Materials and Components, Technology and Application
NOTIZEN

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Plasma Arc Welding of AISI316Ti (EN 1.4571) Stainless Steel: Mechanical, Microstructural, Corrosion Aspects

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In this study, a titanium stabilized including max. 0.7 % Ti (5 times of carbon content of the steel) austenitic stainless steel grade was investigated. Most important alloying elements for this steel are 17 % Cr, 13 % Ni, and 2 % molybdenum. Its mechanical and physical properties appear to be similar to the standard 316 grade, however, its corrosion resistance is better. It could be used at higher service temperatures for longer time without sensitization and with good mechanical properties. It is found to be resistant to marine environment and to the environments including chloride. Its application usually lay in the construction equipment in the chemical or petrochemical industries, for components in offshore modules as well as food processing equipment [1-4].

Regarding AISI316Ti austenitic stainless steel, a number of investigations were published. Material properties such as mechanical, impact and creep properties of AISI316Ti (EN 1.4571) stainless steel at low and elevated temperatures have been investigated by Brnic et al. which could have importance for structure designers [3]. Pardo et al. provided intergranular corrosion properties of AISI316Ti and 321 type austenitic stainless steels [5]. The presence of Mo in AISI316Ti is referred to have an effect in reducing chromium rich carbide precipitation. Because Mo is found to increase the stability of titanium carbides and tends to replace Cr in carbide and intermetallic compound formation. This behaviour is believed to reduce the risk of chromium depletion thus the intergranular corrosion. Mändl et al. investigated the ion implantation of this steel and later correlation between process parameters and corrosion behaviour [6, 7]. Corrosion of AISI316Ti in 50 % KOH was investigated by Torkar [8].

AISI316Ti (EN 1.4571) austenitic stainless steel plates with a thickness of 7 mm were welded by plasma arc welding (PAW) process. Joints were obtained using 316L type filler metal as well as without filler metal called as Weld 1 and Weld 2, respectively. Tensile and bend testing of the joints were carried out. Impact toughness tests carried out at temperatures from 20 °C down to -60 °C have shown encouraging results. Chemical analysis of the weld deposits were made by glow discharge optical emission spectrometry (GDOES). Photomicrographs and photomicrographs of the cross-sections were used to determine ferrite content and hardness. Intergranular corrosion tests in accordance with TSEN 3157/ENISO 3651-2 were carried out. No corrosion sign was reported. The effect of the consumable has the most influence on the toughness properties. Promising mechanical, toughness and corrosion results are useful, considering the implementation of an innovative process, thus PAW of 316Ti stainless steel.

Studies on welding and properties of welded joints of AISI316Ti stainless steel grade mainly focused on shielded metal arc welding (SMAW), gas metal arc welding (GMAW), submerged arc welding (SAW), laser beam welding (LBW), and hybrid welding (HybW). Although laser welding is very efficient due to the increased welding speed compared to conventional arc welding processes and increases productivity as well as attracts high industry attention, the risk of hot cracking represents a specific risk with respect to subsequent stress corrosion cracking, in particular if chloride environments have access to crevices [9-13].

Plasma arc welding (PAW) is an innovative arc welding process. It is similar to gas tungsten arc welding (GTAW). In PAW, the plasma arc could be separated from the shielding gas envelope. PAW has an advantage due to the higher energy of the heat source providing deeper and narrower penetration.
etration and better arc stability. Plasma arc welding (PAW) of stainless steels finds increasing demand, because lower cooling rates could be obtained compared to laser or electron beam welding and higher welding speed providing higher productivity could be reached compared to GTAW. In this context, it could be considered as a bridge welding process between GTAW and laser welding by means of high productivity and lower cooling rates, respectively [14-20].

Although there is an increasing interest in plasma arc welding of stainless steels in recent years both in academic and industrial research, no study was found within reported open research work concentrated on plasma arc welding of AISI316Ti austenitic stainless steel. This stainless steel grade is a stabilized grade and commonly used in chemical, petrochemical and high temperature applications, as well as in applications where resistance to intergranular corrosion is necessary such as welded fuel tanks. Since these applications commonly include welding, industry nowadays looks for welding applications efficient enough for mass production and providing fine mechanical, microstructural and corrosion properties after welding. There is no reported detailed and open study on GTAW or plasma arc welding study for AISI316Ti (EN 1.4571) stainless steel grade, thus this study aims to investigate the mechanical, impact toughness, microstructural and corrosion properties of the PA welded AISI316Ti stainless steel.

