Microstructure, hardness and petroleum corrosion evaluation of 316L/AWS E309MoL-16 weld metal

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ABSTRACT

The current work presents some observations about the effect of welding heat input on the microstructure, hardness and corrosion resistance of AWS E309MoL-16 weld metal, diluted with AISI 316L austenitic stainless steel plates. Such welds are widely used during overlay of equipment in the petroleum and gas industries. Results show that the welds contained δ-ferrite varying between vermicular to lathy morphology, typically encountered in welds which solidify in ferrite–austenite mode (FA). Conversely, contents and morphology of δ-ferrite in the weld metals were altered, showing an increase of welding heat input. The corrosion rate of the weld metal indicated that when higher levels of welding heat input are used the corrosion rate is reduced. This may be attributed to metallurgical changes, especially variations in the proportion of δ-ferrite, caused by changes in cooling rate.

1. Introduction

Austenite stainless steel consumables are widely used in the welding of stainless steel. Typical cooling rates during welding are quite rapid, leading to non-solidification. Such sudden drop to room temperature may result in a microstructure consisting of ferrite and austenite, depending on the chemical composition of the join. In the later case, the ferrite present is usually δ-ferrite formed at high temperatures [1,2].

Several researchers have dedicated themselves to the study of solidification and classification of the microstructure resulting in stainless steel weld metals [3–6]. Their research has made available essential results for the understanding of solidification mechanisms and solid states transformations, as well as data relating chemical composition to phase percentages, solidification form and microstructural morphology.

Several diagrams have been developed to predict the microstructure in the welding of similar and dissimilar metals [7–9]. They also relate various alloy elements in the weld metal that have a remarkable influence on the microstructure. These diagrams are based on two equations. The first one is the chromium equivalent equation (Cr_{eq}) that involves the ferritizing elements. The second one is the nickel equivalent equation (Ni_{eq}) which involves elements that stabilize the austenite phase. These equations, and the correspondent diagram WRC-1992 (Welding Research Council) developed by Kotecki and Siewert [9] are shown below.

$$Cr_{eq} = \%Cr + \%Mo + 0.7\,Nb \quad (1)$$

$$Ni_{eq} = \%Ni + 35(\%C) + 20(\%N) + 0.25(\%Cu) \quad (2)$$

Stainless steel with a Cr_{eq}/Ni_{eq} ratio below 1.2 solidifies in the primary austenite mode. In this mode, initially nucleation of austenite occurs in the liquid metal. As austenite grains grow ferritizing elements are segregated to the liquid, which may solidify as austenite or some δ-ferrite, depending on the level of ferrite promoting elements present in the liquid.

For Cr_{eq}/Ni_{eq} ratios between 1.2 and 1.5, the chemical composition of the liquid becomes favorable for the

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formation of δ-ferrite. Such microstructure is characteristic in the AF (austenite–ferrite) solidification mode. Should the chemical composition of the liquid not be sufficiently rich in ferritizing elements to promote the formation of δ-ferrite, solidification will entirely result in predominant austenitic microstructure (A).

The inconvenience of such solidification mode would reflect on the impurity segregation of elements such as phosphorous and sulphur in the remaining liquid. Additionally, the formation of low-melting-point compounds responsible for hot cracking usually occurs [1,10,11]. According to the literature, welds should contain some percentage of δ-ferrite at room temperature to ensure that noxious elements segregated during the solidification are retained by it, thus reducing hot cracking [11–13].

Influence of the chemical composition of the microstructure in austenitic stainless steel weld metals is well understood, being usually the only variable used to predict microstructure. However, other variables may also influence microstructural characteristics of weld metals, such as the cooling rate.

In the petroleum, gas and petrochemical industries AWS E309MoL-16 electrodes are frequently utilized for both linings and overlay applications. In these cases, dilution represents the main factor evaluated to predict microstructure, even though it usually constitutes a parameter often difficult to determine. In addition, ranges of welding parameters that can be used under these circumstances are often wide, generating alterations in the cooling rate of the weld. As a result, significant microstructural alterations could be obtained and thus influence mechanical properties and corrosion resistance. Under such perspective, the present study compiles observations regarding the effect of welding heat input on the microstructure, hardness and corrosion resistance of AWS E309MoL-16 austenitic stainless steel weld metal, diluted in AISI 316L austenitic stainless steel plates.

2. Materials

The base metal selected for the study was AISI 316L austenitic stainless steel, with a chemical composition shown in Table 1. AWS E309MoL-16 austenitic stainless steel covered electrodes with a diameter of 2.5 mm were selected as the filler metal for the experiments. The chemical composition of the filler metal, according to the manufacturer, is presented in Table 2.

Welding was performed in the plane position on AISI 316L stainless steel plate samples, with dimensions of 50×150×3 mm. Shielding metal arc welding (SMAW) was the technique implemented during the tests. Three weld beads were deposited on each plate, beside each other to form a layer. This procedure was performed manually, with control over the welding speed. A multi-process INVERSAL 450 welding source and a data acquisition system (arc current and voltage) was used. Three levels of welding heat input were used in this task. Specific parameters are shown in Table 3. The interpass temperature was maintained at 150 °C to avoid variations in the cooling rate among the passes.

Table 1 – Chemical composition of the AISI 316L austenitic stainless steel (weight %)

C	Mn	Cr	P	S	Mo	Si	Ni	N
0.022	1.36	16.93	0.03	0.003	2.09	0.47	10.11	411[a]

[a] Value in ppm.

Table 2 – Chemical composition of the AWS E309MoL-16 austenitic stainless steel weld metal (weight %)

C	Cr	Ni	Mo
0.03	23	13	2.5

Metallographic specimens were prepared conventionally through sandpaper and polishing using diamond paste. Etching was carried out using Vilela's reagent (100 mL of ethylic alcohol + 1 g of picric acid and + 5 mL of chloridric acid). For the metallographic analysis the following techniques were used: an optical microscope (OM), a Scanning Electron Microscope (SEM), and an energy dispersive X-ray spectroscopy (EDS). The level of ferrite δ was determined by means of an optical microscopy using the *Image Pro Plus* image analyzer, and through magnetic analysis using a ferritoscope. It should be noticed that each specimen was analyzed with 40 fields of view per data with a magnification of 200×. Vickers Microhardness measurements were also carried out with a load charge of 1 N (0.1 kgf) on each the welded specimen, with an average of 20 tests per specimen at random, and 20 tests for each morphology.

Corrosion tests on weld metal specimens at high temperature (300 °C), and immersed on heavy petroleum for 60 h. Brazilian heavy petroleum (from Campos Basin), kindly supplied by Centro de Pesquisas e Desenvolvimento Leopoldo Américo M. de Mello — CENPES/PETROBRAS, was utilized in the analysis. It is important to note, that the petroleum was not previously treated for the tests. Density, oil viscosity, and sulfur content in the sample were determined. Results of these analyses are shown in Table 4. Upon completion of the experiment, specimens were cleaned in kerosene for subsequent evaluation of their surface, using a SEM and the energy dispersive X-ray spectroscopy test. Corrosion rates in the samples were determined through Eq. (3) shown below, following ASTM G1 standard [14].

$$\text{Corrosion rate (mm/year)} = (K \times DM)/(S \times t \times q) \quad (3)$$

Where:

K constant ((mm h)/(year cm)) – 8.76×10^4;
ΔM mass loss in grams;

Table 3 – Welding parameters

Current (A)	Voltage (V)	Welding speed (cm/min)	Welding heat input (kJ/cm)
80	25	20.0	6.0
80	25	12.5	9.6
80	26	10.0	12.4