MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF THE INCONEL 625 ALLOY WELD OVERLAY OBTAINED BY ELECTROSLAG WELDING PROCESS

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Abstract. *Nickel-based weld overlays are commonly used in oil & gas industry to extend the life of equipments under corrosion environments since the overlays improve the corrosion resistance without a significant increase in the cost of manufacture when compared to massive equipment. Usually the joints are welded by SMAW, GMAW or GTAW processes. In this respect, the electroslag welding process (ESW), which promotes high heat inputs and low dilutions welds, can be an interesting option for this application as it provides high productivity.*
The present work evaluates mechanical, microstructural and corrosion properties of an Alloy 625 weld overlay deposited on a ASTM A516 Grade 70 carbon steel by electroslag welding process (ESW) both in as welded and heat treated conditions. Bending and microhardness tests were conducted in order to verify possible effects of welding thermal cycle on the mechanical properties. Microstructural evaluation was performed using both optical (OM) and scanning electron microscopy (SEM) techniques. Corrosion tests were conducted on samples removed from top layer of the weld overlay cladding deposit according to ASTM G 48 Method A Standard. Low dilution rates and the microhardness values for all regions studied were within the requirements of the standards. Corrosion tests showed no evidence of pitting. All results obtained with this welding process were considered satisfactory.

Keywords: *Overlay, INCONEL 625, Electroslag*

1. INTRODUCTION

An alternative to the use of high cost resistant materials for structural purposes is the cladding of C-Mn steel with nickel-based superalloy 625 (Cortial et al., 1994; Kejelin, 2012; Silva et al. 2012, 2013). The weld overlay with a nickel-based superalloy is an interesting alternative since it improves the corrosion resistance without increasing the cost of manufacture when compared to massive equipment (Kim et al., 2015; Silva et al. 2012). Nickel-based alloys are extensively used in different industries, such as chemical, petrochemical, nuclear reactors, food processing devices and steelmaking facilities (Antoszczyszyn et al., 2014) due to an association of high strength and good corrosion resistance as well as good weldability characteristics (Cortial et al., 1994). The performance of Ni based alloys is associated with the face-centered cubic (FCC) structure of the γ nickel matrix that can be strengthened by solid-solution hardening, carbide precipitation and/or precipitation hardening of intermetallics. Iron, chromium, molybdenum, tungsten, titanium and aluminum are solid-solution hardeners in nickel (Antoszczyszyn et al., 2014).

Weld overlay can be produced via a number of arc welding processes. Shielded metal (SMAW), gas metal arc welding (GMAW), tungsten inert gas welding (TIG), explosion welding and plasma processes are commonly used (Antoszczyszyn et al., 2014; Bedi et al., 2015; Kahar et al., 2013; Kejelin, 2012; Kumar et al., 2010). In some cases a post weld heat treatment (PWHT) is recommended to relive residual stresses, reduce hydrogen content or homogenize the microstructure (Cortial et al., 1994; Du Pont et al., 2009).

According to Kahar et al. (2013), the two most productive systems for the overlay of components which are subjected to corrosion or wear are: submerged arc and electroslag cladding using a strip electrode. Both processes are characterized by a high deposition rate, low dilution and high deposit quality. Both of them are suitable for the overlay of flat and curved objects such as heat exchanger tube sheets and pressure vessel. Submerged arc welding (SAW) is most frequently used, but if higher productivity and restricted dilution rates are requires, electroslag welding (ESW) is recommended. In this respect, Bedi et al. (2015) states that the most efficient technique is Electroslag Strip Cladding (ESSC) due to its unique properties like high deposition rates (up to 52 kg/hour), low dilution (10-15%) and high quality – defect free weld. ESSC process is being increasingly used for the production of corrosion resistant weld overlays in equipments for the offshore, chemical, petrochemical and nuclear industries (Paschold, 2001) and it has established itself as a reliable high deposition rate process.

This work evaluates the mechanical, microstructural and corrosion properties of the INCONEL 625 alloy weld overlays both in as welded and post weld heat treated conditions deposited by electroslag welding process (ESW) on carbon steel ASTM A516 Grade 70 base metal.

2. METHODS AND MATERIALS

A plate of a ASTM A516 Gr. 70 carbon steel of dimensions 50 x 400 x 400 mm was used as the substrate material. A strip with dimensions 0.5 x 60 mm of the class SFA 5.14: EQ-NiCrMo-3 and a flux (E) AS FB 2 according to EN 760 were used to produce a nickel-based superalloy 625 weld overlay. Table 1 shows the chemical composition of the materials.

