PRELIMINARY RESEARCH FOR DEVELOPMENT OF A-TIG WELDING PROCESS OF 316L STAINLESS STEEL IN RATEN ICN

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Abstract

Austenitic stainless steels represent the most used group of stainless steels, due to their very good corrosion resistance and excellent mechanical properties. Thus, they are widely used in nuclear and thermal power plants. The most used method for their welded joint is Tungsten inert gas (TIG) welding, but the welding penetration depth in a single pass is low, which makes the method not very productive. Considering this aspect, a new method is taking shape in the specialized literature, A-TIG, which is based on TIG welding but adds an activation flow in the area where the components are joined. The objective of the present work was to carry out preliminary weldability tests on 316L austenitic steel samples through the two processes, TIG and A-TIG, aiming to implement the second method within RATEN ICN. The experimental activity consisted of performing TIG and A-TIG welding on sections of 316L stainless steel pipe with an outer diameter of 50 mm and an initial wall thickness of 5.2 mm. The welds were made with 4 different current intensity regimes: 50A, 60A, 70A, and 80A. In the case of A-TIG welding, the activation flux used was zirconium oxide. The deposition was done by applying with a brush a solution based on zirconium oxide mixed with ethyl alcohol. Analysis of the welds was performed by optical and scanning electron microscopy (SEM) techniques.

Keywords: *Generation IV, Candidate Material, TIG and A-TIG welding, 316L austenitic steel*

Introduction

(Gas Tungsten Arc Welding – GTAW), also known as Tungsten Inert Gas (TIG) welding, is a fusion welding process in which an electric arc is used to provide the heat required for melting metal contact surfaces. The arc is established between a non-consumable tungsten electrode and conductive base plates in the presence of a sufficient potential difference. The weld area is also protected from unwanted oxidation by the shielding gas, which is usually argon or helium.

The conventional TIG welding process fails to provide economic benefits while joining thicker components due to its limited penetration capability. In a single pass, TIG welding can provide a maximum penetration of 3.0 mm when joining stainless plates face-to-face with an optimal set of process parameters. Consequently, more time-consuming steps such as groove design and groove cutting are desirable whenever the component thickness typically exceeds 3 mm. The presence of the groove also requires more weld passes and more filler material to fill the entire groove. The time and cost factors associated with expensive edge preparation and filler make the conventional TIG welding process uneconomical and unproductive when base components are thicker than 3 mm.

Such a limitation paved the way for the rapid development of other TIG welding processes. As a result, several new variants of the existing process have evolved, namely, activated TIG (A-TIG), flux-bounded TIG (FB-TIG), deep penetration TIG (DP-TIG), high-frequency pulsed TIG (H-TIG), hybrid laser TIG (LATIG), etc [1].

Tungsten inert gas flux activated (A-TIG) welding is an arc welding process in which the contact surfaces and surrounding areas of the base plates are coated with a thin layer of suitable activation flux before the arc is established electric. Similar to conventional TIG welding, it uses a non-consumable tungsten electrode to form the arc. Filler metal, if necessary, can be added separately. Inert shielding gas is also supplied from a gas cylinder to protect the hot weld bead from unwanted oxidation and contamination. From a practical point of view, the application of the activation flux to the base plate is the only difference between A-TIG welding and TIG welding; however, results vary widely.

316L steel weldability issues

Welding is a technique in which two materials are joined by localized coalescence resulting from an appropriate combination of temperature and pressure. The range of temperatures and pressures that allow welding to take place has led to the development of numerous welding processes. Another important consideration is surface cleanliness and possible contamination during the welding process, and different methods use different means of protecting or cleaning the surface [2].

There are two broad categories:

- fusion welding
- welding in a solid state or without fusion.

In fusion welding, actual melting of the metal takes place to form the bond, whereas in solid state welding, no melting process is involved and the bond occurs due to diffusion of atoms.

The fusion zone of a typical weld is essentially a small casting and may exhibit similar characteristics and defects. Fig. 1 shows the crystal structure of a fusion weld. In the center of the weld is an area that is primarily made up of weld metal that has solidified from the molten state.

