Influence of the filler metal on the microstructure of a 2507 super-duplex stainless steel multipass welding

Colaboración
Doris Ivette Villalobos Vera; Ivan Mendoza Bravo; Gabriela Valerio Canales, Tecnológico Nacional de México / Instituto Tecnológico de Veracruz

Fecha de recepción: 28 de mayo de 2024
Fecha de aceptación: 15 de octubre de 2024

RESUMEN: Este trabajo estudia la microestructura de un acero inoxidable superdúplex 2507 después de haber sido soldado mediante el proceso GMAW, utilizando dos materiales de aporte ER 2594 y ER 2209. Posteriormente, se analizaron muestras correspondientes al primer cordón de soldadura mediante microscopía óptica, empleando un ataque selectivo para identificar la ferrita, austenita y fase sigma específicamente. Los resultados mostraron la formación de fase sigma en los límites de grano ferrita/austenita en el metal de soldadura con ER 2594, observándose un incremento en la fase austenita y una disminución significativa de la ferrita, indicando la influencia de los elementos de aleación presentes en el material de aporte como el cromo y molibdeno para la formación de fase sigma y el nitrógeno y níquel en la formación de austenita.

PALABRAS CLAVE: acero inoxidable dúplex, proceso GMAW, microstructura, fase sigma.

ABSTRACT: This work studies the microstructural changes of a commercial 2507 superduplex stainless steel that was multipass-welded with the GMAW process using two filler metals ER 2594 and ER 2209. After welding, both specimens were analyzed by means of optical microsocopy, using selective etching to identify the ferrite, austenite, and sigma phase. The results showed the formation of sigma phase in the ferrite/austenite grain boundaries in the welding metal obtained with ER 2594 filler metal. The austenite fraction increased and the ferrite was reduced,indicating the influence of alloy elements in the filler mnetal such as chromium and molybdenum for the formation of sigma phase and nitrogen and nickel for the austenite formation.

KEYWORDS: duplex stainless steel, GMAW process, microstructure, sigma phase.

INTRODUCTIÓN

The use of superduplex stainless steel (SDSS) has been increasing over the years due to their excellent mechanical properties and high corrosion resistance, reason why they are used in the oil and gas industry [1]. Their microstructure consists in ferrite and austenite combining the stress corrosion resistance of ferritic stainless steel with the high toughness and pitting corrosion resistance of austenitic stainless steel [2]. Its chemical composition is perfectly balanced to stabilize both phases at room temperature and maintain their characteristics and properties. Cr and Mo stabilize the ferrite and Ni and N the austenite [3]. For dúplex stainless steels the formation of secondary phases such as sigma phase, carbides, nitrides, or secondary austenite among others is of main concern because they form at high temperatures in the range of 500°C-1000°C [4]. However, the most detrimental is sigma phase, which is an intermetallic compound with high Fe, Cr and Mo contents [5] and is often precipitated in the ferrite/austenite interface when duplex stainless steels are exposed to a high temperature during welding or post-weld heat treatment (6). For that reason, the amount of ferrite present in the microstructure may be related to the susceptibility of sigma phase formation in duplex stainless steels. One approach to predict the fraction of ferrite is to use the Creq/Nieq ratio which also indicates the solidification mode for stainless steels welding metal based on the chemical composition of the filler metal and base metal. For industrial applications the heat affected zone and the welding metal need to deliver at least the same properties of the base metal. Therefore, the selection of the filler metal should be according to their chemical composition, focusing on the the content of ferrite-promoting elements to relate the fraction of ferrite in the welding metal. For superduplex alloys there are two recommended filler metals: ER2209 and ER2594, which chemical composition is responsible to maintain the austenite/ferrite balance of the base metal after welding. They both have different amounts of chromium, molybdenum, nickel and nitrogen. Consequently, sigma phase may form if the filler metal contains high content of chromium and molybdenum since it may promote a high fraction of ferrite, disturbing the ferrite/austenite balance, and affecting the mechanical properties as well as corrosion resistance [7]. The aim of this work is to study the influence of the ferrite-promoting elements in the filler metal on the microstructure of the superduplex stainless steel after being multipass-welded.