Table 1. Chemical composition of the filler and base metal (wt %)

	C	Si	Mn	Ni	Cr	Mo	Nb	Fe	Ti
ASTM A516 Gr.70 – Base Metal	0.23	0.24	1.11	0.02	0.02	0.01	-	Bal.	-
Nickel-based 625 – Weld Metal	0.015	0.10	0.10	64.7	22.0	9.0	3.6	3.6	0.23

Welding was performed in the flat position with 4 passes and only one layer by the ESW process. Direct current, preheat of 20°C and interpass temperature of 150°C were adopted. The parameters are shown in Table 2.

Table 2. Welding parameters

Current (A)	Voltage (V)	Nominal Heat Input (kJ/mm)	Number of Passes	Number of Layers
1150 - 1250	24-26	11.7	4	1

The overlays were tested in the following conditions: as-welded and after post weld heat treatment (PWHT) performed at 620°C for 10 hours following air cooling.

The metallographic examination was conducted on samples taken transversally to the weld bead. The samples were carefully polished using diamond paste and later etched with a solution of Nital 2% for the base metal and an electrolytic etch of 4 V for approximately 30 seconds in a solution of CrO_3 for the nickel-based superalloy. They then were examined by optical microscopy (OM) and scanning electron microscopy (SEM). Semi quantitative analysis of the main of the main alloying elements in the microstructure was assessed by energy dispersive spectroscopy (EDS) analysis.

Dilution was determined in the transverse cross-section by the ratio between substrate melted area and total melted area with the help of the AutoCAD software. Both areas were measured and the ratio between them was calculated.

Bending tests at room temperature were performed on test specimens removed transversally to the weld deposits according to the ASME IX (2012).

Vickers hardness test with the load of 500 gf were conducted on the transverse cross-section of the deposits at points located on the weld metal, fusion line and substrate.

Chemical analysis was performed at point located at 0, 1, 3.5 and 7 mm from the fusion line.

Finally, corrosion tests according to ASTM G 48 Method A (2009) were done at 40°C for 24 hours on specimens with dimensions of 50 x 25 x 3 mm.

3. RESULTS AND DISCUSSION

The metallographic characteristics of the weld overlay can be seen in Figure 1. It is possible to notice one single layer with low dilution rate as it was expected by the electroslag process. A dilution rate of 4.01% was calculated based on the macrograph presented. This rate can be considered small when compared to other processes. For the flux cored arc welding, for example, a dilution rate of 9.6% was seen in previous studies (Alvarães, C.P., 2014). The lower the dilution, the better the process for the overlay deposition since high dilution rates can lead, among other things, to the formation of solidification microcracks in the weld metal.

