Why Pistons Fail

1. Introduction

From its inception in the late 1800s to the present day, internal combustion engines have not only served a major role in powering various kinds of vehicles all around the world, but also have drastically evolved since then.

A very early case of using an internal combustion engine to power a land vehicle was the Hippomobile. This vehicle featured a rudimentary design that was powered by an engine that displaced 2.5 liters, made 1.5 horsepower, and revved to 100 revolutions per minute. The Hippomobile achieved a top speed of 6 kilometers per hour, or around 3.7 miles per hour.

In today's world, automobiles are capable of much higher top speeds. As a consequence of this, engines are operating at much higher temperatures and engine components experience much higher amounts of stress than before. In addition, studying engine components and why they can fail gives insight into how metals operate at such high temperatures and how to optimize performance at these high temperatures, whether that be better material choice, better heat treatment processes, better design choices, anything else that can be made better in the design/manufacturing process, or even creating a better working environment for these engine components.

One such key component is the piston. Pistons are often referred to as the heart of the engine and their proper and optimal performance ensures peak performance and reliability of the engine. Therefore, this article focuses on pistons and possible ways that they can fail.

2. General Overview of Pistons

A piston is a cylinder that contains a moving disk that is placed in a gas-tight region of an engine. The goal of the piston is to effectively transform heat energy that comes into the chamber to mechanical work. In the particular case of an internal combustion engine, the heat energy that comes in is the energy that is stored within a fuel and air mixture, and the mechanical work is the actual driving of the wheels.

A piston can achieve this using a cyclic thermodynamic process. This simplified process is outlined in the following steps. Note that the process can and will get more complex in different cases. To begin, the fuel and air mixture enters the chamber. Once the chamber is heated, the mixture will expand in volume and cause the piston to be displaced. After the heating stops, the mixture will cool down, causing the volume of the mixture to decrease. This will once again displace the piston to the same position as it was before the mixture was heated.

The movement of the piston in this manner is what drives the crankshaft, and in turn, the crankshaft is what then drives the flywheel, which then drives the wheels. Pistons are a critical component to engines. In the absence of the piston, or the absence of a properly working piston, would lead to a vehicle that cannot be driven efficiently by the engine.

3. Choice of Materials and Manufacturing Process for Manufacturing Pistons

Making pistons requires that many decisions be made about the overall design and how that design can be achieved, while maintaining the needs of all stakeholders involved.

3.1 Material Choice

The preferred choice of material to use for modern pistons in the automotive industry today is a type of aluminum alloy. Earlier, cast iron was used to make pistons because it possessed great wearing quality, coefficient of expansion, and overall suitability to various manufacturing processes. The main disadvantage to cast iron is the weight of the material. When the industry demanded for weight reduction, then the switch to aluminum alloys was made.

Advantages of using aluminum alloys are that they possess a lower density, high thermal conductivity, competent tribological characteristics, and the flexibility that comes with designing alloys. Disadvantages of using aluminum alloys are that they contain a high coefficient of thermal expansion, low wear resistance, and a significant loss of strength characteristics at high temperatures, although these disadvantages can be mitigated by better alloy design, better heat treatment of aluminum, or using a more suitable manufacturing process.

3.2 Choice of manufacturing process

Currently the two most common manufacturing processes to make pistons are casting and forging.

When using casting to manufacture pistons, molten aluminum alloy is poured into a mold and is allowed to cool. Afterwards, the piston is taken out of the mold and any necessary machining is done to get the piston to its final shape. Casted pistons usually contain a certain amount of silicon, usually around 10-12%. Increasing the silicon composition in the piston will lead to a piston that can sustain higher power levels and has better thermal efficiencies.

When using forging to manufacture pistons, a billet of aluminum alloy is placed into dies. From there, extremely high pressures are applied to shape the billet into the general shape of a piston. Compared to casting, forging a piston requires significantly more machining processes and time to machine it to the correct shape. In addition, similar amounts of silicon can be present in forging aluminum piston when compared to casting aluminum pistons, but it largely depends on the type of aluminum alloy configuration being used.

