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Study of Ti-6Al-4V liner Materials Under Bi-axial Loading

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Abstract:
Conventionally the design of any structural component is based on uni axial stress strain curve of the material. But most of the components such as pressure bottles are subjected to bi-axial stress state. Ti-6Al-4V liner materials used in composite spherical pressure bottles in space application are subjected to equi bi-axial loading. The component design based on the uni-axial properties will not predict the actual behavior of the material. Since there is no standard test specimen unlike uni-axial dog-bone specimen, the present study carried out to design the bi-axial test specimen using finite element method. Similarly, since there is no universal bi-axial testing machine exists, 25ton capacity in-plane bi-axial testing facility is designed and established at relatively low cost with the capability of testing uni-axial, bi-axial loading of same and different magnitude and loading along orthogonal directions. The study is further extended to uni-axial and bi-axial testing of Ti-6Al-4V liner materials in three different heat-treated conditions namely beta annealed, mill annealed and Solution Treated & Aged (STA) conditions for both uni-axial and bi-axial loading conditions. 9 to 27% increase in stress under bi-axial loading is observed in all three types of Ti-6Al-4V liner materials compared to uni-axial yield stress.

***Keywords*: Ti-6Al-4V liner materials, Composite spherical pressure bottles, uni-axial loading, Bi-axial Loading, Stress Analysis, Testing.**

INTRODUCTION:

Conventionally the design of any structural component is based on uni-axial stress-strain curve of the material. But in practical engineering applications, most of the components such as pressure bottles are subjected to complex stress state. The design based on uni-axial properties will not predict the actual behavior of the material. The high-pressure spherical gas bottles are used in storing gaseous helium for the pressurization of liquid propellant in satellite launch vehicles. Spherical bottles are generally considered more efficient than cylindrical bottles because they have the smallest surface area per unit volume, meaning they require less material to hold the same amount of liquid. Ti-6Al-4V liner materials used in these spherical composite pressure bottles are subjected to equi bi-axial loading due to symmetry in the spherical pressure bottles.

For biaxial testing there are no standard test procedures available in literature as in uni-axial testing and hence there is no standard specimen geometry to ensure the pure biaxial stress state. Different specimen geometries have been tried by earlier investigators to predict the exact mechanical behavior under biaxial loading.

Shiratori et al. [1] proposed cross shaped flat specimen. The test specimen consisted of one cross-shaped body and eight plates were reinforced to its four arms. Still relatively small area of homogeneous stress filed is obtained in the center zone with stress concentration in the corner fillets. Kelly et al. [2] described that the cruciform specimen with slots and single step reduction factor of two from gripping to gage area was used. Kreisig et al. [3] applied uni-axial and bi-axial load on cross-shaped specimen to find the equivalent cross-sectional area, which is used for calculating the stresses in the specimen under biaxial loading. Ferron et al. [4] used flat cross shaped specimen with slots and thickness reduction of 2mm at gripping area to 0.6mm at gage area. Ellis et al. [5] developed the specimen for testing advanced aero propulsion materials under in-plane biaxial loading. Specimen was developed with slots, blend radius and thickness reduction in gage area and the analysis was carried out using FEA.

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Pascoe et al. [6] established the biaxial testing machine, having four doble acting jacks, with a capacity of 200kN in tension or compression. Hayhurst et al. [8] developed biaxial tensile testing machine for the creep-rupture testing of metallic plate specimens. Parsons et al. [6] developed a bi-axial fatigue testing rig, which employed cruciform specimen loaded by four double-acting cylinders, which could be varied independently. Makinde et al. [4] presented four actuator testing machine for testing cross-shaped specimens. Boehler et al. [7] presented the screw-driven biaxial testing machine for composite plates or rolled sheet metals. Lin et al. [8] presented experimental study of the plastic yielding of sheet metals with the cruciform plate specimen. Muller et al. [9] and Hoferlin et al. [10] described new experiments for determining the yield loci of sheet metal. Cruciform specimen without slots and thickness reduction was used in this study. The plastic strains were not accessible with this type of specimen because the strain hardening effects were not considered in the conversion of biaxial stresses in the gage area from applied loads. Green et al. [11] used biaxial testing apparatus to investigate the elasto-plastic behavior of an Al sheet alloy. To optimize the cruciform specimen geometry, Demmerle et al. [12] proposed mathematical criterion based on standard deviation of stress to avoid stress concentration outside the gage area. Though the stress distribution was improved, the criterion has failed to calculate the effective cross-sectional area.

But the problem of relatively higher stresses compared to the uniformly stressed central area are still exists outside the gage area with the above proposed bi-axial test specimens are not ideally capture the desired bi-axial stress field of the test material. Specimen geometries defined would depend on the type of loading system developed. Hence a detailed finite element analysis is carried out to yield the optimal specimen geometry as described in next section and also suitable experimental test facility is established for performing experiments.

BI-AXIAL TEST SPECIMEN DESIGN:

The most realistic experimental technique to create a biaxial stress state in materials is applying the in-plane loads along two perpendicular directions to the arms of the biaxial specimen. The analysis of the biaxial test specimen is important to produce the homogeneous biaxial stress state. The primary step in the analysis is to select overall specimen dimensions. Consideration is given here to a number of test system features and characteristics including loading capacity at specimen grips, the size of the envelope available within a loading frame for specimen installation and gripping, gripping arrangement, size restrictions imposed by the specimen grips, necessary specimen test section required to fulfill strain measurement requirements and the overall load capacity requirements to strain the test section of the specimen up to its tensile strength.

The analysis of biaxial test specimen needs to consider the following constraints: (1) maximize the region of homogeneous biaxial stress field in the test section, (2) minimize the shear strain in the test section, (3) minimize the stress concentration outside the test section, (4) size the specimen to obtain yielding in the test section itself, and (5) specimen failure in the gage area of the test specimen.

Several design iterations are performed to understand the stress flow with the various specimen designs. To start with square specimens subjected to biaxial loading followed by cross shaped specimens. Then slots with different radii and thickness transitions are introduced and studied. Step by step analysis is carried out using finite element analysis package Ansys to investigate the influence of parameters like blend radii at the intersection of arms, the narrow slots which provide the transversal flexibility and different thickness reduction from gripping area to gage area. FE Model is generated with 8 Node Structural Solid elements having three translational degrees of freedom per node. Ti-6Al-4V isotropic material elastic properties are used as shown in Table 1.

