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An investigation on the friction losses between cylinder liner and piston rings

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Abstract
Historically, the engine crankcase has been made of gray cast iron due to that material's high machinability, damping ability, thermal conductivity, and sensible cost. Despite these advantages and the long-term use of gray cast iron, the vehicle manufacturers predominately use cast aluminum as material of choice for the engine block due to aluminum's density being almost a third of that of gray cast iron, and the aluminum engines have the same durability as gray cast iron while weighing considerably less. However, due to the low wear resistance of aluminum, efforts are needed to improve internal working surfaces such as the use of cast iron cylinder liners or the application of a protective coat is applied to the aluminum surface to increase its resistance. The purpose of this study is to examine which ring materials have the lowest friction with the Twin Wire Arc (TWA) aluminum cylinder liner. An Ansys simulation model accomplishes the experimental work. The steel ring material obviously had the lowest friction with twin wire arc spray aluminum cylinder liner as opposite to the cast iron material which was the worst.

Keywords: Aluminum cylinder liner, Internal combustion engine, Cast iron, Wear

1. Introduction

The friction in the internal combustion engine (ICE) is the main negative influence on performance, emission and fuel consumption of the vehicles [1]. The exacerbation of this problem and the increasing demand on reducing the wear in ICE impels vehicle manufactures to handle this situation. Replacing grey cast iron with aluminum as the material for the engine block was one of the modalities that managed to decrease the friction [2,3]. The thermal expansion and heat conductivity of aluminum are substantially higher than grey cast iron, as well as it provides a weight loss of 40 to 50% [3,4]. The low wear resistance of aluminum requires a wear protective layer such as Twin Wire Arc (TWA) which acts as a barrier layer to safeguard the aluminum from the deterioration and prolong its lifespan [5].

Mechanical friction loss in heavy duty diesel engines contribute to 4-15% of fuel consumption where piston/bore interface consume up to 55% of these losses [6]. Significant studies were carried out in order to decrease the friction losses between piston and cylinder liner, such as Ernst Winklhofer et al. [7] utilized a single cylinder engine with a floating liner to directly assess the influence of liner offset design on friction losses. It was shown that a liner offset design is beneficial at moderate speeds because of the cylinder pressure effects being the leading cause of liner-piston contact forces whereas it has the opposite result at high speeds due to the effects of piston inertia. Piston rings account for 28-45% of the piston-cylinder contact losses where the oil ring is the responsible for up to 75% of those losses [8]. A huge number of experimental studies have been conducted to reduce the rings friction losses and most of them have been implemented by using a test rig. G. Ryk et al. [1] found that partial laser surface texturing compared to a non-textured barrel face piston ring as a baseline showed a 25% reduction in friction between piston rings and cylinder liner. Another study was conducted by Edney Rejowski et al. [9] evaluated the role of diamond-like carbon (DLC) coated cylinder liners in reducing friction and improving tribological performance when pitted against CrN-coated top piston rings. The diamond-like carbon (DLC) coatings showed a decrease in friction and fuel consumption by 19% and 2.5% respectively when compared to uncoated cylinder liner with the same operating roughness. Arthur Rozario et al. [10] showed friction reduction by CrN and TiN coated piston rings. Markus Soderfjall et al. [11] evaluated the friction between piston rings and three different cylinder liners which are known as,” Smooth”,” Plasma” and” Cast iron” in a high-speed component test rig. It was concluded that using a smooth liner is better than using non-smooth liner in regard to friction losses reduction. There are many studies focused on decreasing the friction within the internal combustion engine without upgrading the piston rings. Such as, Abdelrahman M. Youssef et al. [12] showed the most common techniques used in the design of floating-liner systems for measuring piston assembly friction. They reached several conclusions that the most common type of floating liner systems is the pressurized system due to their capability to simulate the entirety of conditions that exists in a firing engine during operation, and non-pressurized floating liners are decent at simulating engines at low intensity of load and are easy to manufacture and use. Moreover, İdris Cesur et al. [13] used Taguchi experimental design approach to investigate the impact of biodiesel and diesel fuels on wear and friction under different loads and speed. The results obtained after the experiments that were carried out, when compared to diesel fuel, biodiesel was shown to have lower friction and wear. In addition to that, Taguchi method has been proven to be a useful tool for investigating the impact of various factors on wear and friction coefficient.