MATERIALS AND METHODS

In this work, commercial 2507 superduplex stainless steel plates were used to make two multipass welding joints with the GMAW process and two different filler metals. Plates were 6 mm-thick, solution treated, and water quenched according to the manufacturer. Two filler metals of the duplex type were used ER 2209 and ER 2594, both 1.2 mm in diameter. All plates were prepared with a single V groove, 45° bevel angle, 1 mm root face and 3.2 mm root opening as indicated in Figure 1. The chemical composition of the materials is shown in Table 1, obtained by Optical Emission Spectroscopy.

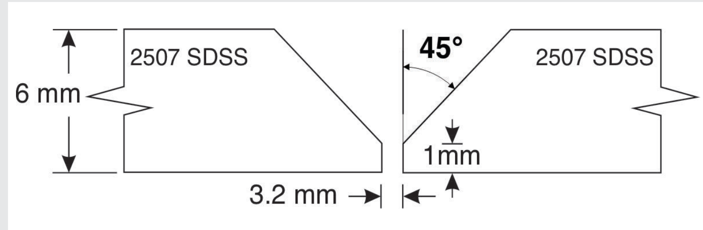

Figure 1. Single V Groove preparation
Fuente: Elaboración propia

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

Material	C	Si	Mn	Ni	Cr	Mo	N	Fe	Creq/Nieq ratio
2507 SDSS	0.05	0.40	0.88	5.78	23.40	3.23	0.27	Bal.	2.02
ER 2594	0.06	0.49	0.50	7.32	21.72	3.00	0.25	Bal.	1.65
ER 2209	0.09	0.45	1.26	7.73	19.98	3.14	0.15	Bal.	1.70

Fuente: Elaboración propia.

To determine the solidification mode for the 2507 SDDS, the Creq/Nieq ratio was calculated using the WRC-1992 diagram formula [8]:

$$Cr_{eq} = \mathrm{Cr} + \mathrm{Mo} + 0.7\mathrm{Nb} \quad \text{Eq.1}$$

$$Ni_{eq} = Ni + 35\mathrm{C} + 20\mathrm{N} + 0.25\mathrm{Cu} \quad \text{Eq.2}$$

Welding parameters

To establish the welding parameters and to obtain full penetration without visible defects, test beads were deposited on a sample of superduplex stainless steel plate. To protect the welding metal, argon was used as a shielding gas. Once the parameters were established (Table 2), three welding passes were needed to join the SDSS plates as shown in Figure 2. The three welding passes were deposited continuously.

Table 2. Welding parameters for specimens W2209 and W2594.

Shielding gas	Current (A)	Voltage (V)	Welding speed (mm/s)
Ar	300	30	3

Fuente: Elaboración propia.

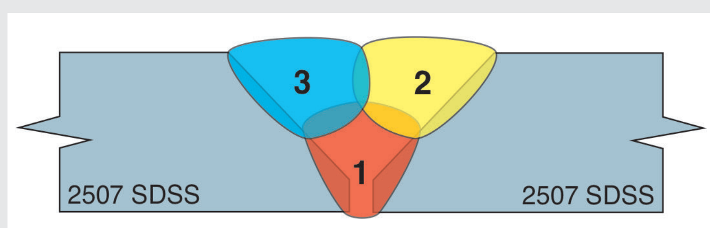

Figure 2. Multipass welding deposition.
Fuente: Elaboración propia.

Microstructural analysis

The microstructural analysis was performed using optical microscopy on samples from the heat-affected zone and the weld metal zone corresponding to the root pass.

The samples were prepared with silicon carbide sandpaper of different grades and polished with diamond paste of 6, 3 and 1 microns. KOH selective etching was used to reveal and identify the secondary phases, which distinguishes between ferrite, austenite, and sigma phase. Subsequently, image analysis was performed to quantify the percentages of the phases present.