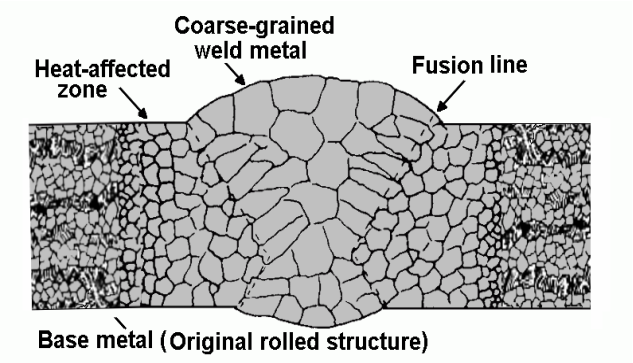


Fig.1 Granular structure of a fusion weld [2]

Since it is cast metal, it cannot be expected to have the same mechanical properties as the forged base metal. The grain structure of the weld metal zone can be fine or coarse depending on the type and volume of the weld metal and the cooling rate. However, contamination from the atmosphere – the absorption of oxygen and nitrogen – and from other gases, such as hydrogen from oil or moisture, is of primary importance in determining the properties of the weld zone.

Over time, a major concern in welding austenitic stainless steels has been the problem of carbide precipitation at the HAZ (Heat Affected Zone) grain boundaries. Chromium carbide precipitation occurs along grain boundaries when stainless steels are heated in the temperature range from 500°C to 800°C. As a result, the neighboring regions along the grain boundaries are saturated in chromium and lose their corrosion resistance. Steel is said to be sensitized and corrosion can occur along grain boundaries (intergranular corrosion). During welding, the sensitization region occurs in the HAZ in bands at a certain distance from the weld. The process is called weld disintegration. This degradation mechanism is shown in Fig. 2.

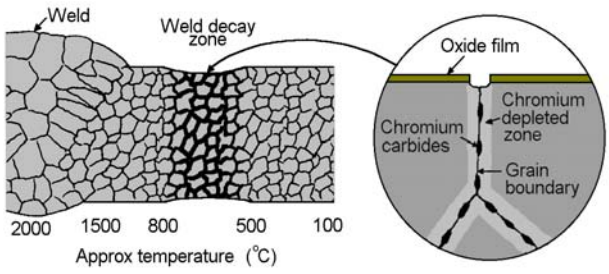


Fig.2 Granular structure of a fusion weld [2]

The amount of carbon precipitation depends on the carbon content, the temperature, and the time held at that temperature. Fig. 3 illustrates the effect of carbon content on sensitization. For example, steel with about 0.06% carbon can be held at 600°C for only about 10 minutes without sensitization, but if contains 0.04% carbon it can be held for over an hour at this temperature. So thinner sections are unlikely to experience sensitization with even 0.06% carbon because they will heat up and cool down very quickly. However, for heavy plates and thicker sections, the time in the critical region will be longer and a lower carbon content is required.

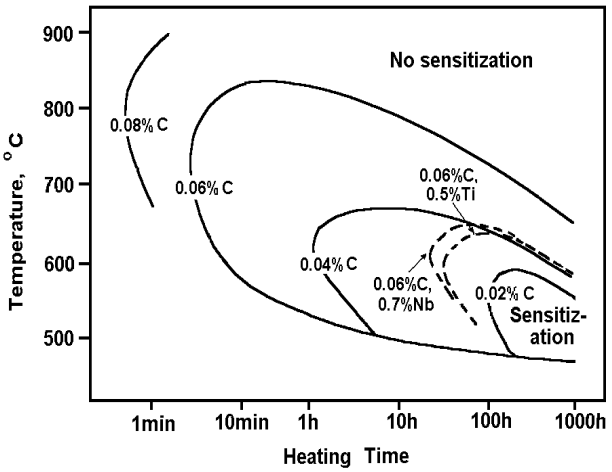


Fig. 3. Sensitization-temperature-time diagram for 304 stainless steel with varying carbon content [2]

If the steel is already sensitized, it can be treated by heating it to 1000 to 1100°C and cooling it in the air. This procedure redissolves the carbides at the grain boundary, releasing the chromium back into the grains. There is, however, a limit to the size of a structure that can be processed and the process can cause distortion.

A-TIG welding process

Versatility, stable heat source, optimal equipment cost, and fine quality welding are the well-known characteristics of the tungsten inert gas (TIG) welding process, making it widely accepted in various industries. However, there is something that offsets the widespread application of TIG welding, regardless of all its advantages [3]. Limited dilution, poor deposition rate, and shallow penetration in a single pass leading to low productivity are the main shortcomings of this process for welding thick plates. Weld penetration or depth of penetration (DOP) is an important factor in TIG welding, which directly influences the production speed in autogenous welding. Edge/groove preparation is the main step to be done for plates or pipes with a thickness of 3 mm or more, which is an uneconomical and time-consuming step to perform in the conventional TIG process.