Material	Young's Modulus [GPa]	Poisson's Ratio
Ti-6Al-4V	112	0.34

Table 1: Ti-6Al-4V Elastic Material properties

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Table 2 describes the design of iterations performed and captured the maximum stress observed corresponding to the design model.

Specimen Type	**Dimensions [in mm]**	**Max von Mises Stress [MPa]**	**Max stress Location**
Square specimen	250 x 250 x 8	1269	Corner edge region
Cross-shaped specimen	250 x 250 (Overall) 60 x 60 (Gage)	1102	At the intersection of loading arms
Slots in the specimen with blend radii	250 x 250 (Overall) 60 x 60 (Gage) 5 slots of (50 x 7) on each loading arm	958	At flexible slot corner region
One step thickness reduction from gripping to gage area	Gripping area (8mm) to Gage area (3mm)	934	At flexible slot corner region
Two step thickness reduction from gripping to gage area	Gripping area (8mm) to Gage area (1mm) with intermediate step thickness of (3mm)	985	Within the Gage area

Table 2: Bi-axial Test Specimen Design Iterations

Because of the symmetry, only one eighth of the specimen is modelled to minimize computational time. The symmetry boundary conditions about X, Y and Z axes are imposed in finite element model. Elastic finite element analysis is adapted to optimize the specimen dimensions. The uniformly distributed load of 130kN is applied on the edges of the loading arms.

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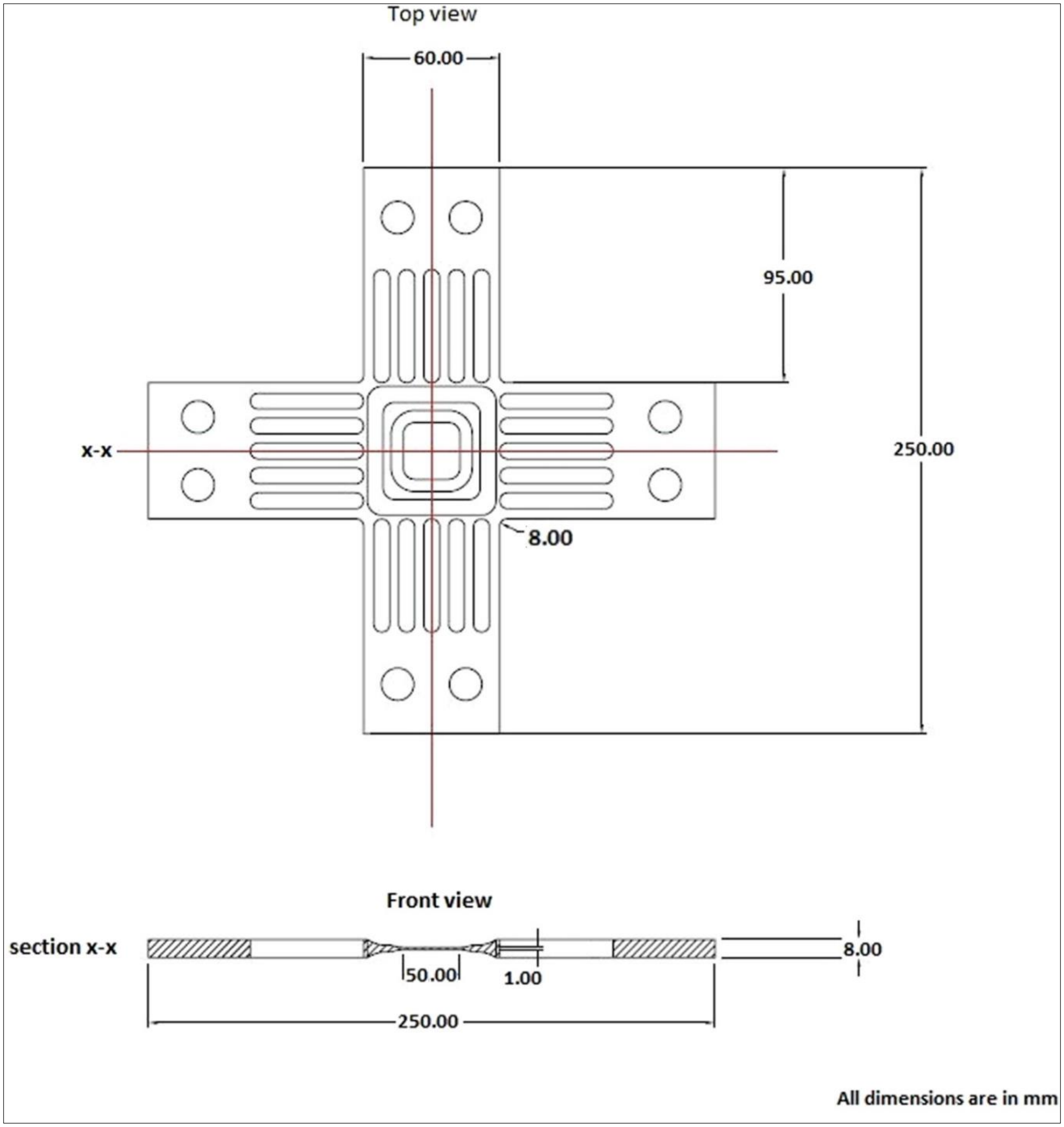
Figure 1: Biaxial Test Cruciform Specimen Geometry



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After finalized the specimen design with optimal geometric parameters, maximum and homogeneous bi-axial stress field achieved with in the gage area. The geometry details of the bi-axial test cruciform specimen are shown in Figure 2.

ELASTO-PLASTIC FINITE ELEMENT ANALYSIS:

To evaluate the effective load redistribution in the specimen under biaxial loading, elasto-plastic finite element analysis is carried out on the same finite element model, which is optimized after several design iterations described in the last section. The material properties and the solution methodology are different from the elastic finite element analysis. The linear elastic material properties are used as mentioned in Table 1. The elasto-plastic model assumes von Mises flow rule and multilinear isotropic hardening. The multilinear stress-strain curve of Ti-6Al-4V liner material is shown in Figure 2. This curve definition gives a more gradual change in the modulus and makes convergence easier. Hence multi linear isotropic hardening material properties are assigned to the present elasto-plastic finite element analysis.