RESULTS

Welding Metal

Figure 3 shows the microstructure of the base metal in the as-received condition. Figure 4 and Figure 5 show the welding metal of specimens W2209 and W2594. The original microstructure in Figure 3 shows a ferrite matrix with austenite islands elongated in the rolling direction and free of secondary phases. In contrast, the microstructure in specimen W2209 (Fig.4) shows polygonal austenite formed along with strings of delta ferrite as well as particles of sigma phase. The fraction of austenite increased to ≈90% and the content of sigma phase is ≈6%. For specimen W2594 (Fig. 5) the microstructure depicts an austenite matrix and strings of delta ferrite with butterfly-sigma phase inside. The fraction of austenite is around ≈90% and for sigma phase ≈10%.

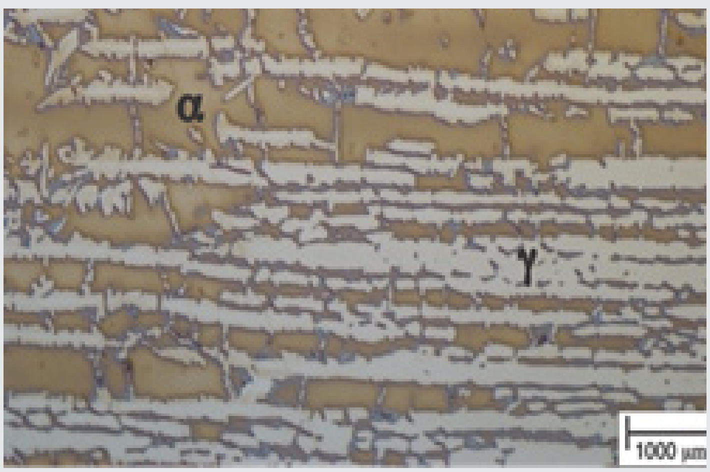

Figure 3. Microstructure of base metal in the as-received condition.
Fuente: Elaboración propia.

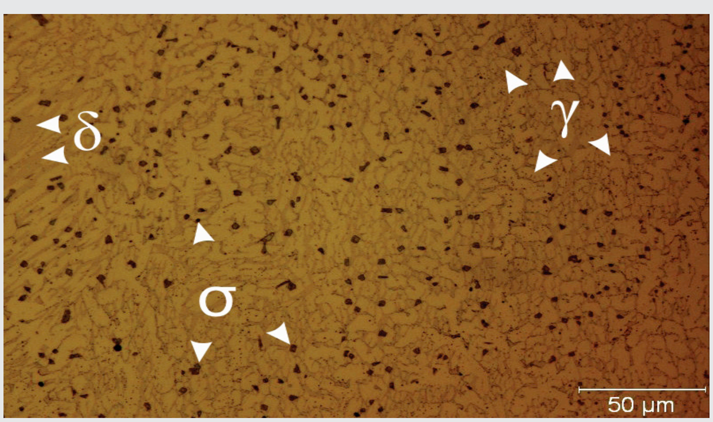

Figure 4. Microstructure of the welding metal in the root pass of specimen W2209.
Fuente: Elaboración propia

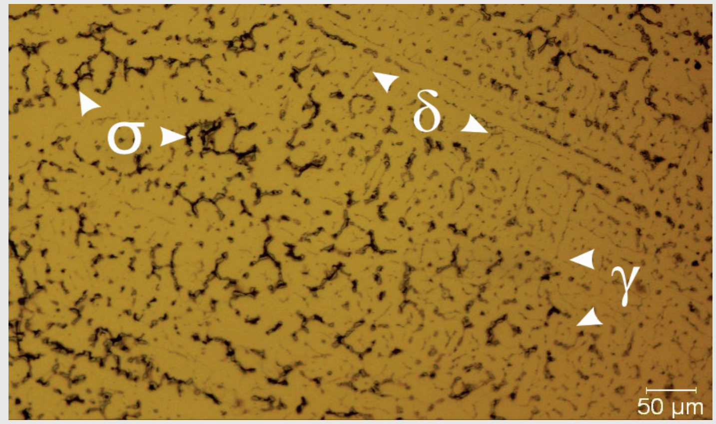

Figure 5. Microstructure of the welding metal in the root pass of specimen W2594.
Fuente: Elaboración propia.

