Design of Piston for an IC Engine

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1 Abstract

In today's world every individual own or wants to own a automotive be it a car, bike, bus, truck, etc. With the increasing population, improving economies and developing industries, the demand for IC engines is at its peak. IC engine comprises of various components and one of them is piston. The piston is one of the most fundamental parts of an IC engine.It converts the available heat energy into mechanical energy using its reciprocating motion. It is one of the most complex components in terms of design. In this paper, we design a piston for an IC engine. We analyze the functions and requirements of a piston and accordingly observe the forces acting. With the help of these forces, we then decided the dimensions and material to be used. We also developed a CAD model according to requirements and function of the piston.

2 Introduction

The piston is one of the most fundamental parts of an IC engine. It is under the hood of moving components. It converts the available heat energy into mechanical energy using its reciprocating motion, i.e it travels up and down in direction while the power is being produced by the engine. The Piston is used to contain the pressure of expanded gases and transfer the force generated by it to the crankshaft through a piston rod, which rotates it. To keep the pressure intact and seal the piston, piston rings are used which act as a seal between the piston and cylinder wall. It is one of the most complex components in terms of design.

Figure 1

2.1 Piston parts and their functions

2.1.1 Piston Ring

They are split-ring pieces that go into the piston's recessed area. There are three piston rings in a typical vehicle engine. The piston ring is supposed to be held in place by the ring mounting grooves, and you may hear something along those lines. It allows for spring movement, which aids in the rings maintaining the optimum piston ring gap. To ensure spring constant under heat, load, pressures, and other conditions, manufacturers use cast iron or steel parts for piston rings.
Piston rings primary function is to seal the combustion chamber and regulate the amount of lubricating oil needed. The rings also aid in heat transmission from the cylinder bore to the atmosphere. The different types of rings are:

- **Compression ring:** The top side ring, which is also closest to the combustion chamber, is known as the compression ring. Its principal role is to keep combustion gases from escaping, therefore it is also known as a pressure or gas ring. It also aids in the passage of heat from the piston to the cylinder walls.
- **Scraper ring:** Between the compression and oil rings is the scraper ring. With a tapered surface, it performs the same function as both rings in sealing the combustion chamber.
- **Control ring for oil:** It's the piston's bottom ring, and it's made up of two thin surfaces with holes all around. Its purpose is to drain extra oil from the cylinder walls as the piston is moving back and forth.

2.1.2 Piston Skirt

The skirt is the cylindrical material that is attached to the piston's round part. Cast iron is the most common material utilised because of its wear-resistant and self-lubricating qualities. It includes gloves for installing piston oil and compression rings.
It guides the piston to move up and below the cylinder. Also the side forces are overcomed which are created by changing angle of the connecting rod. Piston slap is a famous phenomenon which occurs usually in winters when the piston would rock uncontrollably. Two types of piston skirts are:

- **Full skirt (solid skirt):** Has a tubular form and is typically found in large vehicle engines.
- **Slipper Skirt:** This type of skirt is commonly found on pistons in tiny automobiles. It helps to reduce weight while also reducing the contact area between the cylinder wall and the piston.

2.1.3 Piston Pin

The hollow or solid part in the piston skirt is called as the piston pin, wrist pin, or Gudgeon pin. The piston rod pivots and is kept in place by this pin. Piston pins are commonly made of alloy steel, which has a high tensile strength and can be machined to fit the piston bearing. Piton pin assemblies and mounting styles are divided into three categories:

- Free to revolve
- Clamped at connecting rod
- Rigidly mounted to piston bosses

This gives rise to two types of pins:

- **Semi floating:** It pivots on the pin and is screwed to the boss of the piston. It's semi-floating since it's attached to the connecting rod in the centre and may move about freely within the piston bearing.
- **Full floating:** There are no clogs or snap rings attached to the piston bosses, and the pin is not linked to the pin or piston in any other way. As a result, it occludes both the rod and the bosses.

