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Use of titanium in the tokamak physics experiment (TPX)

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Abstract

The titanium alloy Ti–6Al–4V is currently the reference alloy for the vacuum vessel of the tokamak physics experiment (TPX), which will use D–D as fuel. Titanium was selected because it satisfies the requirement of reduced radioactivation of the TPX vacuum vessel. Reduced activation allows the hands-on maintenance of components inside the vacuum vessel during the first two years of operation, with a gradual transition to fully remote maintenance required during the latter phases of TPX's experimental program when the neutron yields are expected to be much higher. It also reduces the eventual waste storage requirements. As part of the R&D program on TPX, two issues on titanium were studied: the impact of the plasma hydrogen absorption on titanium and the welding of thick sections. Based on preliminary analysis, no critical issues were encountered.

1. Introduction

The mission of the tokamak physics experiment (TPX) is to develop the scientific basis for a compact and continuously operating tokamak fusion reactor, using D–D as a fuel. A key element of the TPX is the vacuum vessel. It is designed as a double-walled toroid providing a vacuum boundary suitable for high vacuum conditions within the inner toroid shell and borated water coolant between the inner and outer vessel walls. Material selection requirements for the double-walled vessel include structural, fabrication and reduced radioactivation.

These requirements were used to evaluate potential materials for the vacuum vessel. Aluminum alloys were rejected because they did not meet the structural requirements under TPX operating conditions (steady state temperatures of 150°C with vacuum bakeouts at 350°C). The need for reduced radioactivation essentially eliminates conventional steels and nickel based alloys. Materials which have reduced radioactivation potential include silicon carbide, vanadium and titanium. Silicon carbide was not considered because of cost and difficulties ensuring vacuum compatibility. Vanadium was also eliminated because of cost and the lack of industry wide fabrication experience, product availability and the material data base needed to support the TPX design and fabrication. This essentially left titanium alloys as the most promising material to meet the TPX requirements. Of the various titanium alloys commercially available, the Ti–6Al–4V was selected based on commercial availability, data base availability, and manufacturing experience. The Ti–6Al–4V is considered the carbon steel of the titanium industry. The potential of titanium for use in fusion components, along with the rationale of selecting Ti–6Al–4V, has been previously reported by Davis [1]. Even though Ti–6Al–4V has been thoroughly studied and used in a number of large structures, it has not been used in fusion components and requires additional research before large prototypical components can be fabricated. This program focused on two areas: hydrogen compatibility and weld effects.

2. Hydrogen compatibility

Titanium has an affinity for hydrogen and can be embrittled if the solubility limit is exceeded through the precipitation of hydrides. The hydrides are low strength and cleave at stresses much lower than the parent metal. If enough hydrides precipitate, the metal will become embrittled and catastrophic failures at lower than anticipated

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stresses can occur. Hydrides have also been observed to form in highly stressed regions even though the hydrogen concentration is below the bulk solubility limit. Because of this potential, the factors affecting hydrogen embrittlement in titanium have been extensively studied. One of the things learned by Basel [2] and Waisman [3] is that the addition of aluminum, which is a beta phase former, can significantly increase titanium's tolerance for hydrogen. An alloy found to have one of the highest tolerances for hydrogen is the Ti–6Al–4V alloy. Tests by Rhodes [4] and Pao [5] of Ti–6Al–4V containing 1000 wppm hydrogen found that there was no degradation of room temperature ductility and less than an order of magnitude increase in fatigue crack growth rate. While it appears that the Ti–6Al–4V alloy has a high tolerance of hydrogen, there remains the question: Will the TPX environment produce higher levels of hydrogen in Ti–6Al–4V? The answer to this question is not straightforward. While one can use a Sieverts analysis to determine the total quantity that could be in a material at a fixed temperature, this type of analysis is not valid in a dynamic environment which has variable hydrogen pressures and temperatures along with long periods of no hydrogen pressure. It also does not account for phase transformations which can increase the solubility limit such as the beta phase in titanium.

