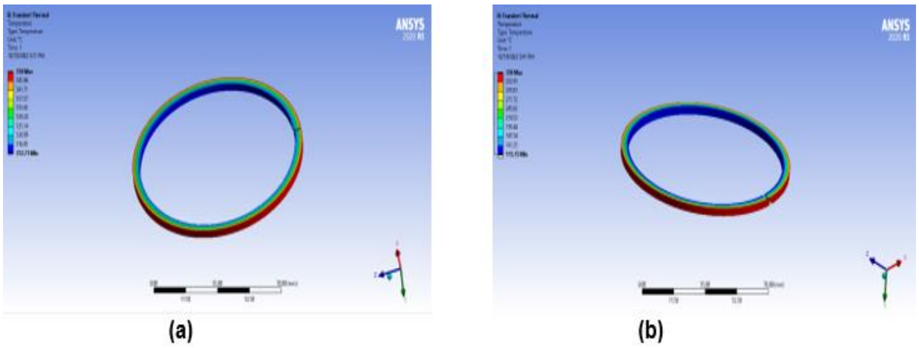


Fig. 2. Temperature distribution at loading condition of 1000ºC (a) AISI 1540 (b) AlTiC-75-2

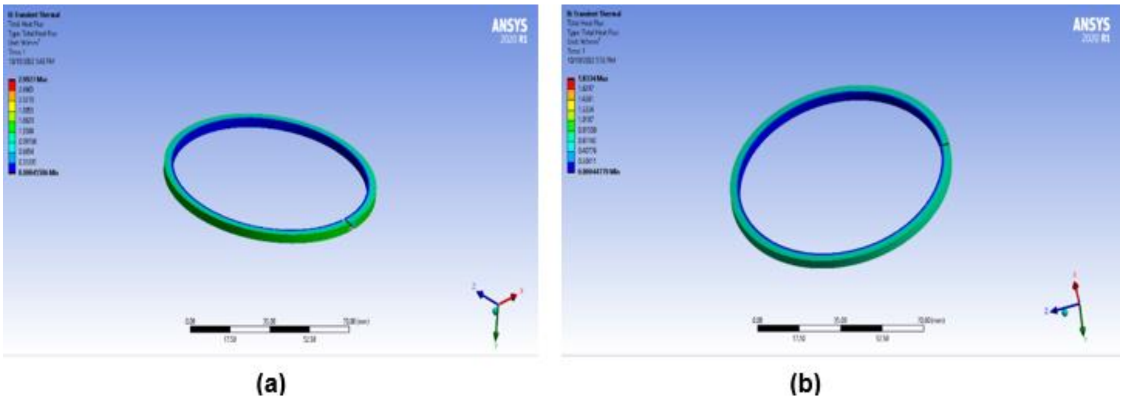


Fig. 3. Total heat flux loading condition of 1000°C (a) AISI 1540 (b) AlTiC-75-2

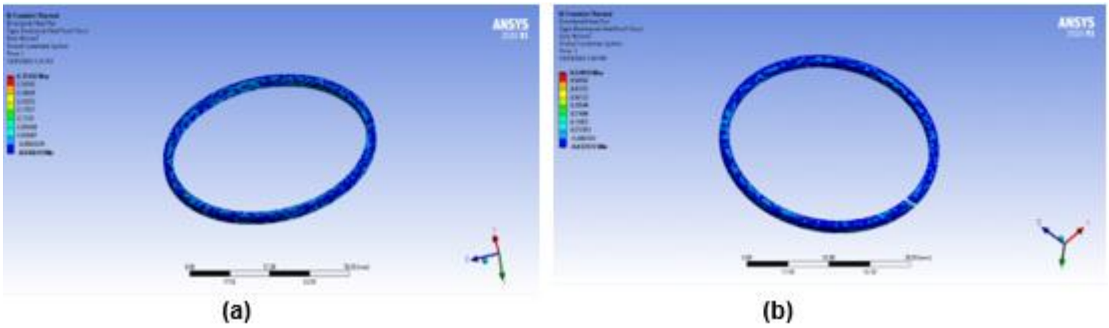


Fig. 4. Directional heat flux loading condition of 1000°C (a) AISI 1540 (b) AlTiC-75-2

