Advanced Materials
Manufacturing & Characterization

journal home page: www.ijammc-griet.com

Role of Material and its Processing for LIGO-India Ultra High Vacuum System

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ARTICLE INFO

Article history:
Received 14 Nov 2012
Accepted 26 Dec 2012

Keywords:
Mirrors,
UHV chambers,
Vacuum system.

ABSTRACT

LIGO, which stands for the Laser Interferometer Gravitational-Wave Observatory, is a large-scale physics experiment aiming to directly detect gravitational waves. LIGO-India has been proposed for construction and operation of a large-scale international observatory in India in collaboration with LIGO, USA. The observatory consists of large number of optics components, viz., mirrors, beams splitters and the interferometer. All these components will be installed in Ultra High Vacuum (UHV) systems. The Ultrahigh Vacuum system consists of 8 kilometers of beam tubes of 1.2 meter diameter and large size of UHV chambers i.e. Beam Splitter Chambers (BSC), Horizontal Access Modules (HAM). This UHV system will be on of the largest vacuum systems in the southern hemisphere. To achieve UHV in such a large system, the selection of material and various surface treatments are very important. Special care should be taken during fabrication, cleaning, transportation, installation and commissioning. This paper presents all the aspects required for the LIGO-India vacuum system.

Introduction

The selection of materials its processes for use in vacuum systems are a very important part of the design and should be considered. Different type of material properties should be considered like mechanical, thermal, gas loading etc. The material must be capable of being fabricated into the required components. It should withstand the required conditions of temperature; pressure imposed on it by the material processes, without limiting the attainable vacuum that is required. The material must have adequate strength at maximum and minimum temperatures to be encountered, and must retain its properties over the expected temperature range. The material's vapor pressure must remain low at the expected working temperature. Materials should be free of cracks and crevices which can trap cleaning solvents and become a source of virtual leaks later on.

Role of UHV for LIGO-India:

LIGO observatory supports UHV chambers and an L-shaped UHV system (Called as Beam Tube), measuring 4 kilometers (2.5 miles) on each side. The laser light wave travels into the beam tube as shown in the figure 1[1].

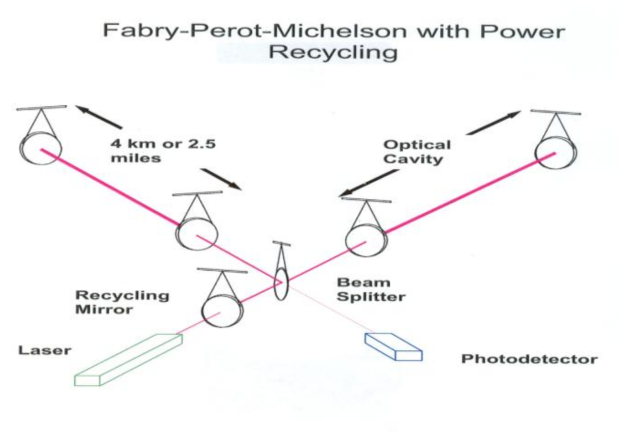

Figure 1[1].

As it is known that strain sensitivity is directly proportional to the vacuum i.e. better vacuum gives more sensitivity. So to increase the strain sensitivity of the system, ultra high vacuum is the first and preferable choice.

Design principles of a UHV system:

In order to design the system, the main parameter will be desired vacuum. A high vacuum system may be required baking up to 150^{o}C depending upon the outgassing and type of pumping system. On the other hand, UHV system needs baking to

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higher temperatures and requires that special precautions be taken to obtain sufficiently-low outgassing. The outgassing rate depends on the material properties, the surface treatment and cleaning procedures. A baked system will reach UHV conditions much faster than an unbaked system, although baking takes hours depending on the baking temperature and gas load. The operating & baking temperature of the UHV system is another important factor to be taken into account. Therefore the material should be used having low outgassing and try to minimize the effects of gas loads in the vacuum system. [2]

Outgassing is primary source of gas load in UHV system; diffusion and permeation are a small part of the total gas load. Gas load contributions by diffusion are similar to permeation however the gaseous species are present intrinsically to the vacuum material. To achieve low vacuum, removal of nitrogen and oxygen species are the main constituents. To achieve high vacuum, removal of water vapor, hydrocarbons also become the main constituents. To reach in the regime of UHV, major constituent to be removed is hydrogen. [3]

Selection criteria of material:

Many factors need to be taken into account to select the suitable material to be used in the vacuum system; vacuum performance, mechanical strength (stability, hardness), thermal conductivity, surface resistivity, materials vapour pressure, how easy the material is for fabrication, joining and cleaning. But to make the UHV system, material selection criteria is

- It must be uniform.
- It has low enough vapor pressure
- It does not include impurities and gas.
- It is not easy to adsorb gas and out gas.
- It can be baked under high temperature or freezed under low temperature

The above mentioned requirements apply to all raw materials used for LIGO-India UHV components.