Both casting and forging are used, and have their advantages over one another. In terms of the strength of the final product, a forged piston will have a greater ductility and a higher strength compared to a piston that was made by casting. In addition, the forged piston is also more dense and it forms a better heat path throughout, allowing heat to be more effectively dissipated from the piston head. However, the single advantage that casted pistons have are that they require less machining and post-processing. When an engine with a higher power output is required, forged pistons are used for the advantages that it provides over casted pistons.

4. Why Pistons Fail

Pistons can fail for many reasons. To simplify things, this article will take a more generalized approach in explaining each of the failures, and assumes that the piston is under normal use and operates in an environment that it was designed for.

There are three general areas to look at when analyzing piston failure: the creation and manufacturing of the aluminum alloy and the pistons itself, the environment in which the piston operates and how that impacts the longevity of the piston, and the nature of which the piston operates cyclically and how that influences its failure.

4.1 Improper Heat Treatment

Although aluminum is widely regarded as a strong material and is appropriate for use in applications such as building a piston, it has to be properly heat treated to be able to sustain the repeated loads. One reason that a piston may be unable to perform as expected can be traced back to the heat treatment. In general, metals are heat treated in order to be able to sustain higher peak static loads or more cyclic loads in the case of fatigue. However, when that heat treatment is done incorrectly, it leads to subpar piston strength.

Most of the issues with heat treating aluminum (which can lead to the manufacturing of a piston that is subpar) include: improper racking of parts, excessive heating/ramp rates, higher residual stress levels than expected, variation in time/temperature/quench parameters, surface blistering/high-temperature oxidation, overaging, underaging, inadequate time at temperature, inadequate temperature uniformity, improper cold working after solution treating, inadequate cooling rate.

4.2 Manufacturing Defects

Generally speaking, a common cause of failure can be traced back to the manufacturing process itself or something that occurred during the process. These potential errors along the way include errors that could have resulted from either the method used to manufacture it, the environment it was manufactured in, human errors during the manufacturing process, and more. While there are a lot of variables that can vary from manufacturer to manufacturer with regards to the steps along the way in the manufacturing process, this article will focus on the errors that occur as a result of the manufacturing process itself.

As mentioned earlier, the two main methods to manufacture pistons are casting and forging. While both are used in the automotive industry (and manufacturing metal components in general), they each have inherent flaws that can lead to eventual failure. The goal of any manufacturer would be to reduce as much of these errors as possible by optimizing the working environment and reducing potential contaminants from entering the final product.

4.2.1 Casting Defects

Overall, casting metals is a relatively complicated process, as it involves applying high pressure to metals, which makes it prone to several unwanted errors. There are many types of casting defects, but they can be categorized into four broad categories: metallurgical defects, defects due to heat, mold material defects, cast shape defects

4.2.1.1 Metallurgical Defects

Metallurgical defects include: gas porosities, shrinkage porosities, sinks, slag inclusions, drosses, and soldering. Most of these defects occur as a result of the design of the mold, design of the part, or suboptimal or inadequate working environment that can allow contamination into the molten metal. A method to prevent these would be to better design the mold to allow for air to escape, ensure that the mold is completely clear of contaminants, and clamp down on any contaminants from entering the mold as the molten metal is being cooled.

4.2.1.2 Defects Due to Heat

Some defects can be caused due to heat, and the nature of working with alloys at such extreme temperatures. A few examples of these defects include: hot tears, cold shut and thermal fatigue. These defects can occur as a result of stresses and strains that occur at very high temperature, as well as possibly attempting to overcorrect the issue by creating a nonoptimal way for temperature to escape. The solution to preventing this is to create a more favorable temperature environment that isn’t too extreme and optimize the cooling process to ensure that the metal isn’t under high stress.

