Thermo-Mechanical Analysis of alloys for Cryogenics Fuel Tank Applications

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Abstract— A theoretical and Simulation of Thermo-mechanical analysis of SS304 and SS316 LN stainless steel composites has been carried out. Effects of extreme low temperatures on the mechanical properties of both composites have been examined by using Computational model. The work is mainly focused to analyze normal stress, shear stress, normal elastic strain, shear elastic strain and total deformation of SS304 and SS316 LN. Results of the analysis show that change in the mechanical properties of SS304 is very less as compared to SS316 LN except shear elastic strain. Shear elastic strain of SS304 is less than SS316 LN but the difference is minor. In order to build DEWAR TANK for storage of cryogenic fuel (such as liquefied hydrogen) the material should be able to withstand the extreme low temperature and must show least changes in mechanical properties. Hence SS304 is best material to build cryogenic fuel storage tank.

Keywords- Thermo-mechanical analysis, cryogenic fuel tank, Stainless steel

I. INTRODUCTION

Cryogenics is study of production, effects and behavior of materials at extreme low temperature. Temperature scale of beginning of cryogenic is not quite clear, however scientists assume it below 123K (-150℃). Over the last decade application of cryogenics has been gradually increased such as cryobiology, cryosurgery, cryoelectronics, cryotronics and cryonics etc. invention of dewar tank in 1892 is considered first step towards cryogenics. William Thomson, an English Physicist in 1848 pointed out that having materials in which all form of motion in particles are ceased is possible .He interpreted this condition as Absolute Zero.The Fuel that are stored at extremely low temperatures are called Cryogenic Fuels. As Combustion is not possible in the absence of oxygen cryogenic fuels are used in the machines that are used in the Saturn V rocket and is still being used. Tupolev, Russian aircraft manufacturer developed a version of Tu-154 with a cryogenic fuel system and it is termed as Liquefied Natural Gas(LNG). They are broadly classified into two types
outer space. Cryogenic fuel is first used in the Saturn V rocket and is still being used. Tupolev, Russian aircraft manufacturer developed a version of Tu-154 with a cryogenic fuel system and it is termed as Liquefied Natural Gas (LNG). They are broadly classified into two types The inert fuels are used to regulate production of gas and generate power in engine.
Some Common inert fuels are: Liquid Nitrogen, Liquid air, Liquid Helium and Liquid Neon Combustible Fuel**:** These fuels use flammable nature and the cryogenic properties of the substance as source of power. Some common Combustible fuels are: Liquid Hydrogen**,** Liquid Natural Gas**,** and Liquid Methane.

II. THERMO-MECHANICAL ANALYSIS

A Thermo-mechanical analysis is a technique, which is used in thermal analysis. it is the branch of material science, which shows the effects on mechanical properties of material due to change in temperature. Various residual and internal stresses are generated, which can be calculated by using this technique. Here in this study change in various mechanical properties due to change in temperature is analyzed. Such as Total Deformation, Normal stress Shear stress, Normal elastic strain and Shear elastic strain.
Lade jayahari et al[1]. investigated effects of warm deep drawing on the parameters of ASS-304 stainless steel at different temperatures. During warm deep drawing at 20 ton force by using hydraulic press it is observed that the formability of austenitic stainless steel ASS-304 is improved at lower punch of speed. To understand the microstructure of ASS-304 stainless steel lade jayahari et al. conducted numbers of warm deep drawing experiments at elevated temperatures and various speeds and also compare the microstructure changes of austenitic stainless steel ASS-304 at ambient as well as elevated temperatures. **Salvador M. aceves et al [2]**investigated transition joints for the application of storage of highly pressurized cryogenic fuel (H_2) and compares copper , titanium and tantalum interlayer fabricated aluminum to stainless steel transition joints with an explosive welding process(EXW). Due to directly explosive welding process in aluminum (al) 6061 to SS304 interlayers are used to avoid any possible interaction between both material al6061 and SS304. Each interlayer material Ti, Ta and Cu are having advantages as well as disadvantages. The disadvantage in most commonly used interlayer material titanium is generation of micro cracks

during EXW while copper has advantage of being compatible with hydrogen, but at the same time it forms brittle intermetallics with aluminum. Tantalum is ductile in nature and bonds well with both materials hydrogen and aluminum, but being costlier among all three interlayer materials become as disadvantage. Results shows that titanium produce very strength joints, tantalum produce ductile joint, but the copper joints failed in both ductility and in strength.