2.1.4 Piston Head

It is the surface that comes into touch with the combustion gases. As a result, it reaches an extremely high temperature. It is constructed of specific alloys, particularly steel alloys, to avoid melting and other undesirable outcomes.
Because of the channels and voids in it, it aids in the creation of a swirl that enhances combustion. Different heads are used for various purposes, and their selection is based on a variety of parameters including desired performance and engine type.

It serves the following major functions:

- Swirl formation for consistent combustion and knocking control
- Creating a heat barrier between the combustion chamber and the piston components.
- Cylinder knock as a result of pressure maintenance.

2.1.5 Connecting Rod

The conrod, which connects the piston to the crankshaft and propels the piston in and out of the combustion chamber, is one of the most important piston components. They're tough and largely forged since they have to withstand a lot of mechanical stress. As a result, steel is used to make these rods. Aluminium is also utilised in cars with modest engines, whereas alloy steel is employed in vehicles with high-performance engines.
It spins the crankshaft, which causes the car to move. A hole in the piston rod transports lubricating oil to the cylinder walls and pins. Conrodes come in a variety of shapes and sizes, including fractured joints, machined joints, angled separation rods, and so on. The connecting rod is made up of several elements.

- **Connecting rod:** Between the small and large sections of the rod, there is a double T structure.
- **Big end:** The part opposite the tiny end is responsible for connecting the crankshaft and has a slit design for mounting it.
- **Small end:** Smaller end of rod which consists of rod eye and piston bushing

2.1.6 Piston Bearings

These are piston pieces that are situated in critical pivotal rotating points. The form is semicircular and fits inside the bores. Composite metals such as copper, silicon, lead, aluminium, and others are commonly used.

3 Design Considerations

3.1 Functions of Piston

- To bear the pressure generated by the expansion of the gas in the cylinder and transmit it to the crankshaft
- To compress the gas during the compression stroke
- To take side thrust resulting from the obliquity of connecting rod
- To dissipate the massive heat generated in the combustion chamber to the cylinder walls
- To act as a guide and bearing for the connecting rod

3.2 Requirements of Piston Material

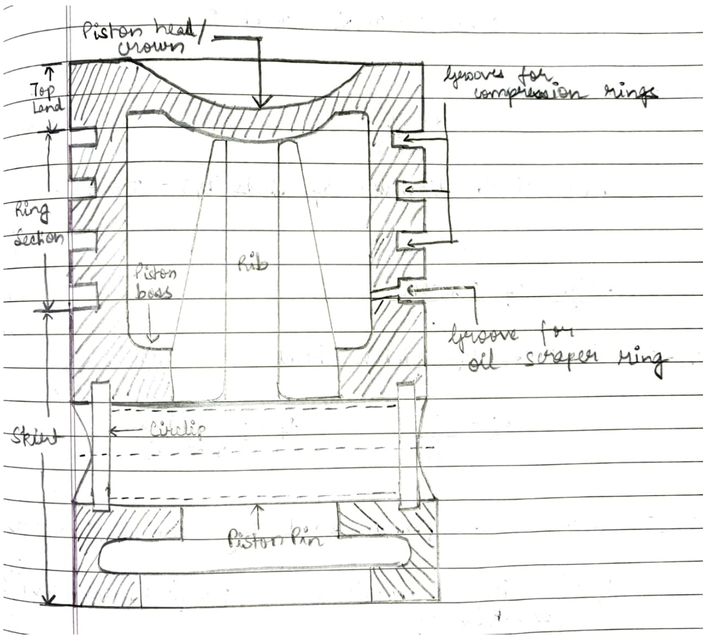
- It should have minimum weight to be able to handle the inertia forces.
- It should be effective in forming oil sealing in the cylinder.
- It should have good wearing properties
- It should provide high-speed reciprocation with less noise.
- To withstand thermal and mechanical distortions, the piston material should be of sufficient rigid construction.
- It should have sufficient support for the piston pin.
- It should have sufficient strength to resist the high gas pressure.
- The material should have low coefficient of thermal expansion and high thermal conductivity ,so it can disperse the heat of combustion quickly to the cylinder walls.
- The material should have good resistance to corrosion It should be able to provide high-speed reciprocation with less noise.
- It should have a low coefficient of friction for minimum power loss