The main disadvantages of TIG welding are the limited thickness of the material to be welded, poor and low productivity [4]. When welding austenitic stainless steels, variable weld penetration has been reported, particularly in autogenous TIG or multi-pass TIG welds.

Sulfur, oxygen, aluminum, and calcium have been reported to affect penetration depth, bead height, and width. The weld penetration depth increases as the amount of oxygen and sulfur in the base material increases, while the bead width decreases. Weld penetration decreases and bead width increases as aluminum and calcium concentrations increase.

To eradicate this problem of low penetration depth in TIG welding, researchers worked on the use of activated flux and introduced a process known as Tungsten Electrode Inert Gas Activated Flux (A-TIG) welding [5, 6] (see Fig. 4).

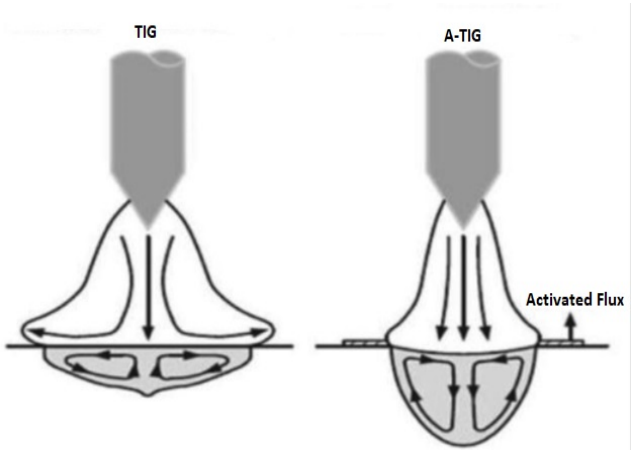


Fig. 4. A-TIG welding penetration mechanism

A-TIG was first introduced in the mid-1960s by E.O. Paton Electric Welding Institute, Ukraine [7]. In this process, a thin layer of flux is applied to the entire joint before welding. The main constituents of the flux are oxides and halides in the form of fine powder. The flux is initially converted from powder to suspension by adding the appropriate organic solvent.

Common carrier solvents are ethanol or acetone which must be mixed with the activated flux in adequate quantity so that the liquid in the paste evaporates in the meantime leaving a layer of flux on the surface. The A-TIG process eliminates filler wire addition, decreases groove preparation time, and enhances weld penetration [7]. Subsequently, providing a single-pass weld with high welding speeds and deeper weld beads. Cross-sections of the weld seam of classic TIG and A-TIG welding using identical process parameters are shown in Fig. 5.

The location of the flux layer on the base metal is a crucial factor as it determines the effectiveness of A-TIG welding in improving penetration and narrowing the weld bead width. It is the basic difference between A-TIG welding and TIG welding. In A-TIG welding, the flux is applied to the mating surfaces of the base plates as well as the surrounding areas (at least 20 mm on each side of the mating surface). If the arc length is longer, then the flux must be applied over a wider area. Approximately, the width of the entire flux layer on the base metal is 2 to 3 times the maximum width of the arc. As pointed out by Vidyarthy et al. (2016), the flow layer width is typically kept between 10 and 15 mm [8].

Two different methods of applying the flux coat to the base plates are reported in the literature – (i) using a brush and (ii) by spraying. Regardless of the application technique, care must be taken to maintain the thickness and consistency of the activation flux layer. On average, 5 to 6 mg of solid flux is typically deposited per square centimeter of metal surfaces. The thickness of the coating layer can be widely varied, in the range from 100 to 500 μm, depending on the size of the flux particles, their density, the method of application of the flux, the desired result, etc. [9].