III. RESEARCH METHODOLOGY

Thermo-mechanical analysis of both types (SS316LN & SS304) of stainless steel composite materials is done by ANSYS 14.5 Workbench. In order to examine the residual stresses generated within the material due variation in coefficient of thermal expansion of reinforcement and filler material, extended finite element method (XFEM) is used.

Extended Finite Element Method (XFEM)

XFEM is a numerical technique based on the Generalized Finite Element Method (GFEM) and the Partition of Unity Method (PUM). This is the advancement of classical Finite Element Method for treating discontinuities by means of enrichment function. XFEM is also called Mesh free Method. Following steps will be followed in methodology

Selection of composite material
Modeling
Discretisation
Meshing
Discontinuity
Boundary conditions
Thermal Load
Analyze
Result

IV. MATHEMATICAL MODEL

According to the previous research resistance behavior in low carbon austenitic stainless steel at extreme low temperature make them ideal composite materials for building DEWAR tank to store the cryogenic fuel. Here in this study we have considered two types of composite materials to investigate

Low carbon stainless steel SS304
Low nitrogen Stainless steel SS316LN

V. SPECIFICATION OF PROBLEM

Consider a rectangular slab of stainless steel (SS316LN & SS304). Geometry of the slab is shown in figure slab is under the cryogenic temperature varying from 60 K to 75 K. two ends of the geometry kept fixed. Change in the mechanical properties of stainless steel composite (SS316LN & SS304) is to be examined. These materials are having low thermal conductivity, least coefficient of thermal expansion and low Poisson ratio which makes them suitable composite material for cryogenic fuel tank application.

VI. GEOMETRY IN ANSYS WORKBENCH

Computational domain of rectangular slab is shown in figure. Isometric view with all dimensions is displayed, the length, width and height of the slab is 100 mm, 50 mm and 5 mm respectively. Here storage of cryogenic fuel for domestic use is mainly considered. The slab is drawn in ANSYS.

Structural meshing is done with high accuracy to gain most accurate result. Total 7688 elements and 37829 nodes are generated during meshing. As we know there are 7688 elements and 37829 nodes has been generated in the rectangular slab. And we can clearly see that the orthogonal quality of mesh is 1. This is best to get fine and accurate result.

VII. THERMO PHYSICAL PROPERTIES

Stainless steel 300 series materials are having relatively low thermal conductivity as compared to other materials. Which makes them best material for use in extreme low temperature conditions. This study is particularly focused on the application of storage of cryogenic fuel. Low thermal conductivity and least Poisson ratio of SS304 and SS316 LN make them best suitable material for this application .here in this study we have examined the change in mechanical properties of the stainless steel composite due change in temperature.

Composition of SS316 LN and SS304

Composition of both composites is shown below in table. This is the percentage of materials in SS316 LN and SS304 composites.