3.3 Forces Involved

There are a lot of forces involved with piston because piston is one of the most important and fundamental part of an IC engine. Some major forces involved are : -

- Force due to explosion and expansion of fuel gases
- Force due to compression of fuel gases
- Forces due to friction at side wall and crank pin hole
- Forces developed due to thermal load
- Forces, majorly inertia force due to high frequency reciprocation of piston

3.4 Sketch of a Typical Piston



3.5 Material Selection for Piston

Despite its reduced weight, Aluminum Alloy is quite soft. As a result of the lubricating oil imbedded in it, the cylinder walls grind or abrade. As a result, life is reduced. It isn't very strong. As a result, thicker pieces must be employed, resulting in an increase in weight. To overcome the limitations of the existing Aluminum Alloy piston, new compositions in the same Aluminum Alloy as well as alternative materials such as cast steel, Nickel chrome alloy, carbon steel, and cast iron are being tested.
As mentioned above the material we choose should follow the basic design considerations, some of them are:

- Good resistance to corrosion
- Minimum weight to be able to handle inertia forces
- Sufficient strength to resist high gas pressure

Based on the following considerations we are suggesting the following material as our base material and also comparing it with traditional Aluminium.

Material is an **Aluminium alloy with the composition 4.5% Cu, 0.6% Mg, 17% Si, 1.3% Zn and 76.6% Al**. Following are it's properties in comparison to some general materials.

From the above table we can conclude that our material is much lighter than Aluminium and Iron since it's density is comparatively less and also we can see that our material can sustain higher loads since it has greater yield stress i.e. it would not easily deform.
As shown in the paper [1], i.e. on performing Analysis of the material in

Material	E Modulus	Poisson ratio	Density	Yield
Our Material	0.7 * 10^5	0.33	2.6*10^{-6}	420
Cast Ai	0.75 * 10^5	0.33	2.7*10^{-6}	380
Cast Iron	1.034 * 10^5	0.28	7.28*10^{-6}	350

ANSYS and determining it's deformations in y-directions, fididing out the Von misses stres, we get the following properties:

Material	Max Deform	Max Induced	Permissible	Yield
Our Material	0.048830	120	210	420
Cast Ai	0.033759	248	190	380
Cast Iron	0.024735	156	175	350

The factor of safety for automotive applications is usually 1.3 to 1.8, but in exceptional cases it can be upto 5 also. Here we can observe that Cast Ai has Maximum induced Stress much more than the permissible stress, therefore we would have to reh=ject that material. Also we can observe that the yield stress (420 N/mm2) is much more than that of Ai and Iron. As we know that yield stress is the minimum stress at which a material would have permanent deformation, therefore we can conclude that Our material would be able to withstand higher pressures and loads. Also we can infer from the above table that our material has the minimum induced stress which is a good factor, this is because lesser the induced stress lesser are the chances of it's breakdown and higher are it's chances of sustaining high loads.
Our material has been subjected to some more experiments and we have received the following results:

Type of Loading	Pressure Value	Deformation	Induced Stress
175%	2.31	0.073	180
200%	2.64	0.081	200
225%	2.97	0.089	220

4 Specifications and Calculations

4.1 Technical Specifications

Honda Shine

Engine Type	4-Stroke, SI, BS-VI
Displacement	123.94
Max. Power	7.9kW @7500 rpm
Max. Torque	11N-m @6000 rpm
Compression Ratio	10:1
Starting	Kick-Start / Self Start
Bore	50 mm
Stroke	63.1 mm

4.2 Calculations

Given ,
Torque (T) = 11 N-m
Power (P) = 7.9 kW
Bore / Diameter (D) = 50 mm
Stroke / Height (h) = 63.1 mm

