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Con-Rod Acceleration, Forces, Displacements
Advanced Engine Design M6X00410

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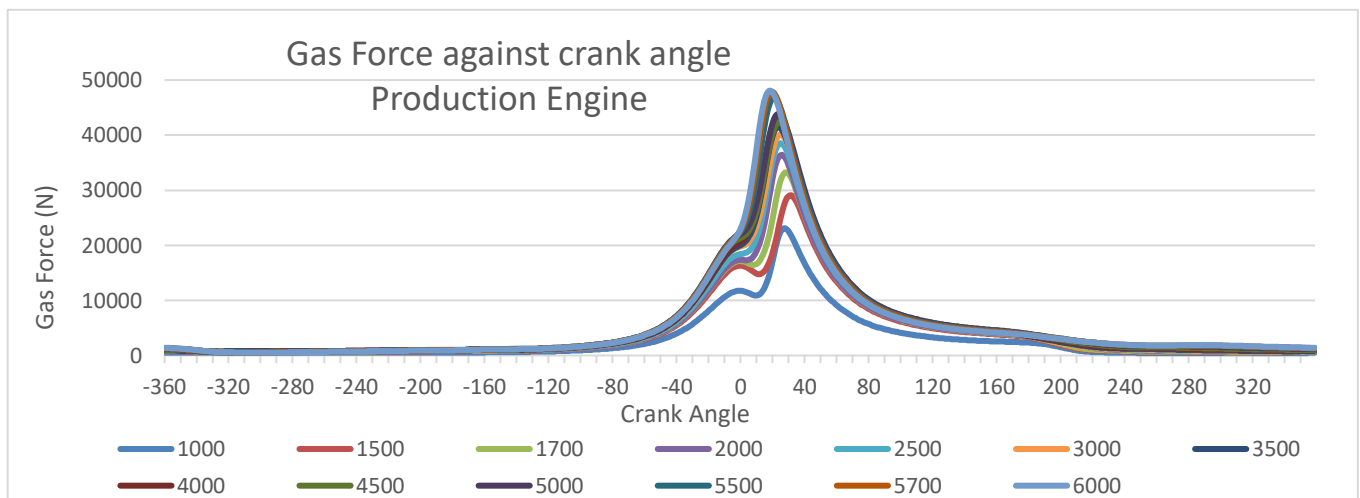
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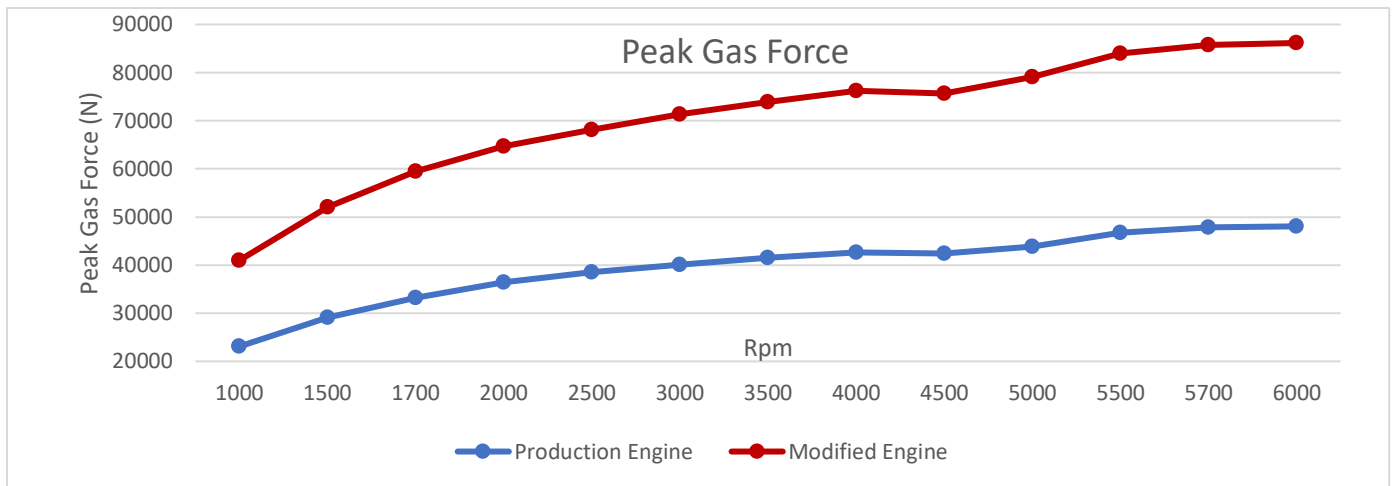
1 Introduction

The study of the stresses within the engine is important as without this, the design of the internals of an engine would be incredibly difficult. So, in this report the author has investigated a Ford 1.6 GDI engine and calculated several factors within the engine. They then modified the engine in a few ways to investigate the effect of the changes. Currently there is a trend for downsizing an engine by removing the number of cylinders and increasing the boost pressure (Severi, et al., 2015) for economic uses. So, the author removed a cylinder and then increased the bore size while keeping the displacement the same so that the capacity of the engine remains the same. The author then investigated the changes that happen when changing the material of the conrod from forged steel to Titanium (Ti4v-6al).

2 Peak Gas Force

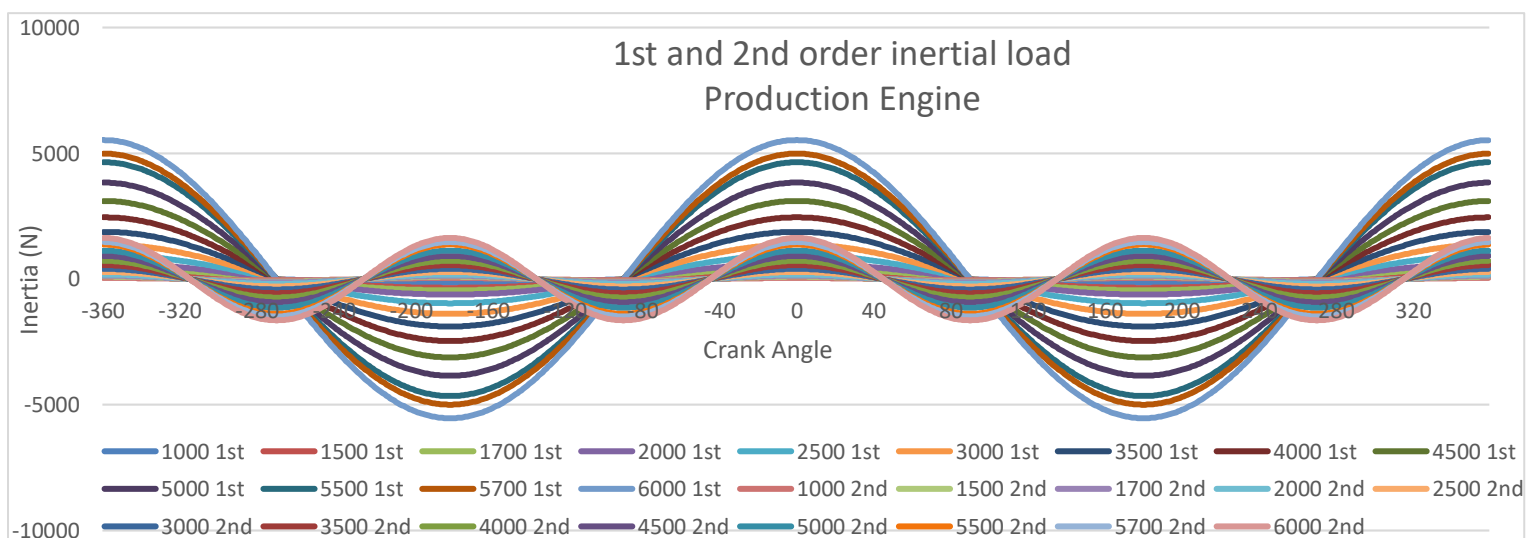
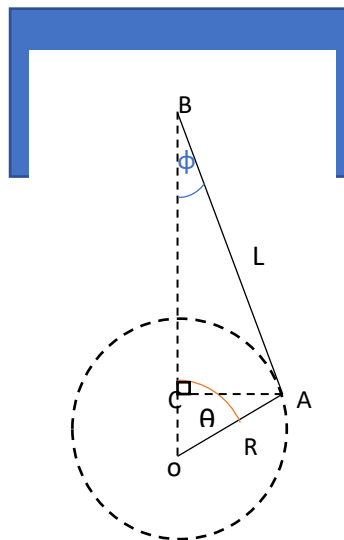


As can be seen the pressure increase at around -80° . This is where the piston is compressing the air-fuel mixture. Then there is a slight dip in the pressure, and this is where ignition is happening around 0° . Then the pressure increases rapidly, and this is the combustion taking place. The pressure then goes down again until there is a slight bump at around 160° and this could possibly be when the exhaust valve closes. To add to that as the rpm increases so does piston speed so the ignition retards to allow the combustion to reach peak pressure at the optimum moment. This is further over when compared to a naturally aspirated engine (n/a) to stop knock. This is because the engine is running much hotter than an n/a engine so need to advance ignition to prevent the fuel combusting at the wrong time. This is more likely to happen at lower rpm as the flame speed is slower so the unburned region is sitting there longer in the cylinder and may auto ignite (Zhi, et al., 2017).