The majority of the tests to minimize friction between the cylinder and piston rings were carried out on cylinder liner made of cast iron. Recently, the vehicle manufacturers have been moving towards replacing grey cast iron with aluminum for the cylinder liner due to the fact that aluminum’s density is almost a third of that of grey cast iron, and the aluminum engines have the same durability as grey cast iron while weighing considerably less [3]. The significance of this research is to consider the new cylinder material and determine which ring material is optimum for decreasing friction. The ring materials used in this study are steel, cast iron and ductile iron. The usage of ductile iron has skyrocketed in the recent decade due to its outstanding toughness and strength, low production costs and mechanical properties [14,15,16], while cast iron was chosen as a material for the rings, due to its great use in the field of engine production and it is less expensive compared to steel and ductile iron [17]. The high performance and the narrower face widths, steel has become popular for the construction of piston rings.

2. Materials and methods

The point of this study is to measure and compare the frictional behavior of three different piston ring materials brushing against a TWA aluminum cylinder liner to deduce which of these materials is better used in manufacturing. The materials that were evaluated are steel, cast iron and ductile iron plasma molly faced. These materials have the properties shown in Table 1.

Table 1. Properties of the ring materials

Materials	Density (kg/m3)	Young's modulus (N/mm^2)	Yield strength (N/mm^2)	Co-eff of thermal expansion (1/K)
Steel	7750	$1.93\ 10^5$	207	$1.7\ 10^{-7}$
Cast iron	7200	$1.1\ 10^5$	276	$1.1\ 10^{-5}$
Ductile iron	7350	$1.63\ 10^5$	296	$1.4\ 10^{-5}$

To examine the friction behavior of the different ring materials, an analysis was conducted over 10 seconds. The engine operated at 1000 RPM for the first two seconds after that the velocity, displacement and friction were observed for each material over the next 8 seconds where the engine is decelerating.

2.1. Model

2.1.1. CAD model

The engine's CAD model was done using the software SOLID WORKS 2021, each part is sketched individually (the engine block, piston, piston rings, crankshaft). Then it is put in an assembly with the other parts where they are aligned while ensuring no overlap or collision, assigned the appropriate materials and mates to produce the complete engine model with the correct movement desired for the pistons (figure 1). The six-cylinder engine has three different ring materials which are steel, cast iron and ductile iron plasma molly faced while the material of the cylinder is Aluminum coated by twin wire arc (TWA). We used TWA as a coating method for Aluminum cylinder liner for being one of the most cost-effective thermal spraying process and it is capable of producing dense, ultra-fine grain structures [18].

2.1.2. Mesh model

It is very difficult to perform analytical calculations on complex geometries. In order to solve this problem, we use the FEA approach by dissecting the geometry into many normal shapes called elements that give us an accurate approximation of the complex geometry which we intend to study. Each element has its own characteristics and a certain number of nodes depending on which type of mesh is used. We used a tetrahedral mesh because tetrahedral elements are the best when it comes to modelling complex geometries with little mesh distortion and because of their easy calculations, tetrahedral components suit arbitrarily shaped geometries well. To achieve an accurate and high-quality meshing, we employed local settings. Local control settings provide additional flexibility in obtaining a refined mesh at specified component locations.

