Manned Submersible Ictineu 3: Design and Construction of the Pressure Hull

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***Abstract** – This paper describes the design and construction of the pressure hull of Ictineu 3, a manned submersible with a maximum operative depth of 1200m. The pressure hull is composed of two stainless steel spheres of 1700mm and 800mm of internal diameter. The material was specifically selected for its excellent mechanical properties and its high corrosion resistance. The main sphere is equipped with a large acrylic spherical sector window that provides the crew with an exceptionally wide field of view. The pressure hull, designed under the ASME PVHO-1-2007 and Germanischer Lloyd rules, will be tested in an autoclave at a test pressure corresponding to 1440m. Finite Element Method (FEM) simulations were performed. The design and manufacturing process is a cumbersome engineering challenge because of the extreme pressure conditions and extremely low tolerances required by the certification agency.*

***Keywords** – pressure hull, austenitic-ferritic steel, pressure test, deep drawing, forging.*

INTRODUCTION

Ictineu 3, the first project of Ictineu Submarins S.L., is a scientific manned submersible for three people and a maximum operative depth of 1200m. The Ictineu 3 has been designed to be able to perform any kind of mission underwater, to be easy in operation, highly automated and efficient. The main goals to be achieved are: high observation capabilities, very low weight (<6 tones), highly operational and passenger access from sea.

PRESSURE HULL DEFINITION

In order to achieve these goals three main challenges had to be solved during the design of the Ictineu3 pressure hull: weight reduction, shape optimization and material selection. The weight is determined mainly by the pressure hull design and material. The sphere is the solid with the minimum surface/volume ratio, hence the most suitable geometry to withstand an external pressure with a minimum weight. On top of the main sphere (Ø 1700mm) there is a second one (Ø 800mm) with an acrylic hatch, through which people can access and leave the submersible. At the front of the main sphere, a large Poly Methyl Methacrylate (PMMA) window (Ø1200mm) enables the crew with a wide field of view. Some major milestones needed to be achieved in this project: the selection of the right material, the calculation of the pressure hull, and the definition of the manufacturing process for the two spheres, in order to satisfy the tolerances required by Germanischer Lloyd.

PRESSURE HULL DESIGN

The pressure hull has been designed under the ASME PVHO-1-2007 and Germanischer Lloyd rules. Every step of the construction process and final tests will be subject to the inspection of a GL Surveyor, in order to obtain final submersible certification and classification.

A preliminary study was first completed to select the most suitable shape and material. Fifteen different materials among titanium, composites and steels have been analyzed to achieve the best compromise between resistance, lightweight and low maintenance. Titanium has a lower density compared to steel but it is much more complicated to weld, it requires a more demanding manufacturing process and has a much higher price. Carbon fibre/epoxy composite is even lighter than titanium but there are no certified pressure hulls employing these materials yet and further investigation is needed. Besides, the manufacturing of a carbon fibre/epoxy sphere by filament winding is extremely expensive. Finally, after a thorough research and calculation, a special steel was selected.

The chosen material is an austenitic-ferritic steel with high Cr, Ni and Mo content compared to a standard austenitic steel (e.g. AISI 316), suitable for marine application because of its high corrosion resistance. This chemical composition gives the steel special properties: high yield strength ($R_{p0,2} \geq 530$MPa), high ultimate tensile strength ($R_m \geq 730$MPa), high elongation (A_5=20%) and excellent properties against corrosion. From the mechanical point of view it is comparable to a high strength steel (e.g. HY-80) but with far superior corrosion resistance. With this material the pressure hull does not need any special protection or painting against corrosion: a simple rinse with fresh water after each dive will guarantee its life. Another advantage is that it is paramagnetic, with no interferences with the surrounding equipments (e.g. compass).

The calculation via Finite Element Method (Fig. 1) has been performed for the design pressure (12,1MPa) and for the collapse pressure (20,9MPa). A buckling analysis showed a high safety factor under the collapse pressure.