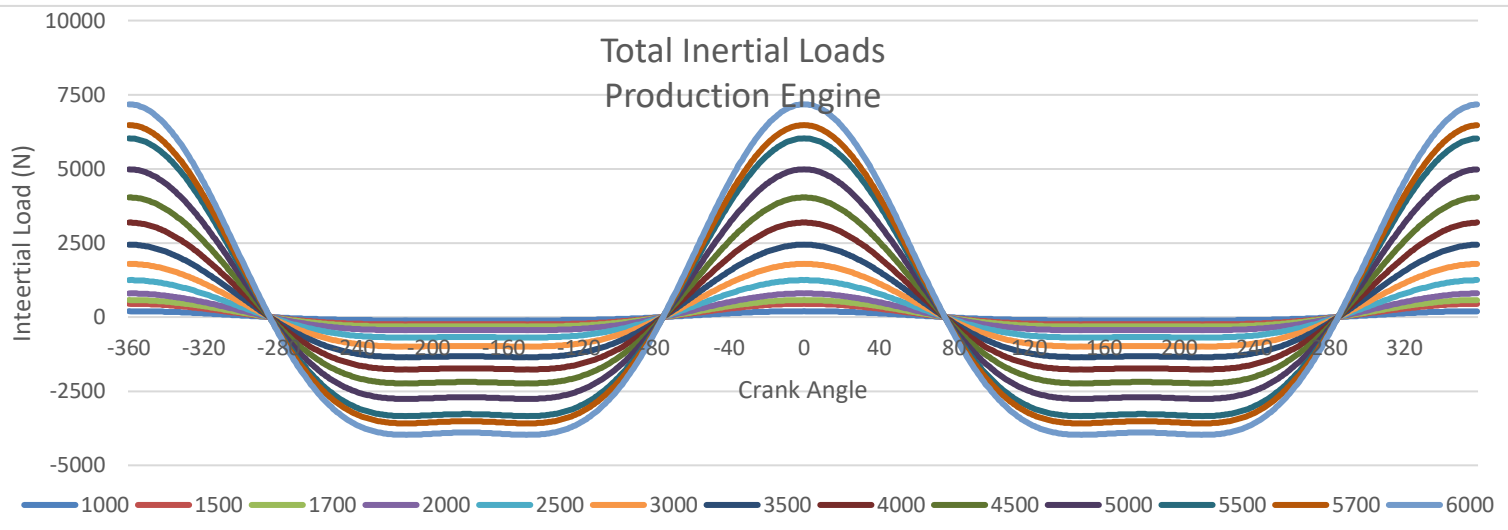


Clearly you can see that as the rpm increases and so does the peak gas pressure. There is also a slight dip at 4500 rpm which could be an error, or it could be that the turbo at this point has not reached boost threshold and the peak pressure levels out but then the turbo kicks in and increases the pressure even more. As can be seen the modified peak pressure is much higher. This is expected as the average pressure is much higher in the modified engine.

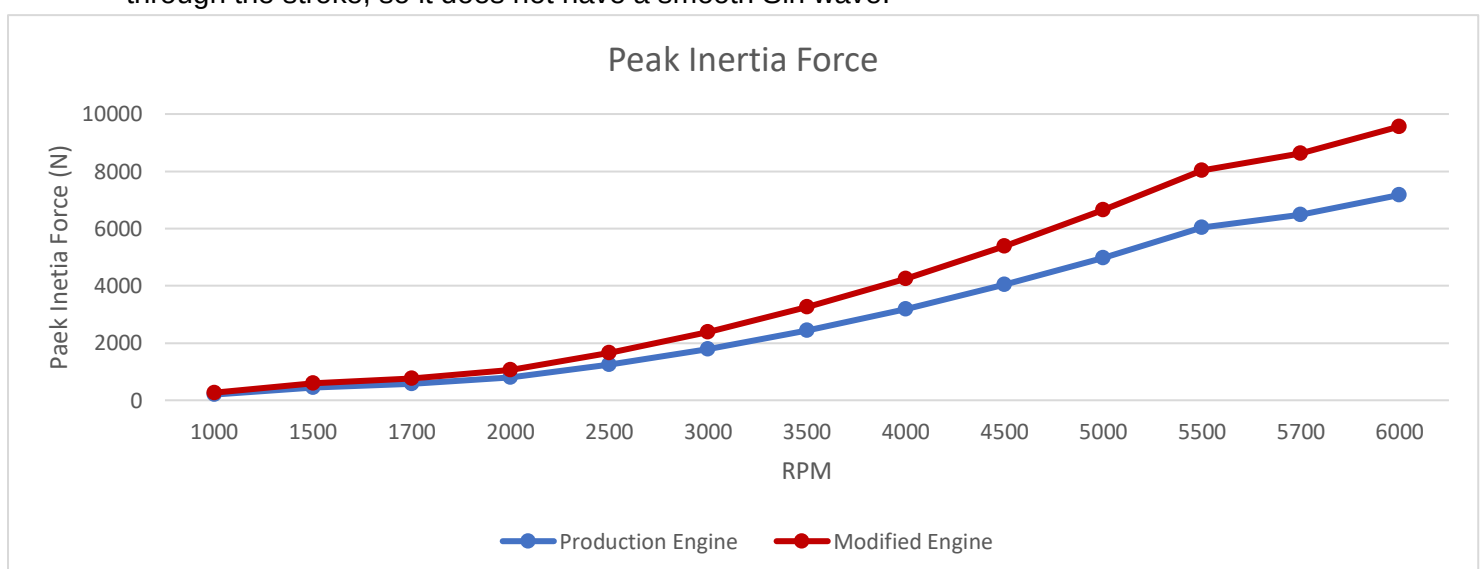
3 Inertia Loads



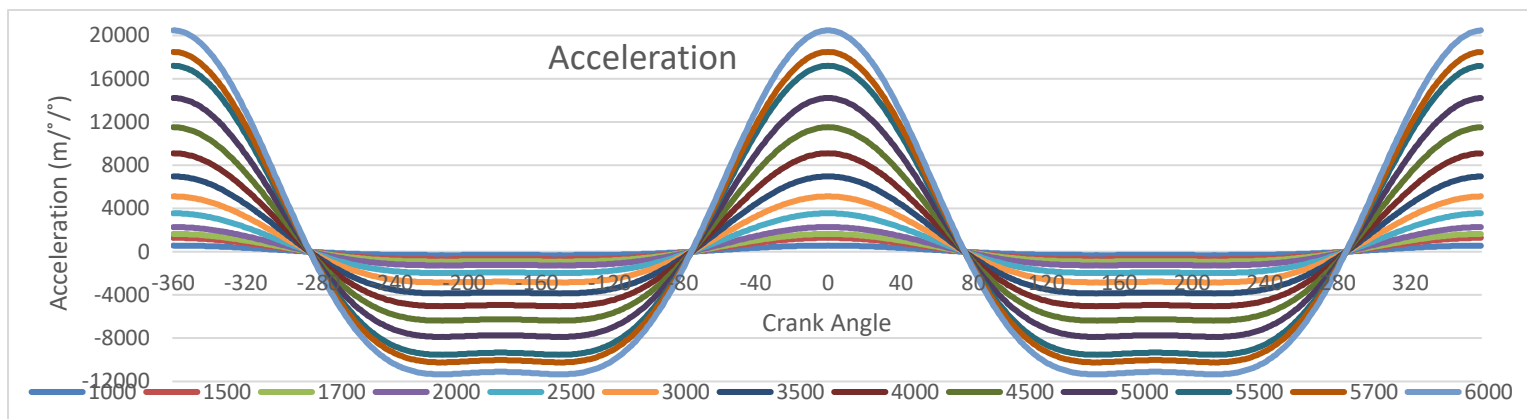
Inertia occurs because the piston moves with simple harmonic motion, so, it has acceleration/deceleration. This accompanied by the mass of the piston creates a force (L.Hosch, 2015). Because this is not counteracted by the other pistons it causes the engine to vibrate. It varies with acceleration which is as expected as it is the same as inertia force just multiplied by the mass from Newton's 2nd law ($F=ma$). As can be seen the 2nd order is twice as frequent as the 1st. This makes engine balancing tricky as it is hard to counteract both orders. However, the first order inertia does have the most effect. The orders then go on, but they become less effective as you go through the orders.



This is just both orders added up together although, you can see it mainly follows the 1st order but, there is a slight change in the middle of the negative values which is down to the 2nd order inertia affecting it as at this point, they are opposing each other rather than adding together. It also does change with acceleration fully as the piston changes its acceleration through the stroke, so it does not have a smooth Sin wave.

