Conceptual Design of a Pressure Vessel

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Abstract— This discusses the result of the work done in development of a pressure vessel. It is a part of the Aero Space application project going on, and aims at the development of a pressurised air vessel for the purpose of cooling in aero space vehicles. Pressurised Air Vessels are used for storage of gases and compressible liquids at high pressure for a large variety of applications. Ex: Fire extinguishers, air bottles and fuel bottles for catering aerospace propulsion system and seeker cooling system etc. It consists of a shell with a thickness depending upon the material and it also varies with the material stored in it and the pressures acting on it at different temperatures. The design of an air vessel project aims at the development of a design procedure for developing a capsule (cylinder with hemispherical ends).

Key words: Pressurised Air Vessel, Thickness, Cooling, Compressible Liquids, High Pressure, Hemispherical Ends, Design Procedure

I. INTRODUCTION

The final goal of the project was to design pressure vessel with two different materials for given design requirements and establishing detailed process plan. Also need to evaluate following things:

1) Evaluation of stresses and factor of safety
2) Evaluating Weight of bottle
3) Selection of material- which shall lead to less weight of the pressure vessel.
4) Tests for finding the welding defects.

II. MATERIAL SELECTION

The aerospace vehicle always demands for less weight for its components for its best performance. Therefore selection of material is very important. Commonly used materials are Al6061, Ti alloys and Steel 304, etc. Their respective properties and a comparative study of these materials are given below. For manufacturing of capsule weld ability of material will be a necessary requirement. Based on the above constraints following materials are considered for present study.

- Aluminium Properties: 6061 Aluminium alloy is one of the most extensively used of the 6000 series aluminium alloys. It is a good heat treatable extruded alloy with medium to high strength capabilities. The only aluminium series which is wieldable is Al-6061.
- Titanium Alloy properties: Grade 2 Titanium is called the “work horse” of the commercially pure titanium industry and it has varied usability and wide availability. It contributes many of the same qualities as Grade 1 titanium, but it is slightly stronger. Both are resistant to corrosion equally. This grade possesses good weld ability, strength, ductility and formability.

A. Design of Pressure Vessel

1) Design Specifications:

Fluid Pressure in bottle = 700 bar
Volume of fluid = 0.5 lt
Max Diameter = 55 mm

2) Design Calculations

Volume of fluid (0.5 lt) = 500 cc.
Working Pressure = 105 MPa
Internal Diameter = 55mm

B. Evaluation of Length of Capsule:

Bottle is designed with two hemispherical ends joined by a cylindrical portion.

Properties Materials	Density (g/cc)	Tensile Strength (MPa)	Hardness (RHN)	Elongation (%)	Poisson Ratio	Young’s Modulus (G Pa)	Shear modulus (G Pa)
SS 304	8	Ult: 505 Yie: 215	70	70	0.29	193-200	86
Ti Grade 2	4.51	Ult: 344 Yie: 410	80	20	0.37	105	45

Table 1: Properties of Materials

Total volume = Volume of cylinder + volume of two hemispheres we can calculate Length of the component.

$$V = \frac{\pi}{4} D^2 L + \frac{\pi}{6} D^3. \quad (1.1)$$

Where V is Total volume
D is inner diameter of the cylinder
L is length of the component

$$V = \frac{\pi}{4} D^2 L + \frac{\pi}{6} D^{3.} \quad (1.2)$$

$$5x10^5 = \frac{\pi}{4} x(55)^2 x\ L + \frac{\pi}{6}(55)^3$$

L= 173.7861 mm
Therefore the length of the cylinder is 173.7861 mm.
Design of capsule is carried with Al 6061 & Ti-Gr2 material, since steel is having higher density.

C. Design Calculations with Al 6061 Alloy:

1) For Aluminium 6061 Grade:

Calculating the various stresses in AA 6061 based on its properties:
Length of the component = 173.8 mm
Yield strength of Al 6061 grade = 276 M Pa.
Design is done for yield strength.
Allowable stress

$$\sigma_t = \frac{Syt}{F.s} \quad (1.3)$$

Where S_{yt} is yield strength
F.S is factor of safety (For Aero Space materials it is assumed as 1.25)

$$\sigma_t = \frac{Syt}{F.s} \quad \text{(where F.s=1.25)}$$

$$\sigma_t = 220.5 \text{ M Pa}$$

Minimum Thickness of the cylinder (Considering failure due to hoop stress)

$$t_c = \frac{P\ X\ D}{2X\ \sigma t} \quad (1.4)$$

$$t_c = \frac{105\ X\ 55}{2\ X\ 220.8}$$

$$t_c = 13.07mm$$

We are assuming that thickness of the cylinder is equal to thickness of two hemispheres.