### Experimental

**Material.** Chemical composition data of the 7 mm thick base metal obtained by glow discharge optical emission spectrometry (GDOES) is presented in Table 1. **Welding.** Two types of plasma arc welded joints of AISI316Ti (EN 1.4571) stainless steel have been accomplished in keyhole mode in one pass in industrial conditions in a production line of an industrial factory.

| Table 1. Chemical composition of AISI316Ti (EN 1.4571) stainless steel base metal |
|------|------|------|------|------|------|------|------|------|------|------|
| Grade | C    | Si   | Mn   | Cr   | Mo   | Ni   | Ti   | V    | W    | Al   | Co   | Cu   | Nb | Fe |
| 1.4571 | 0.07% | 0.54% | 0.95% | 15.60 | 1.82 | 9.98 | 0.348 | 0.089 | 0.04 | 0.023 | 0.20 | 0.6 | 0.01 | bal |

| Table 2. Welding parameters applied for PA welding of AISI316Ti stainless steel |
|---------------|-------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Joint code    | Welding position | Type of consumable | Plate preparation | Welding parameters (V/A) | Plasma gas | Shielding gas | Purge gas | Welding speed mm min⁻¹ | Heat input KJ mm⁻¹ |
| Weld 1        | PA    | (Ø 1.2 mm) ER316L | V / 30° | 30.5 / 220 | Ar | Ar / 5% H₂ | Ar | 30 l min⁻¹ | 190 | 2.11 |
| Weld 2        | 1 pass | | | | | | | | |

The plates were prepared with a V-shape with an opening angle of 30°. Weld 1 was produced with a solid ER316L wire with 1.2 mm diameter and Weld 2 was accomplished without using any filler metal. For the welded plates using filler metal, a wire feed speed of 0 cm min⁻¹ was used. Welding parameters are given in Table 2 below.

**Mechanical, impact toughness, microstructural, and corrosion testing of the welded joints.** Transverse tensile test specimens were prepared in accordance with EN 895 and testing was performed by a servohydraulic Instron test machine at room temperature. The weld metal excess was removed in order not to overestimate the weld metal strength. Transverse face and root bend test specimens were prepared with a nominal specimen width of 25 mm. Bending was carried out till 180° unless critical cracking was observed before. Notch impact test samples were prepared transverse to the weld. Notches were positioned at the weld metal centre (WM), at the heat affected zone (HAZ), and base metal (BM). Impact testing was executed at -60 °C, -20 °C, and at 20 °C, respectively. For microstructural analyses, welded joints were cross-sectioned perpendicular to the welding direction. Specimens were prepared and grinded by 120, 240, 320, 600, 800, 1000 grit abrasive papers, then polished with polishing cloth and 3 μm diamond spray and etched by electrolytic etching in 10% NaOH solution for 15 seconds. Photomicrographs were produced. Photomicrographs of the weld zones were obtained by light optical microscopy (LOM) with 200× magnification. Longitudinal sections entirely located at the weld metal were prepared perpendicular to the plate surface for chemical analysis of the weld deposits. At least two measurements were taken by GDOES. Weld metal ferrite content was first calculated and predicted by chemical analysis results, then was obtained by ferrite test measurements across the weld metal. Vickers hardness measurements under 1 kg load were carried out over the weld cross-sections. To detect susceptibility to intergranular attack, corrosion test in accordance with TSEN 3157/ EN ISO 3652-2 procedure was applied.

### Results and Discussion

**Transverse tensile test.** Transverse tensile test results are shown in Table 3. Transverse tensile tests of the specimens overmatched other results. Rm values between 573 MPa and 576 MPa were measured and fracture of the welded joints was determined to be at the base metal.

**Bend test results.** During 180° bending, no cracks nor undercuts have been observed for the face and root bend samples.