Approved Material for LIGO-Vacuum system:

There are many approved material for the LIGO-Vacuum system like - Aluminum and alloys, Beryllium copper, Copper-nickel alloys, Copper (OFHC), Electroless nickel, Gold, Indium, Molybdenum, Niobium, Phosphor bronze, Platinum, Silver, Silver solder, Maraging Steel (300), Stainless Steels (304), Stainless Steel (316, 303, 18-8, 17-4PH), Titanium, Tungsten, Ceramics (Fired nonpermeable ceramics, Boron Nitride (machinable), Glazed Ceramics (e.g., Porcelain), AremcoCeramabond 571), Crystalline Materials (ADP, Calcite, Diamond, Germanium, Quartz, Sapphire, Silicon Dioxide, Tantalum Pentoxide (hard optical coating)), Glasses (Fused quartz, Pyrex glass, Glass, Black Glass, shade 12/14 Welders), Polymers (Teflon PFA-440HP (Dupont), Teflon insulated wire, Cooner Wire, P/N CZ1104, 3M/DyneonFluorel FC2180, 3M Fluorel V747-75, Dupont Viton E-60C, Vac-Seal epoxy) etc.[4]

For UHV, as per outgassing as the important design criteria, each material has to be checked before selection. Few useful material has been shown with their outgassing in the following table:

Material	Outgas Rate (Torr L/s cm^2)	UHV OK?
Brass	10^{-6} – 10^{-7}	No
Stainless Steel	10^{-8} – 10^{-13}	Yes
Copper	10^{-9} – 10^{-12}	Yes
Polymers	10^{-5} – 10^{-7}	No
Aluminum	10^{-8} – 10^{-13}	Yes

As per the above mentioned table, the options are usually only aluminum and stainless steel. Stainless steel is preferred for systems from strength and fabrication point of view. Most vacuum components are nowadays available in stainless steel. Stainless steel products are however less expensive and are available from a large number of companies. The most common grades of stainless steel are 304, 304L, and 316L. Stainless steel grade 316LN or 304LN are often required for their high mechanical strength and low magnetic permeability. [3]

Importance of Surface roughness of material

All metal components intended for vacuum service shall have quality finishes on all surfaces, suitable for service in an UHV system. These requirements define the restrictions and practices which must be followed for parts to be used in the LIGO UHV system. All final surfaces of all parts are to be machined. Machined surfaced must not have smeared metal or galling because these conditions can trap contaminants which could out-gas when the part is in service in the vacuum environment.[5] Sometimes, the parts of stainless steel only can be electro-polished to remove all surface oxides and potentially embedded contaminants. The most suitable surface finish for UHV should be better than 1-2 micron.

Welding technique:

Most of the parts of the LIGO system will be made of stainless steel and the whole beam tube is of thickness 3mm and made up of stainless steel. For welding LIGO beam tube, Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW) and Gas Metal Arc Welding (GMAW) are most preferable. Vacuum facing component will be welded by GTAW or PAW to insure good quality, free from weld defects of weld and other than vacuum facing component will be welded by and GMAW.

Good quality weld, less distortion and arc stability is prime requirement for the welding. To achieve the aim, for GTAW and PAW welding, controlled pulsed DC with Electrode negative or Direct Current Electrode Negative (DCEN), constant current source will be used and for GMAW welding, short-circuit or pulsed spray transfer with DCEP (Direct Current Electrode Positive) type polarity will be used.

In any cases, hydrogen gas will not be used as shielding gas, because it deteriorates the UHV requirements. For GTAW welding, 100 % Argon or Argon with Helium is most preferable for shielding gas and same for trailing gas. To increase the heat input increase the helium percentage but it will raise the cost of welding. For PAW & GMAW welding, three types of gases is used; plasma gas, shielding gas and trailing/backing gas. Pure Argon or

Argon with helium, carbon di oxide is preferable for Plasma, shielding and trailing gas. These gases have an effect on arc stability, metal transfer mode, weld bead shape and melting rate.