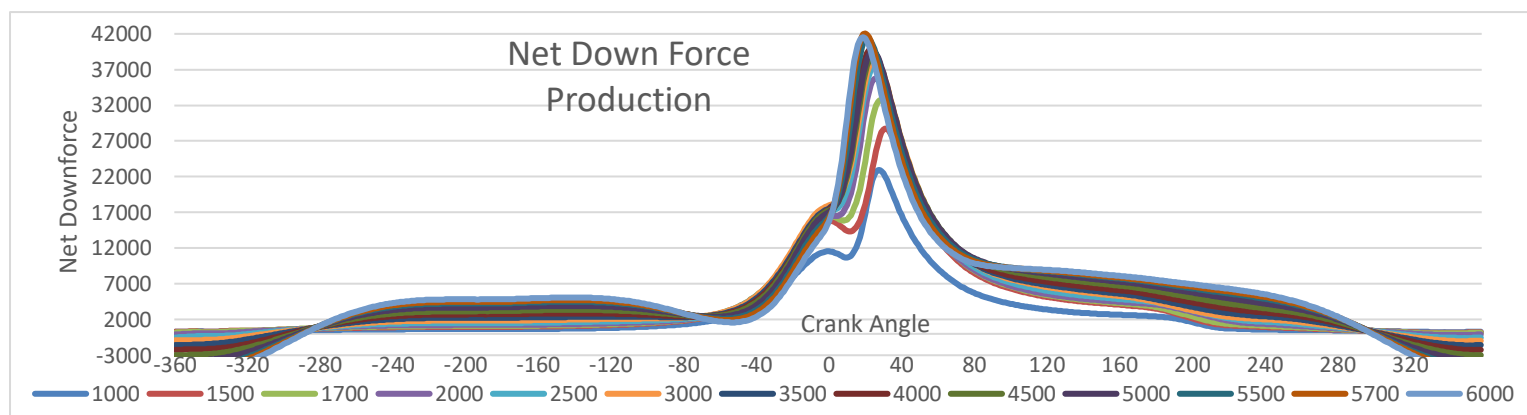


Inertia forces in the modified engine are much larger since the mass of the reciprocating parts is much larger. The inertia increases with rpm as the angular velocity increases.

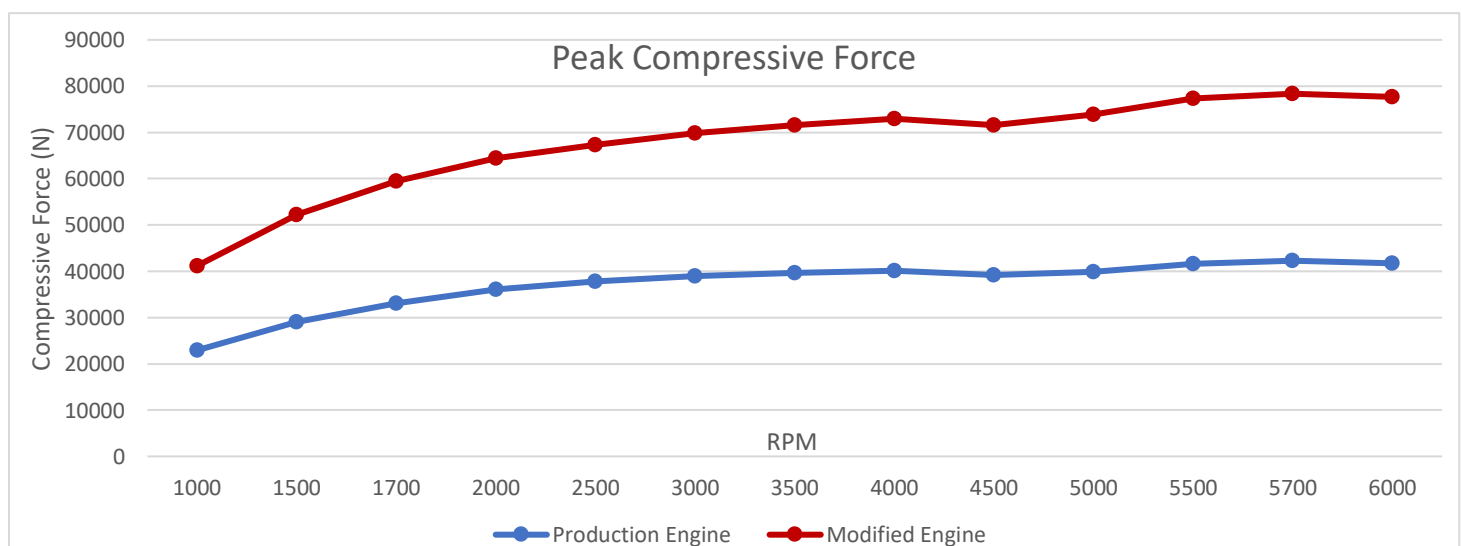


The peak acceleration is different at the top and then it is at the bottom. This is because the piston travels further in the first half of the stroke, than it moves in the second half. This creates unwanted vibration (EPI Inc, 2018). The increase in piston acceleration is much bigger at higher rpm than it is at lower rpm. The piston acceleration is the same for both engines as the angular velocity, conrod length and crank radius is unchanged.

4 Peak Net Compressive Force

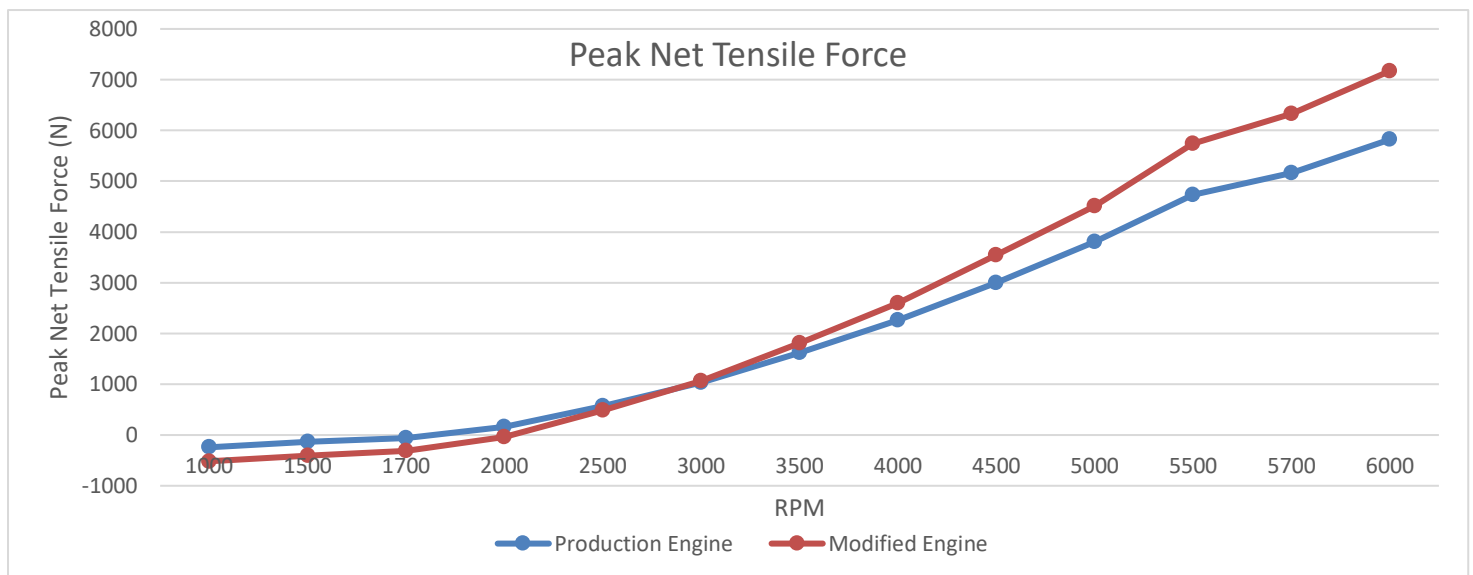


This is Interesting as it has a similar profile for the gas force although around $\pm 300^\circ$ the inertia force becomes greater than the pressure force and the net down force becomes negative. As the rpm increases, the earlier the net down force becomes negative. This follows suit with the ignition timing becoming earlier as mentioned previously.