4.2.1 Pressure in Cylinder

$$Velocity(V) = \frac{2*h*N}{60}$$

$$V = \frac{2*0.0631*7500}{60}$$

$$V = 15.77m/s$$

Now,

$$Force = \frac{Power}{Velocity}$$

$$F = \frac{7.9*10^3}{15.77}$$

$$F = 500.95N$$

Further,

$$Pressure = \frac{Force}{Area}$$

Now,

$$Area = \pi * r^2$$

where r = D/2 = 0.025m

$$P = \frac{500.95}{\pi * 0.025^2}$$

P = 0.2546 MPa (minimum)

Now ,

$$P_{max} = 12 * P_{min}$$

$$P_{max} = 12 * 0.2546$$

$$P_{max} = 3.0552MPa$$

4.2.2 Thickness of Piston Head (t_h)

We use the Grashoff's formula for calculating the thickness of Piston head.

$$t_h = D\sqrt{(\frac{3*P}{16*\sigma_t})}$$

where , P = Maximum pressure in N/mm^2
D = Bore of Piston in mm
σ_t = Permissible tensile stress for material of piston

$$t_h = 50\sqrt{(\frac{3*3.0552}{16*210})}$$

$$t_h = 50*0.05215$$

$$t_h = 2.6mm$$

4.2.3 Radial thickness of piston ring (t_1)

We use the following formula for calculating the thickness of piston ring:

$$t_1 = D\sqrt{(\frac{3*P_w}{\sigma_t})}$$

where, D = Piston Bore in mm
P_w = Pressure of fuel on cylinder wall in N/mm^2
σ_t = Permissible tensile stress for material of piston

$$t_1 = 50\sqrt{(\frac{3*0.05435}{210})}$$

$$t_1 = 50*0.0277$$

$$t_1 = 1.387mm$$

4.2.4 Axial Thickness of Ring (t_2)

We may take the thickness of the ring as

t_2 = 0.7*t_1 to t_1

So, let us take t_2 = 0.85*t_1
Hence,

$$t_2 = 0.85*1.387$$

$$t_2 = 1.1789mm$$

4.2.5 Top land thickness(b_1)

Now , the width of top land lies between t_h to 1.2*t_h.
Let us take,

$$b_1 = 1.1 * t_h$$

$$b_1 = 1.1 * 2.6$$

$$b_1 = 2.86mm$$

4.2.6 Thickness of other land(b_2)

$$b_2 = 0.75 * t_2$$

$$b_2 = 0.75 * 1.1789$$

$$b_2 = 0.8842mm$$

4.2.7 Maximum thickness of barrel (t_3)

We have ,

$$t_3 = 0.03 * D + b + 4.5mm$$

Where , b = t_1 + 0.4

$$b = 1.387 + 0.4$$

$$b = 1.787mm$$

So,

$$t_3 = 0.03 * 50 + 1.787 + 4.5$$

$$t_3 = 7.787mm$$

4.2.8 Open end of the barrel Thickness (T_{open})

At the open end the thickness is calculated as:

$$T_{open} = 0.25 * T_3$$

$$T_{open} = 0.25 * 7.787$$

$$T_{open} = 1.9467mm$$

4.2.9 Gap between the rings (T_L)

$$T_L = 0.055 * D$$

$$T_L = 2.75mm$$

Now, for second ring we have

Second Ring = 0.04 * D
Second Ring = 2mm

4.2.10 Depth of ring groove (D_r)

$$D_r = t_1 + 0.4$$

$$D_r = 1.387 + 0.4$$

$$D_r = 1.787mm$$

4.2.11 Length of Piston(L_p)

We have,

$$L_p = L_{ps} + 3 * t_1 + 3 * D_r$$

Here, L_{ps} is taken as 0.5 of bore (0.5D)
L_{ps} = 0.5D = 0.5 * 50 = 25

$$L_p = 25 + 3 * 1.387 + 3 * 1.787$$

$$L_p = 34.522mm$$

4.2.12 Piston pin outer diameter (P_{do})

P_{do} = 0.3 to 0.45D Here we are taking average value of 0.375 in our calculations:

$$P_{do} = 0.375 * D$$

$$P_{do} = 0.375 * 50$$

$$P_{do} = 18.75mm$$

4.2.13 Piston pin inner diameter (P_{di})

$$P_{di} = P_{do} - t_h$$

$$P_{di} = 18.75 - 2.6$$

$$P_{di} = 16.15mm$$

Parameters	Calculated Values
Thickness of Piston Head	2.6 mm
Radial Thickness of Ring	1.387 mm
Axial Thickness of Ring	1.1789 mm
Top land thickness	2.86 mm
Maximum thickness of barrel	7.787 mm
Open End barrel thickness	1.9467 mm
Gap between rings	2.75 mm
Depth of ring groove	1.787 mm
Length of Piston	34.522 mm
Piston Pin Diameter (External)	18.75 mm
Piston Pin Diameter(Internal)	16.15 mm

5 CAD Model

5.1 Drive Link For CAD Files

Click Here For CAD Files : CAD Files

5.2 Piston Head

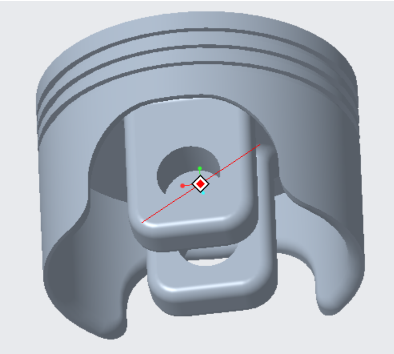


Figure 2

5.3 Piston Rod

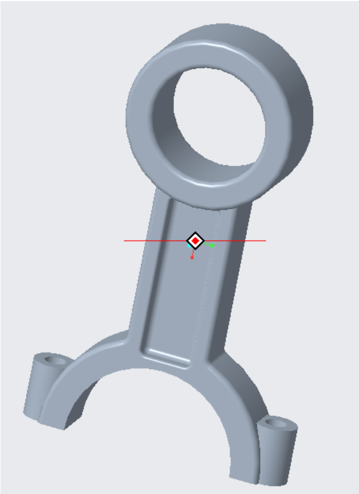


Figure 3

5.4 Piston Rod Cap

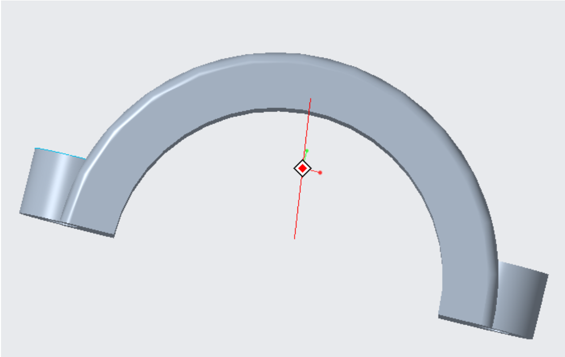


Figure 4

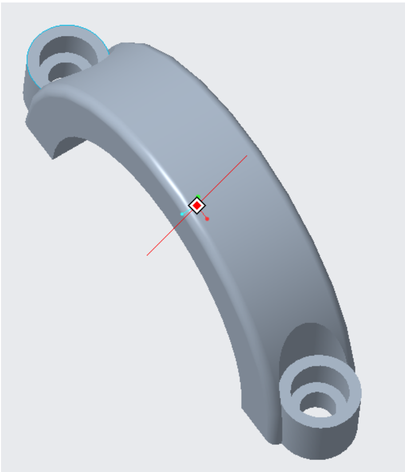


Figure 5

5.5 Piston Pin

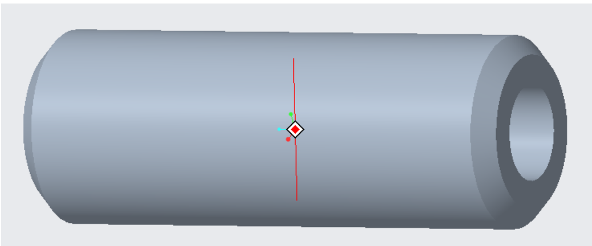


Figure 6

5.6 Assembly

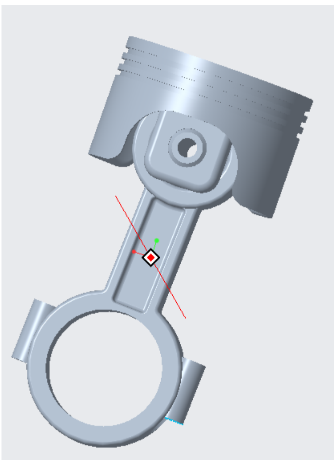


Figure 7

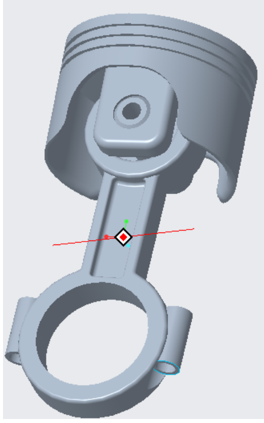


Figure 8

6 Failures in Piston

There are majorly 2 types of piston failure modes :

1. Roughout Failure
2. Wrong out failure

6.1 Sources of Roughout Failure

1. **Damage from Running Unmixed Fuel:** The piston can seize to the cylinder wall due to a lack of lubrication. The visible damage occurred just before the piston became trapped, causing the engine to stall. This type of piston damage can also be discovered on saws that have been running with the carburetor set too lean. If we don't know if the saw was run on unmixed fuel, we'll have to inspect the rest of the piston and the damage to figure out what went wrong.

Figure 9

2. **Damage From Over-Speeding The Engine:**
The piston in the photograph as we can observe is that it is damaged as a result of the engine being overheated. A large portion of the piston material in-between ring lands is gone, and part has been pinched thinner, resulting in a very wide ring land. The top ring's edge has been smoothed over, indicating that it has caught in the outlet port. When this happens, a high-frequency vibration is produced, finally shattering the ring-land.

Figure 10

3. **Damage from Detonation:**
