A study of Internal Combustion engine valves using Nx Nastran

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Abstract

Exhaust and Intake valves are very essential components of internal combustion engines. They are used to seal the working space in the cylinder and are opened and closed to control the fresh inlet air to the cylinder and exhaust the burnt gas to the manifold. It is an important process for a smooth-running engine. This paper studies the stress induced on both exhaust and intake valves due to high temperature inside the combustion chamber, cam force and the spring force. Nx Nastran is used for modeling the valve and simulation. In general, there are standard alloys that are used for making valves, however, this study includes Static thermal and structural analysis on other different materials which give high strength and good corrosion resistance. The results are tabulated and discussed.

Keywords: valves, internal combustion engines, burnt gas, Nx Nastran, strength, corrosion.

الملخص

تعتبر صمامات الطرد والسحب عناصر أساسية في محركات الاحتراق الداخلي حيث تسمح بالتحكم في دخول الهواء النقي إلى غرفة الاحتراق وخروج غازات العادم. إنها عملية هامة لضمان تشغيل آمن ومستقر وفعال للمحرك. هذا البحث يدرس الاجهادات الناتجة على كل من صمامات الطرد والسحب عند درجات الحرارة العالية مع الأخذ بالإعتبارقوة النابض والقوة الناتجة من عمود الكامات على كل صمام. تم استخدام برنامج Nx Nastran في الرسم الثلاثي الأبعاد للصمام وكذلك محاكاة الظروف المطلوبة.

عموماً, هنالك العديد من السبائك القياسية المستخدمة في صناعة الصمامات ولكن هذه الدراسة تتضمن أحمال حرارية وميكانيكية في حالة سكون لمواد أخرى مختلفة لها أيضاً مقاومة لدرجات الحرارة المرتفعة وكذلك مقاومة جيدة للتآكل. تم تجميع النتائج وعرضها في جداول وأشكال بيانية لمناقشتها.

1. Introduction

Valves of the internal combustion engine are precision components. There are different types of them, such as rotary valves, slide valves and sleeve valves, however, poppet valves are used in most engines. The inlet valve also called as intake valve. Inlet and exhaust valves operate once in two revolutions in 4-stroke internal combustion engine. The main components of the valve mechanism are illustrated in figure 1.

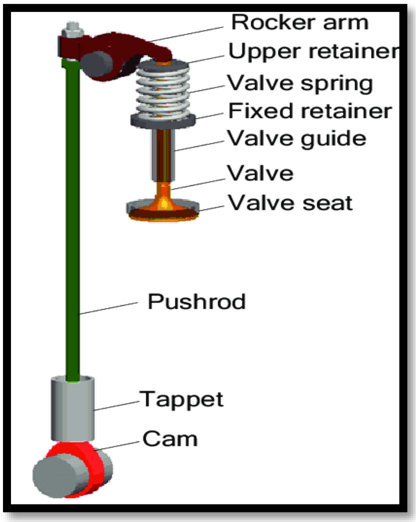

Figure 1 illustrates valve mechanism of internal combustion engine

The cam moves on by the rotating cam shaft which pushes the cam follower. The cam pushes the rocket arm. When an end of the rocket arm is pushed up, the other end moves downwards, which pushes the valve stem down causing the port to be opened. When the rocket arm moves up, the valve released and returns to its seat[1].

1.1.Terminology of The valve.

The engine valve is a flat circular disk of metal with a long rod called the valve stem as shown in figure 2.[2]