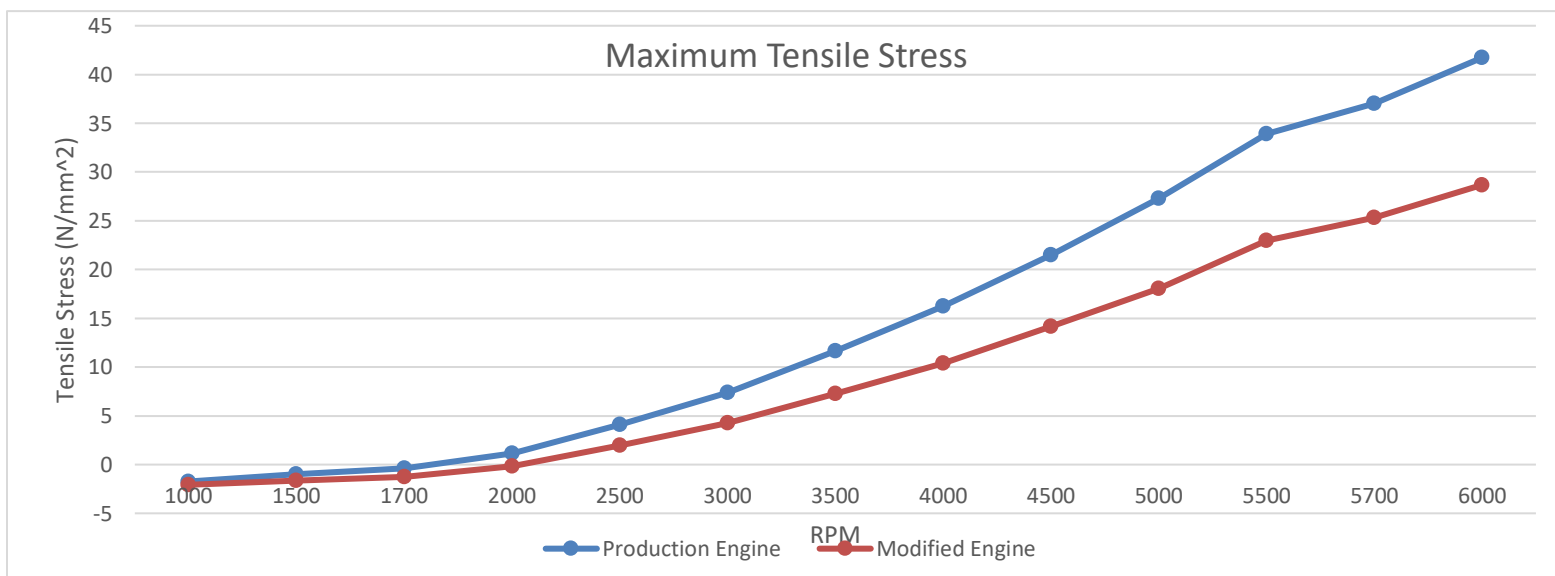
Same as the peak pressure force as the rpm increases so does the compressive force as expected as the in-cylinder pressure increase so there is going to be a greater force exerted on the cylinder. There is also the same dip at 4500rpm which is seen in other results.

5 Peak Net Tensile Force

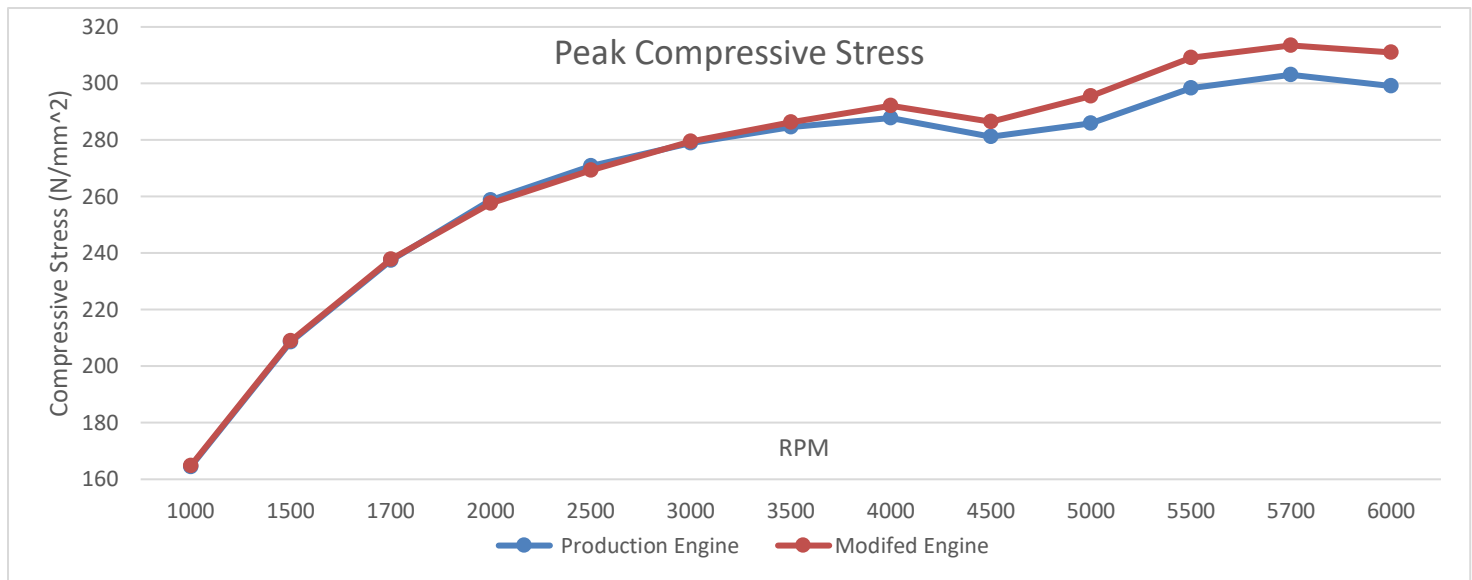


As rpm increases so does the tensile force on the rod this is because as it gets faster there is a bigger acceleration on the reciprocating mass. Therefore, the more inertia it has, the bigger force on the rod.

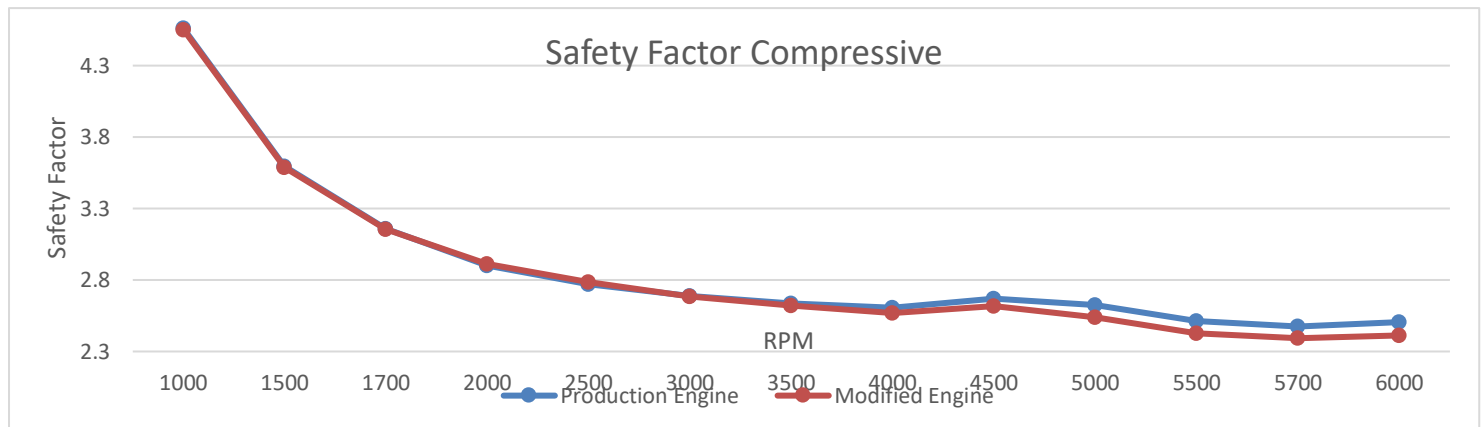
6 Maximum Tensile and Compressive Stresses on Con-Rod



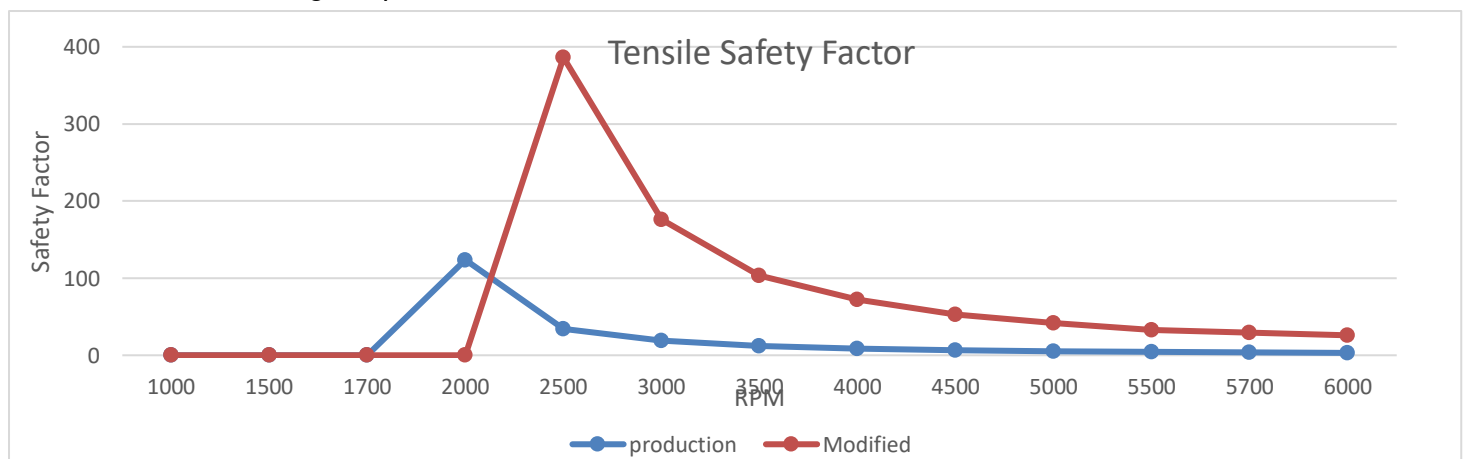
The production engine experiences a higher tensile strength even though it has less of a force acting on it. Due to the modified engine having a larger minimal cross-sectional area, it has much less of a stress put through it as stress is force/area.