In this numerical comparison analysis for cast steel and AlTiC, the following values were recorded according to the directional heat flux of the material. Carbon cast steel had maximum value of 0.35142W/m^2 and minimum of 0.044243W/m^2. AlTiC also had the best directional heat flux of 0.57812W/m^2 as the maximum value and minimum value of 0.072537W/m^2. Under the downward pressure (15 MPa) due to gas load acting on piston head. The piston rings were analyzed by giving pressure and temperature constraints for structural analysis and thermal analysis. Gases in the combustion chamber exerts pressure on the head of the piston during power stroke. The pressure force is taken as boundary condition in structural analysis. Fixed support has been given at surface at the upward surface of the rings. So, whatever the load is applying on piston due to gas explosion that forces cause to maximum pressure load at the frictional surface of the ring was 15 MPa and temperature at the surface of the piston ring at 350°C and ambient temperature of 22°C and convection is 600w/m^2. The resultant out-of-plane deformations of the whole surfaces of heated pistons rings are shown in Fig. 5. The deformation was calculated relative to the center point of the full ring top. These plots indicate a measurable hump (or a deflection peak) located around the rim on the plane of symmetry. If the deformation of the ring is not considered, thermal buckling due to excessive pressure stress can occur as indicated in figure 4. Ji et al [16] responded that through finite element simulation, it was found out that the proposed designs can change the heat-flux for one time directly, just like mirror to the light beam. By circulating the generalized thermal resistance, it can be verified that such thermal reflection meta-device possesses low thermal resistance and high heat transfer ability.

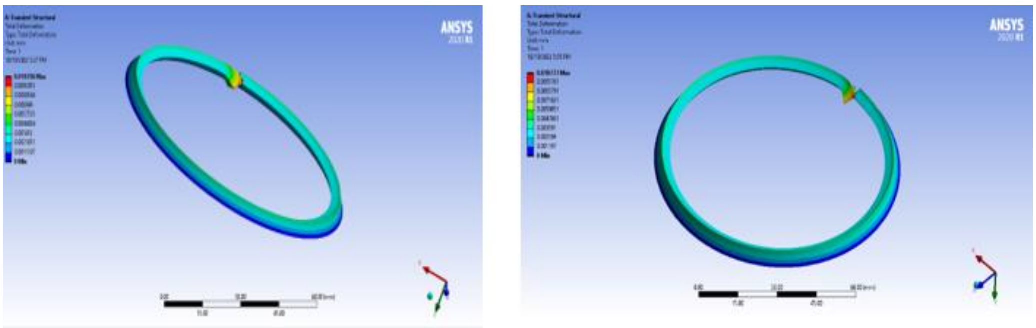
The results recorded for cast steel and AlTiC values were recorded according to total deformation of the material. Carbon cast steel with maximum value of 0.010356 w/m^2 and minimum of 0.0011507 w/m^2, AlTiC also has the best total deformation of 0.010773w/m^2 as maximum and minimum value of 0.001197 w/m^2. The resultant out-of-plane deformations of the whole surfaces of heated pistons rings are shown in Fig. 5. The deformation was calculated relative to the center point of the full ring top. These plots indicate a measurable hump (or a deflection peak) located around the rim on the plane of symmetry. If the deformation of the ring is not considered, thermal buckling due to excessive pressure stress can occur.

Study by Wilson [17] confirms how to overcome the considerable wear problem on cylinder wall and piston ring surface.

Fig. 6 shows the piston ring equivalent strain (von mises) due to the temperature distribution in the internal combustion engine of carbon cast steel and AlTiC-75-2 respectively. The high strain area near the apex of the piston ring had a large expansion, and it gradually decreased away to the lower rim. The equivalent strain distributions showed similar distributions amongst both designs. The maximum equivalent strain value for cast steel and AlTiC-75-2 were discovered to be 4.7336mm and 4.8876mm respectively for the given loading condition. It was observed that the equivalent elastic strain in both models was more profound at the piston rings rim where loading was applied, and this result agrees with [18] as the contact with the groove at the outside edge.

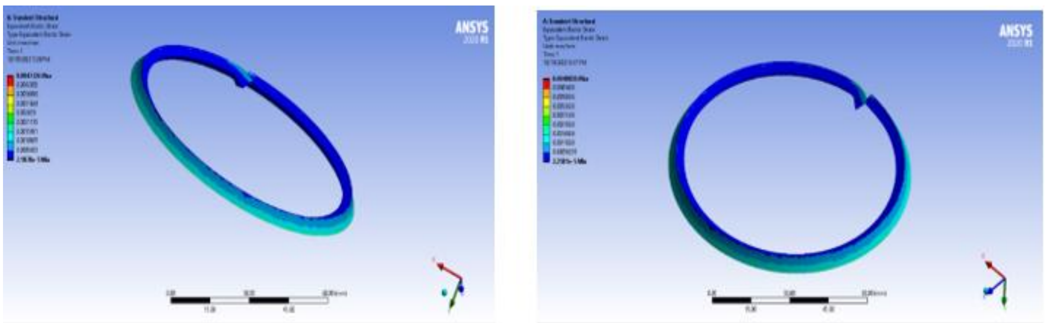
3.2 Stress Distribution on the Piston Rings