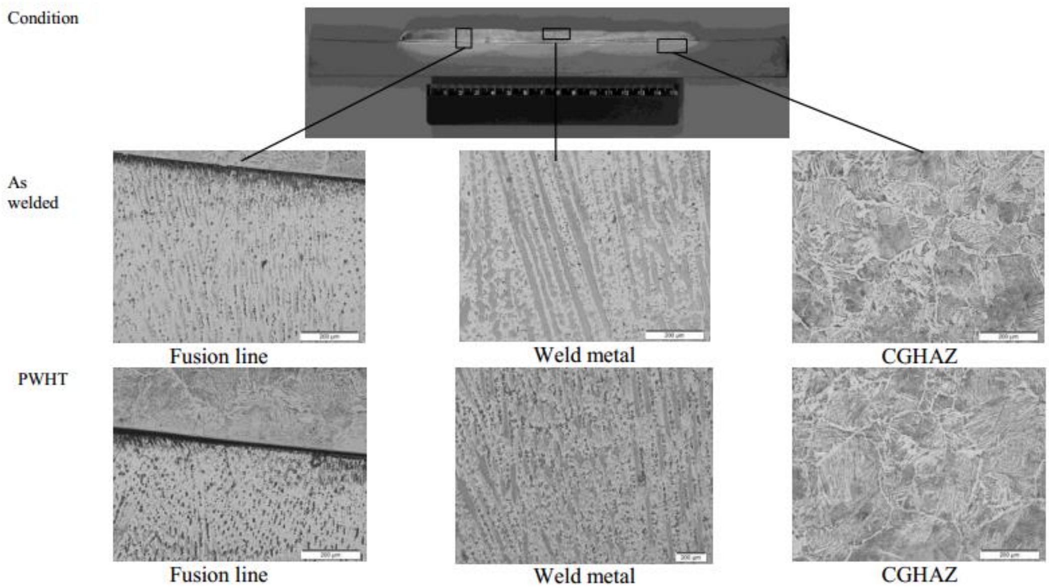

Figure 1. Metallographic characteristics of the welded joint

With respect to the weld metal it was verified a fully austenitic microstructure presenting a high level of segregation (Figure 2) and different types of precipitates (Figure 3). EDS analysis of weld metal in dendritic and interdendritic regions, Figure 4 and Table 3, confirmed that primary face center cubic γ (Ni-FCC) dendrites are rich in Ni-Cr-Mo and the interdendritic regions concentrated in higher percentage the elements Nb and Mo.

According to Cieslak et al. (1989), niobium free alloys solidify in a simple $L \rightarrow \gamma$ transformation without any eutectic-like reaction and exhibit a relatively narrow solidification temperature range. On the other hand, Nb-bearing alloys solidify by an eutectic-type reaction between γ and several Ni-rich phases such as NbC and Laves. Du Pont et al. (2009) states that the following sequence occurs in Nb-bearing alloys: $L \rightarrow L + \gamma \rightarrow L + \gamma + NbC \rightarrow L + \gamma + NbC + M_6C \rightarrow L + \gamma + NbC + M_6C + Laves \rightarrow \gamma + NbC + M_6C + Laves$. A Scheil diagram, Figure 5, was built using the TTNI8 database on Thermocalc software. It shows that it is possible the occurrence of MC carbides and Laves.

Considering the above, the evaluation of secondary phases indicated the enrichment of Mo and Nb, as well as the presence of Si at higher concentrations (Figure 4). Regarding Ni, Fe and Cr a depleted region in the secondary phase was observed. Based on the chemical composition and morphology such particles were characterized as Laves phase rich in Nb. In addition, it was also observed the occurrence of Nb carbides. These results are consistent with the reported by many other authors (Antoszczyszyn et al., 2014; Cieslak et al., 1989, 1991; Cortial et al., 1994; dos Santos, 2013; Du Pont et al., 1996, 2009; Xu et al., 2013).

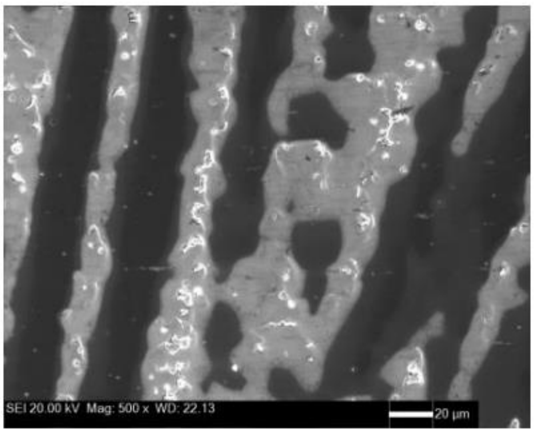

Figure 2. Microstructure of the weld metal (SEM); Etch: CrO_3 electrolytic

Table 3. EDS proportion of alloying elements on microstructure (wt %)

% wt	Cr	Ni	Mo	Nb
ID	22.06	62.87	10.62	4.46
D	25.05	64.15	9.08	1.72
Laves	15.37	45.72	18.85	17.79