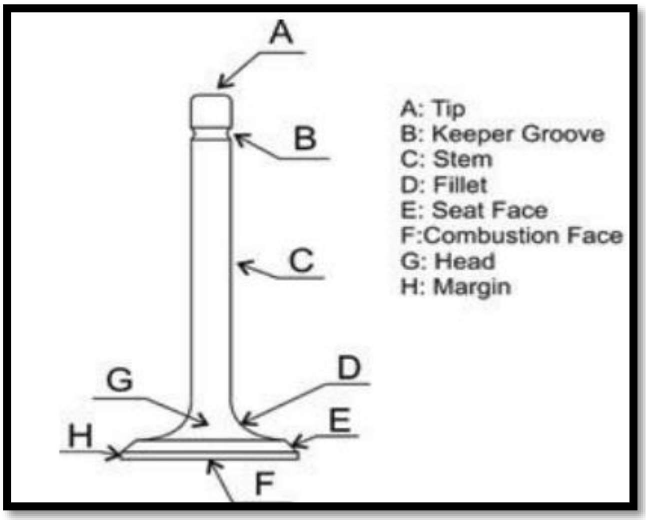

Figure 2 Terminology used for valves

1.2.Valve Materials

Materials which are used for intake valves and exhaust are different because exhaust valves operate in more severe conditions. The inlet valves are not subjected to extreme thermal loading as they are cooled by incoming gases and thermal transmission at the seat [3]. There are many demands on valve material include wear resistance, corrosion and endurance strength at high temperature. In general, Standard valve materials are used in valves which are explained in the following:

The monometallic intake valves are made from the standard choice ferritic-martesitic steels X45CrSi93.It is also exclusively used for the stem in bi-metallic valves. The higher alloy X85CrMoV182 is used when the Cr-Si material does not permit the thermal and mechanical loading. Austenitic steels which include Cr-Mn have proven to be economical choice and its widely used solution is the alloy X35CrMnNiN21(21-4N). it is deemed to be the classic material of exhaust valves.

The transition to high nickel content is the correct remedy when the Cr-Mn steels no longer satisfy the thermal requirements [3].
In this research, three materials used for poppet valve to be studied as following:

- Annealed Inconel718 alloy is used in wide range of applications such as, gas turbines, aircraft components and variety of other applications in corrosive and structural environment involving high temperature [4]. It is a high strength alloy with a nickel-chrome base. Due to its unique properties, it has become useful in different applications ranging from military equipments, manufacturing operations and the aerospace industry [5]. The chemical composition of the material is clarified in the following table (1):

Table (1) composition of Inconel718 alloy

Element	Percentage max %
Carbon	0.08
Manganese	0.35
Sulphur’s	0.015
Silicon	0.35
Chromium	17-21
Nickel	50-55
Molybdenum	2.8-3.3
Columbium	4.75-5.5
Titanium	0.65-1.15
Aluminum	0.2-0.8
Cobalt	1.00
Boron	0.006
Copper	0.3
Tantalum	0.05
Iron	Balance

- S/steel ph15-5-alloy
  It is a martensitic stainless steel with almost 5% Nickel and about 15% chrome. It is a good corrosion resistance and has a high hardness and stress [6]. Table (2) illustrates the chemical composition of the material.

Table (2) composition of S/steel ph15-5-alloy

Element	Percentage max %
Carbon	0.07
Manganese	1.00
Phosphorus	0.04
Sulfur	0.03
Silicon	1.00
Chromium	14-15
Nickel	3.5-5
Copper	2.5-4.5
Columbium and Tantalum	0.15-.45

- Ti-6Al-4V Alloy
  It is a light weight Titanium alloy which has a high tensile strength and toughness with a good corrosion resistance [7]. It is also called a grade 5 alloy which is the most widely used of all titanium grades and the following table (3) illustrates its composition:

Table (3) composition of grade 5 Titanium alloy (Ti-6Al-4V)

Element	Content %
Titanium	87.6-91
Aluminum	5.5-6.75
Vanadium	3.5-4.5
Iron	0.4 max
Oxygen	0.2 max
Carbon	0.08 max
Nitrogen	0.05 max
Hydrogen	0.015 max

2.Valve Design

Operating temperature is a crucial issue for performance of a valve. Temperature of intake valve is less than the exhaust valve. Therefore, the design process considers the exhaust valve as it is exposed to higher temperature and corrosion. Figure 3 shows a model of an engine valve by using Nx Nastran software.

Figure 3 engine valve model

The process of design for the valves includes the following:
Valve seat angle is 45°.
Gas velocity 2200 m/min.
Piston speed 250m/min.
Engine speed 1225 rpm
Max gas pressure 7 N/m^2.
Cylinder bore diameter 125mm.
valve temperature is 700C°.
views and dimensions of the valve which are designed by Nx8.5 Nastran shown in figure 4. According to the sketched model, mass of each material of the valve can be figured out automatically.