Fig. 7 are the results of the Von Mises stress of AISI 1540 and AlTiC-75-2. In the case of piston loading, the maximum stress was found around the ring opening and the rim stretch where there is concentration of both pressure and temperatures in both cases. The pistons rings at maximum local produced von-Mises stresses values of 915.2 MPa and 911.27 MPa for both thermal and pressure loading cases for cast steel and AlTiC respectively. The mean of the film stress was 415 MPa for AlTiC ring at all of the transient steps, which is lower than the constraint value (allowable stress value). Therefore, the stress state of the piston ring satisfies the International Automobile Standard (IAS) criteria. It is also shown in Fig. 7 that the maximum stress intensity is observed in cast steel with 915.2 MPa and minimum in AlTiC with 911.27 MPa. It is observed that the maximum stress intensity is on the bottom surface of the ring and along the edges. Again, in piston ring made of AlTiC moderate stress intensity is founded.



(a) (b)

Fig. 5. Total deformation at a pressure of 15MPa (a) AISI 1540 (b) AlTiC-75-2



(a) (b)

Fig. 6. Equivalent elastic strain at a pressure of 15MPa (a) AISI 1540 (b) AlTiC-75-2

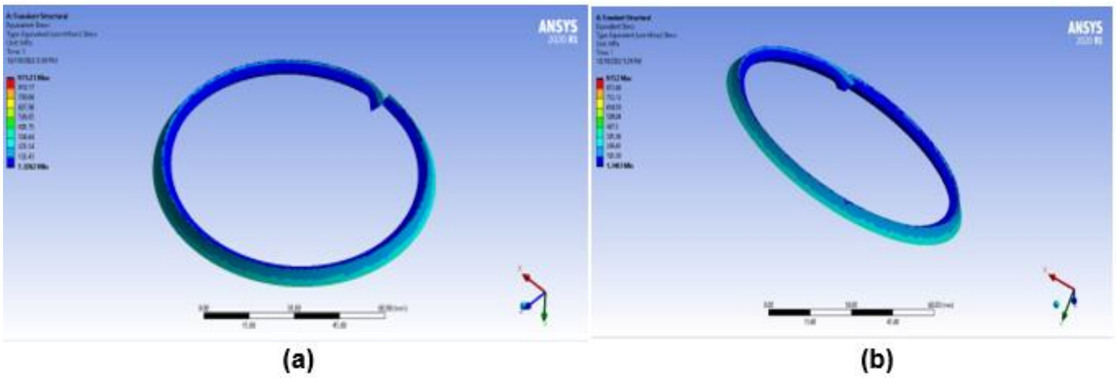


Fig. 7. Equivalent (Von-Mises) stress at a pressure of 15MPa (a) AISI 1540 (b) AlTiC-75-2

3.3 Strain Energy of the Piston Rings

For strain energy analysis of AlTiC and carbon cast steel, the following values were recorded. The carbon cast steel recorded maximum value of 0.11208m^2 and the minimum of 1.194e-6m^2. AlTiC also had the best strain energy of 0.11711m^2 as the maximum value and the minimum value of 1.2763e-6m^2. The strain energy being the energy stored in the piston ring due to all directional deformations, appeared scattered in the ring base edges having a maximum strain energy density of 0.11208m^3 and 0.11711m^3 for cast steel and AlTiC models respectively (Fig. 8). Considering the frictional surface subjected to a downward pressure of 15 MPa at the centroidal part of the piston ring causing deformation through the oriented angle of the spigot direction, the shear strain and the shear deflection.

Generally, the theoretical factor of safety of the piston ring for an internal combustion engine is 6.2. Numerical results show that the factor of safety for both models have maximum and minimum magnitude of 15 and 0.10182 and 15 and 0.094187 for carbon cast steel and AlTiC respectively. The maximum factor of safety was observed to be more profound at the skirt of the piston ring as shown in Fig 9. The theoretical factor of safety value of which is the mean of the difference of maximum and minimum range for both materials is within the range of factor of safety for both models of the piston ring generated numerically, therefore, both models are very safe to use.