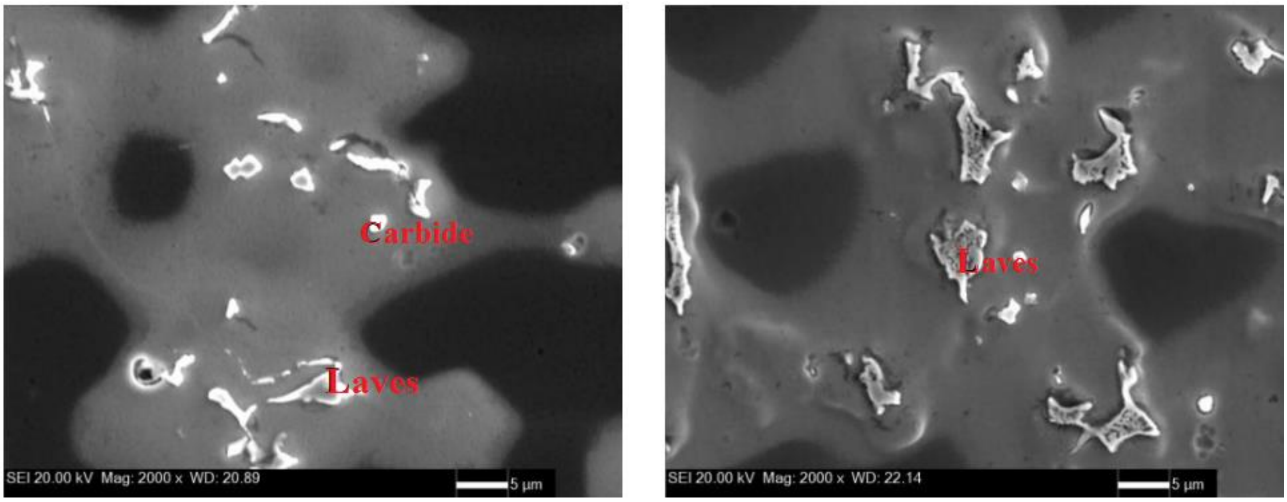

Figure 3. Occurrence of secondary phases on the weld metal (SEM). Etch: CrO_3 electrolytic