Detonation has damaged the piston in the image. The damage can be noticed on the piston's top and edges. Detonation heat led the piston to become extremely hot that the rings became jammed and the piston stopped in the cylinder. On the side of the piston, seizure marks can be seen. Both the cylinder and the piston are frequently destroyed as a result of this injury.

Figure 11

4. **Damage from Heat Seizure:**
Excess heat has caused damage to the piston exhaust side in the image below. Over-revving the saw, running the carburetor adjustment too lean, overlooking the air leakage condition inside the saw's engine, or another type of circumstances can cause this type of damage. The easiest method to avoid a seizure-like this is to use good quality gasoline and blend oil, prevent over-revving the engine, and never operate a saw that shows evidence of an air leak. A partially clogged fuel filter can also cause this type of harm, which is why fuel filters must be updated regularly.

Figure 12

6.2 Sources of Wrong out failure:

1. **Damage from Debris Getting Through the Air Filter:**
The small particles broken off due to wear and tear pass by the air filtration system and damage the nearby piston skirt. The opposite side of the piston is unaffected because it is not exposed to the intake port. The rubble from a leaking filter wedge between the piston and the wall, caused scuff marks on the piston skirt, causing damage to the intake skirt. The damage to the skirt is more noticeable than the hard surface of the cylinder bore because the material of the cylinder is soft. Because of the wear, the space between the piston and wall rises, allowing the piston to shake violently. The shaking worsens as the skirt gets thinner and weaker.

Figure 13

2. **Damage from Bearing Failure:**
The failure of the lower rod bearing or main bearings causes the thin scratches on the piston skirt in the adjacent photograph. This piston damage is caused by little yet hard bits of bearings and retaining cages breaking loose. The crankshaft locks up when this happens. If the engine is kept running, loose bits from the bottom end travel up the transfer valves and in the engine. When the piston passes by, it will smash these components against the wall, shattering them both. Over-revved saw engines are known to suffer from this type of damage.

