Design and Analysis of Poppet Engine Valve for Enhanced Mechanical Properties with Varied Geometric Parameters and Materials
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Abstract
Poppet engine valve is a precision engine component which blocks gas flow ports and controls the exchange of gases in internal combustion engines. The functionality of the valve is to seal the working space inside the cylinder against manifolds by continuously opening and closing of valve according to valve timing diagram. Existing difficulties with poppet engine valve being that it tend to fail due to fatigue after executing about 300 million operating cycles. Thus this research paper aims to establish effect of varied materials and Geometric parameters on mechanical properties of poppet engine valve to improve its performance over life and fatigue life using Ansys software.

Keywords: Poppet engine valve, Geometric parameters, Fatigue life, Mechanical properties, Materials.

Introduction
Design of poppet engine valve intrinsically affects the performance of internal combustion engine. With this view this research paper aims to explore the effect of variation of geometric parameters and materials on the mechanical properties of poppet engine valve with mainly to improve its fatigue life. Both exhaust and inlet valve are vital components of an IC engine and which are controlling the flow of fresh air and burnt gases in and out of engine cylinders. In four stroke engine during suction stroke inlet valve remains in open condition which allows the flow of fresh air inside the combustion chamber and exhaust valve is kept closed. In power stroke both valves remain closed. At the end of power stroke exhaust valve gets opened to remove burnt gases from combustion chamber.

Basic terminology of Poppet engine valve,

Figure1: Basic terminology of popet valve.[1]
Design of poppet engine valve

Figure 2: Dimensions of poppet valve and valve seat

Above figure shows poppet engine valve where all dimensions are in mm.

Specification of Engine for which the poppet valve is designed,
Bore Diameter D = 73.5 mm
Length of stroke L = 73.5 mm
Engine Speed N = 5500 rpm
Break horse power (bhp) @ 5500 rpm = 37

Specification of Poppet engine valve
Diameter of valve port (Dp) = 27 mm
Width of valve (W) = 2 mm
Valve angle (θ) = 45
Diameter of valve head (Dv) = 31 mm
Thickness of valve disk (t) = 2 mm
Margin (M) = 1.6 mm
Diameter of valve stem (Ds) = 12 mm
Maximum valve lift (hmax) = 10 mm

Kinematic motion of poppet engine valve is governed by valve actuating mechanism generally push rod mechanism. This mechanism is driven by motion of crankshaft of engine and as a result of which poppet engine valve continuously open and closes the ports which control the flow of gas through ports.

Poppet engine valve is opened by valve actuating mechanism just before the beginning of exhaust stroke so that exhaust gases are blown out and it is closed by compressed spring just after the beginning of suction stroke. Thus poppet engine valve is continuously under tension and compression alternatively which lead to fatigue failure alternatively which lead to fatigue failure.

Calculation for forces acting on poppet engine valve, [4]

a) Force required to open the valve

\[ F_{\text{open}} = F_i + F_l + F_g \]  

Where,
\[ F_i = \text{Initial spring force} \]
\[ F_l = \text{Force required to lift the valve} \]
\[ F_g = \text{Gas force} \]

Mathematically,
\[ F_i = \frac{\pi}{4} D_v^2 P_s \]  

Where,
\[ P_s = \text{Suction pressure} \]
\[ = 0.002 \text{ to } 0.004 \text{ N/mm}^2 \]

\[ F_l = k \cdot h_{\text{max}} \]  

Where K = spring stiffness
\[ = 10 \text{ N/ mm} \]

\[ F_g = \frac{\pi}{4} D_v^2 P_g \]  

Where P_g = gas pressure
\[ = 0.35 \text{ to } 0.45 \text{ N/mm}^2 \]

Substituting equation (2),(3) and (4) in equation (1),
\[ F_{\text{open}} = 379.11 \text{ N} \]
\[ F_l = 15.08 \text{ N} \]

Calculation for valve timing of poppet engine valve, [4]

Engine under consideration is high speed engine and as a result of which the exhaust valve will open 55 before Bottom dead center and will close 20 after top dead center [3]. This being true theoretically but will deviate from it under practical situation whose consideration is beyond the scope of this research paper.

Total angle of rotation of crank shaft when exhaust valve is open is,
\[ \Theta_1 = 55 + 180 + 20 \]
\[ = 255 \]

Total angle of rotation of camshaft when exhaust valve is open
\[ \Theta_1 = \frac{255}{2} \]
\[ = 127.5 \]
\[ = 2.224 \text{ radians} \]

Speed of camshaft is given by,
Number of rotation of camshaft per second, 
\[ N_{ps} = \frac{N_{cs}}{60} \]
\[ = \frac{5500}{2} \]
\[ = 2750 \text{ rpm} \]

Time required by camshaft to complete one rotation,
\[ T_{1r} = \frac{1}{N_{ps}} \]
\[ = \frac{1}{2750} \]
\[ = 0.0218 \text{ sec} \]

Time for which the exhaust valve is open is given by,
\[ T_{open} = \Theta_1 - T_{1d} \]
\[ = 255 \times 6.06 \times 10^{-5} \]
\[ = 15.453 \times 10^{-3} \text{ seconds} \]

Cycle time for poppet engine valve to once open and close is given by,
\[ T_{total} = 360 \times T_{1d} \]
\[ = 360 \times 6.06 \times 10^{-5} \]
\[ = 21.86 \times 10^{-3} \text{ seconds} \]

Where,
\[ T_{total} = T_{open} + T_{idle} \]

When poppet engine valve opens nature of force acting on its valve stem is compressive in nature and time during which it closes nature of force is tensile in nature, which leads to fatigue loading of poppet engine valve. This loading of poppet engine valve is unidirectional in nature.