Figure 6 and 7 show the microstructure of the heat affected zone in specimens W2209 and W2294. The microstructure in both specimens W2209 and W2294 shows the ferrite matrix with blocky and Widmänstatten austenite. Sigma phase is observed, however, is almost imperceptible in both specimens (<2%). Austenite fraction is around 27% for W2209 and 19% for W2594.

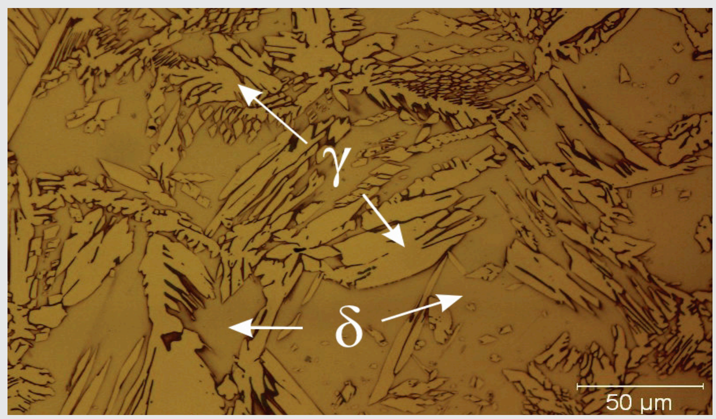

Figure 6. Microstructure of the heat affected zone in the root pass for specimens W2209.
Fuente: Elaboración propia.

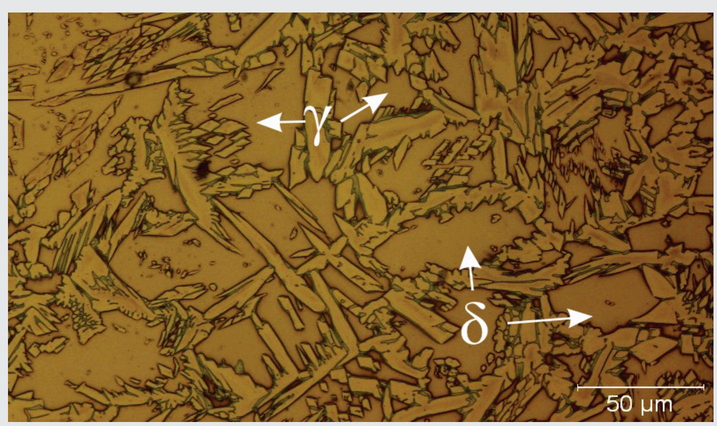

Figure 7. Microstructure of the heat affected zone in the root pass for specimens W2594.
Fuente: Elaboración propia.

Based on the resultant microstructures, the original austenite/ferrite balance is disturbed by the presence of sigma phase and the reduction of ferrite. The microstructure and the properties of the welding metal are generally controlled by the filler metal composition while the microstructure in the heat affected zone is determined by the weld thermal cycle and is therefore very sensitive to variations in the welding conditions [9]. Nevertheless, the sequence of transformation reactions in the welding metal and heat affected zone is the same [10], following:

$$L \rightarrow L+F \rightarrow z\ F \rightarrow F+A$$

According to the Creq/Nieq ratio, all commercial duplex stainless steels solidify as 100% ferrite (Figure 8) and the balanced microstructure depends on the solid-state transformation from ferrite to austenite during cooling. The Creq/Nieq ratio is around 2.25 for the 2507 superduplex stainless steel used in this study, indicating the sequence of phase transformation.