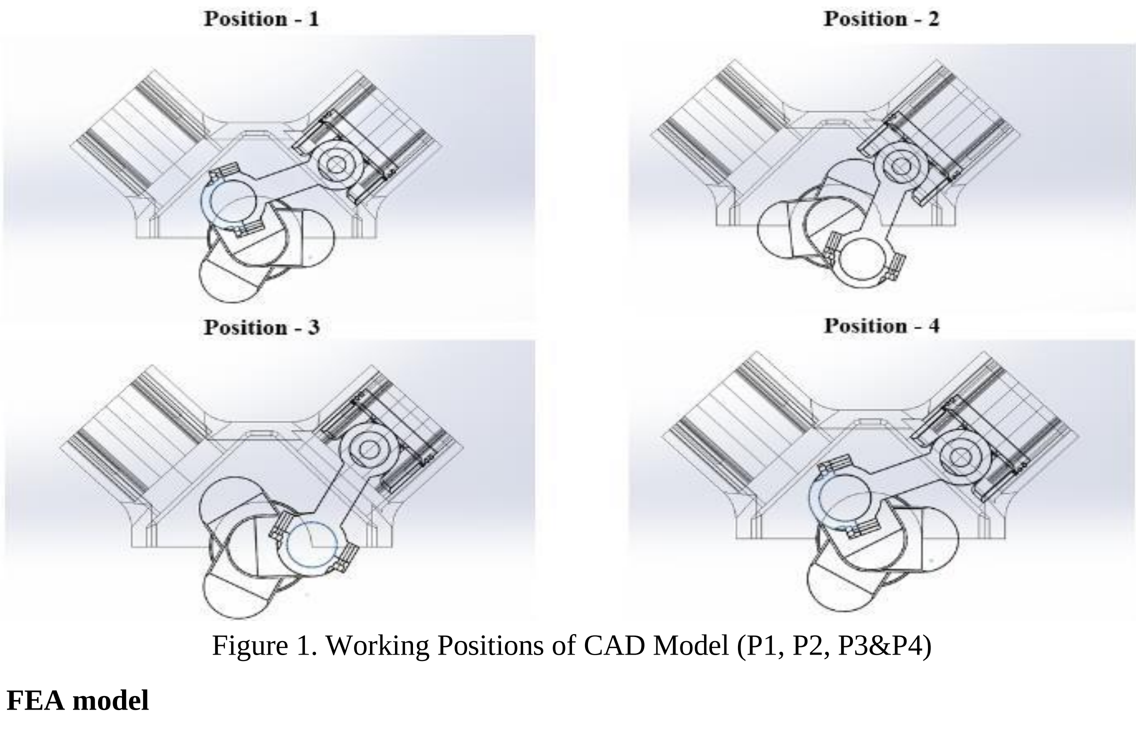

Figure 1. Working Positions of CAD Model (P1, P2, P3&P4)

2.1.3. FEA model

After importing the model in Ansys Workbench, using Mechanical Module we discretized the model in to small meshes (Figure 2). The FEA model serves to study the stress-strain applied on the engine parts, by applying external influences such as temperature, forces, pressure and heat sources. Then splitting the object into small basic shapes called elements. A group of elements is called the mesh and each point between two or more elements is called a node. Having a higher number of elements will increase the accuracy of the result but will also require more computational power. Finally, all the conditions are applied to the nodes which will result in a huge-but finite- number of equations which are then solved by the computer and used to make the numerical analysis.

Figure 2. The mesh structure of each part of the model

2.2. Analysis approach

To examine the frictional behavior of these different piston ring materials, first we assign the appropriate materials and friction coefficients, then turn on the gravitational effects for the Y axis and finally initiate movement. The movement is done over a 10 sec period over two stages, first stage is 2 seconds long where a rotational velocity of 1000 RPM is applied which is shut off at the start of the second stage that is 8 seconds where we'll be studying the deceleration. After that the engine assembly is functioning normally with the pistons reciprocating inside the cylinder, sliding against the liner which due to the friction parameters and inertial effects will eventually cause the pistons to stop. The objective is to observe and conclude which material performs the best under these conditions, having the lowest drop in velocity over time. In Table 2, we list the parameters needed to conduct the analysis in ANSYS. We only need to observe the behavior of each material while the speed is decreasing thus, we only require two steps: one for acceleration, and the other for deceleration. Initial time step is the time after which the first set of sub-solutions are obtained to be used in subsequent steps which in this analysis is equal 0.2 sec. There is process that is called auto time-stepping that divides a step into a certain number of mini steps depending on the time step. There are two values that need to be inserted, the maximum time step (0.6 sec) which is the biggest amount of time that the auto time-stepping can make and the minimum time step (0.1 sec) which is the smallest amount of time that the auto time-stepping can do.

Table 2. Analysis settings

Number of Steps	2	Initial Time Step	0.2 sec
Step End Time (S1)	2 sec	Maximum Time Step	0.6 sec
Step End Time (S2)	8 sec	Minimum Time Step	0.1 sec

3. Results

3.1. Friction force calculation

At the first two seconds where the engine's speed is 1500RPM, the friction force between steel rings and TWA aluminum was 65N (Figure 3-a) while friction force of cast iron and ductile iron plasma molly faced rings were 225N and 147N (Figure 3-b and c), respectively. During the second phase where the engine is turned off, the piston velocity will naturally decrease over the time until the piston stops moving. The major factor in this decrease being the friction force between the rings and the cylinder liner, meaning that the material that has the least amount of friction throughout this phase is the one that manages to retain piston velocity the longest. We observe that the steel piston ring is the one that retained velocity the longest therefore it had the lowest overall friction.