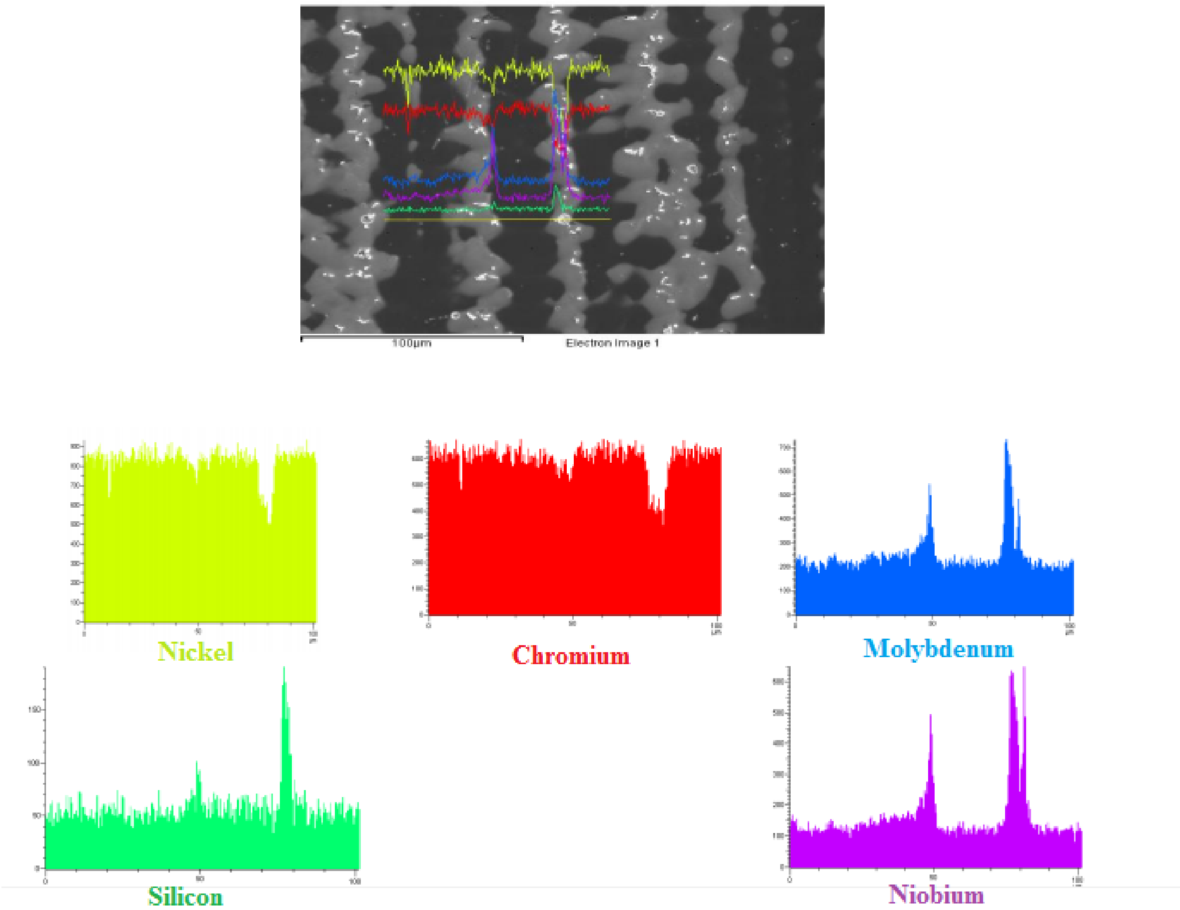

Figure 4. EDS results of weld metal

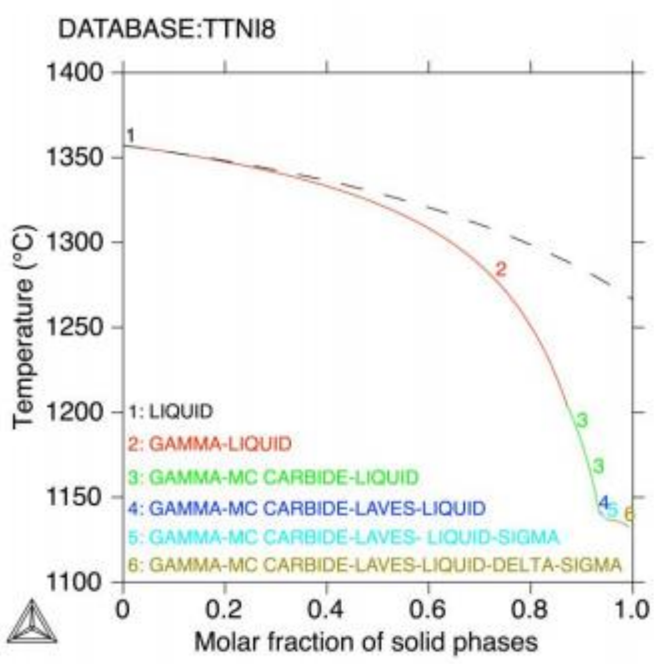

Figure 5. Scheil diagram for weld deposit

Due to high welding energy applied, a microstructure composed by bainite, pearlite and pro-eutectoid ferrite was observed at CGHAZ. This is an interesting result, because usually a martensitic microstructure is observed at this position for other welding processes (Kejelin et al., 2005; Madalena et al., 2013).

The low dilution and a high welding energy also contributed to avoid the occurrence of "Partially Diluted Zones" (PDZ) along the fusion boundary. Figure 6 shows the result of the composition mapped from the weld metal to the base metal material where it can be noted a steep transition at fusion line, Table 4. In addition, the hardness tests (Figure 7) showed results inferior to 350 - 400HV, values that are usually associated to the occurrence of PDZ (Kejelin et al., 2005; Madalena et al., 2013; Silva et al., 2012).

It is important to mention that the percentage of Ni, Cr, Mo and Fe are in accordance with the rules used for the qualification of weld overlays (API 6A, 2004) and particularly the Fe content in weld metal is inferior to 5% for all positions (Table 4).