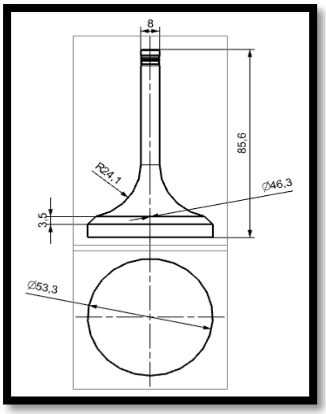

Figure 4 dimensions of the valve in mm

Forces acting on the valve are:
-force due to gas pressure (F_g).
F_g=$\pi/4d^2$ P_c………………………… (2)
d=Valve head diameter in mm
P_c $=$ cylinder pressure in Mpa when the valve opens
F_g= $(\pi/4)(53.3)^2$ 0.45=1003.5 N
- Inertia force when the valve moves up (F_I).
F_I= acceleration *mass………………………… (2)
Mass depends on density of valve material and for the heaviest material Inconel718 is 0.2491 Kg.
Acceleration=(π^2)(ω^2)(h)/ ((2)($\theta_L{}^2$))
ω $=$ (0.5) (1225) (2) (3.14)/ (60) =64.1 rad/s
θ_L=0.5 θ_{cam} = 1.25
Valve lift=15mm
Acceleration=(3.14^2)(64.1^2)(0.015)/((2)(1.25^2))=194.45 m/s^2
F_I = 194.45 *0.2491=48.43 N
- valve spring force to hold the valve in its seat (F_s).
F_s=$(\pi/4)d^2$ P_s………………………… (3)
P_s= Maximum suction pressure in Mpa
P_s=0.025 Mpa
F_s=$(3.14/4)(53.3)^2$ (0.025)=55.7 N
Total force acting on face of the valve F_T=F_g+F_I+F_s
F_T = 1003.5 N + 48.43 N + 55.7N= 1106 N

3 Simulation

The assumption for simulation is to suppose no heat generation and to consider the condition as a steady state, which means the energy to a node is equal to energy from it. There are two cases for simulation to be implemented:

3.1 Load case one: Compression force which is acting on the tip of the valve by the cams during intake stroke.

Boundary Condition

-The required force to push the valve downwards is 1106 Newton.

- The thermal load will be applied on the valve with a temperature $700C^{\circ}$.

-Assuming no force acting on the combustion face of the valve

Constraints

The vertical force from the camshaft is the main impact received by the valve. Therefore, the keeper groove is to be fixed as it holds the entire valve at the engine head which is illustrated in figure 5.