Table 1: Composition of SS304 and SS316 LN

Material	SS316 LN	SS304
Carbon	0.03	0.08
Manganese	2	2
Phosphorus	0.045	0.045
Sulphur	0.03	0.03
Silicon	1	1
Nickel	10-14	8-10.5
Chromium	16-18	18-20
Nitrogen	0.1-0.3	

Physical properties

Physical properties of stainless steel composites (SS316 LN & SS304) are listed below-

Table 2: Physical properties of SS304 and SS316 LN

Property	SS 316 LN	SS304
Density	7.99 g/cm^3	8 g/cm^3
Specific heat (0-100℃)	485 J/kg K	490 J/kg K
Modulus of elasticity	200 GPa	193-200GPa
Electrical resistivity	7.4 Ω/cm	7.2 Ω/cm
Thermal conductivity	16.3W/mK	16.2 W/m K
Coefficient of thermal Expansion	16.5 $^\circ C^{-1}$	16 C^{-1}
Poisson ratio	0.3	0.29

VIII. RESULTS AND DISCUSSIONS

As explained earlier stainless steel composites (SS316 LN & SS304) are having best suitable properties for application in extreme low temperature. Thermo-mechanical analysis is performed on computational domain of both materials. As we already discussed that our main focus is to conclude most suited material for application of storing liquefied gases. Because liquefied gases having extreme low cryogenic temperature. Thermo-mechanical analysis is done on the temperature from 60 K to 75 K.

Different physical properties of both composite materials results different variation in mechanical properties of both materials. In this study several mechanical properties are examined such as-
Normal stress
Shear stress
Normal elastic strain
Shear elastic strain
Total deformation

Variation in normal stress

Normal stress is the normal force per unit of cross-sectional area. Normal stress is basically occurs when the material is subjected to tension or compression. In this analysis computational domain has been kept at cryogenic temperature. Due to extreme low temperature domain contract and normal stress has been induced due to compression. At 60 K normal stress induced in SS304 is 5161.7 Mpa and in SS316 LN it is 5490.8 Mpa.

Table 3: Variation in normal stress of SS304 and SS316 LN

Temperature(K)	60	61	62	63	64	65
Normal stress (SS304) Mpa	5161.7	5139.7	5117.8	5095.8	5073.9	5051.9
Normal stress (SS316 LN) Mpa	5490.8	5467.5	5444.1	5420.8	5397.4	5374.1

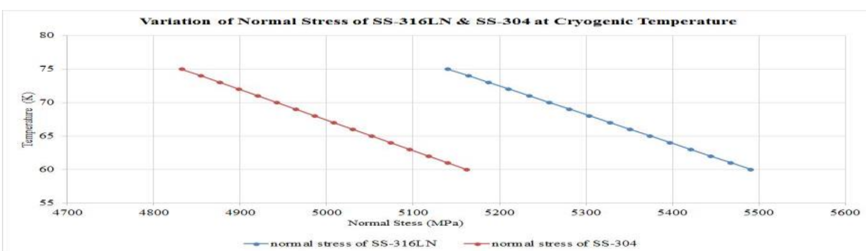

Figure 1 Comparison of normal stress of SS304 and SS316 LN at cryogenic temperature

Variation in shear stress

Shear stress occurs parallel to the surface, when material is subjected to shear force. Due to extreme low temperature material contracts and shear stress is induced in the material. At 60 K shear stress induced in SS 304 is 1918.7 Mpa while in SS316 LN 2059 Mpa.

Table 4: Variation in shear stress of SS304 and SS316 L

Temperature (K)	60	61	62	63	64	65
Shear stress (SS304) Mpa	1918.7	1910.6	1902.4	1894.3	1886.1	1877.9
Shear stress (SS316 LN) Mpa	2059	2050.2	2041.4	2032.7	2023.9	2015.2

Shear stress value on different temperatures shows that Shear stress in SS 304 is very less than SS316 LN at various temperatures Which makes SS304 better than SS316 LN in terms of shear stress. Comparison of results of shear stress at various temperature of both stainless steel composite is shown below