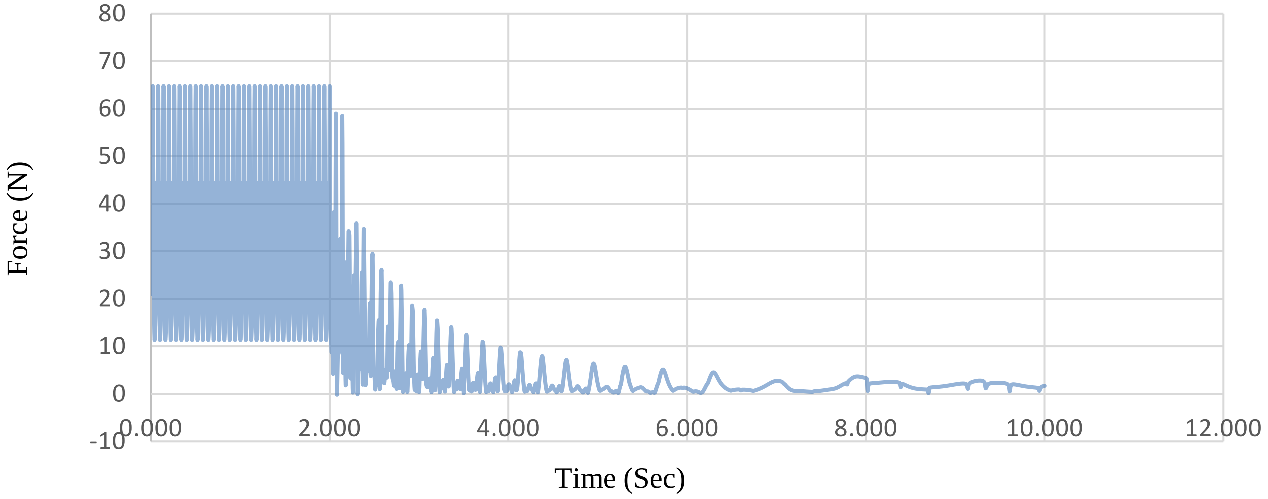

Figure 3. (a) Friction force of steel ring

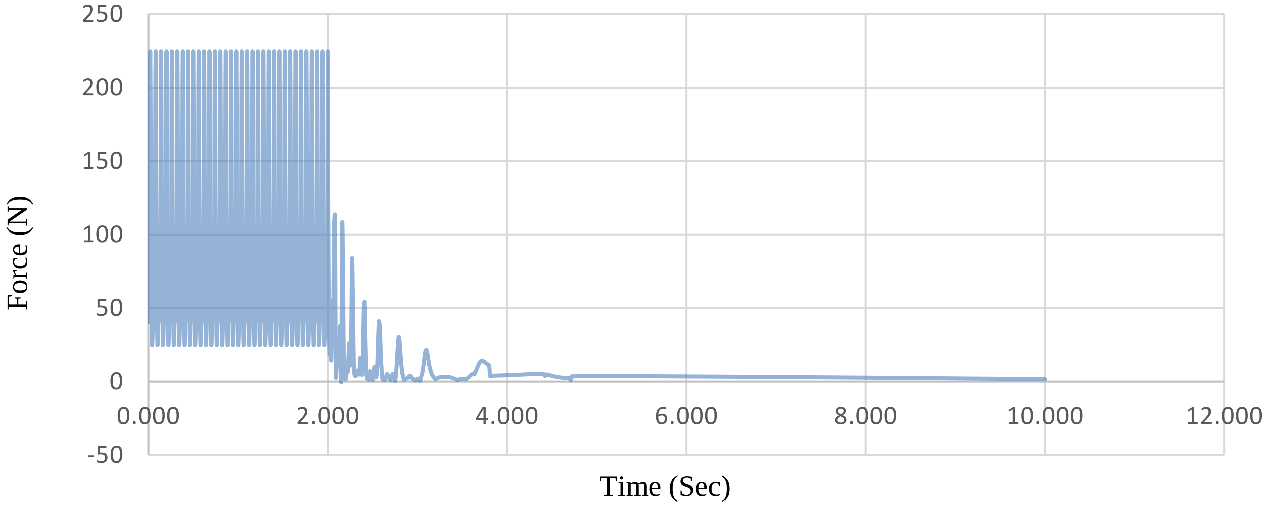

Figure 3. (b) Friction force of cast iron ring

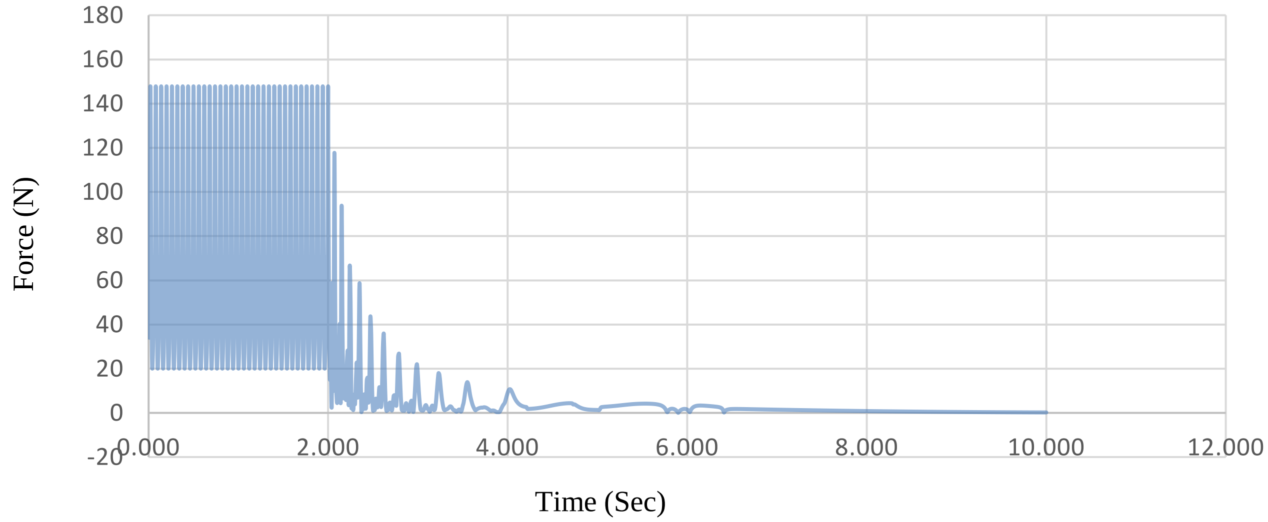

Figure 3. (c) Friction force of ductile iron plasma molly faced ring

3.2. Liner displacement calculation

By looking at the displacement it is observed that the piston is oscillating between the top dead center and the bottom dead center for the first two seconds where the top dead center (TDC) is at around 1120 mm and the bottom dead center (BDC) is around 1040 mm. After about 6 seconds, the piston with the cast iron ring and ductile iron plasma molly faced had stopped moving (Figure 4-b and c, respectively). The steel piston ring had continued reciprocating until the end of the study of period (Figure 4-a).