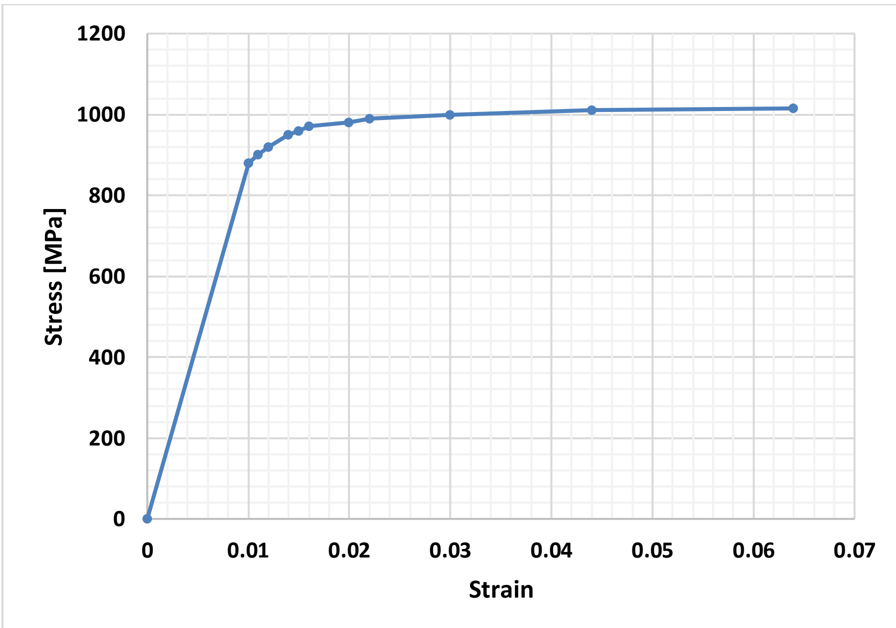

Figure 2: Multi linear stress-strain curve of Ti-6Al-4V liner material

In elastic-plastic finite element analysis, Newton-Raphson method is used to solve unknown displacements. This method is an iterative solution, which uses the previous step results to correct behavior and solve again to converge the solution. Because of symmetry only one eighth of the specimen is considered in the analysis. In elasto-plastic finite element analysis, ramped loading is used. In this type loading, the load increases linearly from the previous step's level to the current load step's final value. The first load step is chosen in such a way that the material does not yield and takes small steps at an abrupt transition and then enters the second load step. The sequence in which pressures are applied and in which plastic responses occur affect the final solution results. To anticipate the plastic behavior of biaxial specimen analysis, loads are applied as series of small incremental load steps, so that the model will follow the load-response path as closely as possible. Total four load steps are provided as input, which is given in Table 3.

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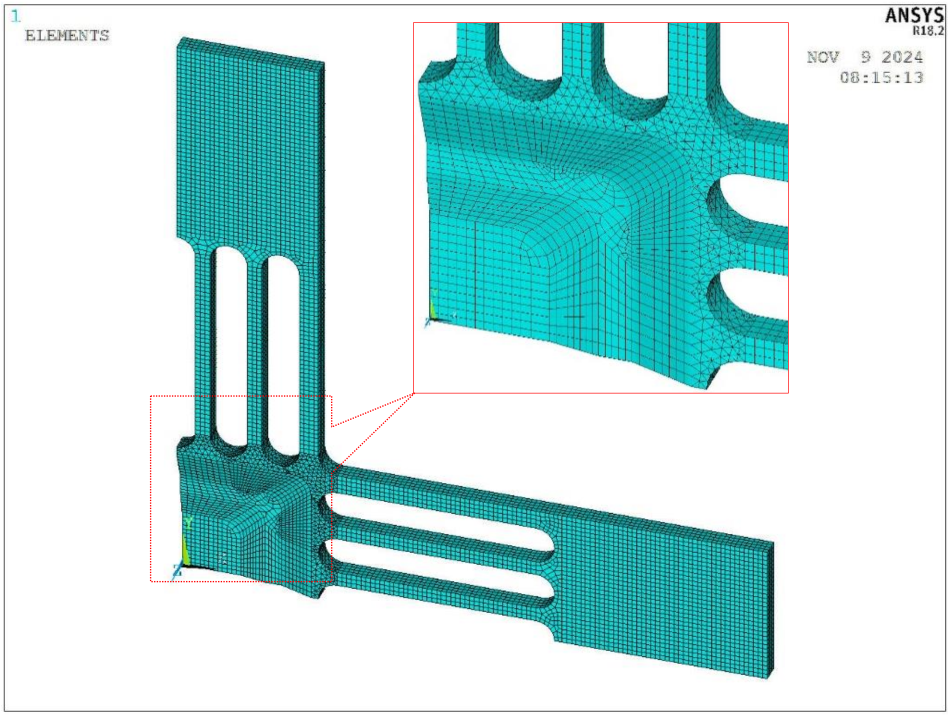

Figure 3: Finite Element Meshing of 1/8th bi-axial test specimen.

Load step	F_X =(F_Y) in kN on each loading arm/direction	Pressure applied on the gripping region (MPa)
1	80	-166.67
2	96	-200.00
3	110	-229.17
4	130	-270.83

Table 3: Input Loads

The load is applied in terms of pressure to stretch the specimen uniformly along the loading directions. The pressure is obtained by dividing the applied load with the cross-sectional area of the gripping area, which is 60mm x 8mm in the present analysis. The maximum stress value of the cruciform specimen is extracted from each load increment. In all the load cases, the maximum stress is developed in the gage area itself. From the stress values, it is observed that yielding takes place at around 93kN. In the first load step, approximately vonMises stress of 760MPa is developed correspond to 80kN, which is lower than the yield stress of the material. Then the load is increased to 96kN, and restart analysis is performed. From the stress distribution in second load step, it is observed that the yielding takes place at around 95kN load. Finally, the failure stresses take place at the end of the fourth load step since the ultimate stress values are developed during this load step.