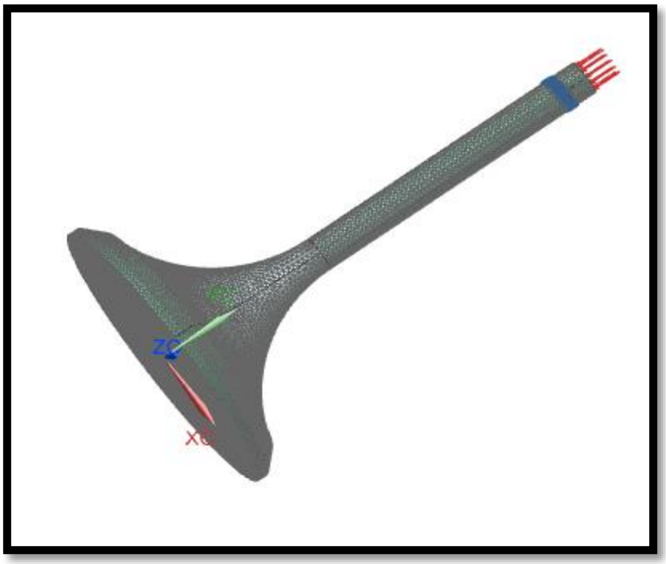

Figure 5 shows simulation case one

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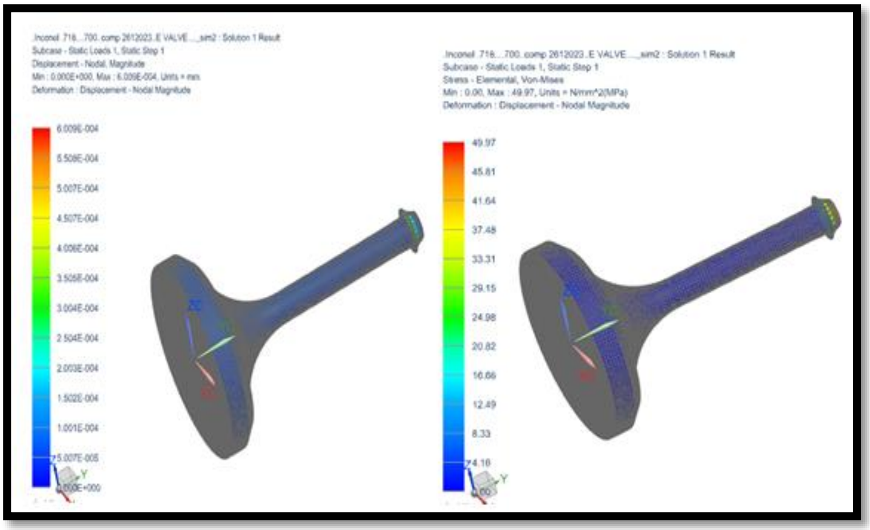


Figure 6 Inconel718 Deformation and vonmises stress at 700C° during compression

The above figure 6 clarifies the deformation and generated vonmises stress on the annealed alloy Inconel718.

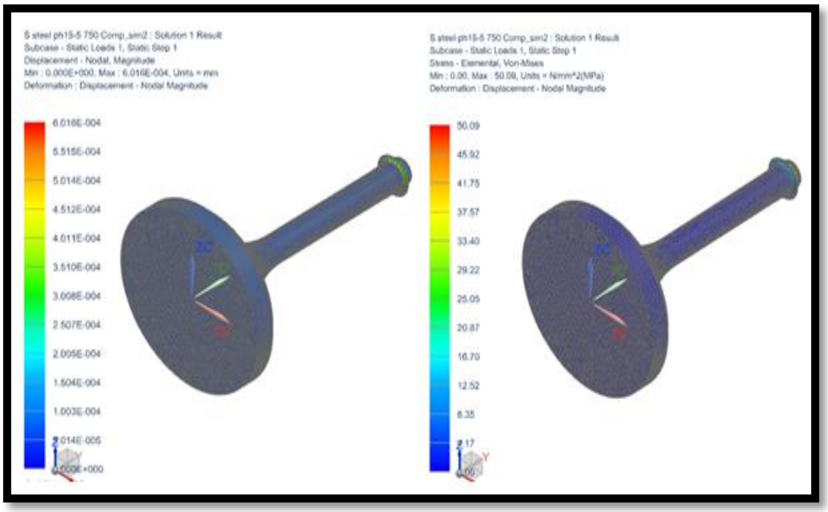


Figure 7 S Steel 15-5 Deformation and vonmises stress at 700C° during compression

Figure 7 shows deformation and generated stress on the stainless steel ph15-5 valve at $700C^{\circ}$ while figure 8 shows the results of the Titanium alloy Ti-6Al-4V.