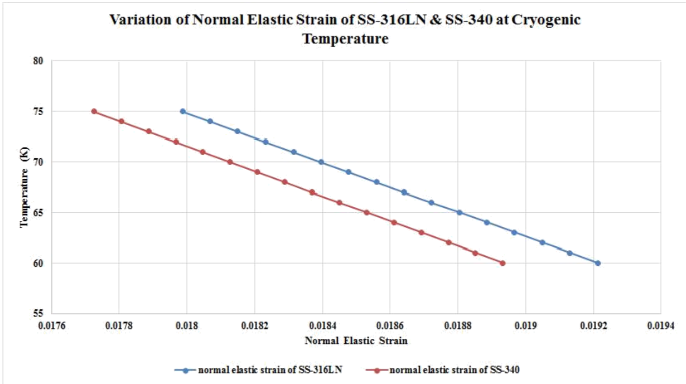

Figure 2 Comparison of shear stress in SS304 and SS316 LN at cryogenic temperature

Variation in normal elastic strain

The strain which has been recovered after removing the cause of stress is generally known as normal elastic strain. At 60 K temperature normal elastic strain of SS304 is 0.018933 while inSS316 LN it is 0.019212.

Table 5: Variation in normal elastic strain of SS304 and SS 316 LN

Temperature(K)	60	61	62	63	64	65
Normal elastic strain (SS304)	0.018933	0.018852	0.018772	0.018691	0.018611	0.01853
Normal elastic strain (SS316 LN)	0.019212	0.019131	0.019049	0.018967	0.018886	0.018804

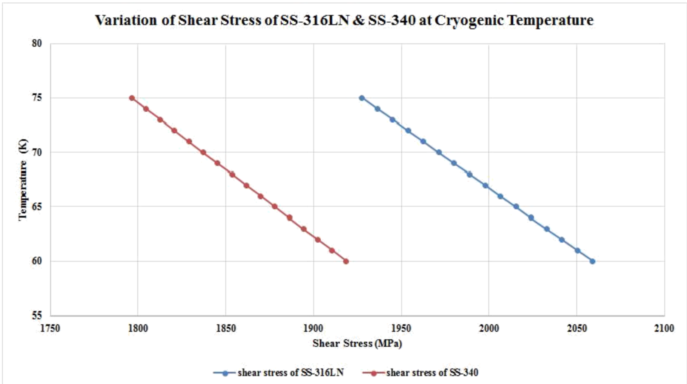

Figure 3 Comparison of normal elastic strain in SS 304 and SS316 LN at cryogenic temperature.

Results obtained from the analysis shows that normal elastic strain in SS304 is always less than the normal elastic strain in SS316 LN. Comparison of the results of both materials is shown below.

Variation in shear elastic strain

Elastic strain occurred parallel to the surface while the material is subjected to shear force is termed as shear elastic strain. At 60 K shear elastic strain of SS 304 is 0.02527 while in SS316 LN it is 0.026766.

Table 6: Variation in shear elastic strain of SS304 and SS316 LN

Temperature(K)	60	61	62	63	64	65
shear elastic strain (SS304)	0.02527	0.025149	0.025042	0.024935	0.024827	0.02472
shear elastic strain (SS316 LN)	0.026766	0.02663	0.026539	0.026425	0.026311	0.026197

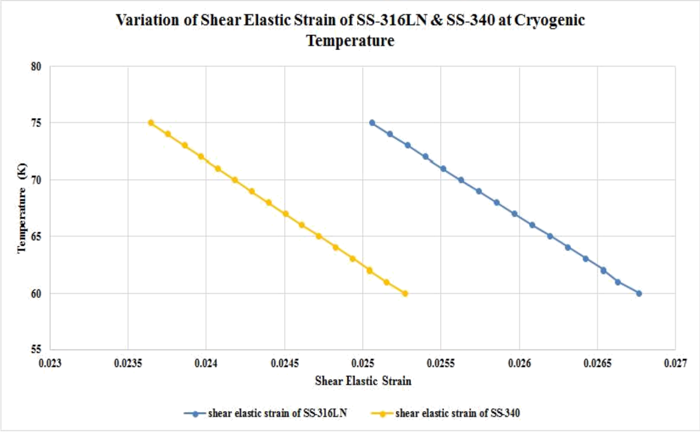

Figure 4 comparison of Shear elastic strain of SS304 and SS 316 LN at cryogenic temperature

Comparison of the results obtained from analysis is shown below. We can clearly see that SS304 having less shear elastic strain at various values of temperature

Variation in total deformation

Total deformation is the vector sum of all directional deformation occured in the system. At 60 K temperature total deformation in SS304 is 0.12566 mm while in SS316 LN it is 0.13072 mm.