The absence of the shear strains in the gage areas confirms that the stresses and strains measured at the center of the specimen are the principal stresses and principal strains. The maximum vonMises stress in the gage area is 979MPa as shown in Figure 4, whereas outside the gage area, it is 974MPa. Hence the specimen failure takes place within the gage area. Based on these observations from the finite element analysis, the cruciform specimen subjected to pure bi axial loading with the negligible shear stresses in the gage area.

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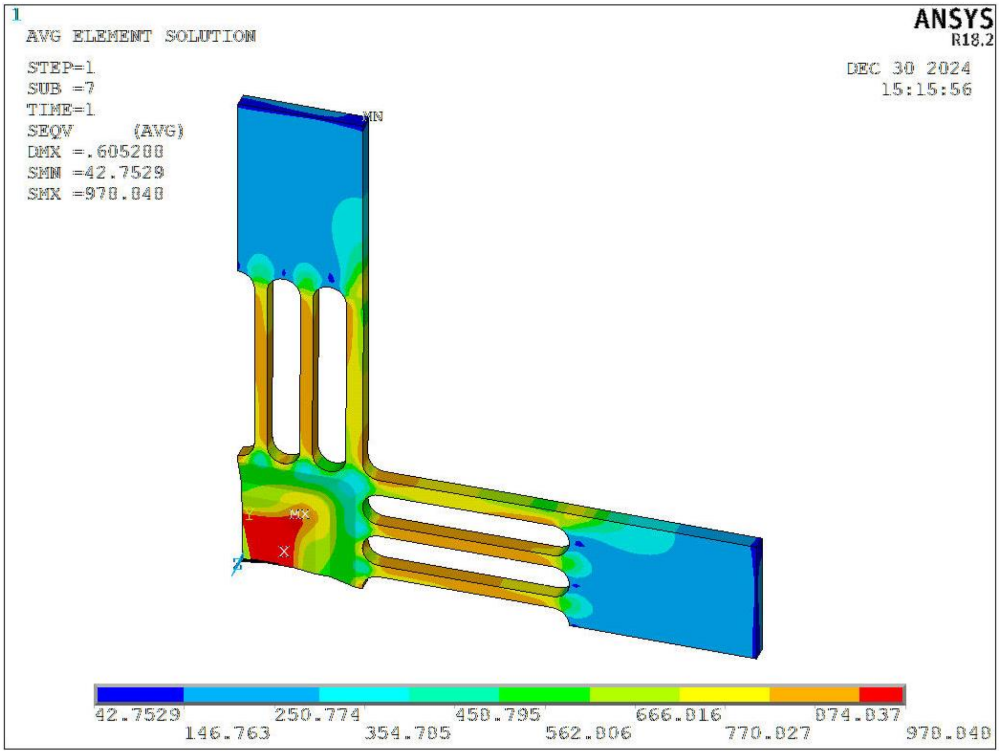

Figure 4: vonMises stress in Bi-axial tensile specimen

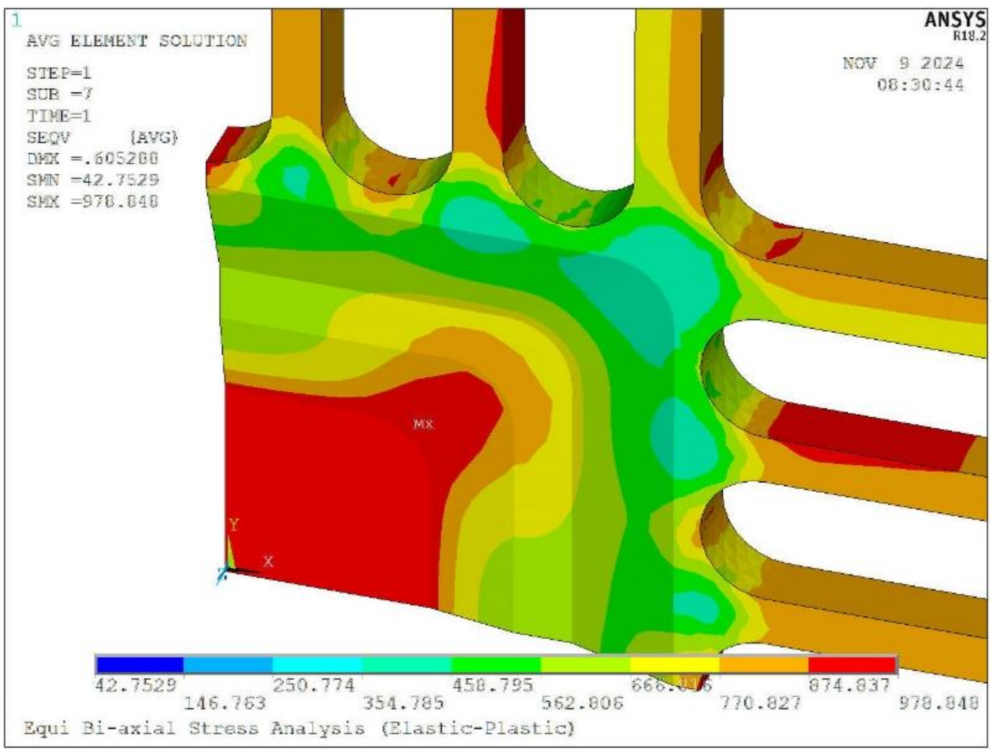

Figure 5: vonMises stress distribution in Gage area

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Figure 5 shows the vonMises stress distribution in the center of the gage area and the deviation observed at the center of the gage area is within 0.04%. Thus, the pure biaxial stress state is evident from the central 15mm x 15mm with in gage area to study the biaxial loading behavior of the tested material.

Specimen location	VonMises stress in elastic FEA [MPa]	VonMises stress in elasto-plastic FEA [MPa]
Maximum stress in Gage area	1237	979
Maximum stress at outside of the Gage area	1207	974

Table 4: Comparison of stresses in Elastic & Elasto-plastic finite element analysis

As shown in Table 4, the gage area stresses in elasto-plastic finite element analysis are reduced by 17.5% compared to elastic finite element analysis for same specimen geometry under same loading and boundary conditions. This is because of the effective load redistribution takes place in elasto-plastic finite element analysis.

