Abstract

Vacuum heat treatment processes such as solution annealing and age hardening are being employed during the manufacture of thin walled Special high strength steel tubes required for “High Speed Machines Program” of the department. Three vacuum furnaces are being used for the past 2½ decades for supporting the heat treatment activities. Innovative maintenance techniques were introduced for enhancing its service life beyond the design life by about 2 folds that avoided expenditure of few crores of rupees, apart from providing energy efficient safe operation. The throughputs from the furnaces have been enhanced considerably by the use of suitably designed fixtures to cater to different sizes of our jobs. From the expertise gained over the period of several years of operation of vacuum furnaces, a furnace has been designed, developed and commissioned indigenously by incorporating additional features providing O&M friendly controls along with safe& energy efficient systems.

Introduction

Special High Strength Steels (SHSS) derive their strength not from carbon but from precipitation of intermetallic compounds and martensitic transformation (1). The commonly available SHSS contain Ni, Co, Mo, Ti and Al. These steels develop very high strength by martensitic transformation and subsequent age-hardening. Hardness comes due to formation of intermetallic phases of Ni₃Ti, Ni₃Mo and Fe₂Mo. SHSS have found applications where ultrahigh strength and high toughness are essential. Due to their high strength/density ratio, SHSS have been used for making thin walled cylindrical tubes. The process of making the SHSS tube is a complex one that involves heat treatment processes such as solution annealing and age hardening at different stages. In order to manufacture the cylindrical tube, flow forming technique is employed. SHSS preforms of about few mm thickness are cold formed by multi stage flow forming operations and are brought down to less than 0.5 mm thick thin walled tubes of desired length. Intermediate solution annealing process is carried out on the pre-forms to make them suitable for further cold working operations. Solution annealing process involves controlled heating of the charge under vacuum to about 900°C and furnace cooling to an intermediate temperature followed by forced cooling using dry nitrogen gas. This process is typically the precursor to an age-hardening operation for precipitation of hardenable alloys. Solution annealing provides complete re-crystallization and ensures the formation of a fully austenitic structure from which martensite can form on cooling. The finished assembly is age hardened that provides the optimum strength and toughness. The nature of the Special high strength hardening mechanism is such that close dimensional control can be maintained in component that are finish machined in the soft, annealed condition and subsequently hardened. The solution annealing and age hardening of the SHSS tubes are carried out in vacuum furnace due to its neutrality of vacuum as a protective atmosphere and the ideal surface quality obtained during the course of heat treatment. In vacuum systems, there is a total separation of the
furnace working area from the environment which permits precise and effective heat treatment processes to be carried out. Additionally, continuous advancement in the area of effective gas quenching makes vacuum furnaces a sophisticated, economical and environmentally friendly alternative to the majority of atmospheric heat-treatment technologies and oil quench.

Three Vacuum Heat Treatment Furnaces (VHTFs) have been installed and operated for the past 2 ½ decades for providing the heat treatment support to our program. Innovative maintenance techniques were introduced to extend its service life beyond the design life, enhance the process throughput and make it energy efficient for safe operation. In this paper, the innovative maintenance techniques followed by us are described.

Use of VHTF for our program

Three vacuum furnaces have been installed and operated for the past 2 ½ decades for providing the following heat treatment support.
- Age Hardening Treatments on finished SHSS rotors.
- Intermediate solution annealing treatment of cold serviced SHSS Preforms.
- Baking of electroless nickel plated components to enhance the adhesion of the coating.
- Heat treatment of Inconel rings.

The vacuum furnaces used for the above applications are made up of double walled stainless steel chamber with all-metallic-hot zone using Molybdenum as heating elements and radiation shields. The hot zones are of modular type having 3 zones of total connected power load of 250 KVA. Effective hot zone size of the furnace is of diameter 700 x 2200 mm height having maximum charge loading capacity of 400 kg at 1000°C. Ultimate vacuum achievable is 1 x10⁻⁶ mbar with vacuum pumping system consisting of diffusion pump, roots pump and rotary vane pumps. It has inbuilt inert gas recirculating fast cooling system.

Innovative Maintenance Techniques Followed

The vacuum furnaces are being operated and maintained in good working condition for more than 25 years till date by adopting innovative techniques for its operation and maintenance. We have successfully carried out few thousands of heat treatment process cycles in each furnace. From the beginning, we have implemented Total Productive Maintenance concepts to make effective use of the equipment and maintain good production conditions. Few of the noteworthy maintenance techniques adopted are mentioned here.

Reconditioning of heat shields for Life enhancement

All metallic hot zone of the vacuum furnaces consists of heating elements, charge carriers and inner two radiation shields made of molybdenum and the outer three radiations shields made of stainless steel (Fig.1). The design life of the molybdenum radiation shields are limited to about 10 years. Replacement of heating shields after its designed service life is essential that incurs a large expenditure in foreign exchange. But we have adopted an innovative technique of overhauling the hot zone that involved multistage buffing followed by ultrasonic cleaning using suitable...
solvents. This process had brought back the original emissivity to the radiation shields enhancing the life of the hot zones apart from providing improved surface quality of the heat treated parts. This maintenance process is a herculean task that involved handling of molybdenum radiation shields which are highly brittle in nature. Implementation of this innovative maintenance concept not only avoided a large expenditure in foreign exchange, but also enhanced the service life beyond 25 years.

**Hot zone cleaning cycle**

The heat treatment process temperature is limited to 900°C for our routine production activities. During this process, there is a possibility of deposition of volatile materials originating from the charges. This may reduce the efficiency of the heat shields. In order to overcome this problem, a hot zone cleaning cycle is implemented for every 25 batch of process. In this cleaning process, the furnace is heated to 1000°C for an hour by which the efficiency of the heat shields is increased as a result of burning out the deposited volatile materials.