3.4 Piston Ring Fatigue Analysis

It is clear from Fig. 10 that the maximum damage and failure concentration areas are observed in the piston ring made of AlTiC and minimum in carbon cast steel. Minimum damage failure is observed at the bottom brim and outside of the ring, with maximum damage safety factor of 0.10182 and 0.094187 nearing zero because of the concentration of high temperatures and pressures around these areas.

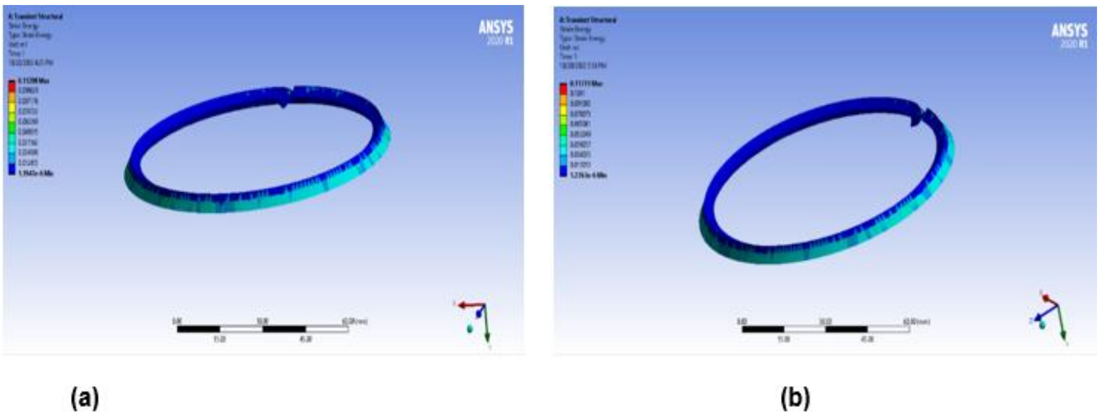
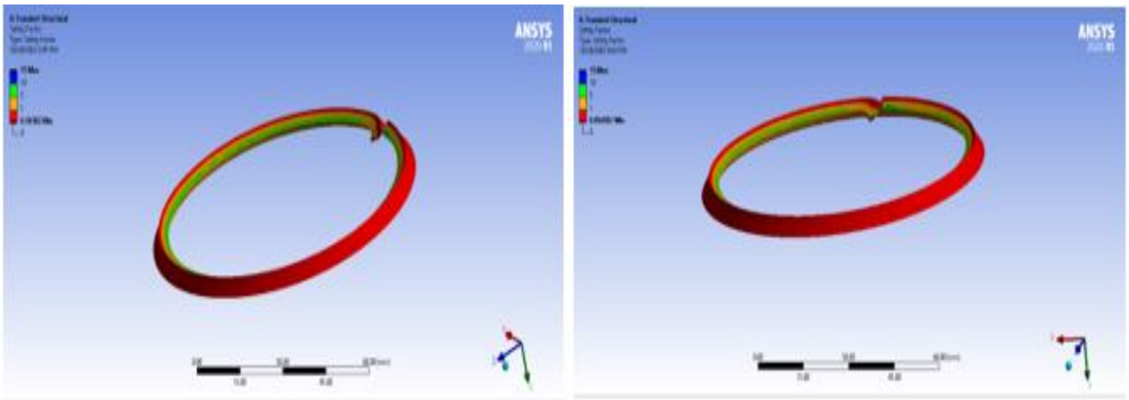
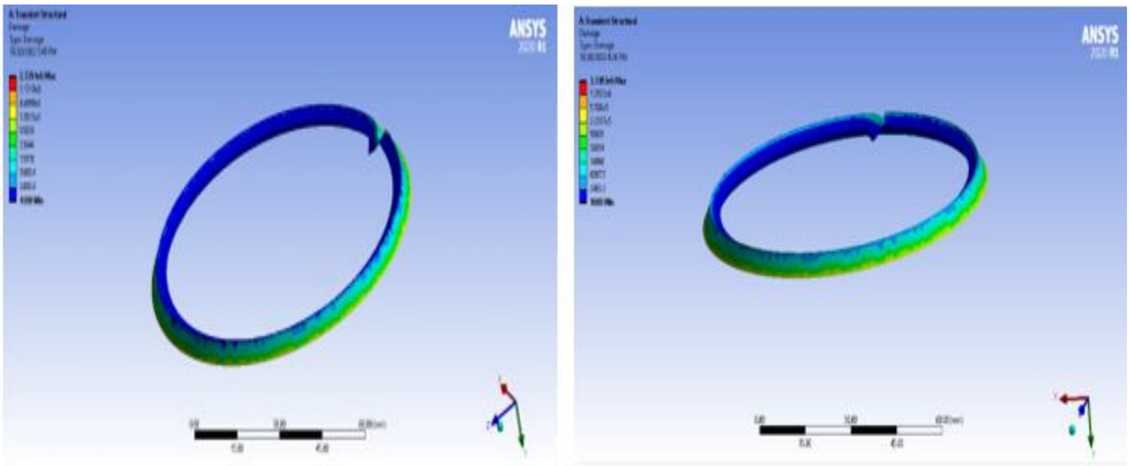