BI-AXIAL TESTING SET-UP:

The in-plane bi-axial testing machine with 25-ton loading capacity is designed and established at relatively low cost. The developed testing set-up has flexibility in characterizing the material under different loading conditions like bi-axial tension, compression and shear loading, and uni-axial loading by activating one set of loading actuators. The test rig mainly consists of loading frame, hydraulic power pack and Windows based 'System 5000' Data Acquisition System to capture test measurement data accurately as shown in Figure 6. The data acquisition system is connected to personal computer to display and monitor the load and strain distribution of the test specimen under loading.

Figure 6: In-plane bi-axial test facility

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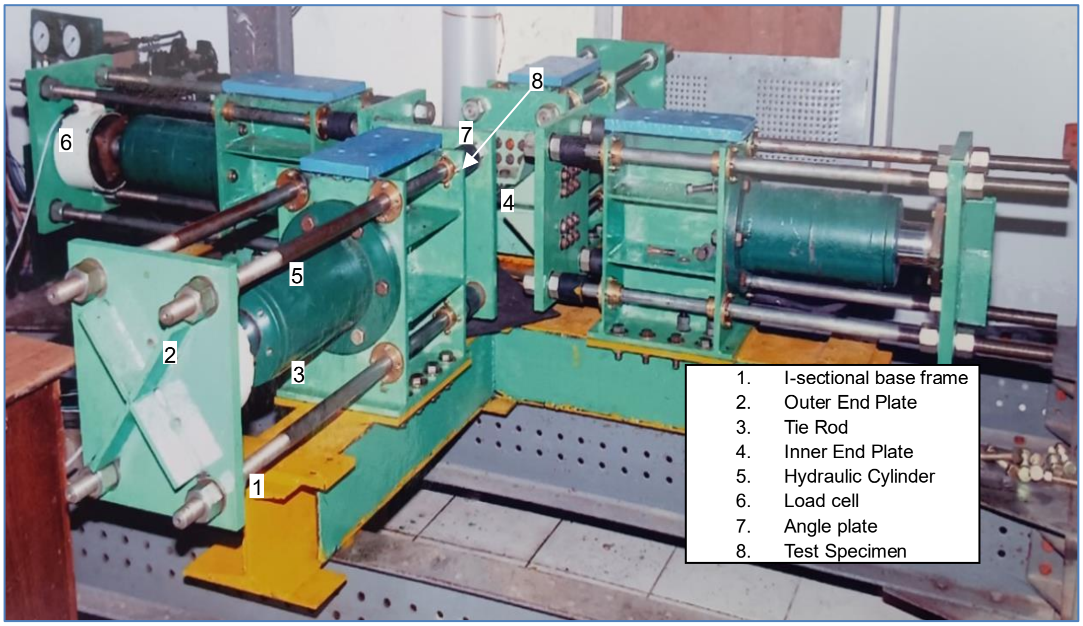

Figure 7: Loading frame components details

The loading frame consists of four double-acting hydraulic cylinders, rigidly fixed with an I-sectional base frame, and thus the center of the test specimen remains in the same position during the test. One hydraulic cylinder is placed at each side on the base frame. The hydraulic loading system is used to load the test specimen with negligible mechanical losses. The fluid pressure in each pair of hydraulic cylinders placed opposite to each other is servo controlled, independently. All the four hydraulic cylinders are connected to the power pack, which primarily consisting of hydraulic pump and solenoid valves. Loadcells are used in each loading direction to measure the load values directly as shown in Figure 7. The data acquisition system is connected to the test facility to extract the strain gage and loadcell readings.

Though these is provision for testing all types of loads, the present study is focused on equi bi-axial tensile loading in all four directions. A stacked rectangular strain gauge rosette is mounted on the center of the test specimen gage area. The specimen is fixing in the loading frame with bolts. After ensuring that the specimen is properly mounted on the loading frame, then the load is applied with regular increments until the specimen failed under bi-axial loading. The strain and load data are collected through the data acquisition system.

EFFECTIVE CROSS-SECTIONAL AREA:

It is not straight forward to find the cross-sectional area of the cruciform specimen due to the two-thickness reduction profiles used from gripping to gage area. Therefore, effective cross-sectional area method is used by testing modified uniaxial test specimen and biaxial test specimens made up of standard mild steel material by applying uni-axial loading in established biaxial testing machine.

The uniaxial tension test is performed on ASTM standard uniaxial specimen in the biaxial test rig, by disengaging the loading arm on Y-direction. Since the cross-sectional area of the uni-axial test specimen is 15mm x 9mm, the stress-strain curve is plotted and derived the modulus of elasticity. The modulus of elasticity is observed to be 214GPa, which is obtained as slope of the elastic portion of the uniaxial stress-strain curve.

Now the cruciform specimen is tested in uni-axial X-direction by disengaging the loading arm on Y direction. The load vs strain curve of the biaxial test specimen is generated. From the modulus of elastic of the material, the load values are converted into stress values by estimated the effective cross-sectional area. Based on adopted cruciform specimen geometry, the effective cross-sectional area is 120.94mm^2.Since the same geometry is used for all the bi-axial cruciform specimens, this effective cross-sectional area is used to convert the test load values into stress values.

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UNIAXIAL TENSILE TESTING OF TI-6AL-4V ALLOYS:

The basic material properties such as modulus of elasticity(E), Poisson's ratio, yield stress and ultimate tensile stresses are obtained from the uniaxial tensile test of Ti-6Al-4V specimens which are prepared according to ASTM E8. Tests performed on full annealed, beta annealed and Solution Treated & Aged (STA) Ti-6Al-4V specimens. The strain gages are mounted on the central gage area of the specimen to capture the strain values from the data acquisition system. The stress-strain curve is plotted for the tested specimen by using the initial cross section area of 12.5mm x 8.6mm.

Material Type	Modulus of Elasticity [GPa]	Yield stress [MPa]	Ultimate stress [MPa]	% elongation
Mill Annealed	123	825	1005	10%
Beta Annealed	114	825	961	7%
Solution Treated & Aged (STA)	86	1005	1136	6%

Table 5: Uni-axial Tensile Test Properties of Ti-6Al-4V alloys

The stress-strain curves of three different heat-treated Ti-6Al-4V alloy materials are shown in Figure 8.

