

# Surface and Bulk Residual Stress in Ti6Al4V Welded Aerospace Tanks

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*The residual stress (RS) in two curved plates cut from a large welded propellant tank for spacecrafts was investigated nondestructively by neutron and laboratory x-ray diffraction. Each plate had two weld beads symmetric to a central monoblock reinforcement. One plate had received a post-weld heat-treatment. The two nondestructive test techniques successfully determined both the bulk (thickness averaged) and the surface stress state, due to the highly different penetration of these radiations in metals. In the as-welded tank, both neutrons and x-rays show a stress level (both in the axial and hoop directions) higher in the heat affected zone (HAZ) than in the weld pool (300 against 160 MPa). A considerable degree of relaxation annealing was observed by neutron diffraction after the application of the heat treatment. In this case, the hoop stress in the HAZ relaxes from about 300 to about 100 MPa. X-rays also permitted the separate determination of the  $\alpha$  and  $\beta$ -phase stresses and the calculation of the macro-RS. The latter showed the bending deformation resulting from the cut of the plates from the original tank. The average stress measured by x-rays was found to be very similar to the RS obtained by neutron diffraction technique. [DOI: 10.1115/1.1763932]*

## 1 Introduction

The standard on-board spacecraft propellant is Hydrazine ( $N_2H_4$ ). This is stored as a liquid in large propellant tanks and fed to small thrusters motors where it is decomposed from liquid  $N_2H_4$  into gaseous ammonia and nitrogen [1].

The hydrazine propellant tanks are fabricated by forging and machining two hemispheres of Titanium alloy Ti6Al4V. Its composition is given in Table 1. The two hemispheres, which have a shell thickness between 2 and 4 mm and an outer diameter of between 0.5 and 2 m are typically joined (girth weld) together by electron beam or Tungsten Inert Gas (TIG) welding.

One failure mode for such welded tanks is known to result from the severe vibration loads, which occur during the launch phase of a spacecraft. In this case rupture takes place in the vicinity of the weld. Furthermore these tanks are submitted to thermal and mechanical cycles during service. It is, then, important that an accurate value is known of the mechanical stress in the welded region of propellant tanks. This is to ensure safety during storage, launch and operational life of the spacecraft.

The stress level caused by the weight of the tank and of the liquid propellant, as well as that due to its pressure, can be easily calculated [2], but in order to evaluate the total stress field it is necessary to detect residual stress (RS) in the component: this has been evaluated in the present work by means of non-destructive x-ray and neutron diffraction techniques.

Very little literature is available on the current subject. RS in Ti6Al4V has been investigated mainly in substrates for coatings [3–5] and biomaterials [6] and in Ti-SiC composites [7,8]. Some Ti6Al4V components have been investigated [9] but, as reported in a preceding work [10], these nondestructive techniques have not been previously applied to titanium alloy weldments.

The complicated microstructure of Ti6Al4V consists of both  $\alpha$  and  $\beta$  phases in the annealed condition. However, the material that has cooled rapidly from the liquid state can result in a wide variety of microstructures that are dependent on the cooling rate. This results in a formidable task for evaluating residual stresses by

means of either neutron or laboratory x-ray diffraction. The use of synchrotron x-rays presents problems of interpretation of the results, due to coarse grain effects.

The present work attempts to assess nondestructively the stress state across the welded region of spacecraft propellant tank, taking into account surface effects, the microstructure and the presence of the  $\beta$ -phase. The efficacy of the standard heat stress-relieving treatment is also tested. The results are also compared with those obtained from destructive RS measurements made using a standard hole drilling/strain gauge technique and with a simple model for RS distributions in welded plates.

## 2 Samples and Microstructure

Two large plate-like samples have been machined from a full size finished propellant tank. These curved plates were identified as X1, as welded, and as X2, after heat treatment. Their size is approximately  $250 \times 250$  and  $250 \times 400$  mm<sup>2</sup>, respectively, and their thickness is 2 mm. Both have been cut with laser technique from a cylindrical tank 515 mm in diameter. The tank was fabricated by joining three forged cylinders using a single-pass tungsten inert gas (TIG) welding technique. The cylinder in the middle has a monoblock reinforcement ring (total thickness 10 mm) at mid-height. The size and shape of the samples are shown schematically in Fig. 1.

The stress relieved sample was heated up to  $485 \pm 8^\circ C$  and held for 4 hours in a  $10^{-4}$  Torr vacuum. A strip about 30 mm wide was successively cut across the weld on sample X2 (along the whole length), again using the laser technique, in order to perform light microscopy and texture analysis. In both cases the cutting procedure is expected to influence the microstructure and the residual stress (RS) state only within a few hundred microns from the cut edge.

From the metallurgical point of view this alloy can be inserted in the titanium ternary alloys near to the pure titanium corner [11]. It is convenient to approach the problem from the binary point of view: this alloy has two coexistent phases, one called  $\alpha$ , with hcp structure and stacking ratio  $c/a=1.59$  (versus the 'ideal' value 1.63), and one called  $\beta$ , having a bcc crystallographic structure. The latter is stable in pure titanium above  $883^\circ C$ , but in this alloy above  $995$  deg C (called the  $\beta$ -transus temperature). This second

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