Weld repair technique:

Weld repair covers, the repair of nonconformities in edge preparation and the repair of unacceptable defects in inspected weld joints. Welded repairs shall be visually inspected after welding or with radiography. Defects shall be removed by grinding with Carbide Burr Cutters only. Abrasive-type wheels and stones are not allowed on vacuum materials. The cavity shall be blended uniformly into the surrounding surfaces. The area prepared for welding can be visually inspected then Re-Welding can be done in accordance with an approved welding procedure.

Abrasive Removal Techniques:

To remove the abrasives, lint – free cloth is permitted for the final surface. No grinding or lapping with abrasive wheels is permitted. Grinding is acceptable if all ground surfaces are machined afterwards. No parts are to be sanded with abrasive techniques e.g. sanding, grinding. Stainless steel wool can be used. The use of Scotch-Brite™ or similar products is not permitted at any time. [5]

Cleaning:

Cleaning is one of the important processes in UHV system. In an UHV system, a low residual gas density can be obtained and preserved only by using constituent materials having a sufficiently low vapor pressure at the working temperature. For the same reason, namely to reduce residual gas pressure, the surfaces facing vacuum of all the constituent parts must be free of organic additives, oils, greases, packaging residues, which were used for instance during the manufacturing process.

Some of the relevant contaminants for UHV systems are various hydrocarbons (oils, lubricants and so on from fabrication process), corrosion inducing elements and compounds (e.g. halogens, sulphur) etc. These contaminants are bad for static and also dynamic vacuum. [6]

Solvent Cleaning is used to remove forms of organic contamination such as oils, grease, hydrocarbon fuels and inks. The approved solvents are acetone, methanol, isopropanol, and Methanol and ethyl ethyl ketone. Acidic Cleaning is used for the removal of inorganic contamination, trace metals and oxides such as scale, (calcium and magnesium) salts and where general metal brightening is required. Ideally this is accomplished with a phosphate-free acid. A high pressure, high temperature steam clean process is used to remove loose debris and contaminants from the surface. Warm tap water is appropriate for inter-process rinsing; Deionized water should be used for final rinsing as it is particularly low in ionic or inorganic contaminates. The entire part will be rinsed and dried thoroughly by blowing clean air. For UHV system, precision and final cleaning should be done in a clean room facility, with workers bearing the appropriate costume.

Reduction of Hydrogen species for UHV:

Reduction of outgassing for H species is very-very important to get UHV. This reduction can be done by decreasing the concentration of the gas from material, by oxide coating to act as a barrier for diffusion of H from the bulk, or by air bake out. The material, SS 304L must be pre-baked at 450^{o}C for 36 hours in dry air, before fabrication, to reduce the outgassing rate of hydrogen. The size of oven should accommodate the raw material. After baking, the oven should be vented using dry air/ Nitrogen gas.

While processing steel, H_2 impurities sit on the interstitial sites in the Fe lattice. During baking above 400 C will drive H_2 towards the walls of the chamber. [3]

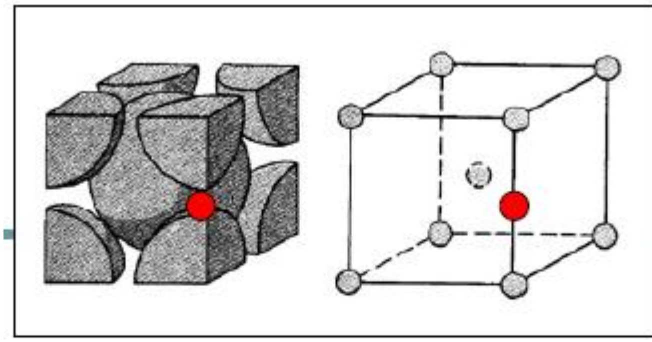

Figure: α-Iron BCC Lattice with Hydrogen Interstitial

After fabrication and installation, baking at 150° C bake for long time, in vacuum to remove species such as H2O, CO, and CO2. Residual Gas Analyzer (RGA) will be used for quantitative partial pressures estimates for different species.

Conclusion:

The role of material and its processes for UHV system is very-very critical. The material should be selected as per the acceptable criteria and requirement of the vacuum system. The reduction of hydrogen species should be carefully handled by different acceptable process for the UHV systems. The re-introduction of hydrogen species should be avoided completely during welding etc. Proper and precise welding & cleaning techniques in clean environment is necessary to achieve UHV.

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