The compressive stress is virtually the same until around 3000rpm when the modified gradually becomes greater than the production engine. It is similar as the author changed the size of the minimal cross sectional area so that the safety factor on compressive stress was a similar to the Ford engine to make sure that the rod would be able to take the loads within the engine. This can be seen below.

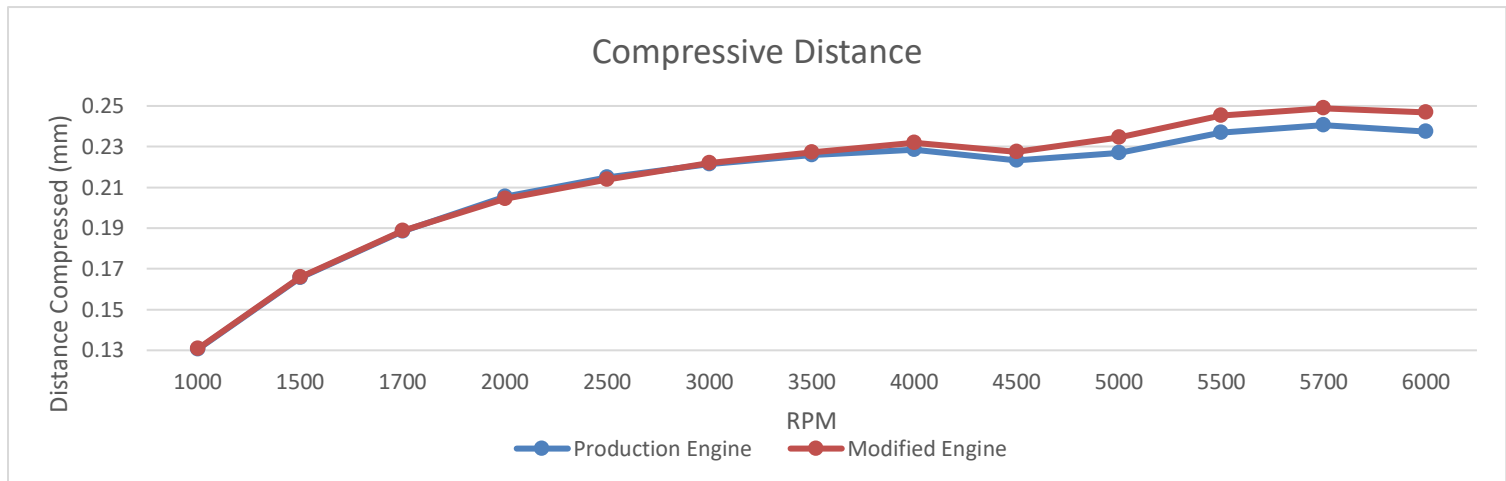


By changing the cross-sectional area, the author has managed to keep the safety factor close to Ford's. This is important as it makes sure that the con rod in the modified engine will not break under load. However, this is still theoretical and may not be the same in real life, but it is still a good point to start from.

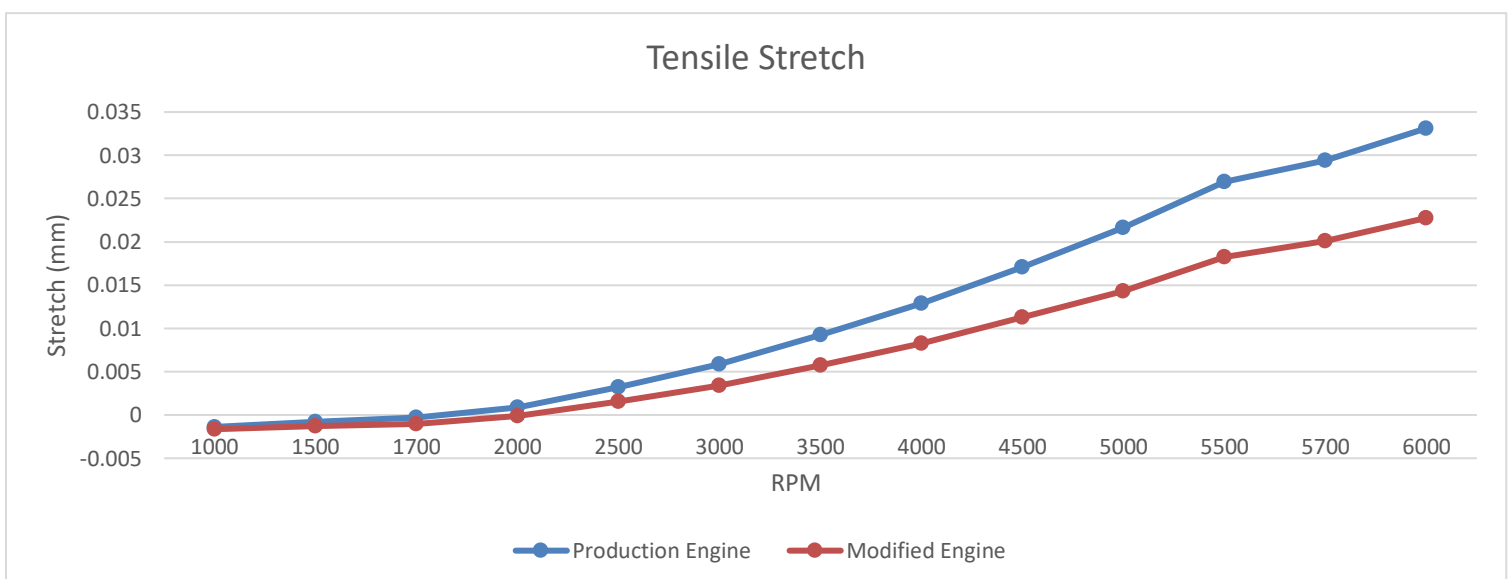


The tensile safety factor is a little more erratic than the compressive. This is down to the tensile stress changing from positive to negative at 1700rpm and 2000rpm. But of course, you cannot have a negative safety factor so for ease of viewing the author has put these to zero. However, the tensile safety factor on the modified is still higher than Ford's so this gives a good indicator that it would still work.

7 Stretch



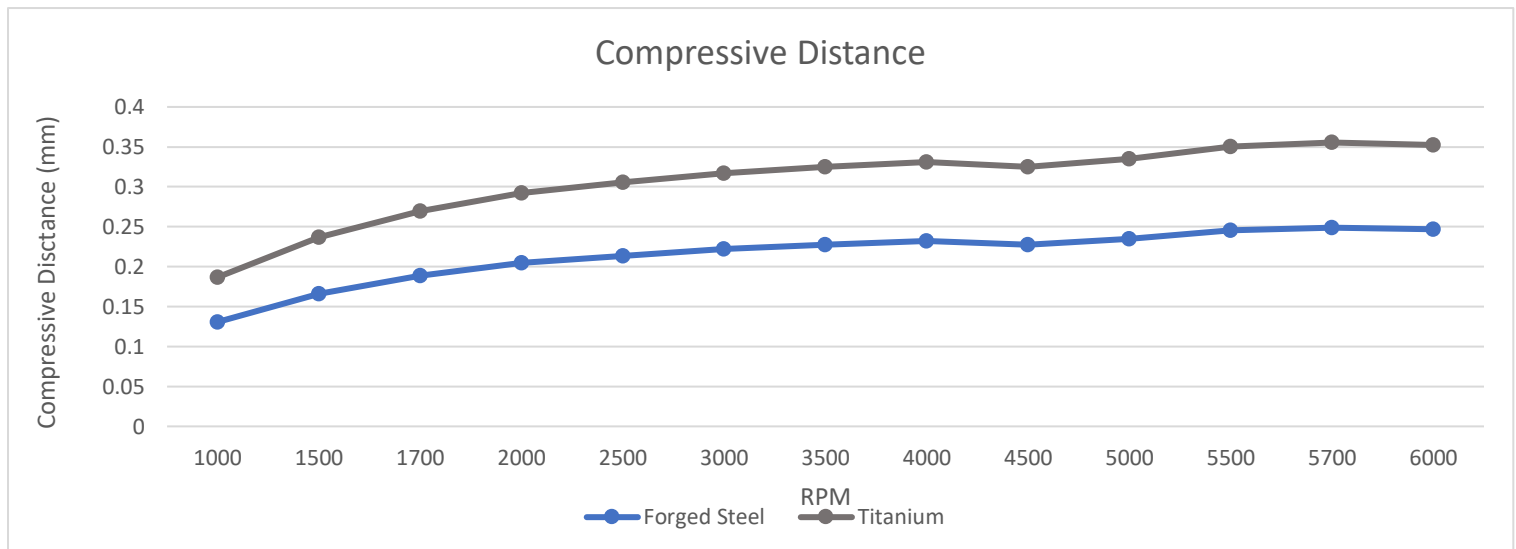
As can be seen the distance the rod can be compressed is slightly more than that of the Ford. It does not vary too much so theoretically could probably be still viable. Furthermore, because the metal compresses the metal absorbs more of the energy from the combustion so that could add to parasitic losses. It also takes the same shape as the peak compressive stress as expected.