4.2.1.3 Mold Material Defects

Defects can also occur in the final product as a result of the mold itself, rather than due to the conditions that the metal is subjected to. These include: cuts and washes, fusion, runout, swells, drops, metal penetration, and rat tails. All of these issues can be traced to designing a mold that doesn't hold up to the requirements of the molten metal being poured into it. Ways to remedy this would be to use a different type of material to build the mold out of, use reinforcements where necessary, and design molds to withstand the pressure from the molten metal which would allow for movement and thus change the shape of the final product.

4.2.1.4 Casting Shape Defects

The last type of defect can occur with the shape of the object being casted. Two defects that can stem from this include mismatches and flashes. Mismatches are caused by loose pins or ones that use an incorrect pattern that would lead to misalignment. Flashes are caused by an insufficient clamping force or an injection speed that is too high. Both can be remedied by adjusting the casting parameters and ensuring that the mold is properly lined up.

4.2.2 Forging Defects

While forging pistons will result in a piston that has good mechanical properties and is preferred in vehicles where the demand for power is significantly higher, the process itself is prone to some defects.

Mainly, these defects will occur as a result of the rapid heating and cooling of the metal (which in this case is the piston), which induces unwanted stresses and strains on the part. These stresses and strains can lead to thermal fatigue, which is the cause behind many defects seen in forging, namely: cold shut, flakes, surface cracking and internal cracks. Forging defects can also occur due to contamination during the forging process from the outside environment or due to poor forging technique, which causes defects to appear in the final result, such as scale pits and die shifts.

To avoid these defects, manufacturers can change the environment that they are operating in to reduce the contaminants that can enter the final product, ensure the proper forging technique is being used, and optimize the cooling process to reduce the stresses and strains that occur in the manufactured part.

To sum up, there are many defects that can occur in the manufacturing process that occur as a result of the environment that the part is being manufactured in, human error during the actual casting or forging process, or inherent issues that are present with the manufacturing technique themselves. Manufacturers can use the general prevention measures that were provided in this article to mitigate the issues that can occur during the manufacturing process, ultimately reducing the risk of manufacturing defects occurring in the final product and creating a stronger product. In addition, manufacturers can also implement good quality control and quality assurance measures.

4.3 Piston Environment and Failure

As mentioned earlier, if the environment in which the piston will be used isn't optimal, then the result will be a piston that doesn't last as long. There are several factors that need to be properly regulated to maximize piston longevity.

The most critical of these factors is using the correct air-to-fuel ratio. Using too much air or too much fuel can cause damage to the pistons by inducing unnecessary stresses and strains that lead to thermal growth, as well as erosion of the piston crown. This damage to the piston is caused by other components (such as the intakes, exhaust, turbo, and fuel pump) being unable to function properly in the environment created by the improper air-to-fuel ratio.

Another factor that can lead to piston failure is improper coolant temperatures. Improper maintenance can lead to improper coolant temperatures, and even a lack of coolant. It can also lead to unnecessary piston growth, which leads to the piston ring, piston skirt, and piston crown being scuffed. In turn, this will lead to piston seizure, which is when the piston clearance disappears and leads to the failure of the piston. In addition, improper assembly can also lead to damaged pistons, as it generates an unfavorable environment for the pistons to be operated in.

The damages that can visually be seen on the piston are an indication of how the piston failed, however, they all trace back to an unfavorable environment, whether that be influenced by poor design choices, by human error, or another such factor.

Damage on the piston crown include seizures, impact marks, fused or melted off material, and cracks in the crown and crown bowl. Seizures can be caused by incorrect installation or overheating of the piston. Impact marks are caused by carbon deposits that are found on the piston crown or incorrect valve timing. Fused or melted off material can be caused by a faulty injection nozzle or ignition delay. Cracks in the crown or crown bowl can be caused by a lack of adequate cooling or insufficient compression.

Damage on the piston ring includes material washout, radial wear, and axial wear. Washouts can be caused by incorrect installation or severe axial wear of the ring groove and piston rings. Radial wear primarily occurs due to fuel flooding, but can also be caused by issues during the combustion process, such as insufficient piston pressure. Axial wear is primarily caused by contaminants such as dirt that enter the engine, and that aren't removed during engine maintenance.