**Impact toughness test results.** Charpy impact test results of the welds with AISI316L type of consumable and without filler metal, respectively, are given in Figure 1.

Considering 27 J as required mean toughness for structural application purposes, it could be concluded that both welds have proven very encouraging impact toughness for all test temperatures. It should be kept in mind that, each point refers to an average value of three measure-
Impact toughness of Weld 1

![Impact toughness of Weld 1](image)

Impact toughness of Weld 2

![Impact toughness of Weld 2](image)

Figure 1. Impact toughness plots at different temperatures for the PA welds a) Weld 1, b) Weld 2

Joint code | Position | C | Mn | Si | Cr | Ni | Mo | Nb | Ti | Al | V | Cu | Co | W | Fe
---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---
Weld 1 | WM | 0.08 | 0.98 | 0.0 | 15.8 | 9.83 | 1.79 | 0.01 | 0.23 | 0.019 | 0.07 | 0.574 | 0.155 | 0.04 | bal.
Weld 2 | WM | 0.08 | 0.93 | 0.44 | 15.4 | 9.85 | 1.78 | 0.02 | 0.36 | 0.019 | 0.08 | 0.63 | 0.17 | 0.04 | bal.

Table 4. Chemical composition of the weld deposits of the PA welds of AISI316Ti stainless steel (data obtained by experimental analysis)

ments of a sample. For all test temperatures, similar results were obtained for the weld metal center (WM) and heat affected zone (HAZ) notched samples. Although impact toughness results of the WM notched samples of Weld 2 represent similar values as Weld 1 at room temperature, better results were measured for the subzero temperatures. This would suggest that plasma arc welding of AISI316Ti stainless steel material without filler metal (Weld 2) could give better low temperature impact performance compared to those welds produced containing 316L filler metal (Weld 1). The difference could be explained with the use of filler metal.

Figure 2. Photomicrographs of welded joints of PA welds a) Weld 1, b) Weld 2

Chemical analysis. Chemical composition of the weld deposits are provided in Table 4.

Amount of Ti decreased for Weld 1 compared to Weld 2 and compared to the base metal, due to the dilution of 316L filler metal (which does not include titanium) and with AISI316Ti base metal.

Microstructural analysis. The microstructural investigation has been done on the weld cross-sections. Macrophotographs obtained from each weld are presented in Figure 2. Both welds show a reasonable weld profile.

The investigation of the weld zones was performed including base metal (BM), heat affected zone (HAZ) and weld metal (WM) with 200× magnification, see Figures 3 and 4.

Figures 3a and 4a show the microstructure of AISI316Ti stainless steel base metal after electrolytic etching. The microstructure is an austenitic single-phase structure. As illustrated in Figures 3b and 4b, the microstructure of the HAZ in the welded joints could be characterized by an increase in grain size. Figures 3c and 4c show the microstructure of the weld zone with columnar grains where δ-ferrite can be found. All these facts indicate that the microstructure of the AISI316Ti base metal was modified as a result of the PAW process.

Ferrite content results. During welding, austenitic stainless steel in general solidifies as a mixture of austenite and ferrite as AF solidification mode. The ferrite in the welds is metastable. During cooling, the incomplete transformation of ferrite to austenite occurs, thus there is retention of some δ-ferrite in the weld metal. A certain amount of retained δ-ferrite in austenitic stainless steel welds is recommended since
this δ-ferrite has a beneficial effect on reducing hot cracking susceptibility. It has shown that higher energy density decreases cracking, this means that the heat input also considerably affects the formation of hot cracking [21].

Due to data of chemical composition, and by calculating Cr eq and Ni eq of base metal and filler metal, an austenite + ferrite structure has been predicted for the weld metal microstructure in accordance with Schaeffler and WRC diagrams. For the weld metal, it is expected to have about 5% ferrite due to Schaeffler diagram and about a ferrite number of 9. Since WRC is more recent and accurate [1], it would give more reliable estimation of weld metal ferrite content. Below 10, ferrite number and ferrite percentage are accepted as almost equal. Depending on the ferrite content investigation by Fisher Ferritscope, weld metal ferrite number data was obtained for the metallography samples approx. between 9 FN and 11 FN, see Figure 5. The measured ferrite number data are in general compatible with the predicted data, in particular with WRC diagram.