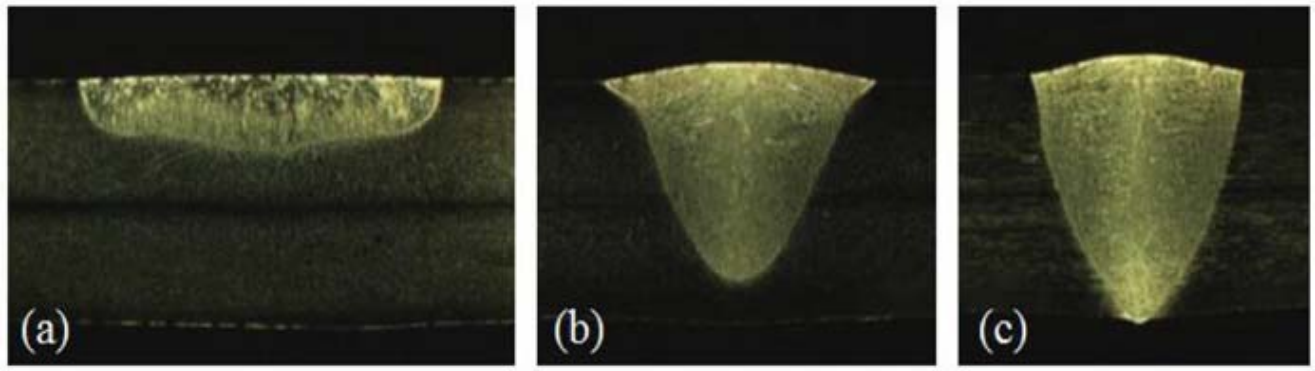


Fig. 5. Cross sections obtained for welds with the same process parameters on AISI 316L steel plates:
(a) conventional TIG, (b) TiO2 A-TIG flux, (c) SiO2 A-TIG flux

The basic steps of A-TIG welding are listed below:

- The coating surfaces and surrounding areas of the components to be welded are first properly cleaned to remove coatings, paint, rust, dirt, grease, etc. Cleaning can be done with a suitable chemical solution (especially acetone is used for this purpose). Proper cleaning is essential to achieve a flawless weld seam.
- Several activator flux powders are then mixed in a predetermined proportion. Care must be taken to mix the flux powders homogeneously. If the single-component flux is used, then mixing is not required.
- The appropriate solvent (mostly acetone or ethanol) is then added to the flux powder. The ratio of flux powder to solvent is not crucial because the solvent is the most volatile. A soft brush (those used for painting) can be used to properly mix the flux with the solvent to obtain a semi-solid paste ready to be applied to the baseboards. No water should be added for flux preparation or at any other stage during A-TIG welding.

- This paste is then applied to the coating surfaces and surrounding areas of the components. It can be applied with a soft brush (either manually or automatically). The thickness of this flux coating must be maintained according to the predetermined level.
- Sufficient time must be allowed to automatically vaporize the solvent (present in the flux paste) from the substrate surface. It is not very long, because the solvents are very volatile and thus evaporate in a few seconds.
- Once the flux layer on the base plate is dry, the arc can be formed. It is usually difficult to establish the arc on the flux-coated surface of the base plate. Thus, a separate backing plate can be placed on the input side to stabilize the arc, and then the torch can be fed over the flux-coated base plate at a predetermined rate. Current, voltage, frequency, arc length, shielding gas flow, etc. are also required to be set before the arc is established. The filler metal can also be fed continuously.
- Once the entire weld is complete, the arc can be finished. It is usually recommended to terminate the arc at another support plate held at the end.

The experimental assembly

The welding regimes, to which the samples that will be analysed were subjected, were assured with the help of the experimental assembly developed in RATEN ICN, within the Nuclear Fuels laboratory.

The main components of the experimental setup are the following:

- welding source TRANSTIG 800 FRONIUS – with the help of which the welding program is created (Fig. 6);
- the device for rotating the welding assembly (Fig. 7) – allows fixing and rotating the materials to be welded. Using the various fixing devices (Fig. 8) made within RATEN ICN, a wide variety of diameters can be welded;
- Fronius FCU 20 control device – control unit that synchronizes the motor movement (welding speed) with the welding program selected on the source. This device allows setting the geometric characteristics of the material, the welding speed, and also the type of welding (Fig. 9);
- welding distance control device (Fig. 10).



Fig. 6. FRONIUS source (left - TRANSTIG 800 JOB G/F module; right - PLASMA MODULE 10)



Fig. 7. The device for rotating the welding assembly



Fig. 8. The device for fixing tubular specimens



Fig. 9. Fronius FCU 20 control device



Fig. 10. The welding distance control device

Welding of 316L stainless steel specimens

Two welding techniques were used: TIG and A-TIG. The parameters were identical for both techniques, namely:

- the welding speed was kept constant at 10cm/min;
- the electric current intensity varied; four regimes were used: 50A, 60A, 70A and 80A;
- the protective gas was spectral argon (Argon 5.0);
- the root gas was technical argon (Argon 4.8).

Four welding cords were made on each sample according to the established electric current intensities. To obtain the welded specimens, sections of 316L stainless steel pipe with an outer diameter of 50 mm and an initial wall thickness of 5.2 mm were used.