Figure 14

7 Joining Methods

A piston is made by manufacturing the first and second sections of the piston separately, each of which has at least two connecting surfaces. The joining surfaces in spaced relation to each other support the parts. The connecting interfaces are heated to a higher temperature while spaced, then the heat is turned off and the joining surfaces are placed in contact with each other to establish a welded joint between them.
Various methods for joining separately made portions of a piston to obtain a piston structure are : -

1. Friction Welding
2. Resistance Welding
3. Induction Welding

7.1 Friction Welding

In friction welding, one part of the piston is turned at a high speed while being forced against the other, with the frictional energy providing enough heat to bind the two parts together.

Figure 15

Advantages

- There is no need for filler metal, and no flux is employed.
- In a short cycle time, it is possible to make high-quality welds.
- Surface imperfections and oxide films are at low levels.
- Simple to use and not time intensive

Disadvantages

- When working with high carbon steel, removing flash is difficult.
- The process is only applicable to angled and flat butt welds.
- It's only utilized for the tiniest of components.
- To generate high thrust pressure, heavy rigid machinery is required.

7.2 Resistance Welding

In resistance welding, the metals are heated and eventually melted at localized areas indicated by the configuration of the electrodes and piston components by passing a strong current through the two parts of the piston. Throughout the transmission of the current, a force is always applied to constrain the area of contact at the weld interfaces to forge the two sections together.

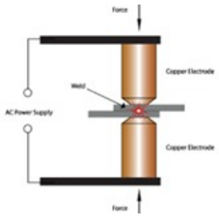


Figure 16

Advantages

- Higher speeds, less than 0.1 seconds for automobile spot welding, and a shorter process time are all advantages.
- 1/4 inch thickness is ideal for sheet metal applications.
- There are no filler metals needed , hence it is clean and environment friendly procedure
- Due to the low voltage needs, it is relatively safe
- The joint that has been formed is reliable.

Disadvantages

- Electricity requirements are high.
- No visual inspection is possible.
- Low tensile strength and fatigue resistance
- Electrode wear at a high-level

7.3 Induction welding

The coils are exposed to the sidewalls of the interacting joining interfaces in induction heating to induce energy and hence heat at the junction. These side presentation of the induction coils has the effect of heating the areas of the joining interfaces close to the edge of the material adjacent to the coils at a quicker rate than those areas further away from the coils, resulting in a variation in heat transfer and high - temperature zone in the area of the material adjacent to the interface.

Figure 17

Advantages

- It is possible to attain a very rapid heating ratio in the range of 5 kW/ cm2.
- As a result of the controlled heating of the contact area, there is less wasted heat.
- With the use of timers, the total heat transmitted to the workpiece may be closely monitored and controlled.
- It is also possible to change the temperature automatically using feedback.
- Working conditions are nice because the procedure is orderly and clean.
- We can operate it with relatively unskilled laborers because the operation is so basic.
- There are no byproducts of the induction heating method.

Disadvantages

- The equipment and process costs are both extremely high.
- Heating efficiency is poor, with many cases falling below 50
- The work item will be heated more in the areas closest to the heating coil. This signifies that the heat is distributed unevenly.
- Coil should, in general, have the geometry of the work item, which can be inconvenient in practice.
- The heating will be concentrated in the work piece's corners.

8 Conclusion

In this paper we learned and studied about the piston in depth. The study involved research about various components of the piston along with their functions. The design requirements consisting of functions of piston, requirements of piston material and forces involved was researched and worked upon. We then selected appropriate material from the available materials in the market which were aligned with our requirements.We have used Honda Shine engine specifications for our calculation. Piston can experience failure and the various types of failures have been listed in the paper. Coming to joining methods , various joining methods have been discussed along with their advantages and disadvantages.

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