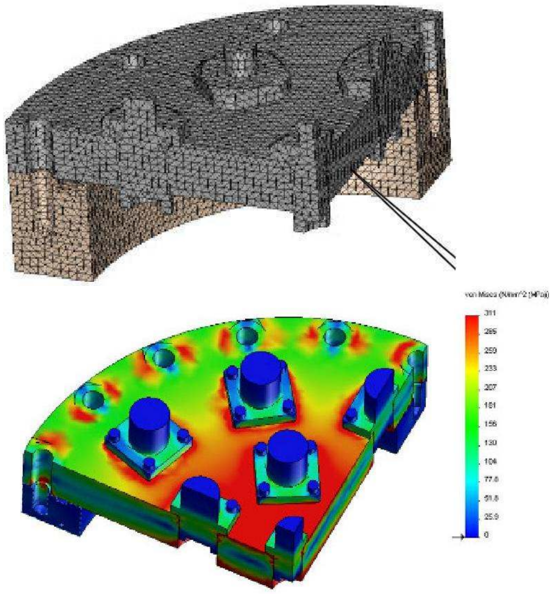

Fig. 1. Mesh definition (above) and CAE calculation (below) of a detail of a pressure hull penetrator plate.

The windows are made of Poly Methyl Methacrylate (PMMA). An extensive study has been performed to design them according to [1], [2], [3].
The Ictineu 3 will be the first submersible to dive deeper than 1000m with a large acrylic window. All the submersibles known for similar or higher depths have only small portholes (Ø200mm). A 1.5m external diameter front dome will allow a wide field of view with great comfort for the passengers. This geometry was quite challenging for the design and calculation of the PMMA hemispheres and their sealing/support system.
Thermal expansion and compression have been considered, to guarantee a proper sealing and stability of the windows when on surface, in a wide range of conditions: from cold to hot regions, with a considerable temperature variation (-15/+50ºC).
The design temperature is 18ºC, considering the mean value in between internal (24ºC) and external temperature (12ºC) at the design pressure. The design service life is 20 years or 10,000 pressure cycles [1], [2]. The two windows are spherical sectors, with opening angles of 150º (main dome) and 160º (top hatch). They weigh 500kg and 45kg respectively and they will be tested together with the steel structure at 14,5MPa inside a hyperbaric chamber, with a 1,2 safety factor compared to the design pressure (12,1MPa).

MANUFACTURING PROCESS

Steel Body. The manufacturing of the pressure hull of the Ictineu 3 is now being carried out among several specialized factories with previous experience in pressure hulls construction. The selection of the workshops able to guarantee the specified tolerances was a cumbersome task. The process is long and complex, mainly because of the low tolerances required for the certification. In order to obtain the two spheres, a steel plate 46mm and 30mm thick respectively was used. After the deep drawing (Fig. 2) and the heat treatment of the dished heads (Fig. 3), a machining process is necessary to meet the "out of roundness" tolerance. The sphere is obtained welding together two heads along the equatorial line. The welding process has to be carried out by certified welders, with low heat input and very low interpass speed, in order to avoid deformation of the steel along the welding line. Once the reinforcing flanges and penetrators are welded, the two spheres are assembled together through a reinforcing ring: this object, closed with the two acrylic windows, represents the pressure hull of the Ictineu 3.

Fig. 2. Deep drawing of one hemispherical dished head of Ictineu 3 pressure hull (courtesy of ATB Riva Calzoni S.p.A.).

The mechanical tests and dimensional checks are carried out under the strict supervision of a Germanischer Lloyd Surveyor. Tests results showed values well above the minimum specified by the steel manufacturer (Table 1): the yield and tensile strength are at least 10% higher than the minimum; the elongation is almost the double and the impact strength is three times the minimum; hardness is very close to the typical value.