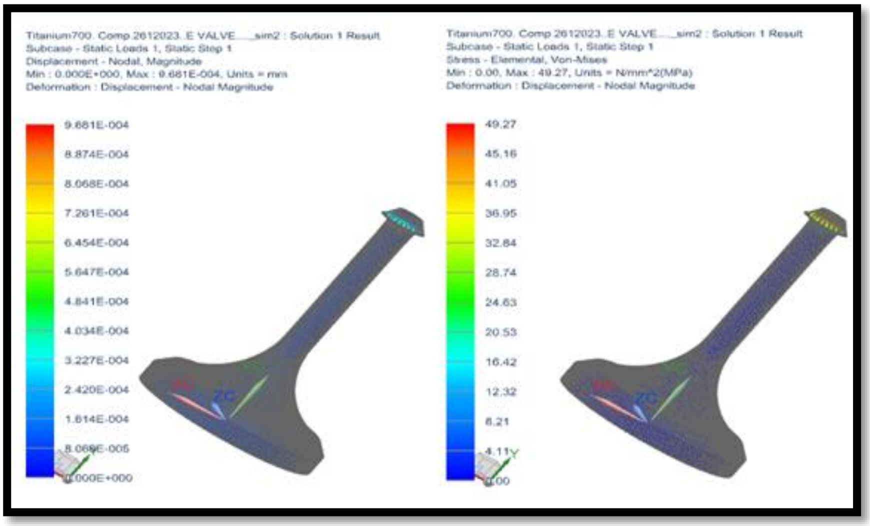


Figure 8 Ti-6Al-4V Deformation and vonmises stress at $700C^{\circ}$ during compression

3.2 Load case two: It resembles the expansion force acting on the valve during the combustion stroke as explained in figure 9.

Boundary Condition

-The required force to push the valve downwards is 1106 Newton.

- The thermal load will be applied on the valve is a $700C^{\circ}$.

Constraints

The vertical upward reaction force from the spring to the camshaft and the expansion process are the main two impact on the valve during the combustion stroke.

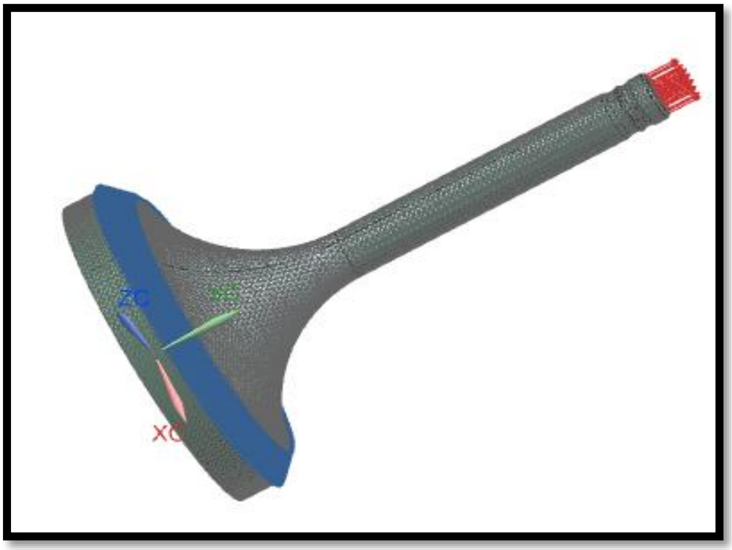
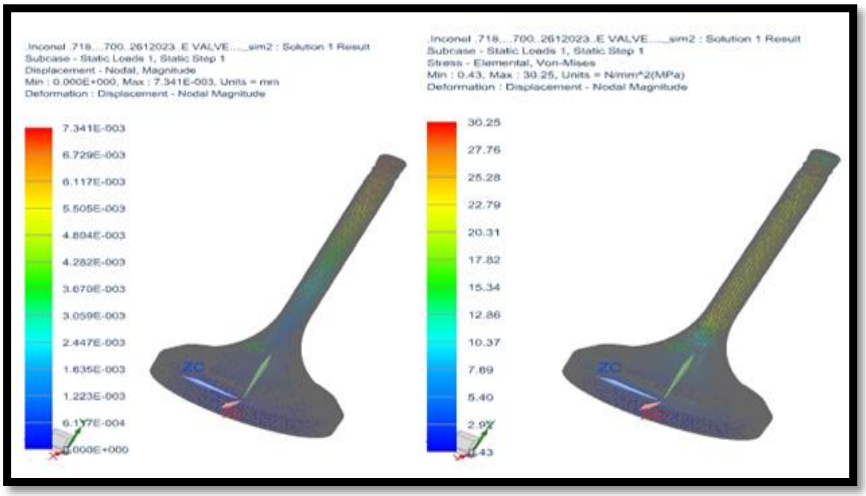