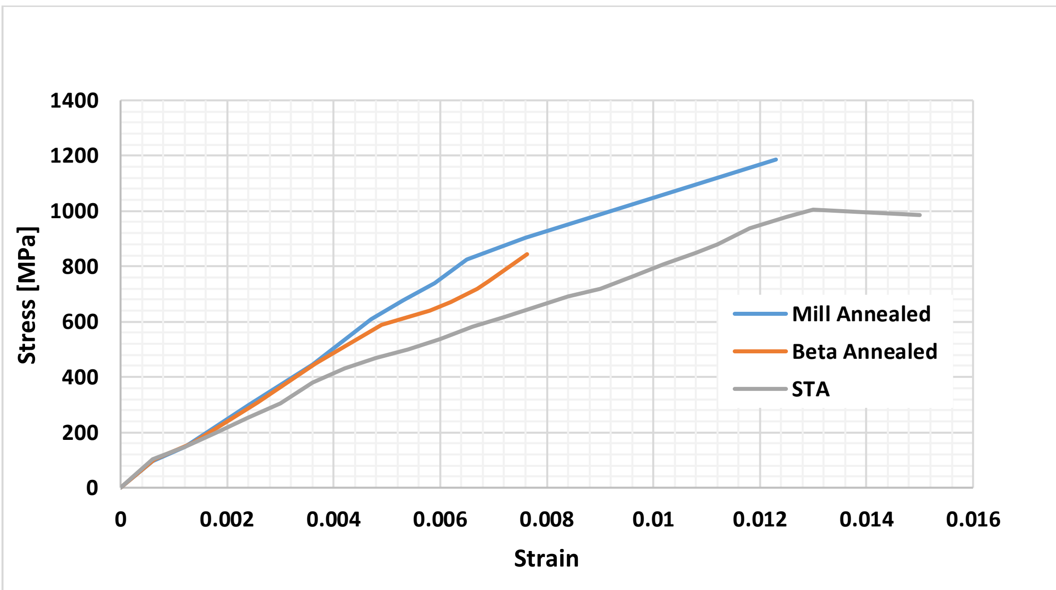

Figure 8: Uni-axial stress-strain curve of Ti-6Al-4V alloy materials

BIAXIAL TENSILE TESTING OF TI-6AL-4V ALLOYS:

To investigate the biaxial tensile behavior of Ti-6Al-4V liner material in spherical gas bottles, the cruciform specimens with designed dimensions of 250mm x 250mm x 8mm are tested under equi-biaxial loading conditions. The failure modes of all three types of heat-treated Ti-6Al-4V liner specimens are tested using the established 25ton biaxial testing machine. A loadcell is included in each loading direction to get the load values directly. Strain components in X and Y- Directions in the gage area of the specimen are measured using rosette strain gages. The output of both loads and strains are measured continuously using data acquisition system.

Set of Ti-6Al-4V cruciform specimens each two from Mill annealed, beta annealed and Solution Treated & Aged are subjected to equi-biaxial tensile loading. The stress uniformity is very important in the study of

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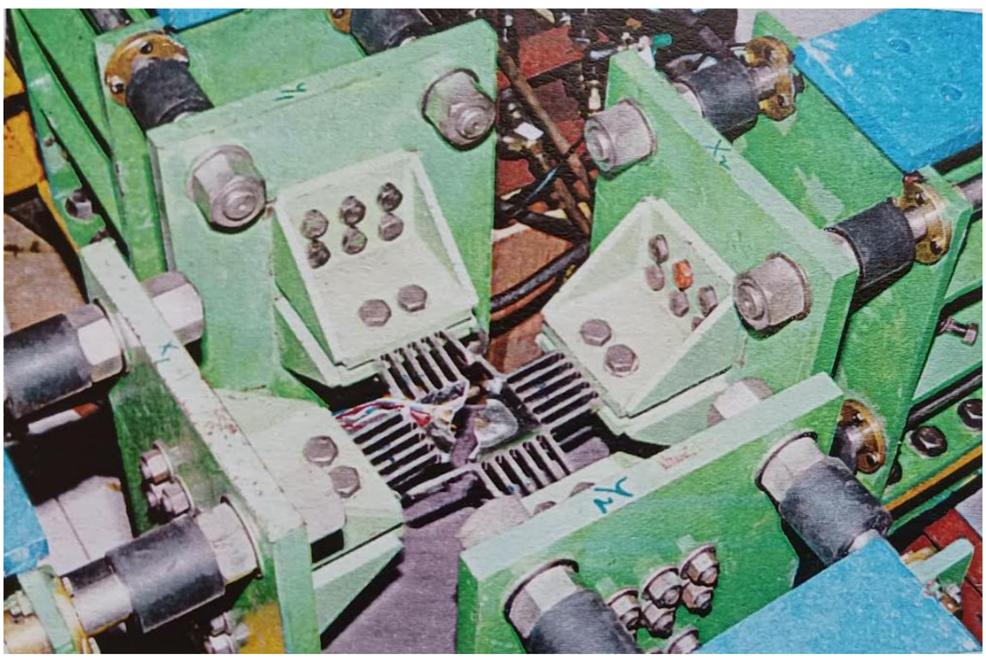
biaxial behavior. To ensure the stress uniformity, initially the specimen is preloaded to small extent to avoid the clearances of bolted joints while loading the specimen. Couple of trails are also carried out to cross check the equality of strain values in the top and bottom surfaces of the cruciform specimen. The pressure is applied at the rate of 2.5kg/cm^2 per 30 seconds. The scan rate is provided at one scan per second to capture the elastic and plastic strains of the material. The normal strain components in X and Y direction are measured by using the biaxial strain gages (post-yield rectangular rosette gages) mounted on both top and bottom of the gage area of the specimen. Almost equal strain distribution observed at both top and bottom strain gages based on load vs strain curves plotted in Figures respectively. The straightness of the cruciform specimen under biaxial load leads to equal strain values at both top and bottom surfaces of the gage area. Also, it is very evident that the biaxial strain values in both X and Y directions are almost equal.