Damage on the piston skirt includes an asymmetrical wear pattern, 45° seizure, and fuel damage. An asymmetrical wear pattern is caused by issues with the connecting rod and cylinder bores being installed incorrectly. A 45° seizure can be caused by a narrow fit of the piston pin (which can be caused by improper design or installation). Fuel damage can be caused by insufficient compression or misfiring.

Damage on the cylinder liner includes cavitation and bright spots on the upper cylinder area. Cavitation can be caused by an unsuitable cooling agent being used or an operating temperature that is too high or too low. Bright spots can be caused by carbon deposits that land due to either increased emissions of blow by gasses or frequent idling.

Note that this article only provides a surface-level look into what damage can occur on the piston as a result of the environment it operates in, and provides only superficial reasons as to why it may occur.

To sum up, the environment that the piston operates in plays a key role in the longevity of the piston. Optimizing the environment will increase the longevity of the piston, and subsequently, the engine.

4.4 Fatigue Failure

While metals are ideal for how lightweight and durable they are, they tend to get destroyed at cyclic loads at a much lower stress level than compared to static loads. This type of fracture is known as fatigue, and it is caused by the formation and propagation of small cracks through the material.

4.4.1 Evidence of Fatigue Failure in Pistons

In the case of the piston, the initiation of the crack occurs because of the large thermal stress that is experienced by the piston crown and the surrounding area of the piston crown. This thermal stress is repeated and induces a cyclical loading onto the piston. The loading comes in the form of expansion mismatches on the piston crown and the surrounding area of the piston crown. Eventually, the fatigue strength of the aluminum piston will be reduced and small cracks will begin to emerge. Once the initial cracks form, the repeated stresses will lead to the crack growing larger and propagating through the material.

While there are many forms of fatigue that a piston may go through, this article will focus on thermal fatigue failure of these components. Applying excess heat to the system will accelerate this damage. If the intercooler air temperature is too high, it can overheat the piston and the chamber. This high heat will cause more damage to the pistons. Fatigue cracks can also appear in other components of the piston.

As the cylinder wall wears, the clearance between the piston and cylinder wall becomes higher. This will increase the stress applied on the piston ring , and subsequently, the piston groove. Improper placement of the piston ring can accelerate the appearance of the fatigue crack formation.

Another side effect of this increased gap between the piston and cylinder wall is that the piston will get misaligned over time. Over time, this allows the piston skirts to make contact with the wall and cause damage to the piston. These contact points induce a flexural load on the piston skirt, which may not be designed to accommodate such a load, and as a result, get damaged.

The piston pins transfer the energy from the combustion into the crankshaft through transferring a compressive load. A main reason why fatigue cracks show in the pins is because of unbalanced forces that will be propagated through the pins, such as through incorrect assembly of the component or misalignment of the piston. In addition, any non-metallic inclusions that are present can also decrease the fatigue strength and allow fatigue cracks to show up and propagate much faster.

4.4.2 Preventing Fatigue Failure in Pistons

While there are many ways that fatigue failure can be prevented in pistons, this article will cover a few preventive measures that can be taken to ensure piston longevity: changes in the operating environment and changes in the design.

Reducing the temperature is critical to optimizing the system performance, as once temperature levels drop, reducing the peak temperature that the pistons are operating at, the temperature gradient within the piston would also reduce. It would cause less stress to be present throughout the product. This reduction in stress levels will increase the longevity of the piston, since there will be less fatigue that is induced on the piston. Using an appropriate coolant would mitigate these issues.

The design of the piston can also be modified to help reduce the temperatures in the system and mitigate these issues. It can be changed in many ways, for example, using new materials and modifying the geometry. New aluminum alloys can be made to help improve fatigue performance by increasing the fatigue strength or by dissipating the heat better throughout the system. The geometry of the piston can be modified to allow for smoother transitions and better longevity of the pistons. However, there is a fine line of what can be changed, as changing too much might cause deformations and stresses in unwanted areas, like the bowl rim.

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