Hardness test results. Hardness measurements of Weld 1 and Weld 2 were carried out as a line under 1 kg load over the weld cross-sections. Over 10 measurements were taken for each position, face and root for both joints, respectively. Hardness distribution of the welds is given in Figure 6. Weld metal hardness values varied between 155 HV1 and 166 HV1 for Weld 1 and between 155 HV1 and 174 HV1 for Weld 2. Maximum hardness values of 166 HV1 and 174 HV1 for the Welds 1 and 2, respectively, were measured at the weld metal. Some hardness increase occurred at the weld metal compared to base metal due to the welding process.

Corrosion properties. To detect susceptibility to intergranular attack, intergranular corrosion test was applied to the plasma arc welded samples of AISI316Ti stainless steel in accordance with TSEN 3157/EN ISO 3651-2 procedure. Sulfuric acid and copper sulfate test were applied and the samples were subjected to boiling solution for twenty hours. According to TSEN 3157/EN ISO 3651-2 procedure, after boiling the samples in corrosive media, bending should be applied. After bending the test samples, no crack, meaning no corrosion sign, was observed for samples from both welds.

Depending on the data of corrosion test

![Figure 4. Photomicrographs of Weld 2 a) BM, b) WM + HAZ, c) WM](image)

![Figure 5. Ferrite number measurements of Weld 1 and Weld 2 obtained by ferritscope](image)

![Figure 6. Hardness profiles of a) Weld 1 and b) Weld 2](image)
samples, it could be concluded that Weld 1 and Weld 2 were both very resistant against intergranular corrosion attack. Although using a non-stabilized filler metal 316L, no corrosion occurred which is very promising. Since 316L type of filler metal is an easily accessible electrode in industry. For the sample obtained by the plasma arc weld without filler metal, Weld 2, also showed no crack and good resistance against intergranular corrosion which is very promising as well, since using filler metal increases costs under industrial conditions. Thus, recommendation of producing plasma arc welds of AISI316Ti stainless steel without using any filler is feasible due to the advantages of corrosion aspects.

Conclusions

This study on plasma arc welding of 7 mm thick AISI316Ti austenitic stainless steel conforming to ASTM 316Ti and EN 1.4571 has revealed the following conclusions:

- Plasma arc welding of AISI316Ti stainless steels could be successfully accomplished in keyhole mode in one pass instead of multi-passes which means increase in efficiency in particular for mass production.
- Welds without filler metal and with 316L filler metal overmatched in tensile properties. Face and root bend tests with 180° bending have not revealed any defect. This is promising from the point of view of mechanical properties of the welded joints.
- Charpy impact toughness testing at various temperatures showed encouraging results for both joints also in welds produced without using filler metal.
- Maximum hardness was found to be at the weld zone below 175 HVI. This is in accordance with the international regulations, where maximum hardness is recommended to be below.
- Measured ferrite content of the weld metal for both welds range between 9-11% ferrite which is within the acceptable range due to international welding regulations. This is promising for critical applications in petrochemical or chemical industries.
- Intergranular corrosion was not determined after testing for both welds. This is very encouraging in particular for welds with using a non-stabilized, meaning using a more intergranular corrosion sensitive filler metal.
- Plasma arc welding is a more productive process by means of welding speed compared to SMAW and GTAW. The industry appears to use this process increasingly in recent years for welding of stainless steels. For this study, plasma arc welding of AISI316Ti steel without filler metal showed very promising properties by means of mechanical, toughness, microstructural, and corrosion aspects compared to welds produced with 316L steels. Importantly all data, it could be concluded that the toughness properties are mainly affected by the type of the consumable.
- Encouraging results of this study have shown that plasma arc welding of austenitic stabilized AISI316Ti stainless steel could be achieved with and without using a non-stabilized filler metal. Thus, depending on the industrial application area, this grade could be successfully welded without filler metal or with even using a non-stabilized filler metal such as 316L, providing promising mechanical, microstructural, and corrosion properties.

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Abstract


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