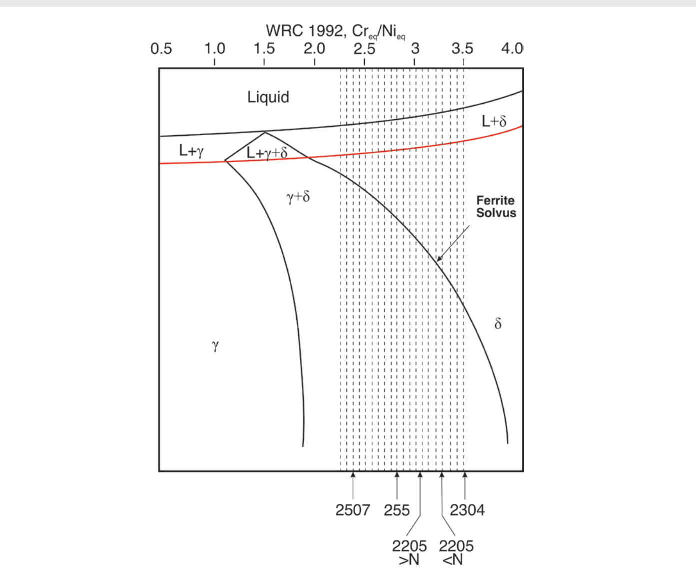

Figure 8. Biphasic region at high temperature in duplex alloys. Dotted lines correspond to the commercial duplex alloys. Fuente: Recuperada de Referencia [11].

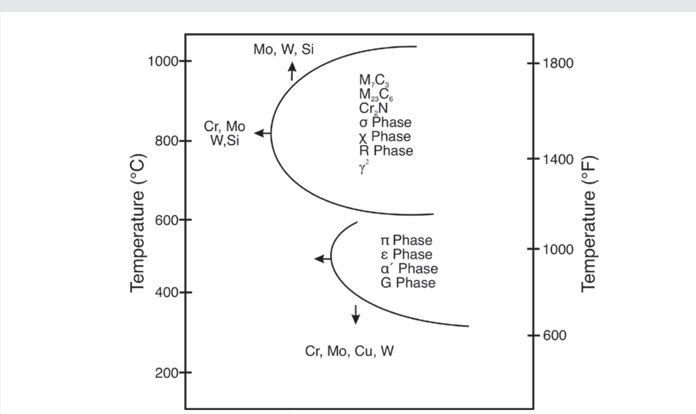

Figure 9. Diagram of secondary phases formation in duplex alloys. Fuente: Recuperada de Referencia [11].

Austenite phase can only nucleate and grow below the ferrite solvus. By controlling the processing temperature and cooling rate from that temperature, the proportion and distribution of both phases can be controlled [11]. During cooling, austenite phase will start to form when the temperature drops below ferrite solvus, and the transformation will increase at a rate controlled by the diffusion of nitrogen in the delta ferrite [12].

Therefore, welding a material that implies only one welding pass, the microstructural balance can be maintained if the cooling from the liquidus temperature is slow enough to permit the solid-state ferrite-austenite transformation, which can be considered as an equilibrium condition. However, during a multipass welding the cooling rate from the liquidus temperature is slow, allowing not only the ferrite-austenite solid state transformation but also the precipitation of secondary phases such as sigma phase in all zones of the joint.

The presence of sigma phase in the welding metal implies that high temperatures and slow cooling were experienced. Based on the diagram of secondary phases precipitation for duplex alloys in Figure 9, the range of temperature was around 1000°C - 600°C, where sigma phase can form along with other secondary phases. Despite there are some other secondary phases in that temperature range, only sigma phase was identified in the specimens.

Sigma phase is an intermetallic phase, hard and brittle which has a complex tetragonal crystal structure with a large unit cell [13]. Sigma is enriched in Cr and Mo relative to the nominal composition of the alloy, and because of this, it grows from the ferrite phase, which is also enriched in these elements, so that sigma nucleates and grow from ferrite with the simultaneous formation of secondary austenite by the eutectoid transformation ferrite→secondary austenite + sigma phase [13]. In duplex stainless steels, sigma phase particles normally nucleate at ferrite-austenite interphase boundaries and grow into the adjacent ferrite grains in the form of a cellular structure consisting of sigma phase and new austenite at temperatures between 675°C and 975 °C [14].

