Thick SS316 materials TIG welding development activities towards advanced fusion reactor vacuum vessel applications

B Ramesh Kumar 1, R Gangradey
Institute for Plasma Research, Bhat, Gandhinagar-382428.
1E-mail: buddu@ipr.res.in, brkumar75@gmail.com

Abstract. Advanced fusion reactors like ITER and up coming Indian DEMO devices are having challenges in terms of their materials design and fabrication procedures. The operation of these devices is having various loads like structural, thermo-mechanical and neutron irradiation effects on major systems like vacuum vessel, divertor, magnets and blanket modules. The concept of double wall vacuum vessel (VV) is proposed in view of protecting of major reactor subsystems like super conducting magnets, diagnostic systems and other critical components from high energy 14 MeV neutrons generated from fusion plasma produced by D-T reactions. The double walled vacuum vessel is used in combination with pressurized water circulation and some special grade borated steel blocks to shield these high energy neutrons effectively. The fabrication of sub components in VV are mainly used with high thickness SS materials in range of 20 mm- 60 mm of various grades based on the required protocols. The structural components of double wall vacuum vessel uses various parts like shields, ribs, shells and diagnostic vacuum ports. These components are to be developed with various welding techniques like TIG welding, Narrow gap TIG welding, Laser welding, Hybrid TIG laser welding, Electron beam welding based on requirement. In the present paper the samples of 20 mm and 40 mm thick SS 316 materials are developed with TIG welding process and their mechanical properties characterization with Tensile, Bend tests and Impact tests are carried out. In addition Vickers hardness tests and microstructural properties of Base metal, Heat Affected Zone (HAZ) and Weld Zone are done. TIG welding application with high thick SS materials in connection with vacuum vessel requirements and involved criticalities towards welding process are highlighted.

1. Introduction
The development of fusion reactors like ITER and upcoming Indian DEMO are having material challenges in terms of their compatibility with operational conditions[1,2,3]. The stringent conditions like structural, thermo mechanical and neutron irradiation are the major challenging issues towards the development of the reactor sub system components. Fusion reactor construction utilizes different stainless steel materials like SS 304L, 316 and 316 L(N) for the fabrication of various components like vacuum vessel, plasma facing first wall components, mechanical support structures and other subsystems. The SS 316 grade materials are primary structural material candidates in fusion reactor components due to their superior mechanical and corrosion resistant properties[4]. The fusion reactors plasma are proposed by using D-T plasma operation and produces high energy 14 MeV neutrons.
which can damage the other structural components in longer. The new design concepts by employing double walled vacuum vessel with using shields blocks of Borated steel materials in combination with water circulation are planned [5]. The steel blocks and water in combination shield effectively the energetic neutron generated from the fusion plasma reaction. In this regard, the fabrication of vacuum vessel and its associated sub systems materials selection is a challenging task in terms of their mechanical and irradiation properties compatibility. The fabrication of vacuum vessel sector components will be carried out with different type of welding processes for joining of SS materials in various forms of shells, ribs and key components to make final sector modules [6,7]. TIG welding is one of the major technique used for joining of the stainless steel plates for fabrication of different vacuum vessel components[8,9]. Some technical codes and standards are followed for the fabrication with welding procedures in ITER vacuum vessel components[10]. Thick materials welding is challenging as per the demands like 20 mm – 60 mm range in different type of steels. The present paper reports characterization of TIG welded samples with 20 mm and 40 mm thick SS 316 material. The characterization of these samples for Tensile tests, Bend tests, Impact tests and Hardness measurements have been carried out to analyze weld joint strength. Microstructural analysis for weld zone and HAZ are carried out.

2. Samples preparation with TIG welding process
SS 316 materials with 20 mm thick and 40 mm thick are obtained and prepared for the TIG weld process as per standard procedure. The elemental analysis was carried out for 20 mm and 40 mm thick SS 316 base materials. The filler wires used are ER 316 grade and 2.4 mm diameter. The chemical composition data is shown as per Table 1. Rest other elements are in balanced range as per required. The 20 mm base metal properties are UTS 589MPa, Yield strength ~310 MPa and Elongation 55%. For 40 mm thick plate, base metal properties UTS~ 596 MPa, Yield strength ~389 MPa and Elongation 59%. These measured with test pieces in laboratory.