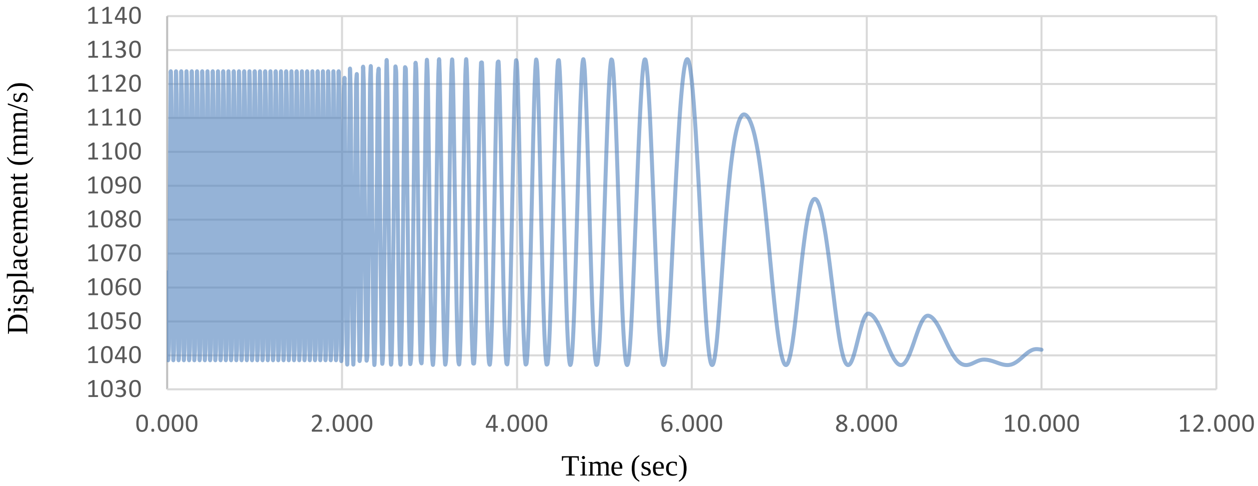

Figure 4. (a) Liner displacement of steel ring

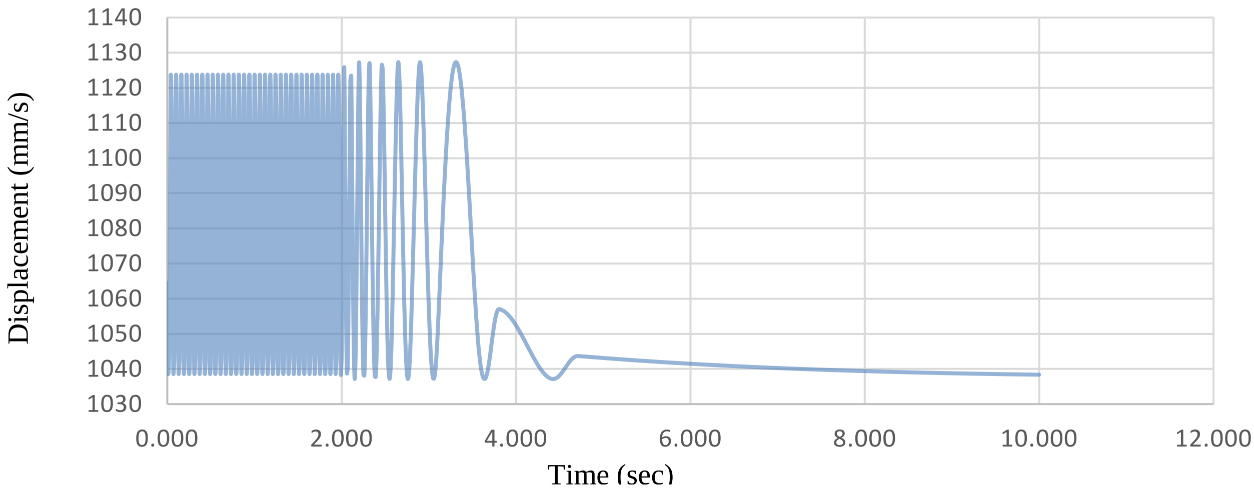

Figure 4. (b) Liner displacement of cast iron ring

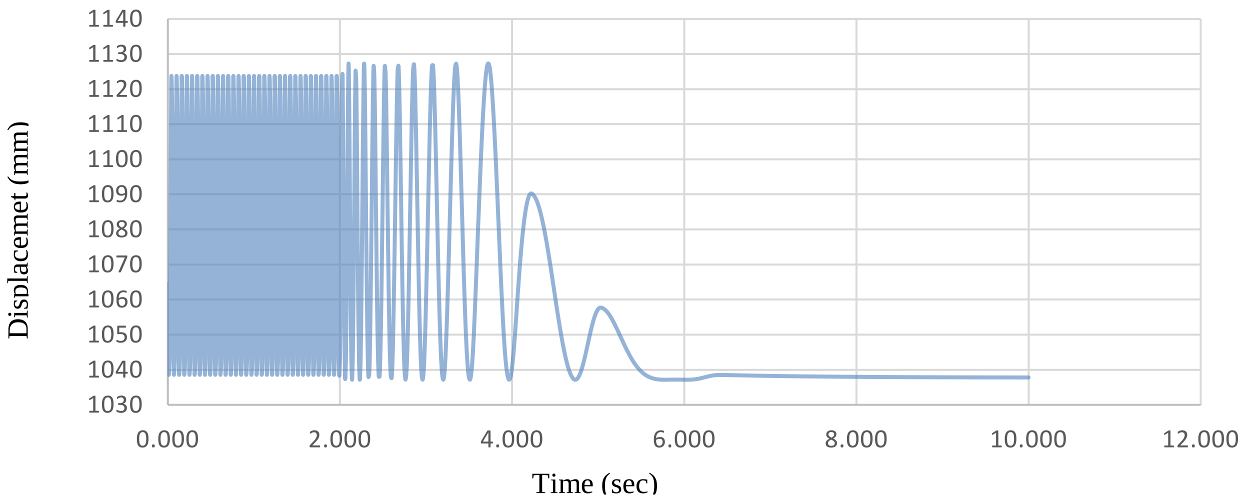

Figure 4. (c) Liner displacement of ductile iron plasma molly faced ring

3.3. Velocity calculation

In addition to the analysis on friction force and liner displacement, the velocity was measured as well. At the first stage of the period the velocity was 7000 mm/s for all materials. The velocity of the cast iron ring has dramatically decreased to reach its null at around 4 seconds (Figure 5-b) which indicates a significantly higher friction than ductile iron plasma ring that retained its velocity until a little more than 5 seconds (Figure 5-c). At the same time that ductile and cast-iron rings had lost of all their velocity, the steel ring's velocity was 2000 mm/s at 4 seconds and declined to arrive 1000 mm/s at 6 seconds (Figure 5-a).