a) Hoop stress in hemisphere

$$\sigma_{hs} = \frac{P\ X\ D}{2\ Xtc} \quad (1.5)$$

$$\sigma_{hs} = \frac{105\ X\ 55}{2\ X\ 13.07}$$

$$\sigma_{hs} = 220.9 N/mm^2$$

b) Longitudinal Stress in cylinder

$$(\sigma_L)_c = \frac{P\ X\ D}{4\ X\ tc} \quad (1.6)$$

$$= \frac{105\ X\ 55}{4\ X\ 13.07}$$

$$(\sigma_L)_c = 110.462\ N/mm^2$$

c) Circumferential Strain in Hemisphere

$$\epsilon_{ci} = \frac{PD}{4t\ E}(2 - \frac{1}{m}) \quad \text{(ref. from strength of materials (Ramamrutham)} \quad (1.7)$$

$$(\frac{1}{m} = \text{poisons ratio})$$

Poison ratio for Al 6061= 0.33
E = Modulus of elasticity for Al 6061 is 68.9GPa

$$\text{Therefore } \epsilon_{ci} = \frac{105X55}{4X13.07X689X100}(2 - 0.33)$$

$$= 0.002677$$

d) Longitudinal strain in Cylinder:

$$\epsilon_{c2} = \frac{PD}{4t\ E}(1 - \frac{1}{m}) \quad (1.8)$$

$$\epsilon_{c2} = 0.001079$$

e) Weight of the component:

Mass= Volume X Density (1.9)
Volume of the component

$$V = \frac{\pi}{4} D^2 L + \frac{\pi}{6} D^3 \quad (1.10)$$

$$V = \frac{\pi}{4}((D_o)^2 - (D_i)^2) L + \frac{\pi}{6}((D_o)^3 - (D_i)^3) \quad .(1.11)$$

Where
Do = Outer diameter of the component
Di = Inner diameter of the component

Di = given diameter =5.5cm
Do = Inner diameter + Thickness of the component
Do = 5.5 + 0.85 = 6.3cm

$$V = \frac{\pi}{4}(6.8^2 - 5.5^2)\,17.3 + \frac{\pi}{6}(6.8^3 - 5.5^3)$$

V = 294.78 cc
Now we know volume of the hollow component to calculate the weight of the component.

Weight (w) = volume (V) X Density (ρ) (1.12)
(Volume*Density of capsule)
W = + (1.13) (mass of gas stored in the capsule)

Density of the aluminium is 2.7 g/cc.
And Density of nitrogen gas: (at 300K & 70 M Pa)

$$P\,V = m\,R\,T \quad (1.14)$$

$$1050\ X10^5\ X\ 500\ X\ 10^{-6} = m\ X\ 287\ X\ 300$$

$$m = \frac{1050\ X10^5\ X\ 500\ X10^{-6}}{287\ X\ 300}$$

$$= 0.6097Kg$$

W = (294.78 X 2.7)/1000 + 0.6097 Kg
= 0.796+0.6097 = 1.405 Kgs

Therefore Total mass of the capsule alone is 0.796Kgs
Therefore Total mass of the capsule along with Air is 1.405Kgs.

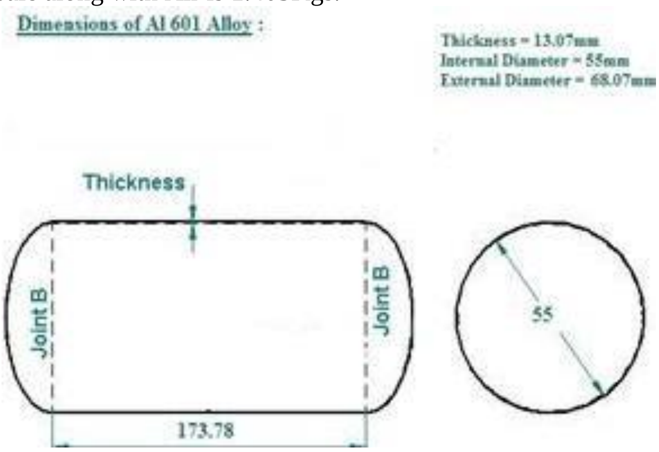

Fig. 1: Dimensions of Al 6061

D. Design Calculations with Titanium grade 2 Alloy:

a) Calculating the various stress in Titanium based on its properties:
Length of the component = 173.7861mm.
Yield strength of Ti grade 2 = 275 - 410 MPa.
b) Allowable stress