| Table 1. Chemical composition of SS 316 L 10 mm material. |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| Element (in %) | C   | S   | P   | Si  | Mn  | Cr  | Ni  |
| SS 316- 20 mm  | 0.02 | 0.012 | 0.020 | 0.4 | 1.5 | 17.7 | 13.10 | 2.85 |
| SS 316- 40 mm  | 0.024 | 0.015 | 0.037 | 0.43 | 1.25 | 16.55 | 10.39 | 2.05 |
| Filler wire ER 316 | 0.019 | 0.003 | 0.024 | 0.470 | 1.570 | 18.5 | 12.20 | 2.30 |

2.1 TIG welding 20 mm thick plate
The SS 316 sample welded plates of 20 mm thickness are fabricated by TIG welding process. The sample plates of dimensions 150 mm X 300 mm X 20 mm are made cut from SS 316 single plate sheets. The final welded sample size is 300 mm X 300 mm X 20 mm. The samples are fabricated with single V groove edge preparation and joined with multipass TIG welding process by keeping the root gap of 2 mm. The developed 20 mm thick sample was shown in figure 1(a) for reference. The process parameters used for TIG welding for both the samples are mentioned in Table 2.

![Fig. 1(a). 20 mm welded sample](image1.jpg)

![Fig. 1(b). 40 mm welded sample](image2.jpg)
2.2. TIG welding 40 mm thick plate
The SS 316 sample welded plates of 40 mm thickness are fabricated by TIG welding process. The sample plates of dimensions 150 mm X 300 mm X 40 mm are made cut from SS 316 single plate sheets and final welded sample size is 300 mm X 300 mm X 40 mm. The samples are fabricated with double V groove (60°) design edge preparation with 2.5 mm root gap and joined with multipass TIG welding process. In initial 3 passes, the current of 80A was used and after 4th pass onwards 100A current was maintained with constant voltage of 12V. The process parameters used for TIG welding are shown in Table 2. The developed 40 mm thick weld sample was shown in figure 1(b). The developed samples are subjected to non destructive examination by X ray radiography and Ultrasonic tests. Both the samples are reported with no significant detectable defects like pores, voids or incomplete penetration.

3. Mechanical properties characterization
The TIG welded SS 316 samples are subjected to Tensile properties, standard Bending tests (180°) side bend, hardness tests, Impact fracture V notch tests. In addition optical macro and microstructures are carried out. The details of the tests and results are described in the following sections.

3.1. Tensile tests
The SS 316 TIG weld samples are prepared as per the standard tensile test specimens. FIE make Universal testing Machine (model UTES-40) is used for the testing of the samples. All the tested specimens were broken out of the weld region, in base metal indicating of the higher strength of the welded joints compared with base metal.

![20 mm Tensile samples](image1.png)  ![40 mm Tensile samples](image2.png)

Fig. 2 (b). 20 mm Tensile samples  Fig. 2 (b). 40 mm Tensile samples

| Sample type | Base Metal (UTS) | Weld sample (UTS) |
|-------------|-----------------|-------------------|
| 20 mm thick | 589 MPa          | 609 MPa, 609 MPa  |
| 40 mm thick | 595 MPa          | 598 MPa, 608 MPa  |

The tensile properties data obtained with this weld process is used for the data base generation purpose and comparison to the optimum conditions of fusion reactor structural material data [5,10]. The welded samples tested for tensile test results are shown in figure 2(a) for 20 mm sample and
figure 2(b) for 40 mm sample. The samples indicate the broken region which is away from the weld region indicating of good weld quality joint strength. The obtained tensile parameters are given in the Table 3.

3.2. Bend tests
The TIG welded SS 316 samples are further tested for bend tests in order to check the weld joints mechanical strength and weld quality. The fabricated samples are subjected to the standard 180° bend tests. The 20 mm thick weld samples are machined as per the required standard size and are subjected to side bend tests. Some examples with bend test samples are described in figure. 3(a) and 3(b). The samples as shown in figure. 3(a) have no apparent defects on welded joint surface after bending test for 20 mm thick sample. This in addition represents complete penetration of filler material and no pores or voids inside the weld joint. Figure 3(b) was shown with 40 mm thick weld samples subjected to side bend tests. These samples exhibited good weld joint strength and without any opening on the weld line or shown any defects like cracks or openings. The samples are successfully passed for the subjected bend test requirements.