Figure 9 shows simulation case two



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.Inconel .718....700..2612023..E VALVE...._sim2 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Displacement - Nodal, Magnitude
Min : 0.000E+000, Max : 7.341E-003, Units = mm
Deformation : Displacement - Nodal Magnitude
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.Inconel .718....700..2612023..E VALVE...._sim2 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Stress - Elemental, Von-Mises
Min : 0.43, Max : 30.25, Units = N/mm^2(MPa)
Deformation : Displacement - Nodal Magnitude
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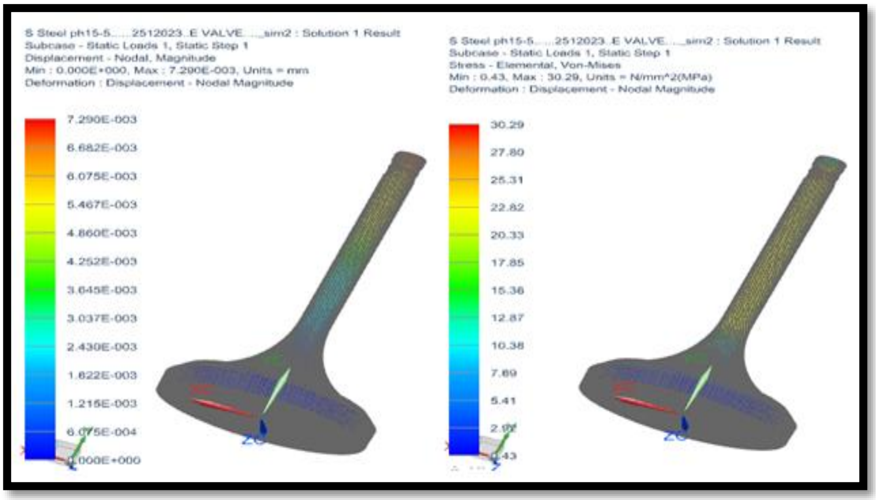
Figure 10 Inconel718 Deformation and vonmises stress at $700C^{\circ}$ during expansion

The above figure 10 clarifies the deformation and generated vonmises stress on the annealed alloy Inconel718.

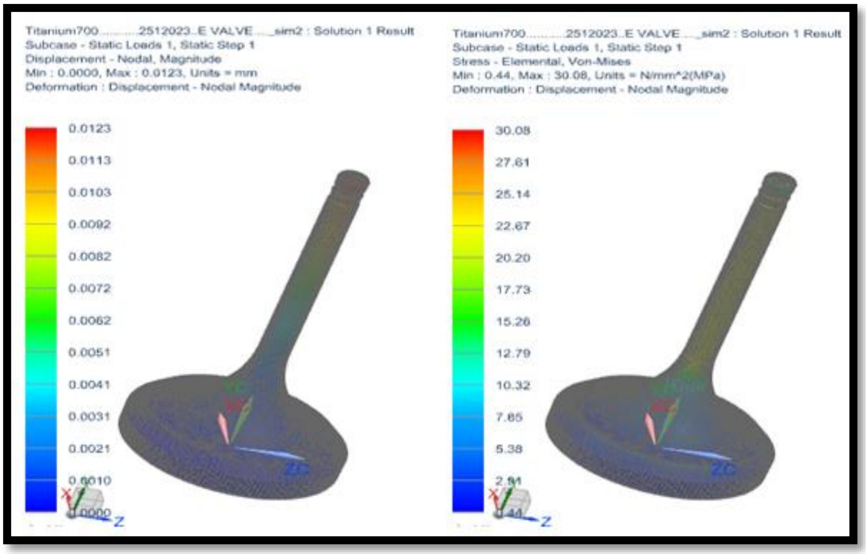


S Steel ph15-5.....2512023..E VALVE...._sim2 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Displacement - Nodal, Magnitude
Min : 0.000E+000, Max : 7.290E-003, Units = mm
Deformation : Displacement - Nodal Magnitude

S Steel ph15-5.....2512023..E VALVE...._sim2 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Stress - Elemental, Von-Mises
Min : 0.43, Max : 30.29, Units = N/mm^2(MPa)
Deformation : Displacement - Nodal Magnitude

Figure 11 Steel 15-5 Deformation and vonmises stress at $700C^{\circ}$ during expansion

Figure 11 shows deformation and generated stress on the stainless steel ph15-5 valve at $700C^{\circ}$ while figure 12 shows the results of the Titanium alloy Ti-6Al-4V.