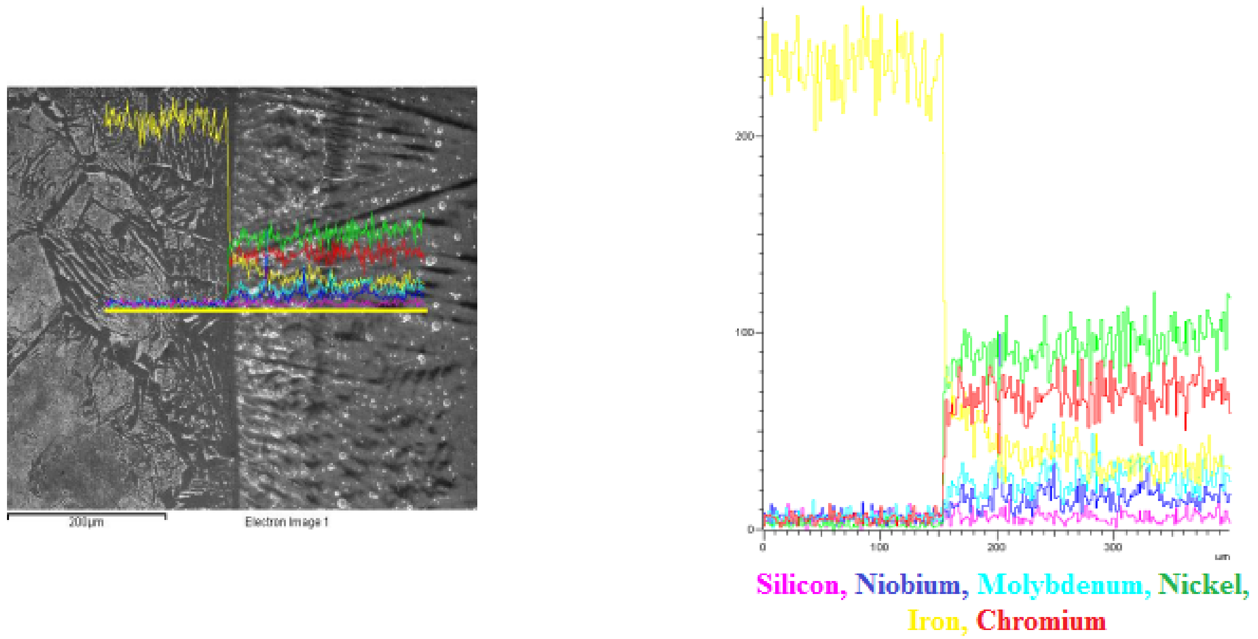

Figure 6. Line mapping at interface

Table 4. Chemical composition at different positions

Element (wt %) Position (*)	C	Cr	Ni	Mn	Si	Mo	Nb	Ti	Fe
6.44	0.019	21.66	61.52	0.05	0.17	8.50	3.55	0.02	4.44
4.41	0.018	21.37	62.04	0.05	0.34	8.37	3.30	0.04	4.35
2.41	0.018	21.43	62.19	0.05	0.33	8.34	3.27	0.04	4.26
1.41	0.020	21.12	62.68	0.05	0.34	8.34	3.25	0.04	4.39
0.41	0.019	21.30	62.03	0.05	0.35	8.39	3.28	0.04	4.46
-0.59	0.180	0.030	0.0100	1.08	0.20	0	0	0.001	98.41
Required [23]	-	20-23	58 (min)	-	-	8-10	-	-	5 (max)

(*) distance from the fusion line

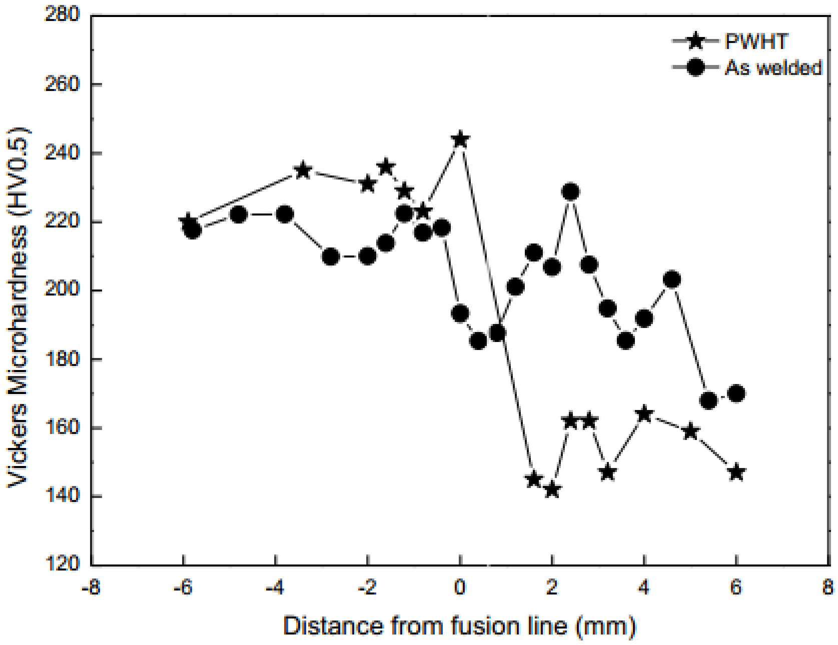

Figure 7. Results of hardness tests

Although the mechanical properties of solid solution strengthened nickel-based alloys are often sufficient in the as-welded condition, PWHT is sometimes recommended to relieve residual stresses, reduce hydrogen content or homogenize the microstructure (Du Pont, 2009). In this respect, Cortial et al. (1994) studying the effect of PWHT at temperatures comprised between 650°C and 1000°C on the microstructure and mechanical properties of the superalloy 625 welds observed an increase in mechanical strength values and a reduction in the ductility and impact strength linked to the precipitation of body-centered tetragonal intermetallic γ” Ni_3Nb phase in the interdendritic space for temperatures superior to 750°C. For lower temperatures, between 600°C and 700°C no major microstructural changes were observed. However, in recent works from Suave et al. (2014a; 2014b) involving the impact of thermal aging of superalloy 625 on the microstructure and mechanical properties, it was observed that the precipitation domains of the γ” are 550 – 750°C. Consequently, the increase in hardness results at weld metal after PWHT is probably due to the γ” precipitation (Cortial, 1994; Du Pont, 2009; Suave, 2014a; 2014b).