3.3. Vickers Hardness tests
The developed SS 316 TIG weld samples are tested for Vickers Hardness values for base metal, HAZ and weld zone. A standard load of 10 Kg is applied onto the all welded samples for the hardness measurements. The values of Micro Vickers hardness measurements for each Base metal, HAZ (Heat affected zone) and WZ (weld zone) are shown in Table 4. The measurements indicate low hardness values at base metal region in comparison with higher hardness values at weld zone and heat affected zone region due the work hardening during heating and cooling of weld process.

| Weld sample | BM | HAZ | WZ |
|-------------|----|-----|----|
| 20 mm Thick | 190| 226 | 210|
| 40 mm Thick | 205| 233 | 240|

3.4. Impact tests
The TIG welded SS 316 samples of 20 mm and 40 mm are subjected to the Impact fracture tests for Base metal, HAZ and Weld zone. This impact energy value which indicates the material resistance limit towards the applied sudden stress intensity or fracture energy which it can absorbs. In nuclear reactor grade components the ductile to brittle transition temperature range for the SS grade materials is very important parameter to qualify them for the structural integrity. The standard ASTM A 370 specification with 2 mm was prepared with standard Charpy V notch with 45° angle with all the samples before subjecting to the impact energy tests.. The SS 316 weld samples were tested for Impact tests at 0°C temperature. The specimens are prepared with standard size 10 mm X 7.5 mm X 55 mm from Base metal, HAZ and Weld Zone. In case of 20 mm sample the weld zone has exhibited higher impact energy (187J) compared to base metal(160J) which is indicative of good quality of
welded region. Where as in case of 40 mm sample, the welded zone has shown less impact energy (71J) in comparison with base metal(119J) and HAZ(71J). values.

| Sample | BM | HAZ | WZ |
|--------|----|-----|----|
| 20 mm  | 160 J | 139 J | 187 J |
| 40 mm  | 119 J | 110 J | 71 J |

3.5. Macro & Micro structures
The TIG welded SS 316 samples are subjected to optical macro and microstructural analysis. The weld samples are chemically etched for the HAZ and weld zone clear identification.

3.5.1. 20 mm weld sample.
The 20mm sample was analyzed for optical macrostructures which was in shown in figure 4(a) clearly indicated with multipass weld zone. In figure 4(b) the weld zone microstructures are found with fine grain boundaries with austenitic structures. Figure 4(c) indicates the HAZ and weld zone region. In this Base metal structures are also seen in away regions.

3.5.2. 40 mm weld sample.
The macrostructures of 40 mm thick SS 316 welded samples are shown in figure 5(a). Weld zone microstructures are shown in figure 5(b). The grain boundaries with austenite nature are observed in these samples also. The HAZ structures are shown in figure 5(c). In the same figure base metal microstructures can be seen in away regions. The weld zone structures in both cases were observed with a coarsened fine grain boundaries with austenitic structures. In addition the weld zone structures are free from any kind weld defects like cracks or inclusions.

5. Critical challenges with high thickness plate welds in Vacuum vessel
Advanced upcoming fusion reactors like ITER, Indian DEMO etc. are being planned with double walled vacuum vessel geometry for the safe operation and protection of the reactor subsystems from the 14MeV neutrons. In this regard the fabrication of the vacuum vessel components has to be done.
by taking the considerations like welded joints mechanical stability, integrity, corrosion resistant materials and long life. In this regard, the fabrication of majority of the components are to be developed with different weld processes in both thin and thick plates SS materials of various grades. The double wall supporting structures, thick plates, joining ribs, shells and key components are fabricated with variety of joint configurations like plane plates, curved plates like D shape or near to D shapes and T type butt welds [5-7]. VV components are directly in contact with high pressure water circulation to remove heat loads on vessel and in addition to thermalization of high energy neutrons and shielding them to protect other subsystems. In this regard the components of the weld joints should be of leak proof and free from any kind of weld defects with higher mechanical properties. In addition, other advanced weld techniques like Laser beam welding, Electron Beam welding and Hybrid Laser TIG processes also will be used to develop the vessel structural components. In case of Laser welding process high thick materials welding is a challenging as these are limited due to the limited penetration depths and higher thick SS welds are still challenging. Hence Hybrid Laser TIG process is under consideration for the development of some critical components in VV modules. In case EBW, the vacuum based welding process, higher penetration depths (60 mm) are possible but are very expensive and limited with dimensional requirements. In addition, this is very expensive and industrially needs to be established to cater the upcoming fabrication requirements for large scale jobs.

6. Summary and Outlook
The present work reports the TIG welding process characterized 20 mm and 40 mm thick SS 316 materials. The 20 mm and 40 mm samples are characterized for mechanical Tensile properties, Bend tests, Impact tests. Further Hardness measurements and microstructural studies are carried out. Microstructures reveal the good weld process and produced no significant defects. The thick SS material welding processes have to be established for the requirements of VV components towards upcoming fusion reactor components fabrication and development.

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