The Cr and Mo atoms would be absorbed from the matrix nearby sigma phase as the sigma precipitation occurred. Hence the corrosion resistance surrounding sigma phase decreased owing to the depletion of Mo and Cr at that local region. This decrease of corrosion resistance is detrimental to the material because that means that in certain service conditions, the material would fail due to the holding at high temperatures below the ferrite solvus for a certain time.

CONCLUSIONS

The formation of sigma phase due to the multipass welding in a 2507 super duplex stainless steel has been investigated, allowing to summarize the following findings:

1. ER2294 filler metal promotes a high fraction of sigma phase in the welding metal compared to ER 2209 filler metal.
2. Sigma phase forms preferentially in the microstructure of the welding metal due to the high temperature experienced during the deposition of welding passes.

Although the ER2594 and ER2209 are recommended to weld the 2507 superduplex stainless steel it is highly recommended to control the interpass temperature below. (800°C) during the deposition of welding passes. This will reduce the susceptibility of sigma phase formation and will assure the microstructural balance of ferrite and austenite to maintain the mechanical properties and corrosion resistance of the material.

ACKNOWLEDGEMENTS

The authors express their acknowledgement to TecNM/Instituto Tecnológico de Veracruz for the financial support.

REFERENCES

[1] Alhoud, A. R., Renton, N. C., y Deans, W. F. (2010). Hydrogen embrittlement of a super duplex stainless steel in acid solution. International Journal of Hydrogen Energy, 35(12),6455-6464.

[2] Magnabosco, R., y Alonso-Falleiros, N.(2005). Pit Morphology and Its Relation to Microstructure of 850°C Aged Duplex Stainless Steel. Corrosion 61, 130–136.

[3] Chail, C.K. (2016). Super and hyper duplex stainless steels: structures, properties, and applications. Structural Integrity Procedia 1755-1762.

[4] Goshm, S.K y Mondal, S. (2008). High temperature ageing behavior of a duplex stainless steel. Materials Characterization 59 1776-1783.

[5] Nishimoto, K., Saida, K. y Katsuyama, O. (2006). Prediction of Sigma Phase Precipitation in Super Duplex Stainless Steel Weldments. Weld World 50, 13–28.

[6] Yutaka, S. Sato y Kokawa, Hiroyuki. (1999). Preferential precipitation site of sigma phase in duplex stainless steel weld metal, Scripta Materialia, Volume 40, Issue 6, 659-663.

[7] Magnabosco, R. (2009) Kinetics of sigma phase formation in a duplex stainless steel. Materials Research 12, 321-327.

[8] Kotecki, D.J. y Siewert, T.A. (1992). WRC-1992 Constitution Diagram for Stainless Steel Weld Metals: A Modification of the WRC-1988 Diagram. Welding Research Supplement,171-178.

[9] Hemmer, H. y Grong, Ø. (1999). A process model for the heat-affected zone microstructure evolution in duplex stainless steel weldments: Part I. the model. Metallurgical and Materials Transactions A 30, 2915-2929.

[10] Davis, J.R. ASM Specialty Handbook Stainless Steels, ASM International, 1994.

[11] Lippold, J.C. y Kotecki, D.J. (2005). Welding Metallurgy and Weldability of Stainless Steels, first ed., Wiley, New York.

[12] Hall, E.O. y Algie, S. H. (1966) The Sigma Phase, Metallurgical Reviews 11 (1), 61-88.

[13] Villanueva, D., Junior, F., Lesley, R. y Padilha, A. (2006). Comparative study on sigma phase precipitation of three types of stainless steels: Austenitic, superferritic and duplex. Materials Science and Technology 22, 1098-1104.

[14] Hosseini, V.A., Karlsson, L., Wessman, S. y Fuertes, N. (2018). Effect of Sigma Phase Morphology on the Degradation of Properties in a Super Duplex Stainless Steel. Materials 11, 933.