Maximum valve lift is calculated to be 10 mm which corresponds to unidirectional displacement of poppet engine valve during lift to be 10mm so that it opens the port in one direction and displacement to be 10mm during fall so that it closes the port in opposite direction.

Consider the unidirectional displacement of poppet engine valve in following table.

**Table 1: Displacement of Poppet valve with time.**

<table>
<thead>
<tr>
<th>Sr.no</th>
<th>Span of time (seconds)</th>
<th>Poppet Engine valve condition</th>
<th>Magintude of force acting on valve stem head (Newton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0</td>
<td>to 6.41 \times 10^{-3}</td>
<td>Valve is Idle</td>
</tr>
<tr>
<td>2.</td>
<td>6.41 \times 10^{-3}</td>
<td>to 9.918 \times 10^{-3}</td>
<td>Valve opens</td>
</tr>
<tr>
<td>3.</td>
<td>9.918 \times 10^{-3}</td>
<td>to 18.398 \times 10^{-3}</td>
<td>Valve is open and Idle</td>
</tr>
<tr>
<td>4.</td>
<td>18.398 \times 10^{-3}</td>
<td>to 21.86 \times 10^{-3}</td>
<td>Valve closes</td>
</tr>
</tbody>
</table>

Table 1: Poppet valve condition with time.
With a view to analyze the effect of Geometric parameters and materials on mechanical properties of poppet engine valve, specially to improve fatigue strength following geometric parameters and materials are considered for purpose of analysis which form the scope of this research paper.

**Geometric parameters under consideration,**
- a) Valve angle
- b) Diameter of valve head
- c) Thickness of valve disk

**Materials selected under consideration,**
- a) Inconel 625
- b) Ti-4.5Al-3V-2Fe-2Mo
- c) Ni - Cr - Mo Steel SAE8640_361_QT

Range of magnitude of geometric parameters selected are such that they lie on higher side and some on lower side of designed value.

Range of magnitude of geometric parameters is as follows,

<table>
<thead>
<tr>
<th>Sr. no</th>
<th>Geometric parameter</th>
<th>Range of magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Valve angle</td>
<td>30,34,38,40,45.</td>
</tr>
<tr>
<td>2.</td>
<td>Diameter of valve head</td>
<td>22mm,25mm,28mm,34mm,37mm,40mm.</td>
</tr>
<tr>
<td>3.</td>
<td>Thickness of valve disk</td>
<td>1mm,2mm,3mm,4mm,5mm,6mm.</td>
</tr>
</tbody>
</table>

Transient structural analysis was performed on Ansys Workbench 14.5 on poppet engine valve with above mentioned variation of geometric parameters and materials. In order to analyze the effect of these variation on mechanical properties of poppet engine valve other geometric parameters other than one under consideration is held same for purpose of comparison.

**Results and discussion**

Transient structural analysis was used in Ansys workbench 14.5 to obtain following results,
Consider graphical representation of above results,
Figure 3: shows Equivalent elastic strain for poppet engine valve of Ni - Cr - Mo Steel SAE8640_361_QT for 34 mm valve head diameter.

Figure 4: shows Equivalent stress for poppet engine valve of Ti-4.5Al-3V-2Fe-2Mo for 22 mm valve head diameter.
Table 6: the variation of Equivalent elastic strain and Equivalent stress with variation of Valve angle for material under consideration.

<table>
<thead>
<tr>
<th>Material</th>
<th>Valve angle</th>
<th>Equivalent Elastic strain(mm/mm)</th>
<th>Equivalent stress(Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconel 625</td>
<td>30</td>
<td>0.0001303</td>
<td>24.81</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>0.00011733</td>
<td>22.286</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>0.00089712</td>
<td>172.68</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.000125</td>
<td>23.077</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>0.000010929</td>
<td>21.117</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.000012526</td>
<td>23.337</td>
</tr>
<tr>
<td>Ti-4.5Al-3V-2Fe-2Mo</td>
<td>30</td>
<td>0.000011931</td>
<td>13.006</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>0.000010711</td>
<td>11.65</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>0.00001039</td>
<td>11.599</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.000011429</td>
<td>12.059</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>1.94E-05</td>
<td>10.988</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.00011465</td>
<td>12.22</td>
</tr>
<tr>
<td>Ni - Cr - Mo Steel SAE8640_361_QT</td>
<td>30</td>
<td>0.00012116</td>
<td>23.087</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>0.0001091</td>
<td>20.739</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>0.00010677</td>
<td>20.856</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.000011623</td>
<td>21.475</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>0.00010163</td>
<td>19.65</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.00011647</td>
<td>21.717</td>
</tr>
</tbody>
</table>

Consider graphical representation of above results.
Figure 5: shows Equivalent elastic strain for poppet engine valve of Inconel 625 for 45 degree valve angle.
Figure 6: shows Equivalent stress for poppet engine valve of Ti-4.5Al-3V-2Fe-2Mo for 42 degree valve angle.