In the weld area, the two sections to be joined were mechanically turned over a length of approximately 15 mm until a wall thickness of 3 mm was obtained for one set of specimens and 2 mm for another set of specimens. The welds were made with 4 different current intensity regimes: 50A, 60A, 70A, and 80A.

In the case of A-TIG welding, the activation flux used was zirconium oxide. The deposition was done by applying with a brush a solution based on zirconium oxide mixed with ethyl alcohol.

Four samples were obtained (Fig. 11) as follows:

- Sample 1 – TIG welding, wall thickness 2 mm;
- Sample 2 – A-TIG welding, wall thickness 2 mm;
- Sample 3 – TIG welding, wall thickness 3 mm;
- Sample 4 – A-TIG welding, wall thickness 3 mm.



Fig. 11. Welded 316L specimens

In a more detailed presentation, the differences between the two types of welding: TIG and A-TIG can be observed through a visual examination (Fig. 12). In the case of TIG welding, it is observed that the thermally affected area is larger compared to A-TIG welding regardless of the intensity of the current that has been used.

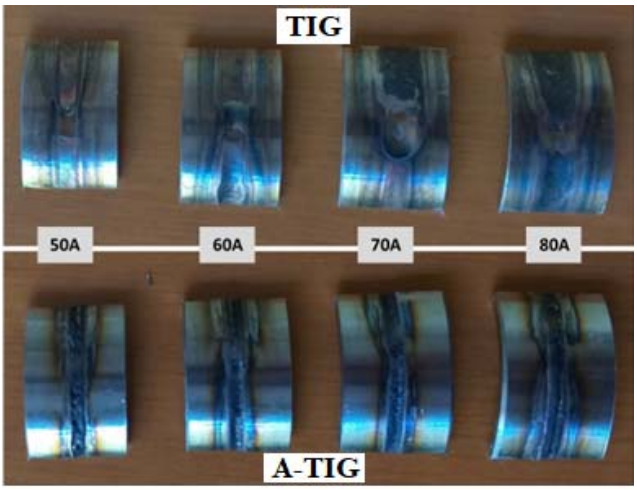


Fig. 12. Appearance of samples for microstructural investigations

The next stage was the extraction of samples for microstructural analyses. Thus, a cutting sketch was drawn up according to which the samples were extracted (Fig. 13). As can be seen, the welded areas with different current intensities were delimited. The numbering was done as follows: sector I represent the welding with 50 A, sector II represents the welding with 60 A, sector III represents the welding with 70 A, and sector IV represents the welding with 80 A. Each sector obtained is cut centrally and a sample of 5 mm from the left and right of the center area as indicated in the sketch.

The samples for the microstructural investigation were obtained and these are presented in Fig. 14.

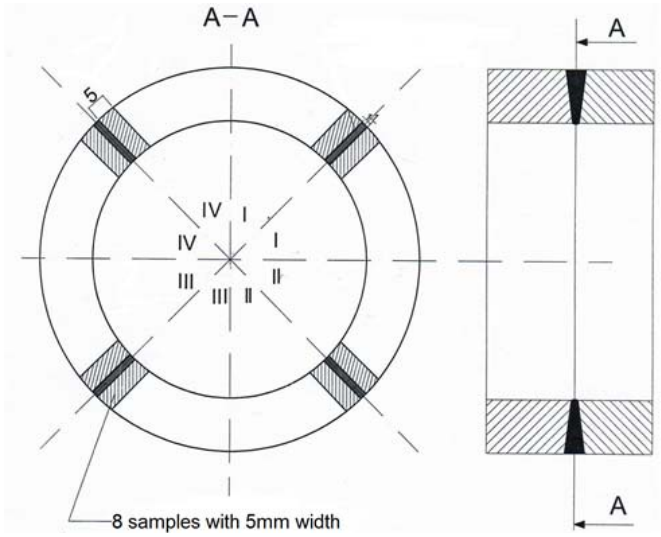


Fig.13. Sketch of sample cutting for microstructural analyses



Fig. 14. Appearance of samples for microstructural investigations

Microstructural evaluation of welded joints

Optical microscopy

The microstructural evaluations carried out by optical microscopy aim to analyze the areas welded by the two processes: TIG and A-TIG. For this, several preparatory steps were necessary:

- embedding the samples to be analyzed;
- polishing of the embedded assembly. Fig. 15 shows the samples after embedding and grinding. Polishing was done using abrasive paper with successive grits (240 µm, 320 µm, 600 µm, 1200 µm, 2400 µm and 4000 µm).