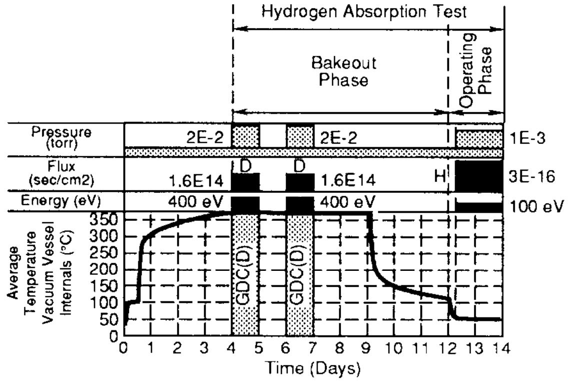

Fig. 1. TPX VV: Operating scenario.

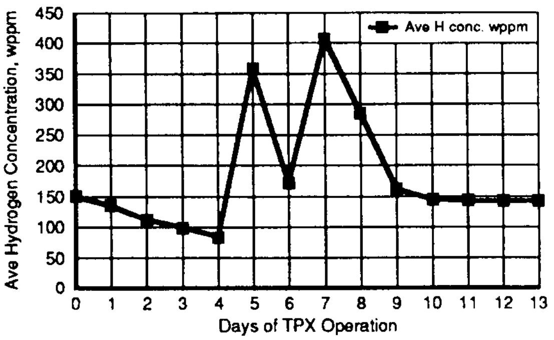

Fig. 2. Bulk hydrogen concentration of Ti–6Al–4V based on Fig. 1 operation parameters.

In looking at the operation of the TPX, the most likely scenario in which the vacuum vessel would pick up hydrogen is during the glow discharge cleaning portion of the bakeout cycle. A vacuum bakeout cycle for the TPX is shown in Fig. 1. From this figure it can be seen that, for the first 4 days (96 h) of operation, the vacuum vessel is evacuated to a pressure of 10^{-8} Torr and the first wall is slowly heated to 350°C. On the 5th day (24 h), the wall is cleaned using the glow discharge process which has an atmosphere consisting of 10% hydrogen, 10% deuterium and 80% helium. The surface temperature of the vacuum vessel is maintained at 350°C. The apparent hydrogen partial pressure is 10^{-2} Torr. Following this period, the vessel is maintained at 350°C for 24 h under a vacuum pressure of 10^{-8} Torr and then the glow discharge cycle is repeated. After the second glow discharge cleaning operation, the vessel is outgassed for roughly 60 h and then slowly cooled to 50°C over approximately 80 h. At this time the plasma operation of the reactor begins. The vacuum bakeout operation is repeated approximately two times a year or after the vacuum vessel is opened. In examining this cycle, it appears that the most likely event in which the Ti–6Al–4V alloy will absorb hydrogen is during the glow discharge cleaning operation, particularly since the hydrogen will be in the atomic state rather than as a molecule. To determine how much hydrogen would enter, a detailed diffusion analysis was made using the experimental results of Basel [2] and Waisman [3]. The diffusion coefficient calculated agrees with the model proposed by Waisman. The diffusion model is based on Fick's Laws [6,7]. The hydrogen absorption/desorption was calculated as a function of depth for every 24 h cycle. A bare titanium surface (free of the normal adherent oxide) was assumed in all cases. The summary results of these calculations are shown in Fig. 2 for an average hydrogen concentration within the bulk material. The surface composition will be significantly higher than these values depending upon whether hydrogen is diffusing in or out. Fig. 2 shows that, at the start of the cycle during initial bakeout, the average hydrogen concentration is decreasing due to outgassing. During the glow discharge cleaning, because of the high temperature and higher hydrogen pressure, the average concentration rapidly increases. However, once the chamber is evacuated and the wall temperature maintained, the hydrogen begins to rapidly diffuse out. This phenomenon has been observed both experimentally and in production in the hydrogen outgassing of sheets and plates. Recycling of hydrogen can occur because hydrides are not formed and the hydrogen exists in solid solution. In the titanium alloys which contain alpha–beta structure, the bulk of the hydrogen exists in the beta phase, whose solubility limit for hydrogen is roughly 40 at%. During the second glow discharge cleaning cycle, the hydrogen concentration is again increased and subsequently decreases on the cooling. In practice, if the hydrogen is not sufficiently reduced, an additional day at 350°C could be added to the schedule to reduce the hydrogen content. Based on the analytical model, it appears that hydrogen would not be a problem during the glow discharge cleaning, which is deemed to be the most critical event. To verify this assumption, testing is in progress at Sandia National Laboratories using their tritium plasma experiment (TPE). In this experiment the operational profile will be simulated and the amount of hydrogen recycled will be determined for bare and TiN coated Ti–6Al–4V specimens. In previous experiments, the TiN coating has been found to significantly reduce the absorption of hydrogen in titanium and could be a viable solution if the analytical analysis is not confirmed by experiment. Depending on the results, other impurity coatings such as TiC and TiO_2 will also be studied.