Titanium700..........2512023..E VALVE...._sim2 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Displacement - Nodal, Magnitude
Min : 0.0000, Max : 0.0123, Units = mm
Deformation : Displacement - Nodal Magnitude

Titanium700..........2512023..E VALVE...._sim2 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Stress - Elemental, Von-Mises
Min : 0.44, Max : 30.08, Units = N/mm^2(MPa)
Deformation : Displacement - Nodal Magnitude

Figure 12 Ti-6Al-4V Deformation and vonmises stress at $700C^{\circ}$ during expansion

Results

According to the simulation which applies forces and different materials acting on the valve, the results are gathered in table (4).

Table (4) Distributed Stress and Deformation

Material	Comp-Vonmises stress (Mpa)	Comp-deformation (mm)	Expan-Vonmises stress (Mpa)	Expansion deformation (mm)	Yield strength at 700C (Mpa)	Mass (kg)
Inconel718	49.97	0.0006009	30.25	0.007341	800	0.249
S-Steel15-5	50.09	0.000601	30.29	0.00729	300	0.237
Ti-6Al-4V	49.27	0.000968	30.08	0.0123	150	0.134

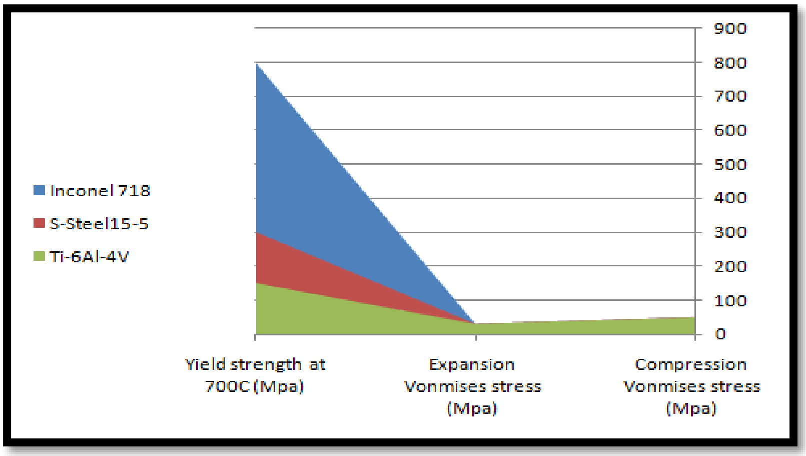


Figure 13 Generated stress and yield strength

According to figures 13 and 14, there is a slight difference in the generated stress of all three materials at $700C^{\circ}$, however, the yield strength is significantly different. In addition, deformation of titanium is relatively high during compression. Grade 5 titanium alloy is a light material, however, by increasing temperature the yield strength decreased significantly.

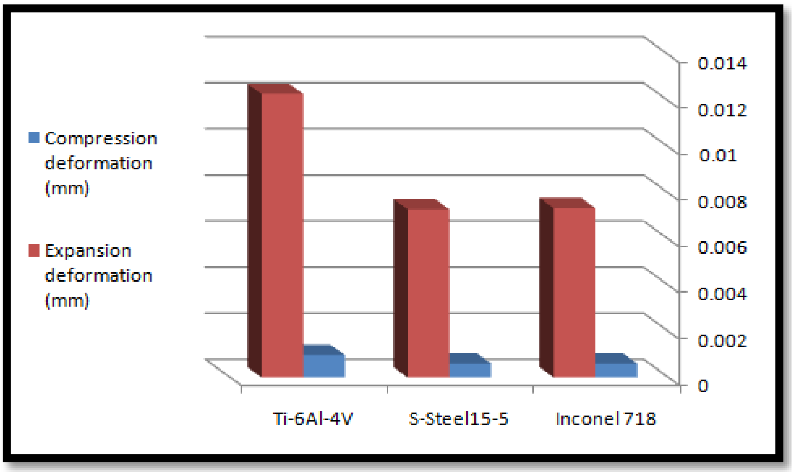


Figure 14 Deformation of materials

Factor of safety

In the design process, factor of safety is defined as the ratio of the maximum stress to the working stress.