For the chemical attack to reveal the microstructure, a solution of oxalic acid and demineralized water was used.

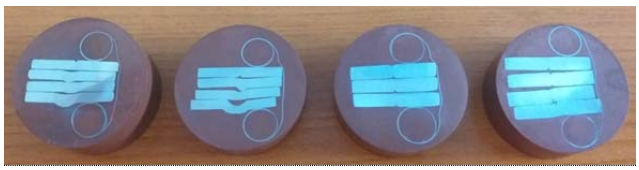
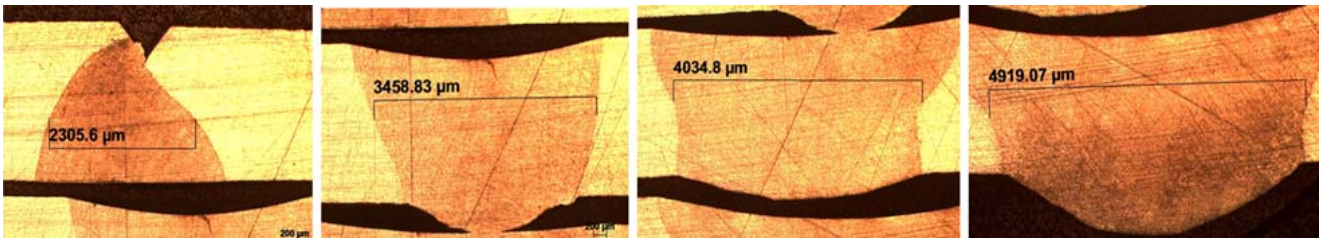


Fig. 15. Mounted specimens layout

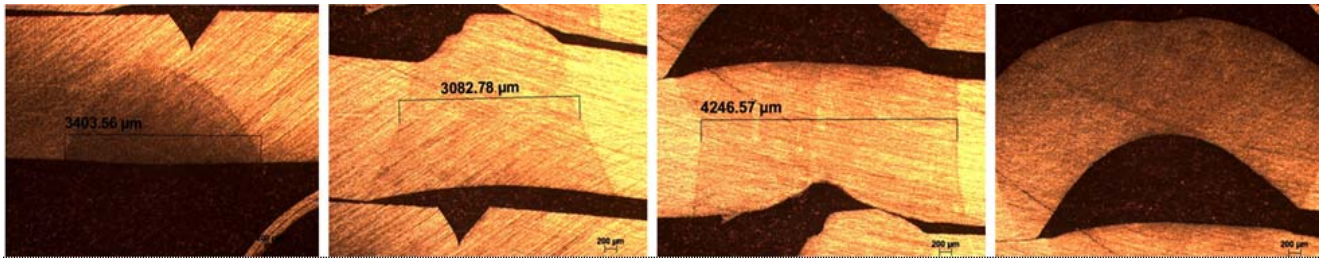
The metallographic aspects of analysed samples according to the welding conditions are presented, as follows:

- TIG welding on a 2 mm thick 316L SS tube (Fig. 16);
- A-TIG welding on a 2 mm thick 316L SS tube (Fig. 17);
- TIG welding on a 3 mm thick 316L SS tube (Fig. 18);
- A-TIG welding on a 3 mm thick 316L SS tube (Fig. 19).



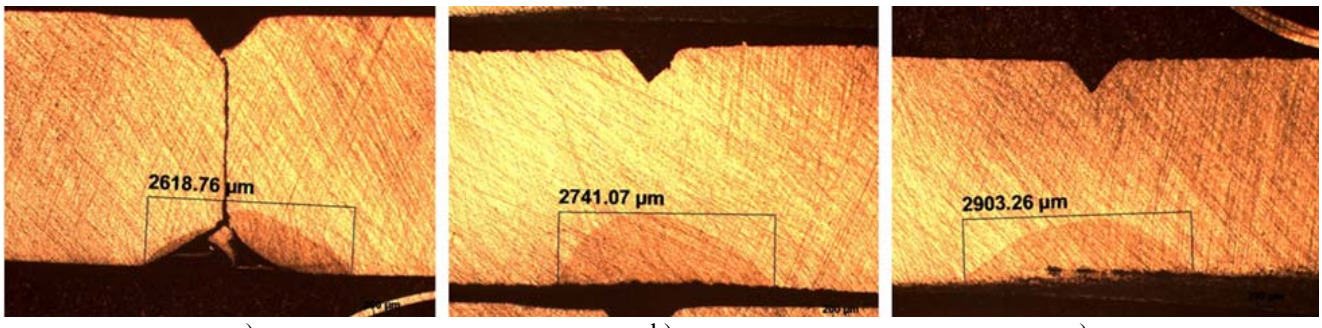
a) b) c) d)