3. Weld development

Because interstitial elements such as oxygen can contaminate the welds in titanium, it is usually welded in an inert environment or a vacuum chamber. However, the shear size of the vacuum vessel will require it to be fabricated in air, and the welding will have to be accomplished using specially designed weld equipment. The welding is further complicated because: (1) the thickness of titanium (12.5 mm) means that it will take longer to cool the molten metal, increasing the risk of contamination and (2) the double walled design typically limits access for weld equipment to one side of the joints. Even though there is limited access to the root of the weld, the root must still be thoroughly shielded with inert gas during welding. It is because of these concerns that a weld development program was initiated to identify the practice to use in welding thick structures. A secondary objective of this study was to see if the vacuum bakeout cycle could be used to reduce the residual stresses in the weld. A low temperature stress relief is desired to minimize the residual stresses remaining in the weld area after final assembly at the Princeton Plasma Physics Laboratory. It is essentially impossible to perform a typical 540°C stress relief in-place on a structure nominally 4 m high and 8 m in diameter considering the size and also temperature limits of insulation materials on the vacuum vessel.

Welds on typical joint designs expected for TPX were made by Bolser [8] using manual and automatic gas tungsten arc (GTA) techniques on both single and double-sided weld joint geometry and trailing gas shields for both the face and root of the welds. The gas shields were specially designed based on experience welding large titanium components for space applications. Results of these studies confirmed that automatic welds resulted in less distortion of the structure than the manual welds since there are fewer weld passes in the weld joint and therefore less heat input. A comparison of the two weld joints is shown in Fig. 3. From this figure, it can be seen that, by using automatic equipment, a full penetration weld can be achieved in 4 passes while, when using manual techniques, the same joint requires 16 passes. The greater the number of passes the greater the amount of distortion and also increased fabrication cost.

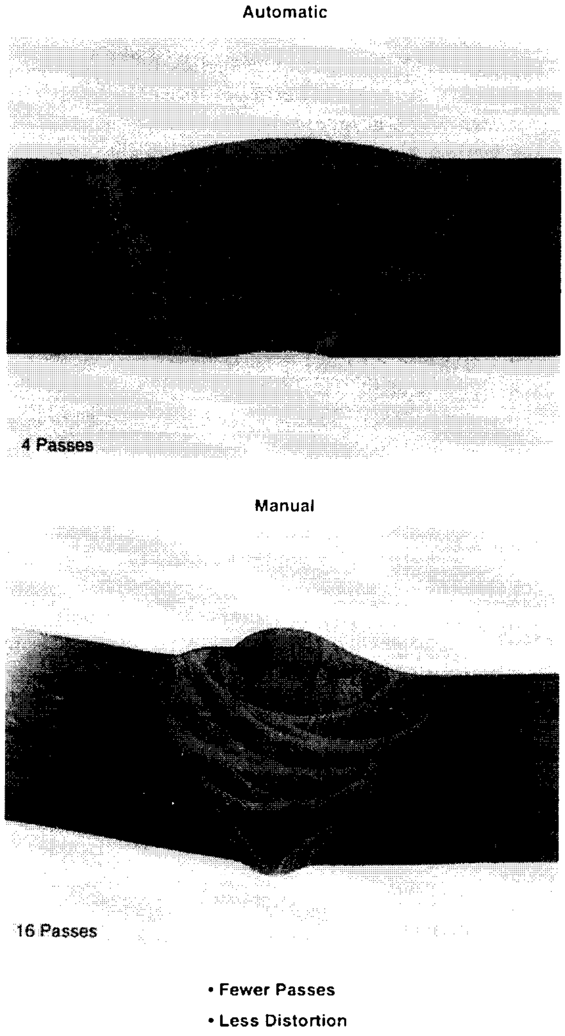

Fig. 3. Automatic GTA methods preferred.