$$\sigma_t = \frac{Syt}{F.s} \quad (2.1)$$

Where S_{yt} is yield strength
F.S is factor of safety
For lowest Yield strength S_{yt} = 275 M Pa

$$\sigma_t = \frac{275}{1.25} \quad \text{(where F.s=1.25)}$$

$$\sigma_t = 220\ M\ Pa$$

For higher Yield strength S_{yt} = 410 M Pa

$$\sigma_t = \frac{410}{1.25} \quad \text{(where F.s=1.25)}$$

$$\sigma_t = 328\ M\ Pa$$

c) Thickness of the cylinder
For lower yield strength

$$t_c = \frac{P\ X\ D}{2X\ \sigma t} \quad (2.2)$$

$$= \frac{105\ X\ 55}{2\ X\ 220} = 13.07mm$$

For higher yield strength

$$t_c = \frac{P\ X\ D}{2X\ \sigma t} \quad (2.3)$$

$$= \frac{105\ X\ 55}{2\ X\ 328} = 8.80\ mm$$

Considering the smaller thickness among the both stresses as t_c= 8.80 mm

We are assuming that thickness of the cylinder is equal to thickness of two hemispheres.

d) Hoop stress in hemisphere

$$\sigma_{hs} = \frac{P \, X \, D}{2 \, X t_c} \qquad (2.3)$$

$$\sigma_{hs} = \frac{105 \, X \, 55}{2 \, X \, 8.80}$$

$$\sigma_{hs} = 328.01 \text{ N/mm}^2$$

e) Longitudinal Stress of cylinder

$$(\sigma_L)_c = \frac{P \, X \, D}{4 \, X \, t_c} \qquad (2.3)$$

$$= \frac{105 \, X \, 55}{4 \, X \, 8.80} = 164.24 \text{ N/mm}^2$$

f) Circumferential Strain in Hemisphere

$$\epsilon_{ci} = \frac{PD}{4t \, E}(2- \frac{1}{m}) \qquad (2.4)$$

$$(\frac{1}{m} = \text{poisons ratio})$$

Poison ratio for Al 6061= 0.37

E = Modulus of elasticity for Aluminium is 105 G Pa

Therefore

$$\epsilon_{c1} = \frac{105X55}{4X8.8X105X1000}(2 - 0.37)$$

$$= 0.00254$$

g) Longitudinal strain in Cylinder

$$\epsilon_{c2} = \frac{PD}{4t \, E}(1- \frac{1}{m}) \qquad (2.5)$$

$$\epsilon_{c2} = \frac{105X55}{4X8.8X105X1000}(1 - 0.37)$$

$$\epsilon_{c2} = 0.000984375$$

h) Weight of the component:

Mass= Volume X Density (2.6)

Volume of the component

$$V = \frac{\pi}{4} D^2 L + \frac{\pi}{6} D^3 \qquad (2.7)$$

$$V = \frac{\pi}{4} ((D_o)^2 - (D_i)^2) L + \frac{\pi}{6} ((D_o)^3 - (D_i)^3) \quad (1.24)$$

Where

Do = Outer diameter of the component

Di = Inner diameter of the component

Di = given diameter =5.5cm

Do = Inner diameter + Thickness of the component

Do = 5.5 + 0.88

Do = 6.38cm

$$V = \frac{\pi}{4}(6.38^2 - 5.5^2) \, 17.3 + \frac{\pi}{6}(6.38^3 - 5.5^3)$$

$$V = 190.71 \text{ cc}$$

Now we know volume of the hollow component to calculate the weight of the component.

Weight (w) = volume (V) X Density (2.8)

W= (Volume X Density of Titanium grade 2) + (mass of gas stored in the component)

Therefore Density of the titanium is 4.51 g/cc.

And Density of nitrogen gas:

$$P \, V = m \, R \, T \qquad (2.9)$$

$$1050 \, X10^5 \, X \, 500 \, X \, 10^{-6} = m \, X \, 287 \, X \, 300$$

$$m = \frac{1050 \, X10^5 X \, 500 \, X \, 10^{-6}}{287 \, X \, 300}$$

$$= 0.609 \text{ Kg}$$

W = (190.71 X 4.51)/1000 + 0.609 = 0.860Kgs + 0.609

Therefore Weight of the component is 0.860 Kgs.