**Upgrade of furnace control system enhancing the availability factor**

The originally supplied furnace had relay logic based hard wired control system, making it impossible to maintain the equipment in good working condition. Furnace has been upgraded to PLC & HMI based control system that provides flexibility to alter program logic sequences, apart from providing supervisory control and data acquisition. Subsequent to the implementation of the PLC based Control System, a number of modifications in the process interlocks and their sequence were introduced. The additional logic introduced in the sequence of operation for the pumping system has resulted in energy saving of the order of 100 KWH per process cycle amounting to 40% reduction approximately.

**Introduction of Safety interlocks**

The overall safety features of the High Temperature High Vacuum Furnaces have been enhanced considerably by adding a number of safety interlocks as detailed below.

- Introduced a pre-condition to initiate fast cooling cycle, ensuring elimination of accidental admission of dry nitrogen gas at elevated temperature.
- To avoid accidental incident of switching on the pumping system when furnace lid is in open condition, proximity sensor was mounted which acted as fail safe pre-condition to initiate the process cycle.
- Position sensors were also incorporated in the fore-vacuum rough-vacuum and holding line valves ensuring fail safe operation.

**Reconditioning of ceramic insulators**

The furnace has three heating zones each of which is equipped with cylindrical Mo sheet as heat reflector and Mo heating wire. All-Metallic- Hot zones of these furnaces are separated from the furnace body with the aid of high purity alumina based ceramic electrical insulators. Each furnace has around 200 such ceramic insulators in the shape of bobbins and sleeves. After few years of operation, we have observed frequent blowing of fuses in the thyristor based heater control systems. This was finally attributed to electrical short circuiting in the heater assemblies. Upon investigation, the ceramic insulators were found to be coated with Mo to few microns thickness as confirmed by EDXRF spectrometer. Deposition of Mo over the ceramic insulators has taken place due to the use of Mo radiation shields/heating elements in vacuum condition during the operation of furnace over a period of several years. This resulted in deterioration in the insulating property of the ceramic insulators. As spare ceramic insulators of special dimensions are not readily available, a special reconditioning procedure was developed. All the insulators were removed from the furnace and subjected to suitable chemical treatment process for the selective removal of Mo deposits from the ceramic insulators. All the insulators are salvaged by adopting this innovative chemical treatment process and reassembled successfully for the safe operation. Based on this experience, this reconditioning procedure has been included in the Total Preventive Maintenance protocol.
**Design and fabrication of fixtures**

We had designed and fabricated different fixtures for loading tubes as well as the finished products for annealing/age hardening respectively in the vacuum furnaces. The requisite design & material selection for the fixtures were based on the properties at elevated temperature of the order of 1000°C.

**Fixtures for age hardening and annealing**

In our earlier design of the fixture used for age hardening, the rotors are directly resting on the fixture’s bottom plate, which in turn are placed on the hearth of the furnace. This fixture cannot be used for our newer designs of the work, having flexible elements, due to the possible distortion on the thin sections. So, we had developed a different design of fixture as shown in Fig 2. In this design, the long ‘Tube-Assemblies’ are loaded in the suspended conditions from the top plate. An intermediate plate takes care of guiding at the bottom. This design eliminates the possible distortion of the Tube-Assemblies.

In order to reduce the inventory of fixtures for different sizes/designs of the finished products, we had also developed fixtures that can be universally used for accommodating different sizes/designs of the finished products/tubes in multi tire orientation. This resulted in enhanced throughput apart from considerable cost saving in manufacturing of multiple fixtures. Similarly universal fixture as shown in Fig.3 is fabricated for annealing treatment of SHSS preform tubes for increasing the process throughput. In this design, regular diameter pre-form tubes are placed inside the higher diameter pre-form tubes.

**Fixture for vacuum baking of Nickel plated components**

Few of the carbon steel components of the HSR machines are coated with nickel to few micron thickness by the process of electro less nickel plating. During the process of nickel plating, hydrogen gas is likely to be trapped in the coating, which needs to be removed. Vacuum baking at about 200°C for few hours often relieves the hydrogen and also enhances the adhesion of the deposit (2). Furnace used for baking operation imposed a limitation on the length of plated components such as housing whose length is about 2
meters. In order to accommodate such lengthy components for baking, special fixtures had been designed & fabricated to load the job in an inclined manner as shown in Fig. 4 taking the advantage of increased space diagonal of the effective hot zones.

**Indigenous development of Vacuum Furnace**

Based on the expertise gained over the decades of operation and maintenance of the furnaces, work was undertaken to design and develop Vertical Vacuum Furnace Indigenously in association with NFC, Hyderabad. The following additional features were also incorporated in the indigenously developed vertical vacuum furnace (Figs. 5-6).

- Wide Band Heating Elements for uniform heat distribution.
- Fully Automatic operation through PC mode and also manual mode through Control Desk mode.
- Doped Molybdenum based Hot Zone for life enhancement.
- Low Voltage across Heating Elements
- Health monitoring gauges for individual pumps for easy maintenance.
- Incorporation of quadruple mass spectrometer gas analyzer.
- Gas Plenum for effective fast cooling.

- Avoided looping of cooling water circuits by providing individual cooling water line to the chambers.
- Load hanging fixtures for flexible membered tubes.
- Drain ports for complete removal of water from the jackets to avoid corrosion.
• Wheels on the bottom lid frame for easy maintenance.

Conclusions

From the past experience gained during the operation and maintenance of industrial vacuum furnaces for heat treatment applications, a number of design features have been incorporated for the indigenously developed vacuum furnace, which results in safer and energy efficient operation.

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