Table 7: Variation in total deformation of SS304 and SS316LN

Temperature (K)	60	61	62	63	64	65
Total Deformation (SS304)	0.12566	0.12513	0.12459	0.124061	0.12352	0.12299
Total Deformation (SS316 LN)	0.13072	0.13017	0.12961	0.12905	0.1285	0.12794

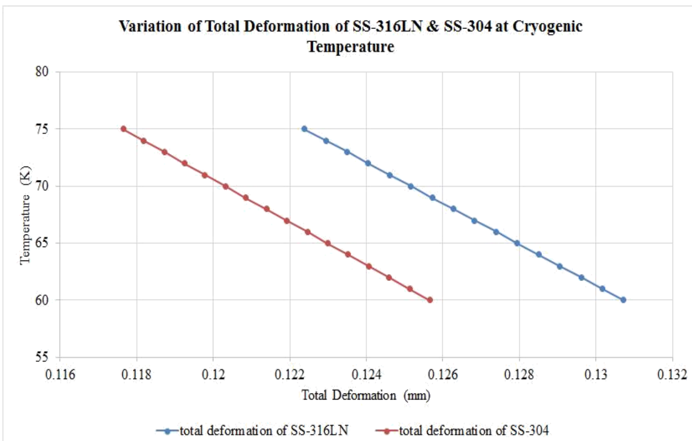

Figure 5 Comparison of total deformation in SS304 and SS316 LN at cryogenic temperature

Results shows that total deformation in SS304 is less than total deformation in SS316 LN at different temperature. Graphical comparison of total deformation for both materials is shown below.

CONCLUSION AND FUTURE SCOPE OF WORK

In this chapter salient accomplishments and the conclusion of the analysis has been shown. And the future scope of the work is also explained for further work.

IX. CONCLUSION

In this work normal stress, shear stress, normal elastic strain, shear elastic strain and total deformation of SS304 and SS316 LN has been investigated at different cryogenic temperature (60 K to 75 K).and results obtained from the investigation has been compared graphically for considered mechanical properties individually. And it has been concluded that-

- Normal stress, shear stress, normal elastic strain, shear elastic strain and total deformation induced in SS304 stainless steel are very less as compared to stresses in SS316 LN respectively.

- Applications in extreme low conditions such as storage of cryogenic fuel, SS304 is best suitable material to build DEWAR tank.

- Since the residual stresses in SS304 are less than SS316 LN, generation of micro cracks in SS304 will be less. Which makes SS304 less permeable at cryogenic temperature

- Thermo-mechanical properties ofis SS304 are compatible with low temperature. SS304 shows higher strength and stiffness at cryogenic temperature

- As SS304 is easy to fabricate and cheaper than SS316 LN, hence it is most suited material for storage of cryogenic fuel

XI. FUTURE SCOPE OF WORK

Cryogenics is having wide variety of application now days. Cryogenic fuel is most commonly used in aerospace. Most of the rockets (such as – PSLV, GSLV) are using cryogenic fuel for combustion. Since it is very important to select right type of material to build cryogenic fuel tank in order to get most favorable results. This study concludes SS304 as best suitable material to build cryogenic fuel tank. Future scope of this work is listed below

- Best design of cryogenic fuel tank to with stand hoop stresses and high pressure, made of SS304 stainless steel composite material.
- The work is further extended to design a equipment to check the permeability experimentally.

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