Table 7: illustrate the variation of Equivalent elastic stain and Equivalent stress with variation of Thickness of valve disk for material under consideration.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness of valve disk(mm)</th>
<th>Equivalent Elastic strain(mm/ m m)</th>
<th>Equivalent stress(Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconel 625</td>
<td>1</td>
<td>0.00010658</td>
<td>20.47</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td><strong>0.00012526</strong></td>
<td><strong>23.337</strong></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.00011973</td>
<td>23.093</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.00011998</td>
<td>23.125</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.00012139</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.00011717</td>
<td>22.251</td>
</tr>
<tr>
<td>Ti-4.5Al-3V-2Fe-2Mo</td>
<td>1</td>
<td>9.72E-05</td>
<td>10.689</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td><strong>0.00011465</strong></td>
<td><strong>12.22</strong></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.00011097</td>
<td>11.933</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.00010844</td>
<td>11.981</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.10E-04</td>
<td>12.175</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.07E-04</td>
<td>11.619</td>
</tr>
<tr>
<td>Ni - Cr - Mo Steel</td>
<td>1</td>
<td>9.91E-05</td>
<td>13.049</td>
</tr>
<tr>
<td>SAE8640_361_QT</td>
<td>2</td>
<td><strong>0.00011647</strong></td>
<td><strong>21.717</strong></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0001131</td>
<td>21.276</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.0001091</td>
<td>20.739</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.00011287</td>
<td>21.868</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.000010895</td>
<td>20.706</td>
</tr>
</tbody>
</table>

Consider graphical representation of above results,
Inconel 625
Ti-4.5Al-3V-2Fe-2Mo
Ni - Cr - Mo Steel SAE8640_361_QT

Equivalent Elastic strain

Thickness of valve disk (mm)

Equivalent stress (Mpa)

Equivalent stress (Mpa)

Thickness of valve disk (mm)
Above figure shows Equivalent stress for poppet engine valve of Ni - Cr - Mo Steel SAE8640_361_QT for 6 mm valve disk thickness.

Table 8: the variation of fatigue life with variation of geometric parameter and materials,

<table>
<thead>
<tr>
<th>Material</th>
<th>Fatigue life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconel 625</td>
<td>1.00E+06</td>
</tr>
<tr>
<td>Ti-4.5Al-3V-2Fe-2Mo</td>
<td>1.00E+07</td>
</tr>
<tr>
<td>Ni - Cr - Mo Steel SAE8640_361_QT</td>
<td>1.00E+11</td>
</tr>
</tbody>
</table>

Above figure shows fatigue life of Ni - Cr - Mo Steel SAE8640_361_QT.

Conclusion
Based on results obtained by transient structural analysis following conclusion are deduced,

a. Equivalent elastic strain unequally and uniformly reduces on both sides of designed magnitude for diameter of valve head, which being true for all materials under consideration. Least equivalent elastic strain is obtained for Ni - Cr - Mo Steel SAE8640_361_QT as 0.000010901 for 34 mm valve head diameter which most desirous.

b. Equivalent stress unequally and uniformly increases sides of designed magnitude for diameter of valve head, which being true for all materials under consideration. Least equivalent stress is obtained for Ti-4.5Al-3V-2Fe-2Mo as 11.492 MPa for 22 mm valve head diameter which most desirous.

c. Equivalent elastic strain unequally and non uniformly increases as valve angle decreases below 45 degree, which being true for all materials under consideration. Least equivalent elastic strain is obtained for Inconel 625 as 0.000012526 for 45 degree.

d. Equivalent stress unequally and non uniformly decreases initially and then again increases as valve angle decreases below 45 degree, which being true for all materials under consideration. Least equivalent stress is obtained for Ti-4.5Al-3V-2Fe-2Mo as 10.988 MPa at 42 degree valve angle.

e. Equivalent elastic strain unequally and non uniformly decreases as thickness of valve disk increases above 2 mm, which being true for all materials under consideration. Least equivalent elastic strain is obtained for Ni - Cr - Mo Steel SAE8640_361_QT as 0.000010895 at 6 mm valve disk thickness.

f. Fatigue life remains almost unaffected by change in geometrical parameters but is altered by change in material. It is evident from above result that Ni - Cr - Mo Steel SAE8640_361_QT has highest fatigue for all values of geometrical parameters as 1.00E+11 which is most desirous.

References

3. Internal combustion engine and air pollution.—Dr. R. Yadav 2007.