Fig. 16. TIG welding on a 2 mm thick 316L stainless steel tube: a) 50A, b) 60A, c) 70A, d) 80A



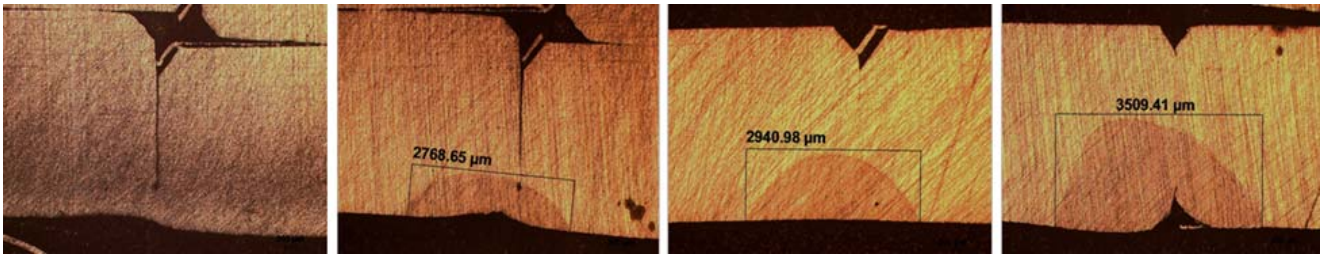
a) b) c) d)

Fig. 17. A-TIG welding on a 2 mm thick 316L stainless steel tube: a) 50A, b) 60A, c) 70A, d) 80A



a) b) c)

Fig. 18. TIG welding on a 3 mm thick 316L stainless steel tube: a) 60A, b) 70A, c) 80A



a) b) c) d)

Fig. 19. A-TIG welding on a 3 mm thick 316L stainless steel tube: a) 50A, b) 60A, c) 70A, d) 80A

Analysing the metallographic aspects of the welds highlighted in Figs. 16 – 19, the following observations can be made:

▪ For the 2 mm thick samples, the results obtained by both welding methods are not conclusive for the current intensities used in the work. The main characteristics that should be observed for the two types of welds are the depth of penetration and the weld bead thickness. The depth of penetration cannot be brought into question because, as can be seen in Figs. 16 and 17, the welds are penetrated throughout the material thickness and the weld bead "is running". The width of the weld bead is relatively the same regardless of the chosen welding method, so no difference can be made between TIG and A-TIG welding;

▪ Consequently, for material thicknesses of 2 mm, it is recommended to use a lower current intensity;

▪ For the 3 mm thick samples, differences were found between the TIG and A-TIG welds. The weld bead width shows an undue increase for A-TIG welds (presented in Table 1). The penetration depth at higher currents (70A and 80A) increases as expected (see Fig. 20); the increase is 15% at 70A and 55% at 80A, respectively (see Table 2).

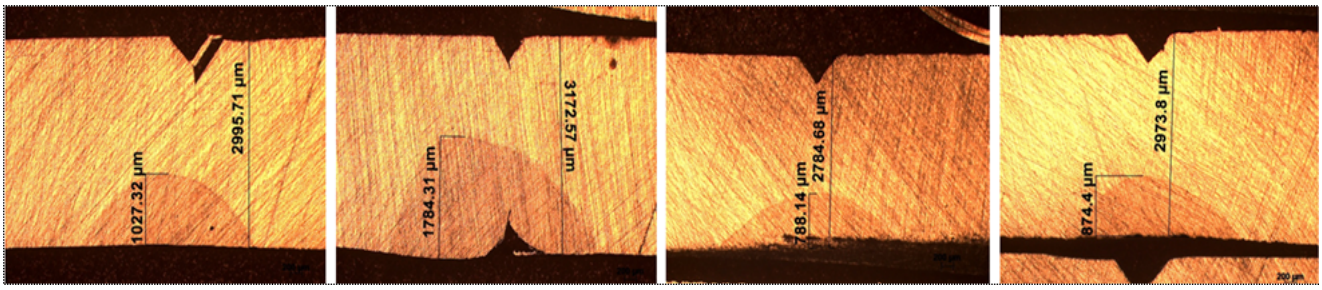
▪ The improvement of the two characteristics of interest (the depth of penetration and the width of the weld bead) followed by the type of A-TIG welding is observed in the case of tests with the current intensity of 70A and higher, therefore it is recommended to further carry out tests starting from 70A intensity of current.