MILL ANNEALED TI-6AL-4V:

The mill annealed specimen failed at 124kN.The crack is initiated in the gage area and is propagated along the diagonal direction of the gage area as shown in Figure 9. The diagonally propagated crack in the gage area represents that equal amount of load is transferred to the gage area from the orthogonal loading arms. The necking phenomenon is observed at the outer end of the flexible slots exists in loading arms due to uniaxial load distribution from gripping area. The failure is initially taken place in the gage area due to higher stresses compared to the stresses observed in the flexible slots. By using effective cross-sectional area, the biaxial stress values are calculated from the load values and plotted the biaxial stress-strain curve as shown in Figure. The 0.2% offset yield stress of the typical stress-strain curve of the Mill annealed Ti-6Al-4V under biaxial loading is 950MPa whereas in uniaxial stress strain curve, the yield stress is 825MPa. Therefore 15.2% increase in the yield stress of the liner material is observed under biaxial loading compared to uniaxial loading, which is due to the biaxial strengthening effect of liner material in spherical pressure bottle.



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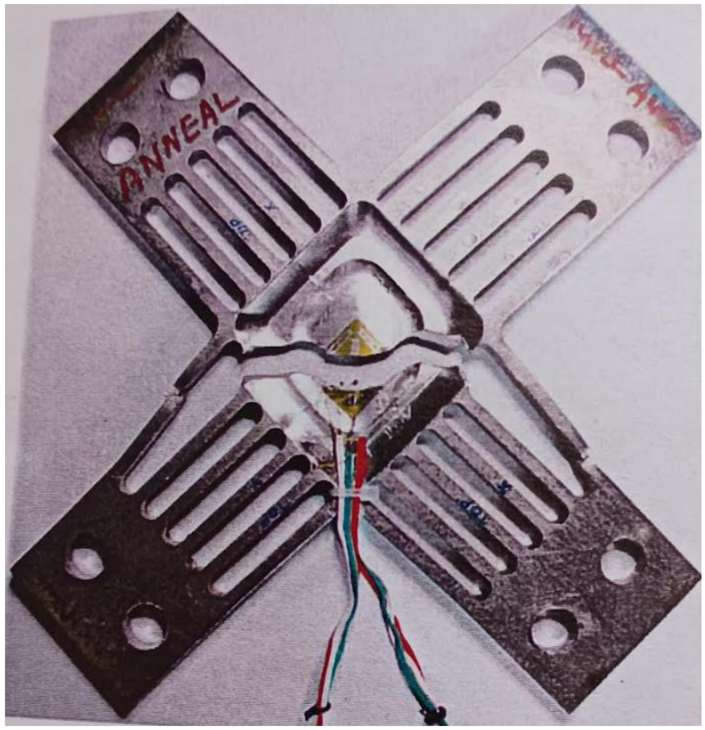

Figure 9: Mill annealed Ti-6Al-4V specimen under equi-biaxial loading

BETA ANNEALED TI-6AL-4V:

Like the Mill annealed Ti-6Al-4V specimen, equi-biaxial tensile test is performed on the beta annealed Ti-6Al-4V specimen. The specimen failed at 168kN, which is higher than the failure load observed in Mill annealed specimen. The crack is initiated in the gage area and propagated diagonally as shown in Figure 10. By using the effective cross-sectional area, the biaxial stress-strain curve is plotted. From the biaxial stress-strain curve, the offset yield stress of the Beta annealed Ti-6Al-4V specimen is observed as 1045MPa against the uniaxial yield stress value of 825MPa. Hence the biaxial yield stress value increased by 26.7% compared to uniaxial yield stress.

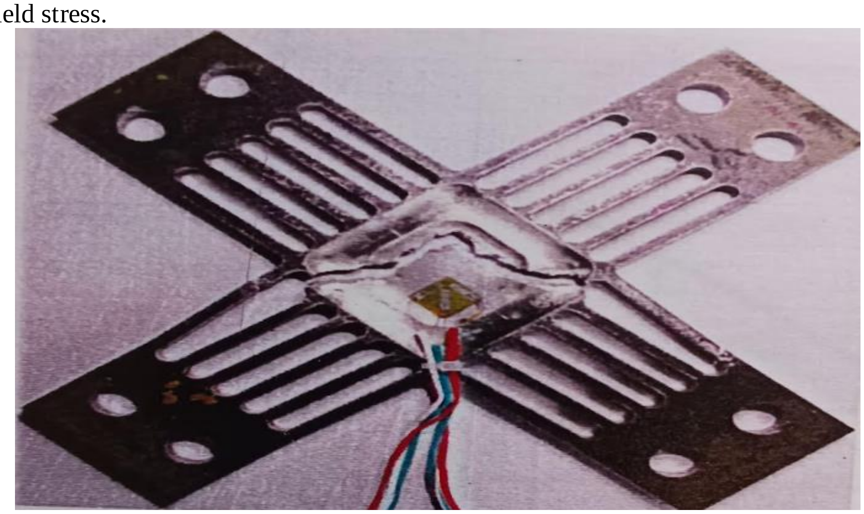

Figure 10: Beta annealed Ti-6Al-4V specimen under equi-biaxial loading

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SOLUTION TREATED & AGED (STA) TI-6AL-4V:

Solution Treated & Aged (STA) Ti-6Al-4V specimen is subjected to equi-biaxial tensile loading and the specimen failed at 135kN. The crack is initiated in the gage area and is propagated along the diagonal direction of the gage area as shown in Figure 11. The strain values measured in both X- and Y- directions are almost equal, which ensures that equal amount of load is applied in both the directions simultaneously. The yield stress of Solution Treated & Aged (STA) Ti-6Al-4V specimen under biaxial loading is 1100MPa whereas under uniaxial loading the yield stress value is 1005MPa. Hence approximately 9.45% increase in yield stress observed under biaxial loading compared to uniaxial loading.