Therefore Weight of the capsule along with gas is 1.41 Kgs.

Since capsule made with Al 6061 is weighing less weight, this material is preferable for manufacturing of capsule compared to Ti Gr 2 alloy.

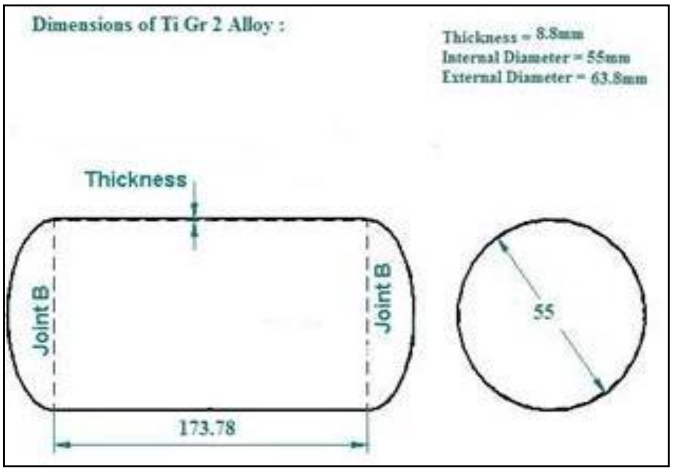

Fig. 2: Dimensions for Ti Gr 2 Alloy

Material	Thickness (mm)	Hoop Stress in hemisphere(N/mm2)	Long. Stress in cyl. (N/mm2)	Hoop strain in hemisphere	Long strain in hemisphere	Capsule mass(Kgs)
Al 6061	13.07	220.9	110.462	0.002678	0.00179	0.796
Ti Gr2	8.8	328.01	164.00	0.00254	0.000984	0.860

Table 2: Design Calculations

III. RESULTS AND DISCUSSIONS

Calculated results of the design calculations are presented in the below table 2.
Since capsule made with Al 6061 is weighing less weight, this material is preferable for manufacturing of capsule compared to Ti Gr 2 alloy.

IV. TESTS FOR FINDING THE WELDING DEFECTS

A. Liquid Penetration Test:

Procedure for Liquid Penetration Test:

1) Pre-Clean Part
2) Apply Penetrate
3) Remove Penetrate
4) Apply Developer
5) Evaluate Indications
6) Post Clean Part

B. Radiography Testing:

This method of welding test makes use of X-rays produced by an X-ray tube or gamma rays, produced by a isotopic radioactive. The basic instance of radiographic inspection of welds is the same as that for medical Radiography. Radiation is passed through a solid object. The amount of energy absorbed by the object depends on thickness and density of materials. Energy not absorbed by the object will cause exposure of the radiographic film. These areas will be darkened when the film develops. Areas of the film exposed to less energy remain lighter. Therefore, at some areas of object where the thickness will change by discontinuities, such as porosity or cracks, will appear as dark outlines on the film.

C. Ultrasonic Testing:

This method of testing makes use of mechanical vibrations similar to sound waves but they use a higher frequency. A Ultrasonic energy associated beam is directed into the object to be tested. This beam passes through an object with insignificant loss, except if it is intercepted and reflected by a discontinuity. Here the ultrasonic contact pulse reflection technique will be used. This system uses a transducer that changes electrical energy into mechanical energy. The transducer gets excited by a high-frequency voltage, which causes a crystal to vibrate mechanically. The crystal probe will be the source of ultrasonic mechanical vibration. These vibrations will be transmitted into the test piece by a coupling fluid, generally a film of oil, called a coolant. When the pulse of ultrasonic waves experiences a discontinuity in the testing piece, it will be reflected back to its point of origin. Thus the energy returns to the transducer. The transducer will serve as a receiver for the reflected energy. The initial signal or main bang, the returned echoes because of the discontinuities, and echo at the rear surface of the test piece will be displayed by a trace on screen of a cathode-ray oscilloscope. The detection, location, and evaluation of discontinuities become possible because of the velocity of sound through a given material is nearly constant, making distance measurement possible, and relatively amplitude of a reflected pulse is more or less proportional to the size of the reflector.

V. CONCLUSIONS

Thus with the given inputs, design of capsule is carried out and inspection techniques are followed to manufacture the vessel.

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