Table 1. The weld bead width [µm]

Weld type \ Current	60A	70A	80A
A-TIG	2768.65 µm	2940.98 µm	3509.41 µm
TIG	2618.76 µm	2741.07 µm	2903.26 µm

Table 2. The penetration depth [µm]

Weld type \ Current	60A	70A	80A
A-TIG	641.49 µm	1027.32 µm	1784.31 µm
TIG	725.41 µm	874.40 µm	788.14 µm



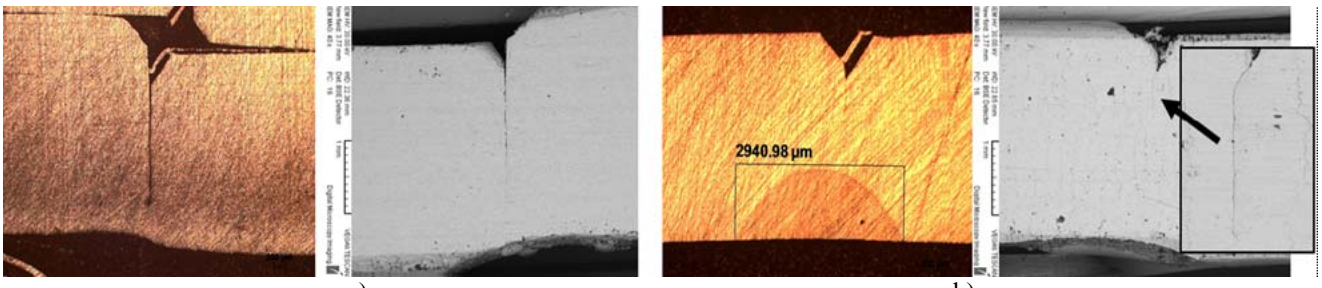
a) b) c) d)

Fig. 20. Evaluation of penetration depth on 3 mm thick 316L stainless steel tube:
a) A-TIG 70A, b) A-TIG 80A, c) TIG 70A, d) TIG 80A

Scanning electron microscopy

The scanning electron microscopy (SEM) analysis had as its objective the general evaluation of all the welds made within this work and the explanation of some unclear aspects noticed by the optical analysis. In this way, a contact limit was detected highlighted by electron microscopy (see Fig. 21).

Thus, in the case of A-TIG welds on the 3mm samples, in the images obtained by optical microscopy, the penetration of the weld is observed, but on the rest of the thickness, the limit between the two samples is not observed, as can be seen from the SEM analysis.



a) b)

Fig. 21. Highlighting the joint area of two 3 mm 316L stainless steel specimens (A-TIG welding):
a) 50A optical and SEM, b) 70A optical and SEM, including SEM detail

Conclusions

The objective of the work was to carry out preliminary weldability tests on 316L austenitic steel samples by two processes, TIG and A-TIG, to implement the second method within RATEN ICN.

The welding regimes to which the samples were subjected were carried out with the help of the experimental setup developed in the Nuclear Fuels laboratory.

To obtain the welded specimens, sections of 316L stainless steel pipe with an outer diameter of 50 mm and an initial wall thickness of 5.2 mm were used. In the weld area, the two sections to be joined were mechanically turned over a length of approximately 15 mm to a wall thickness of 3 mm for one set of specimens, and 2 mm for another set of specimens. The welds were made using 4 different current intensity regimes: 50A, 60A, 70A, and 80A. In the case of A-TIG welding, the activation flux used was zirconium oxide. The deposition was done by applying with a brush the solution based on zirconium oxide mixed with ethyl alcohol.

The microstructural evaluations carried out by optical microscopy and SEM aimed to analyze the areas welded by the two processes: TIG and A-TIG.

Following the analyses, for material thicknesses of 2mm it is recommended to use a lower current intensity, and for material thicknesses of 3mm, it is recommended to carry out tests starting from 70A.

Considering the results of this work, and further research activities for the evaluation of the weldability of 316L steel, the following are considered:

- Correcting the welding parameters by lowering the current intensity below 50A for samples with thicknesses of 2 mm or less, and increasing the current intensity starting from 70A for samples with thicknesses of 3 mm or more;
- Changing the method for application of the activation flux, from brush (used in the present paper) to spray application.

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