Pressure Hull Design and Construction of the Manned Submersible Ictineu 3

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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 is the first project of Ictineu Submarins S.L., a scientific manned submersible designed to operate at a maximum depth of 1200m. The most critical part in the design of a manned submersible is the pressure hull, which must provide safety to passengers under the external pressure. Therefore, its design must be done according to strict rules imposed by international certifying agencies. Moreover, every step of the construction process must be certified and subject to quality control, that will provide high precision allowing to meet very low tolerances. 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: this is why a sphere has been chosen to host the three crew members. 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. Two major difficulties have had to be solved in this project: from one side the selection of the right material and the calculation of the pressure hull; on the other side the definition of the manufacturing process for the two spheres to satisfy the tolerances required by Germanischer Lloyd.

THE PRESSURE HULL

The pressure hull has been designed under the ASME PVHO-1-2007 and Germanischer Lloyd rules. A preliminary study was first completed to select the most suitable shape and material. The aim was to obtain a pressure hull as light as possible while maintaining safety. The sphere is the ideal geometry for a solid submitted to an external pressure. After a thorough research and calculation between different materials, a special steel was selected. Titanium has a lower density compared to steel but it is much more complicated to weld: it was discarded because of the more demanding manufacturing process and because of the higher price. Carbon fibre/epoxy composite is even lighter than titanium but there are no certified pressure hulls employing these materials. Beside, the manufacturing of a carbon fibre/epoxy sphere by filament winding is extremely expensive.
The selected 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 material special properties: high yield strength ($R_{p0,2} \geq 530$MPa), high ultimate tensile strength ($R_m \geq 730$MPa), high elongation (A_5=35%) and excellent properties against corrosion. From the mechanical point of view this material 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 not magnetic, 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.

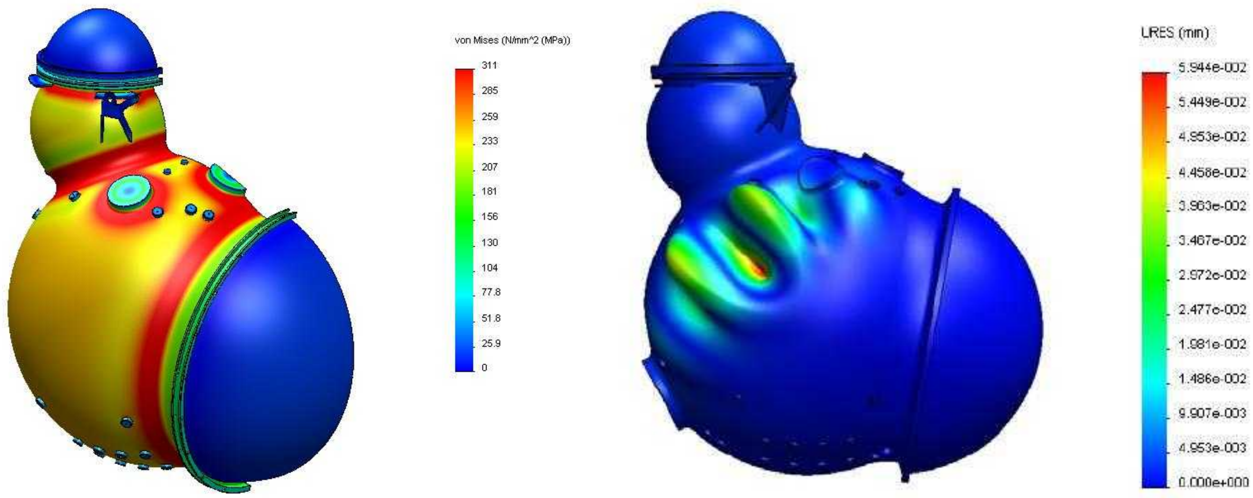

Fig. 1. CAE calculation of stresses at design pressure (left) and of buckling at collapse pressure (right)

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 took many months. The majority of them were discarded because they could only perform part of the job, without being able to meet the strict tolerances. The process is long and complex, mainly because of the low tolerances required for the certification. To obtain the two spheres, a steel plate 46mm and 30mm thick respectively was used. After the deep drawing and the heat treatment of the dished heads (Fig. 2), 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.

The mechanical tests and dimensional checks are carried out under the strict supervision of a Germanischer Lloyd Surveyor. 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. 3) 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. A final machining gives the correct shape to the rings. Because of the low tolerances and the high dimensions of these components, the selection of the suitable supplier was extremely challenging.


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

Fig. 3. Forged ring before heat treatment (courtesy of Special Flanges S.p.A.)

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.

THE ACRYLIC WINDOWS

The acrylic is a thermoplastic with excellent environmental stability and low water absorption (0.25% in 24h). It is almost completely transparent (92% light transmission) and it has a lower density (1.19kg/dm^3) and a higher impact strength than the glass. For all these reasons it has been used for underwater applications for the last 60 years with excellent results. An extensive study for the acrylic windows has been performed, according to [1], [2], [3]. The aim was to design suitable windows for external view, able to withstand the design pressure (12,1MPa) 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 (Fig. 4), 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).
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. The casting is then put into an autoclave to cure and be heat treated. 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.
The Ictineu 3 will be the first submersible for 1200m with an acrylic window of 1.5m external diameter. All the submersibles for similar or higher depths have only small portholes (Ø200mm).

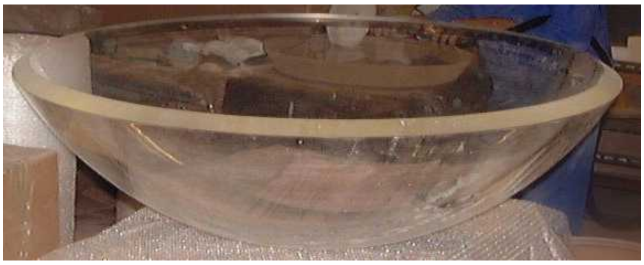

Fig. 4. Acrylic window (courtesy of Stanley Plastics)

SUMMARY

The pressure hull of the Ictineu 3 has been designed to operate at a maximum depth of 1200m. It is manufactured in austenitic-ferritic steel with excellent mechanical and corrosion properties. It has two acrylic windows for external view, designed for the same operative pressure. The construction of the pressure hull is due to be completed at the end of 2009. 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.

ACKNOWLEDGEMENTS

We would like to acknowledge the Museu Marítim de Barcelona, Departament de Medi Ambient i Habitatge, agència Acc1Ó de la Generalitat de Catalunya, Centro para el Desarrollo Tecnológico Industrial (CDTI), Obra social de la Caixa, Caja Navarra, Fundación Española para la Ciencia y la Tecnología, subprograma Torres y Quevedo, and Caixa Terrassa for their support.

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