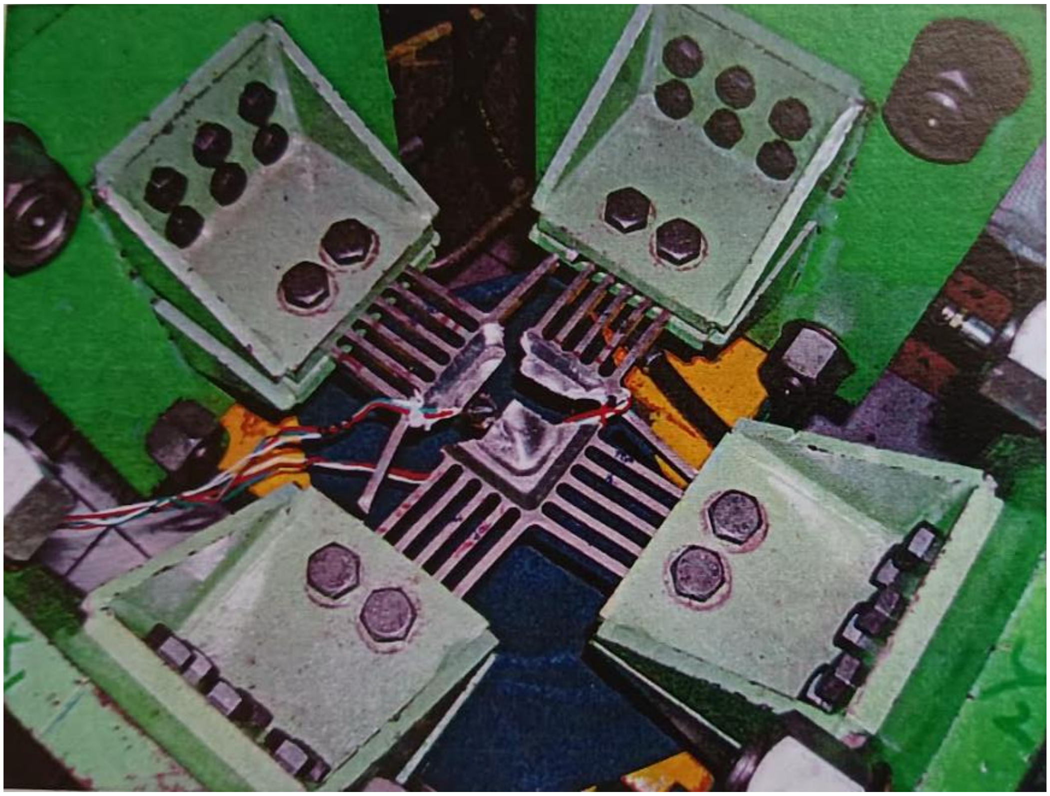

Figure 11: Solution Treated & Aged (STA) Ti-6Al-4V specimen under equi-biaxial loading

COMPARISON OF ALL THREE TYPES OF TI-6AL-4V:

Figure 12 shows the comparison of stress-strain curve of three different heat-treated conditions namely mill annealed, beta annealed and Solution treated & aged (STA) Ti-6Al-4V specimen subjected to equi-biaxial tensile loading. It is observed that the high percent of elongation and ultimate stresses are observed in beta annealed material compared to other treated heat-treated specimens.

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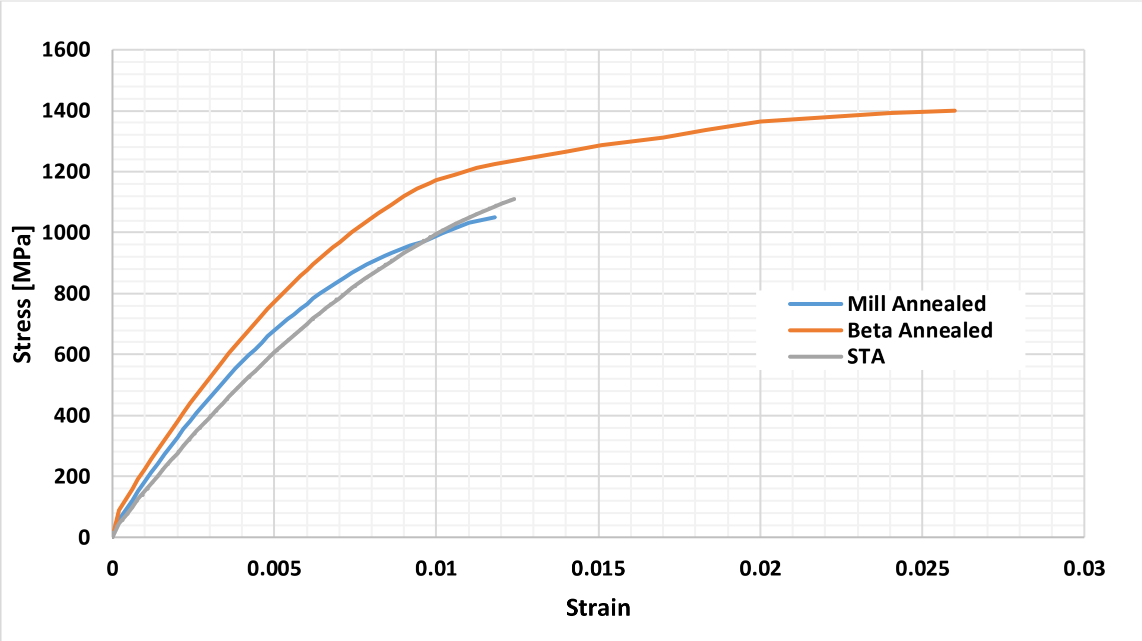

Figure 12: Bi-axial stress-strain curve of Ti-6Al-4V alloy materials

Table 6 shows the comparison of uni-axial and bi-axial test results and observed 9 to 27% increase in yield stress under biaxial loading compared to uni-axial loading with the maximum percentage of 27% in Beta annealed material and the minimum percentage of 9.45% in Solution Treated & Aged Ti-6Al-4V liner material.

Material Type	Failure load [kN]	Uniaxial yiled stress [MPa]	Biaxial yiled stress [MPa]	% increase in yield stress [%]
Mill annealed	124	825	950	15.2
Beta annealed	168	825	1045	26.7
Solution Treated & Aged (STA)	135	1005	1100	9.45

Table 6: Comparison of Bi-axial & Uni-axial Tensile Test Properties of Ti-6Al-4V

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