	Typical values					
	$R_{p0,2}$ [MPa]	R_m [MPa]	A_5 [%]	Kv [J]	Hardness [HB]	
	≥ 530	≥ 730 ≤ 930	≥ 20	≥ 90	250	
Transverse tensile test	637	815	39,8			Head 1 (Ø780, 30mm) RIM
Longitudinal tensile test	637	818	39,6			
Transverse impact test				258 286 288		
Longitudinal impact test				266 290 298		
Brinell Hardness					249 245 253	
Transverse tensile test	586	804	40			Head 2 (Ø1690, 46mm) RIM
Longitudinal tensile test	612	809	42,8			
Transverse impact test				274 298 298		
Longitudinal impact test				297 298 298		
Brinell Hardness					234 235 247	

Table 1. Mechanical test results on the rim of two dished heads of Ictineu 3 pressure hull.

As said previously, the out of roundness of the two spheres is the most critical parameter to be satisfied: a measuring device (spherometer) was developed to detect any variation from the ideal spherical surface. To certify the pressure hull, a milestone will be the pressure test at 14,5MPa in an autoclave.
Another challenge was the design of the lifting gear. The submarine will be lifted through three lugs welded to both spheres. The design of this structure is quite demanding because of the high safety factor required: the lifting points have to withstand 8 times the Safe Working Load, defined as the total weight of the submersible plus a 10% for unsymmetrical lift. The lugs have been designed against failure (tensile strength R_m).
A further critical point is related to the reinforcing flanges (Fig. 4, 5) at each opening of the pressure hull. The rings are hot forged and then heat treated in order to obtain the highest mechanical properties of the steel.

Fig. 3. Hemispherical dished heads of Ictineu 3 pressure hull (courtesy of ATB Riva Calzoni S.p.A.).

Again the tests showed good material properties, above the minimum values specified by the steel manufacturer: tensile and impact strength, hardness, chemical composition. A final machining gives the correct shape to the flanges.
Forging results in a metal that is stronger than cast or machined metal parts. As the metal is pounded the grains deform to follow the shape of the part, thus the grains are unbroken, with a high strength-to-weight ratio.

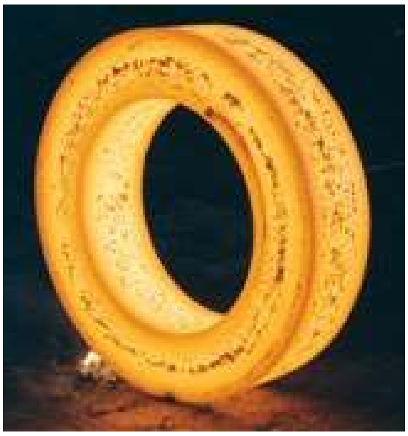

Fig. 4. A forged ring before heat treatment (courtesy of Special Flanges).

Fig. 5. Forged rings of Ictineu 3 after heat treatment, ready to be machined (courtesy of Special Flanges).

Acrylic windows. The manufacturing process is quite long because of the different steps that have to be followed. The process involves mixing a polymer with a monomer to a creamy solution and then this is poured into a mould (Fig. 6). The casting is then put into an autoclave to cure and be heat treated (at 65ºC for 10 days). The curing time is very long because the heat has to be transferred before to the metallic mould and then to the acrylic, that has a considerable thickness. In addition PMMA has a very low thermal conductivity, so this increases further the time. A machining of all faces to the finished dimension and a polish follow. Once polished and inspected, a final anneal removes any residual stress.
The main sealing between acrylic window and steel support ring is an elastomeric (NBR) o-ring, that will prevent the water to leak in when the submarine is on surface. After the first meters, the sealing is obtained along the contact surface in between the window and the support ring.

Fig. 6. Acrylic cast of Ictineu 3 window (courtesy of Stanley Plastics).

SUMMARY

The construction of the pressure hull is due to be completed at the beginning of 2010. After the pressure test in a hyperbaric chamber, all the submersible systems will be fitted and the outer hull will be mounted. The first sea trials of the Ictineu 3 submersible are scheduled in the second half of 2010.

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