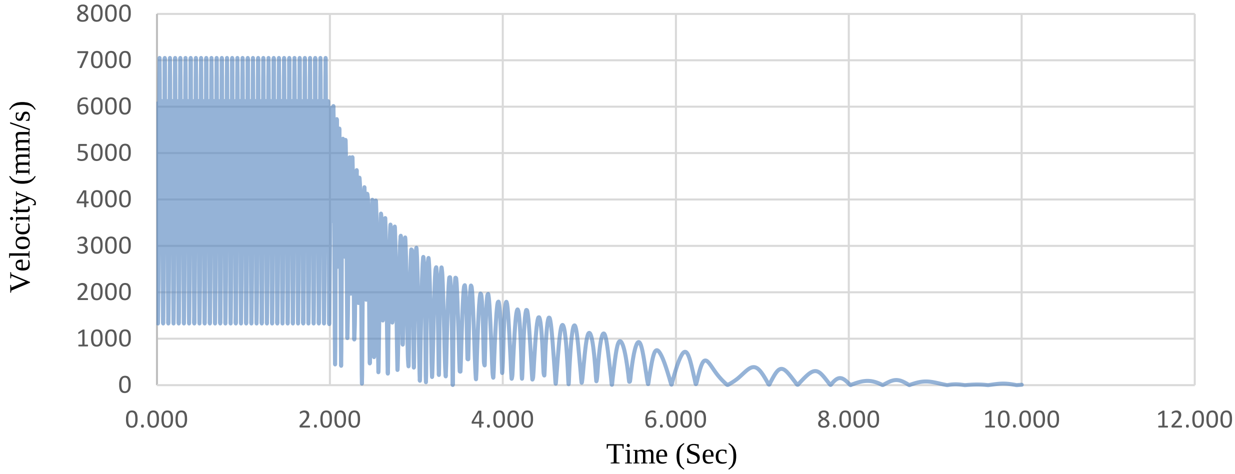

Figure 5. (a) Velocity of steel ring

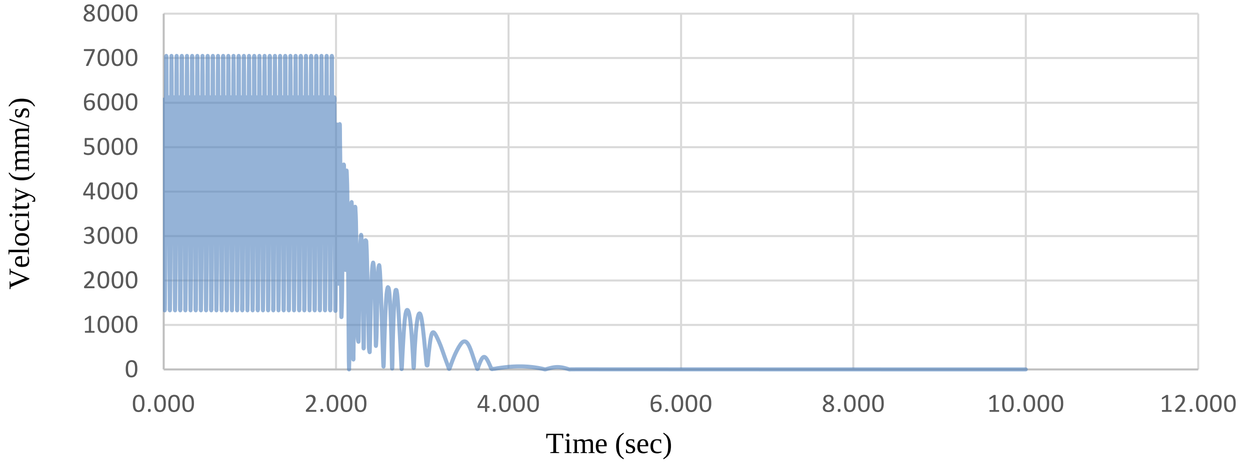

Figure 5. (b) Velocity of cast iron ring

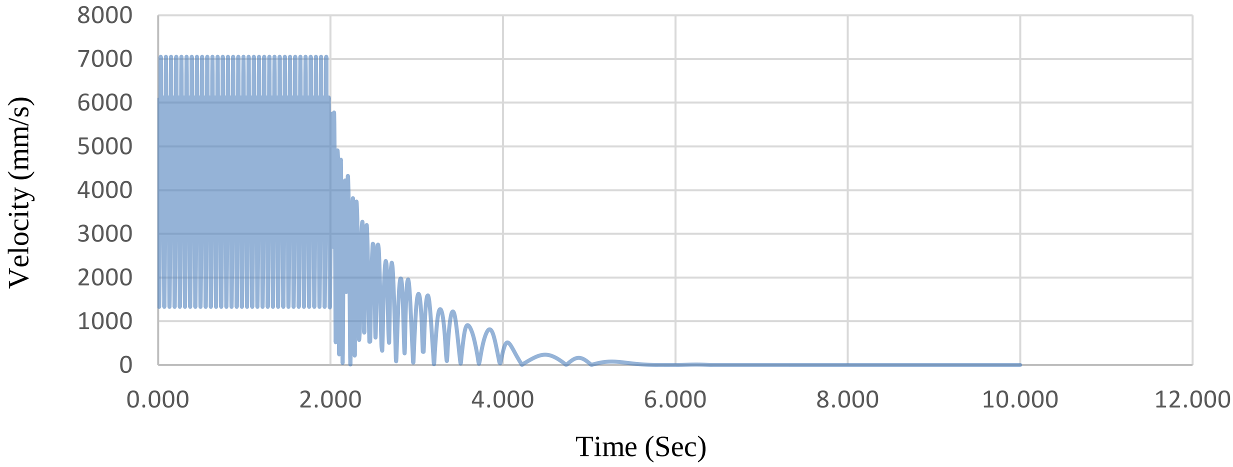

Figure 5. (c) Velocity of ductile iron plasma molly faced ring

4. Discussion

Friction and wear rate vary depending on interfacial conditions such as temperature, sliding speed, type of materials, geometry and so on [19]. Steel ring material has obviously shown superiority in having less friction with TWA aluminum cylinder liner compared to the two other materials, cast iron ring and ductile iron plasma molly faced ring. The smooth surface of steel gives the lowest overall friction among these materials, this was investigated by Viktoria Westlund et al. [20] which concluded that smooth sliding surfaces were consistently and strongly related to low sliding friction. The results of our study have showed that ductile iron is still better choice for friction than cast iron. A study comprising several wear test methods has been carried out to evaluate the wear resistance of ductile iron as alternative to gray cast iron, it has been reached that the wear resistance of ductile iron is significantly higher than grey iron [21]. Cast iron had the highest friction and that is because cast iron is more fragile and has less tensile strength in comparison to steel and ductile iron but economically, cast iron is the lowest expensive. The results of our study also clearly show that steel had the lowest overall friction which is scientifically accurate due to several scientific facts. Young's modulus is a material property that defines how easily the material deforms under pressure. In our experiment, steel has the highest young's modulus which is 1.93GPa. This gives steel an advantage over the other two materials since it will resist deformation at high pressures during engine operation more. The coefficient of thermal expansion dictates how the size of a material varies in relation to changes in temperature. It is the proportion of change in size per degree change in temperature at a constant pressure. Having a lower coefficient means that the material will change size the least. Steel had the lowest coefficient of thermal expansion ($1.7\ 10^{-7}$) which helped it to retain a low level of friction throughout the analysis due to the fact that the steel ring increased in size the least, thus maintaining ring-liner clearance which ensures that the boundary friction will not increase. Regarding surface smoothness, the steel rings had the lowest surface roughness in the experiment which plays an integral role in reducing the friction between surfaces.