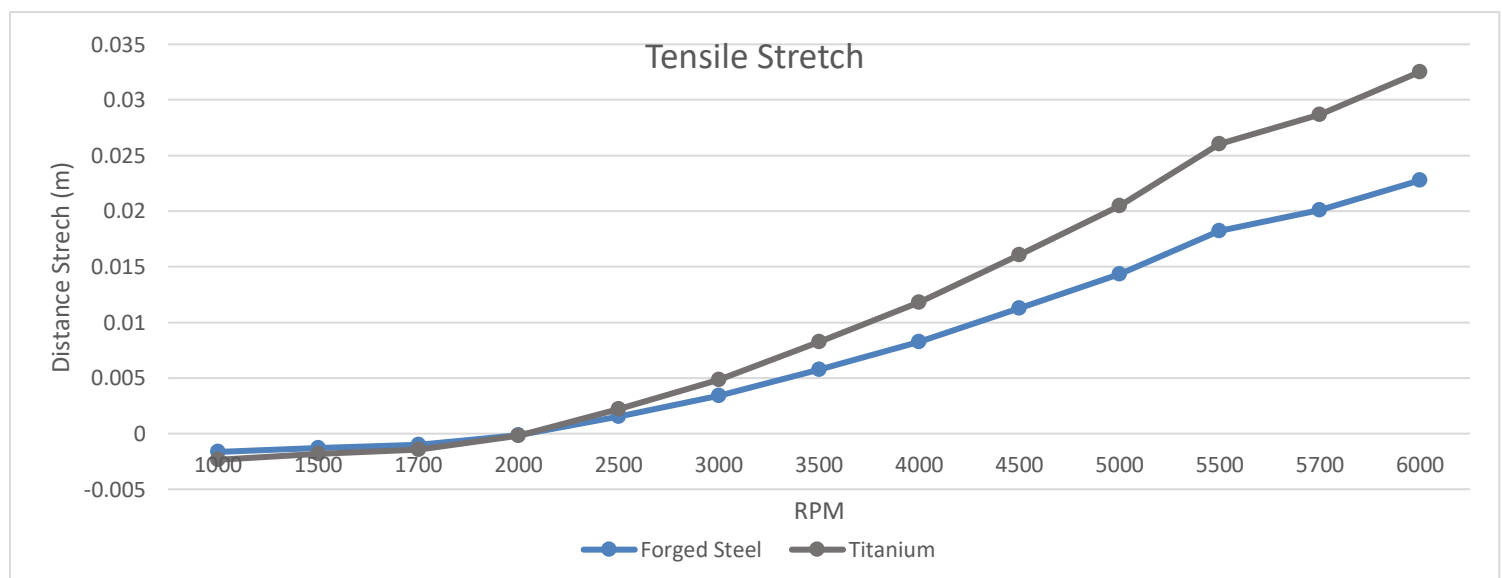
The modified engine rods do not stretch as much as the rod is much thicker so there is more material to pull. On a molecular level there are more atoms linked together which means there are more bonds to change so there must be a much greater force exerted on the rod to stretch it.

8 Effects of changing to Titanium

The author then tested out what would happen if the rod of the modified engine was changed to titanium (Ti4v-6al).



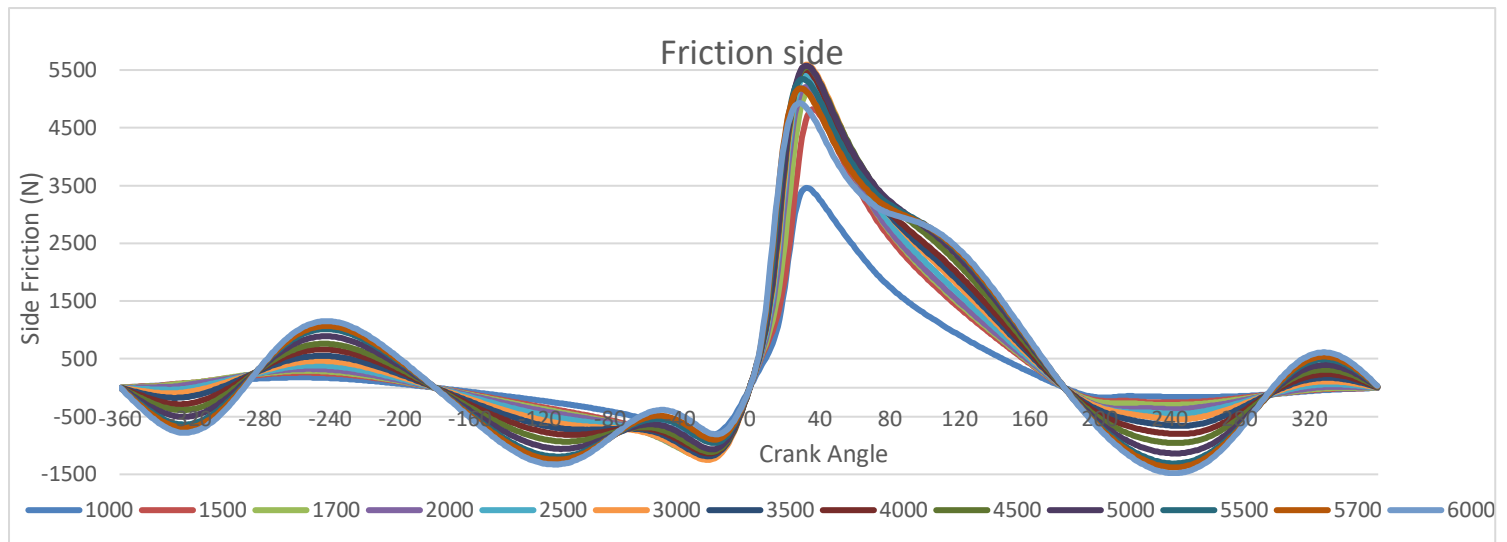
The titanium is a much more compressible material. This is because it is a much less stiff material, so it is more giving when put under loads. The stiffness of the steel con-rod is $3.149 \times 10^5 \text{ N/mm}$ and the titanium $2.205 \times 10^5 \text{ N/mm}$.



The titanium also stretches in tensile more than the steel. This is because the young's modulus of titanium is 119 KN/mm^2 where the steel is 170 KN/mm^2 . This mean that the titanium can be pulled with less force than steel. However, titanium does have its advantages as its mass is significantly less than steel. This is because the density of steel is around 7850 kg/m^3 where aluminium is around 2712 kg/m^3 (Engineering Toolbox, 2004). So, it is still used in certain applications such as in race engines where weight is a big concern.