At the heat affected zone (HAZ), PWHT promoted the tempering of bainite with the consequent reduction on hardness (Figure 7). In general, PWHT performed at 620°C did not cause significant changes on the mechanical properties. The same satisfactory behavior of the as-welded condition as also observed for bending (Figure 8) and corrosion tests (Table 5).

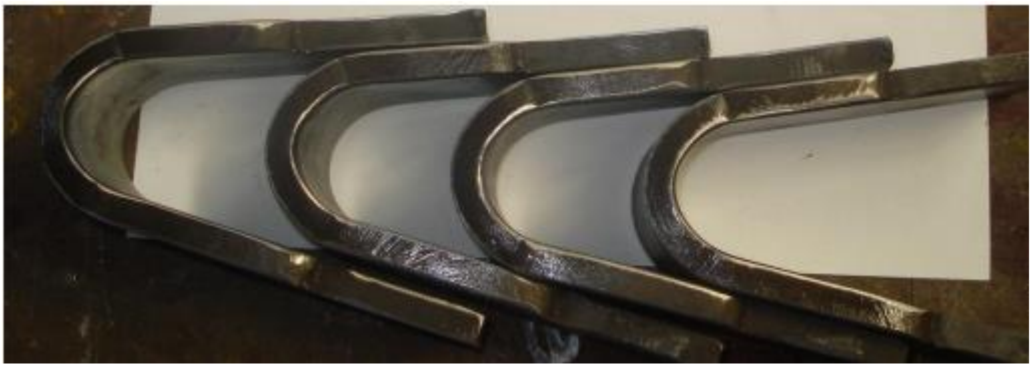

Figure 8. Detail of samples after bending tests

Table 5. Results of corrosion tests

Condition	Pitting	Weight loss (g/m²)
As-Welded	No	0.00
Post Weld Heat Treatment	No	0.17
Required (Norsok, 2004)	No	4.00 (max.)

4. CONCLUSIONS

Based on the aspects discussed in the present work, the main conclusions are:

a) Weld overlay performed by ESW process resulted in satisfactory mechanical and corrosion properties;
b) Electroslag process promoted a low dilution rate when compared to other processes previously studied;
c) PWHT did not cause significant changes on the microstructure and properties of the cladding.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Alvarães, C.P., 2014. “Efeito do TTAT no Desempenho de Revestimentos Metálicos com a Liga INCONEL 625 Obtidos por Processos ao Arco Elétrico”, B.Sc., Thesis, CEFET/RJ, Rio de Janeiro, Brazil.

Antoszczyszyn, T.J., Paes, R.M.G, Oliveira, A.S.C.M and Scheid, A., 2014. “Impact of Dilution on the Microstructure and Properties of Ni-Based 625 Alloy Coatings”, Soldagem & Inspeção, vol.19, n°. 2, p. 134-144.

API 6A/ISO 10423:2004 – “Specification for Wellhead and Christmas Tree Equipment” – 19th Edition.

ASME, 2012. Qualification Standard for Welding and Brazing Procedure.

ASTM G 48, 2009 – Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride, 2009.

Bedi, H.S., Arora, H. and Bansal, M., 2015 – “Microstructures, mechanical properties & corrosion behavior of duples 2209 in electroslag strip cladding over low carbon steel substrate: a Review Paper”, Int. Journal of Engineering Research and Applications, vol. 5, n°. 3, p.72-73.

Cieslak, M.J., Knorovsky, G.A., Headley, T.J. and Roming Jr., A.D., 1989. “The Solidification Metallurgy of Alloy 718 and Other Nb-Containing Superalloys”, In Proceedings of the Superalloy 718. Warredale, PA.