Fig. 8. Strain energy at a pressure of 15MPa (a) AISI 1540 (b) AlTiC-75-2



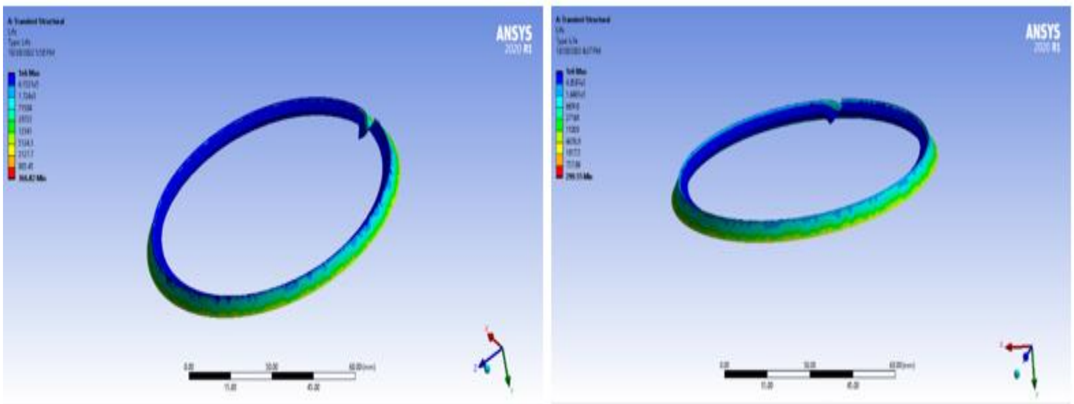
(a) (b)

Fig. 9. Factor of safety at a pressure of 15MPa (a) AISI 1540 (b) AlTiC-75-2



(a) (b)

Fig. 10. Fatigue damage at a pressure of 15MPa (a) AISI 1540 (b) AlTiC-75-2



(a) (b)

Fig. 11. Fatigue life at a pressure of 15MPa (a) AISI 1540 (b) AlTiC-75-2

Also, Fig. 11 displays fatigue life of cast steel and AlTiC. The figures recorded in both show the maximum of 1e6w/m^2 and 366.82w/m^2 as minimum for the carbon cast steel and 1e6w/m^2 as maximum for the AlTiC and 299.55w/m^2 as minimum. In this case the performance of the engine for the two materials has two slightly different values. With AlTiC having a high strain value than carbon cast steel. It means AlTiC can a longer life in operating conditions under normal temperature conditions, as compared to cast steel, AlTiC is suggested as a possible alternative material for the piston ring.

4. CONCLUSION

This numerical study considered two methods of analysis including transient structural and thermal. The parameters that were considered under the study includes total deformation, equivalent elastic strain, equivalent Von Mises stress, Strain Energy, factor of safety, fatigue damage and fatigue life of the two rings made with AlTiC-75-2 and AISI 1540. The results of the study showed that, the stresses induced in the two pistons materials were far below the yield strengths of the individual materials, thus, both piston rings could withstand the structural pressure that were imposed on them. The weights of the piston rings were also compared and the results showed that the weight of the AlTiC was 37.2% lower than the carbon cast steel piston. Simulation result of AlTiC produces less stress concentration as compared to carbon cast steel for the same loading condition. Hence, the reliability was higher for AlTiC as compared to carbon cast steel. Result showed that AlTiC ring was capable of withstanding heavy loads under very severe environments, and also offers high strength retention on ageing. Though, numerical results showed that both rings have a good temperature distribution under heavy loads. However, AlTiC-75-2 piston rings are more preferable because of lower stress concentration and deformation.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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