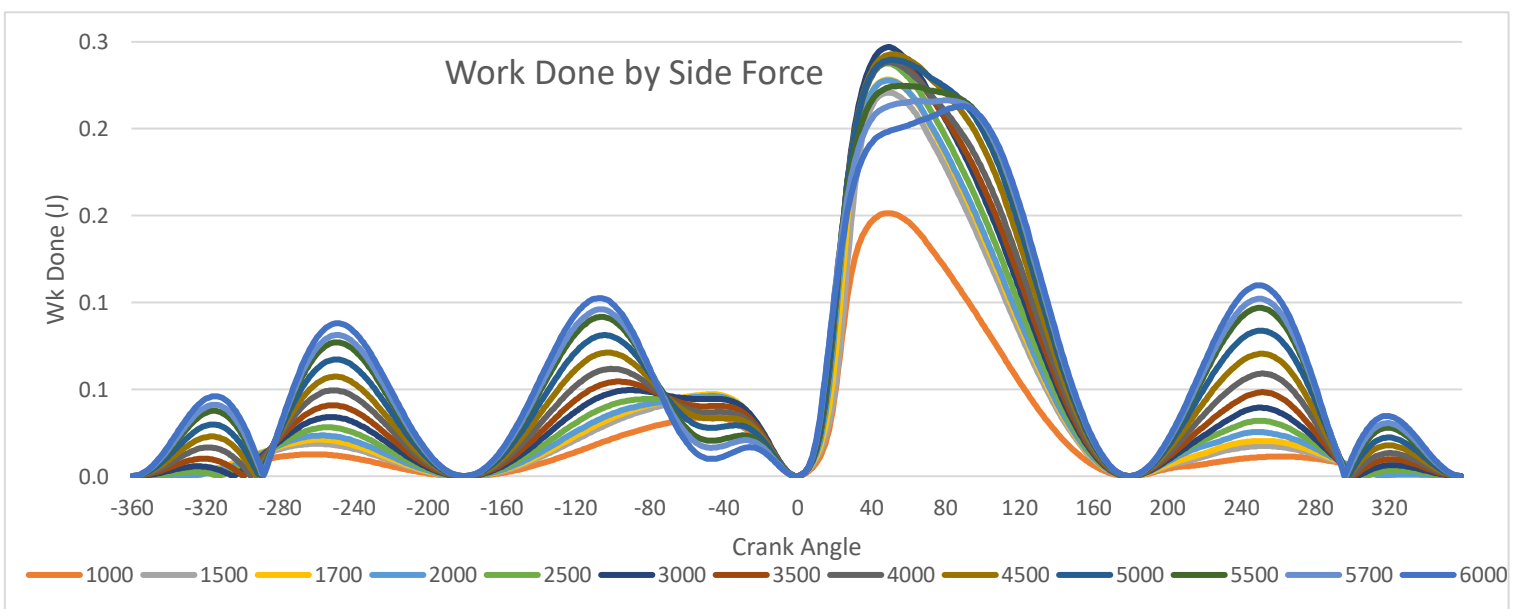
9 Extras

9.1 Side Friction



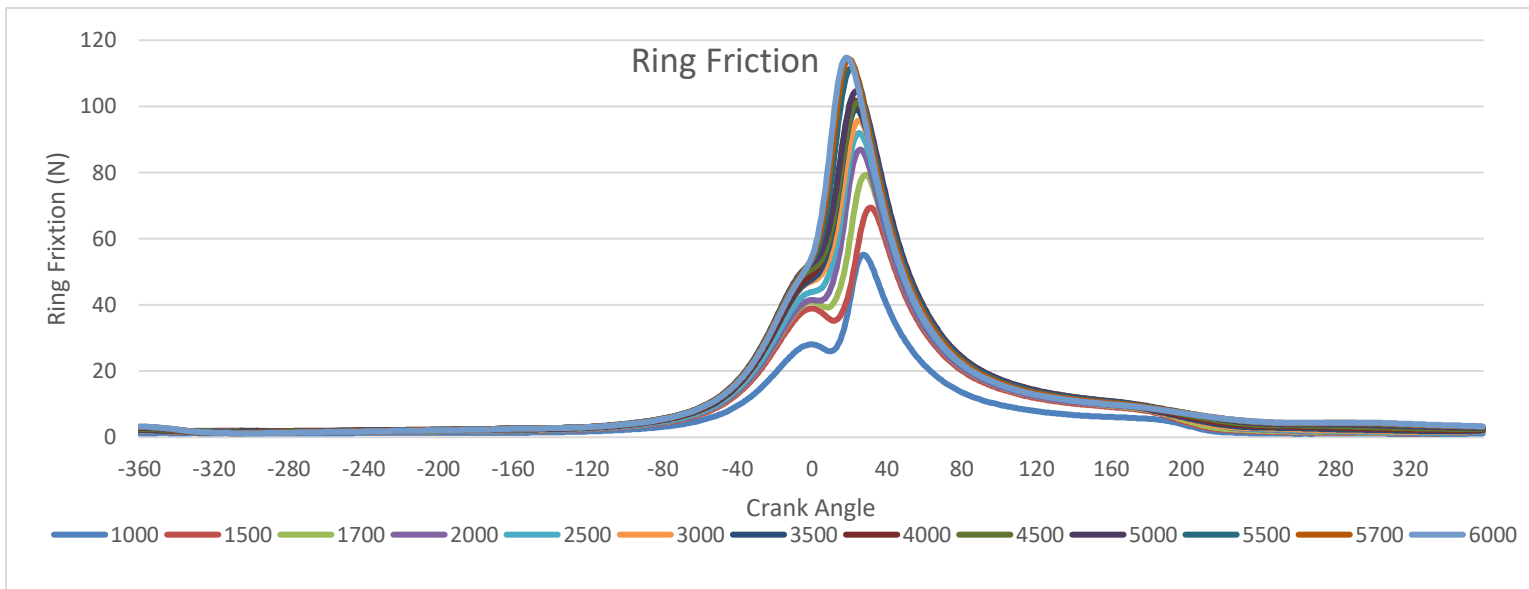
This is an intriguing graph as the shape suggests that when on the combustion stroke there is a greater friction. This could be down to the piston being pushed against the cylinder liner more than when it is just inertia pushing it against the wall. You can also see when the piston is at TDC and BDC the friction is zero, as it slows down and it stops for a moment.

9.2 Work Done by Side Friction



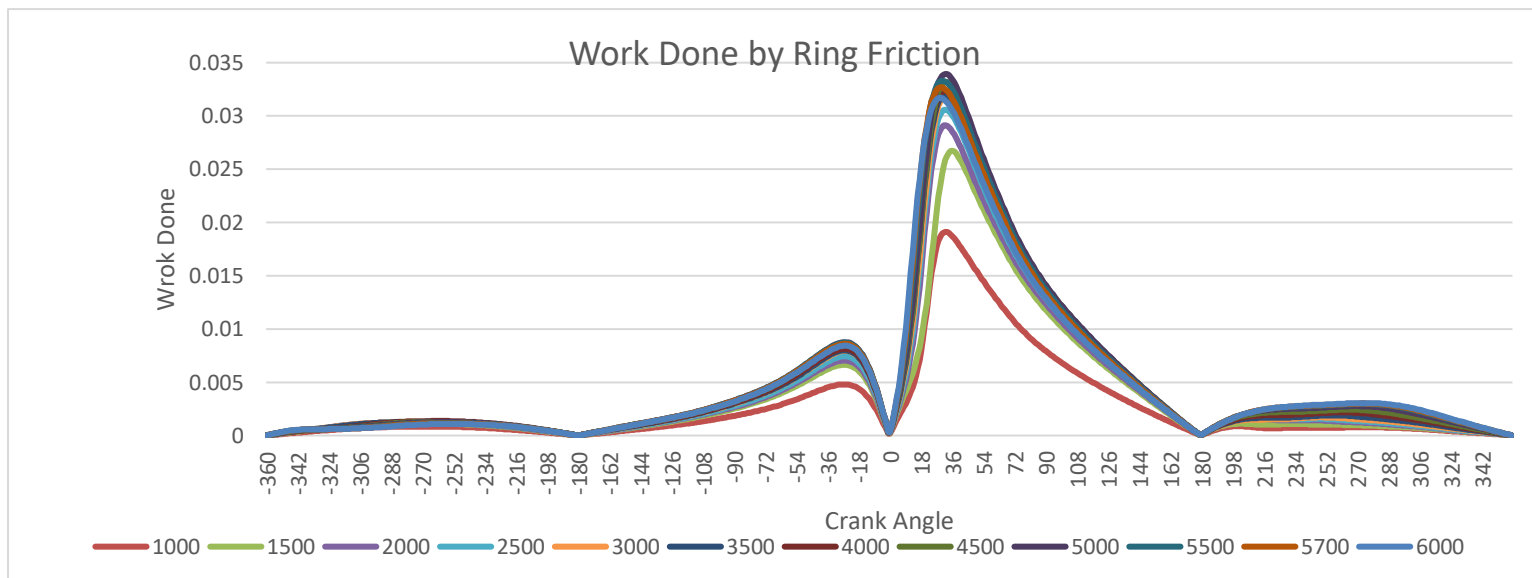
This is an interesting graph because the peak work done by the side friction is not at 6000 rpm where the peak is at other graphs. On this one it goes to a peak at 3000 rpm then starts to decrease again. This may explain why there is a dip in the peak tensile load at that rpm. or it could be perhaps a coincidence.