Cieslak, M.J., 1991. “The Welding and Solidification Metallurgy of Alloy 625”, Welding Journal, v. 70, n°. 2, p. 49-56

Cortial, F., Corrieu, J.M. and Vernot-Loier, C., 1994. “Heat Treatments of Weld Alloy 625: Influence on the Microstructure, Mechanical Properties and Corrosion Resistance”, In Proceedings of the Superalloys 718, 625, 706 and Various Derivatives, The Minerals, Metals & Materials Society, p. 859-870.

Du Pont, J.N., Lippold, J.C. and Kiser, S.D., 2009. Welding Metallurgy and Weldability of Nickel-Based Alloys, John Wiley & Sons, Inc., New Jersey.

Du Pont, J.N., 1996. “Solidification of an Alloy 625 Weld Overlay”, Metallurgical and Materials Transactions A, v.27A, n°.11, p. 3612-3620.

Kahar, S.D. and Baba Pai, K., 2013. “Corrosion behavior of electro-slag strip cladded weld overlays in different acid solutions”, International Journal of Engineering Research and Applications, vol.3, n°. 4, p. 2620-2627.

Kejelin, N.Z., Buschinelli, A.J.A., Pope, A.M., 2005. "Effect of Welding Parameters on the Partially Diluted Zones Formation at Dissimilar Metal Welds", Proceedings of the 18th International Congress of Mechanical Engineering, Ouro Preto, Brazil.

Kejelin, N.Z., 2012. Soldagem de revestimento de aços comuns C-Mn com superliga a base de níquel Inconel 625, D.Sc. Thesis, UFSC, Santa Catarina, Brazil.

Kim, J.S., Park, Y.I. and Lee, H.W., 2015. "Effects of Heat Input on the Pitting Resistance of Inconel 625 Welds by Overlay Welding", Met. Mater. Int., vol. 21, n°. 2, p. 350-355.

Kumar, V., Lee, C., Verhaeghe, G. and Raghunathan, S., 2010. "CRA Weld Overlay – Influence of welding process and parameters on dilution and corrosion resistance", Proceedings of the Stainless Steel World America 2010, Houston, USA.

Madalena, F.C.A, Jorge, J.C.F., Souza, L.F.G., Costa, H.R.M. and Cabral, T.B., 2013. "Estudo de propriedades mecânicas e microestruturais do aço inoxidável superaustenítico AISI 904L utilizado como revestimento interno em vasos de pressão fabricados em aço carbono ASTM A-516 grau 70", Proceedings of the 7° Brazilian Congresso f Manufacturing Engineering, Penedo, Brazil.

NORSOK M 601 – Welding and inspections of piping, Rev. 4, July 2004.

Paschold, R., 2001. "Electroslag strip cladding for corrosion resistance", Svetsaren, vol. 56, n°. 2-3, p. 62-67.

Silva, C.C., Afonso, C.R.M., Ramirez, A.J., Motta, M.F., Miranda, H.C. and Farias, J.P., 2012. "Aspectos Metalúrgicos de Revestimentos Dissimilares com a Superliga a Base de Níquel Inconel 625". Soldagem & Inspeção, vol. 17, n°. 3, p. 251-263.

Dos Santos, A., Possebon, S. and Martins, F.J.S., 2013. "Soldagem de tubulações revestidas utilizando metal de adição NiCrMo-3 (liga de níquel 625): Aspectos metalúrgicos", Proceedings of the 39° Brazilian Welding Congress, Curitiba, Brazil.

Silva, C.C., Miranda, H.C., Motta, M.F., Farias, J.P., Afonso, C.R.M. and Ramirez, A.J., 2013. "New insight on the solidification path of an alloy 625 weld overlay", Journal of Mater. Res. Tech., vol. 2, n°. 3, p. 228-237;

Suave, L.M., Cornier, J., Villechaise, P., Soula, A., Hervier, Z., Bertheaud, D., and Laigo, J., 2014a. "Microstructural evolutions during thermal aging of alloy 625: impact of temperature and forming process", Met. Mat, Trans. A, 45A, p. 2963-2982.

Suave, L.M., Cornier, J., Villechaise, P., Soula, A., Hervier, Z., Bertheaud, D., and Laigo, J., 2014b. "Impact of microstructural evolutions during thermal aging of alloy 625 on its monotonic mechanical properties", MATEC Web of Conference 14, 21001.

Xu, F., Liu, Y., Shu, F., He, P. and Xu, B., 2013. "Microstructural evolution and mechanical properties os Inconel 625 alloy during pulsed plasma are deposition process", Journal of Materials Science and Technology, 29(5), p.480-488.

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