$$\text{Factor of safety} = \frac{\text{Maximum Stress}}{\text{Working Stress}} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \;(4)$$

When designing parts of a vehicle or any machine, it is important to keep the stress (working stress) lower than the maximum stress at which failure of the material takes place. [8]. In ductile materials, the yield point is clearly defined and considered as the maximum stress.

$$\text{Factor of safety} = \frac{\text{yield point Stress}}{\text{Working Stress}} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \;(5)$$

The relation for static loads

In brittle materials, the yield point is not clearly defined. Therefore, factor of safety is based on ultimate stress.

As the maximum generated stress on the engine valve is a compressive as shown in table (5). Therefore:

$$\text{Factor of safety} = \frac{\text{Maximum compressive Stress}}{\text{Working Stress}} \;\ldots\ldots\ldots\ldots\ldots \;(6)$$

Table (5) factor of safety

Material	Working Stress (Mpa)	Maximum Stress at $700C^{\circ}$ (Mpa)	Factor of safety
Inconel718	49.97	800	16
S-Steel15-5	50.09	300	6
Ti-6Al-4V	49.27	150	3

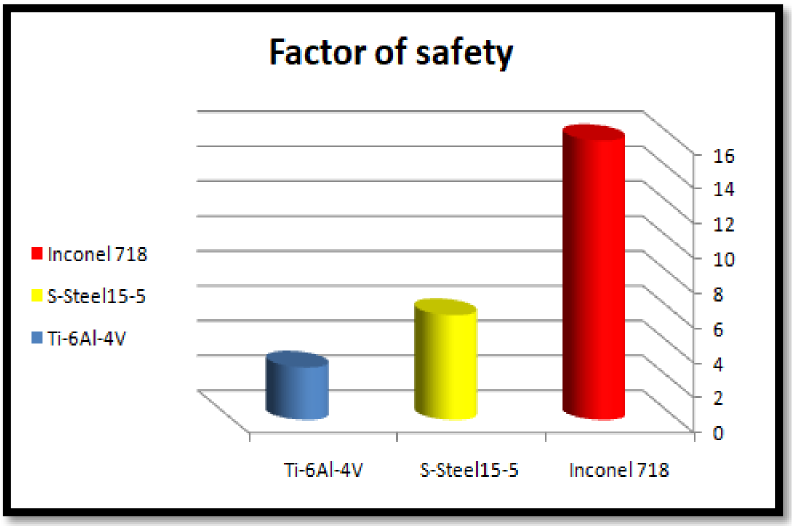


Figure 15 factor of safety

In Fig 15, it is obvious that the highest factor of safety is for Inconel718 alloy, while the titanium material with the lowest factor. In addition, the safety factor of S-steel ph15-5 is 62.5% lower than the Inconel718 safety factor.

Conclusion

Design of valves depends on so many factors like fatigue strength, oxidation of valve material, dynamics of the exhaust gas, shape of the port and the coolant flow. The most important parameter affecting the valve is the operating temperature. From Nx Nastran analysis results, it is concluded that the deformation of titanium alloy valve is slightly higher than the other two materials. Valves with better material strength can give significant benefits in reducing weight and cost reduction. The mass value of the titanium alloy is almost 50% lower than the value of the other two materials, however, material cost should be taken into account. It is also noticed that the annealed alloy Inconel718 is the best choice at high temperatures with a good factor of safety, subsequently it can be a proper material for exhaust valves. Stainless steel alloy ph15-5 has an acceptable factor of safety, however, grade 5 titanium alloy has the lowest factor of safety and both materials can apparently be used for intake valves. Heat treatment of valve steels makes it possible to further improvement in their technical characteristics. In many cases, it can obviate the need for using higher-quality alloys.

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