9.3 Ring Friction



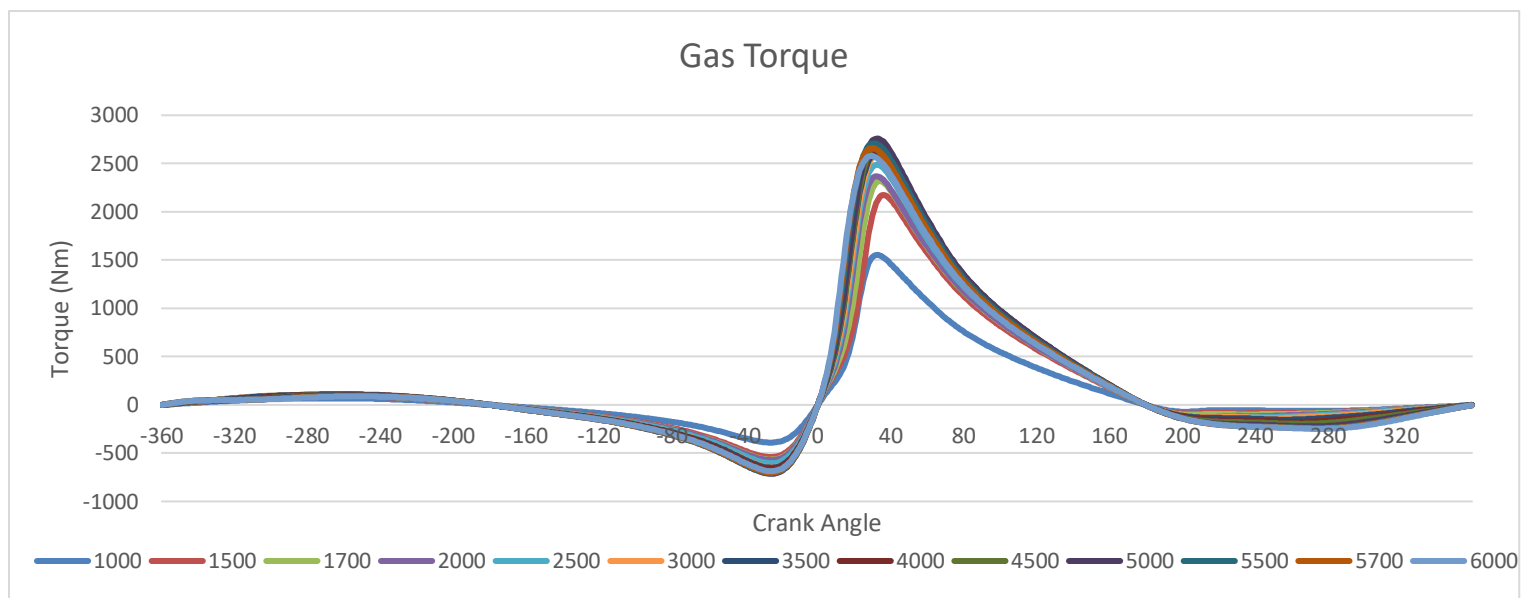
This follows the same as the cylinder pressure graph as it is the cylinder pressure which pushes the piston ring out and against the wall of the cylinder. So, the higher the cylinder pressure the more the ring gets pushed out more, causing greater friction.

9.4 Work Done by Ring Friction



The shape of the graph follows the cylinder pressure graph. However, at zero degrees it goes to zero. This could be because the piston has stopped moving and to add to that the valve is also open so there is change of pressure from that just before it drops to zero. This also happens at 160° as this is where the exhaust valve is probably closing so there is an increase in pressure there.

9.5 Gas Torque



This is the torque created from the gas force only and not including the inertia. The gas torque increases with cylinder pressure as expected. Although, what is interesting is that as the cylinder begins to get to 0° the gas torque is negative. This is because the pressure within the cylinder is working against the movement of the piston as it compresses the air and fuel mixture. As the rpm increases so does the gas torque this is because the cylinder pressure increases so therefore so does the torque.

10 Equations

10.1.1 Equation 1

$$\text{Gas Force} = \text{Cylinder Pressure} \times \frac{\pi \times \text{Bore}^2}{4}$$

10.1.2 Equation 2

$$1^{\text{st}} \text{ Order Inertia Force} = M_{\text{reciprocating}} R \cdot \omega^2 \cdot \cos \theta$$

10.1.3 Equation 3

$$2^{\text{nd}} \text{ Order Inertia} = M_{\text{reciprocating}} \frac{R}{L} \cdot R \cdot \omega^2 \cos 2\theta$$

10.1.4 Equation 4

$$\text{Total Inertia Load} = M_{\text{reciprocating}} \cdot (R \cdot \omega^2 \cdot \cos \theta + \frac{R}{L} \cdot R \cdot \omega^2 \cos 2\theta)$$

10.1.5 Equation 5

$$\text{Acceleration} = R \cdot \omega^2 \cdot \cos \theta + \frac{R}{L} \cdot R \cdot \omega^2 \cos 2\theta$$

10.1.6 Equation 6

$$\text{Net Down Force} = \text{Gas Force} - \text{Inertia Force}$$

10.1.7 Equation 7

$$\text{Rod Angle } (\phi) = \sin^{-1} \frac{R}{L} \times \sin \theta$$

$$\text{Force down Rod } (F_{\text{rod}}) = \frac{\text{Net Force}}{\cos \phi}$$

10.1.8 Equation 8

$$\text{Peak Compressive Force} = \text{MAX}(F_{\text{rod}})$$

10.1.9 Equation 9

$$\text{Peak Net Tensile Force} = \text{Min}(F_{\text{rod}})$$

10.1.10 Equation 10

$$\text{Stress} = \frac{\text{Force}}{\text{Area}}$$

10.1.11 Equation 11

$$\text{Max Tensile Stress} = \frac{\text{Tensile Force}}{\text{Minimum cross-sectional area}}$$

10.1.12 Equation 12

$$\text{Max Compressive Stress} = \frac{\text{Compressive Force}}{\text{Minimum cross-sectional area}}$$

10.1.13 Equation 13

$$\text{Stiffness (K)} = \frac{\text{Young's Modulus} \times \text{Area}}{\text{Length}}$$

$$\text{Stretch} = \frac{\text{Force}}{K}$$

10.2 Extras

10.2.1 Equation 14

$$\text{Side Force} = \text{NetForce} \times \text{Con rod angle}$$

$$\text{Side Friction} = \text{Side Force} \times \mu$$

10.2.2 Equation 15

$$\text{Piston Travel (S)} = R + L - R \cos \theta - L \cos \phi$$

10.2.3 Equation 16

$$\text{Wk Done} = \frac{F_{\text{side1}} + F_{\text{side2}}}{2} \times S_2 - S_1$$

10.2.4 Equation 17

$$\text{Radial Force} = \text{Pressure} \times \text{Bore} \times \text{Piston ring height}$$

$$\text{Ring Friction} = \text{Radial Force} \times \mu$$

10.2.5 Equation 18

$$\text{Wk Done}_{\text{Friction}} = \frac{\text{Friction}_1 + \text{Friction}_2}{2} \times S_2 - S_1$$

10.2.6 Equation 19

$$\text{Gas Torque (Nm)} = \text{GasForce} \times L \sin(\phi + \theta)$$

11 References

Engineering Toolbox, 2004. *The Engineering ToolBox, Metals And Alloys - Densities*.

[Online]

Available at: https://www.engineeringtoolbox.com/metal-alloys-densities-d_50.html

[Accessed 31 October 2019].

EPI Inc, 2018. *epi-eng.com*. [Online]

Available at: http://www.epi-eng.com/piston_engine_technology/piston_motion_basics.htm

[Accessed 30 October 2019].

L.Hosch, W., 2015. *Inertia*. [Online]

Available at: <https://www.britannica.com/science/inertia>

[Accessed 30 October 2019].

Severi, E. et al., 2015. *Numerical Investigation on the Effects of Bore Reduction in a High Performance Turbocharged GDI Engine. 3D Investigation of Knock Tendency*. Modena, Elsevier Ltd, pp. 846-855.

Zhi, W., L., H. & Reitz, R. D., 2017. Knocking combustion in spark-ignition engines. *Progress in Energy and Combustion Science*, July, Volume 61, pp. 78-112.

12 Appendices

Constants	Production Engine	Modified Engine	Titanium rod production	Titanium Rod Modified Engine
Piston Mass (kg)	0.2577	0.2577	0.2577	0.2577
Con rod Mass (kg)	0.2674	0.46182796	0.2674	0.2674
Reciprocating Mass	0.3504	0.4672	0.4672	0.4672
Con rod length (m)	0.13495	0.13495	0.13495	0.13495
Crank Radius (m)	0.04000	0.04000	0.04	0.05
Piston ring height	0.0015	0.0015	0.0015	0.0015
Bore (m)	0.08	0.10666667	0.08	0.1
UTS (N/mm ²)	750	750	950	950
Min Cross Sectional Area of con rod (mm ²)	139.5	250	250	250
Young's Modulus con rod (KN/mm ²)	170	170	119	119
Stiffness of Con rod (N/mm)	1.757E+05	3.149E+05	2.205E+05	2.205E+05
Mu	0.10	0.10	0.10	0.10