5. Conclusion

Less friction between cylinder liner and piston rings would result in an increase in engine efficiency and a decrease in emissions and fuel consumption [22]. This study compared three different ring materials (steel, cast iron and ductile iron plasma moly faced), coupled with an aluminum cylinder liner coated by twin wire arc (TWA) to figure out which ring material has the lowest friction. This analysis was done by using ANSYS simulation and the engine was modeled using SolidWorks. The smoothness of the surface contributes greatly in the amount of friction it produces once sliding against another surface [23]. This was the major factor in deciding which material was going to have the least overall friction. Other factors like the thermal expansion coefficient also played a significant role in dictating the performance of each material under normal engine operation conditions. Overall, the results we obtained showed a clear advantage in using steel as a ring material due to its superior surface smoothness and better performance at typical engine conditions. Results also revealed that ductile iron is slightly better than grey cast iron. For the future studies, high surface smoothness, wear resistance and good behaviour at normal engine speed and temperature should be the main characteristics when choosing ring material in order to decrease overall friction between liner and rings. The outcome of this study should be considered for future scientific research about optimizing the engine efficiency through minimizing friction losses. When considering material choice there should be an inclination towards picking a material that has decent strength properties with emphasis on surface smoothness, as it is the main contributor to friction losses and a low thermal expansion coefficient to maintain ring-liner clearance during operating temperatures.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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