A structure with the complexity of TPX will undoubtedly require some manual welding. In these cases, double-sided welds are preferred to minimize the distortion during welding. In all cases, both the root and face of the welds must be shielded during welding to prevent contamination.

The weld development program for TPX included manual and automatic welds in downhand, horizontal, and vertical positions. Mechanical properties of representative welds were determined in order to verify that the properties of these welds are equivalent to welds made in an inert

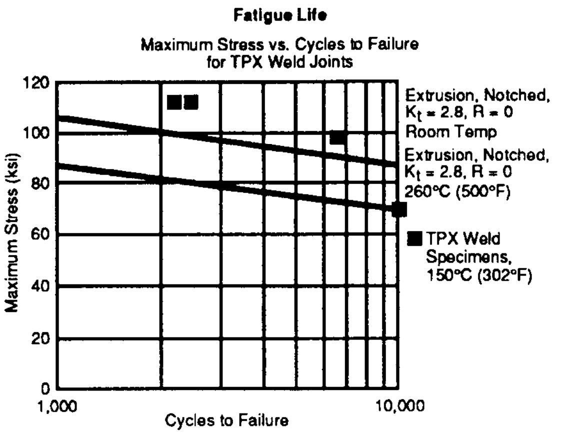

Fig. 4. Fatigue life of welds compared to wrought material.

gas chamber. The results of all mechanical properties tested exhibited properties equivalent to those of wrought material. No degradation of properties was observed because of welding with external shielding. Welds tested at 350°C with the weld beads intact exhibited yield strengths of 565 MPa (82 ksi) and an ultimate strength of 106 ksi which are well above the design allowables of 540 MPa (77.5 ksi) ultimate and 650 MPa (94.5 ksi) yield [9,10]. The calculated fracture toughness (k_{IC}) values of 62 MPa m$^{1/2}$ (56 ksi in$^{1/2}$) and 134 MPa m$^{1/2}$ (122 ksi in$^{1/2}$) at room temperature and 150°C, respectively, compare quite favorably with a design allowable of 55 MPa m$^{1/2}$ (50 ksi in$^{1/2}$). Fatigue tests conducted at 150°C with the weld beads intact exhibited fatigue lives comparable to those of wrought material tested with a $K_t = 2.8$ and $R = 0$ as shown in Fig. 4. The welds were tested with the beads intact to check for any stress concentration effects associated with the weld bead geometry. There was no apparent degradation.

The 'normal' stress relief for a welded titanium structure is 540°C for several hours, depending upon the thickness of the components. However, the final assembly will be such that the entire vacuum vessel could not be stress relieved in place because of the other details close to the vessel. Localized stress relief is typically not effective. The options were to not stress relieve the final assembly or use a lower temperature stress relief to remove some of the stresses. The major concern was not structural integrity, but potential structural relaxation or movement during operation of the machine. Such movement may alter the location of critical details within the device. Tests indicate that the 500 h, 350°C long-term vacuum bakeout will relieve stresses to reduce the risk of movement during operation.

The crack growth of the welds tested at 350°C also compared favorably with wrought material when tested using a standard ASTM 647 compact tension specimen. The crack growth rate was typically about an order of magnitude lower than the reference data [9,10].

4. Conclusions

While more experimental work needs to be accomplished, preliminary results confirm that the Ti-6Al-4V alloy remains a viable structural material for the TPX vacuum vessel. Analytical modeling of the dynamic hydrogen environment at 350°C indicates that hydrogen will be recycled. Further work needs to be performed to understand the impact that stable surface oxides (TiO) and carbide impurities have on both the adsorption and desorption. These contaminants will likely occur during the glow discharge cleaning.

The results of the welding tests confirm that GTA welding with local shielding is feasible and welds with properties equivalent to parent metal are achievable. Care must be exercised to assure complete inert gas coverage of the weld area during and immediately after welding to prevent detrimental weld contamination. Automatic welding procedures are preferred from both a reduced distortion and reduced fabrication cost standpoint. A 500 h, 350°C long-term bakeout should reduce stresses sufficiently to minimize structural movement during TPX operation.

Acknowledgements

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