EFFECT OF EXTERNAL ELECTROMAGNETIC FIELD ON CORROSION FATIGUE OF DUPLEX STAINLESS STEEL 2205 WELDED JOINTS

O. L. BILYY, J. GONZÁLEZ-SÁNCHEZ, C. ALEXANDRO DE LEÓN GOMEZ

Centre for Corrosion Research of Autonomous University, Mexico

Duplex stainless steel 2205 (DSS) is an alloy containing 22% of Cr and 5% of Ni. The steel microstructure is a matrix of *d*-ferrite BCC with *g*-austenite FCC grain islands in a 50:50 ratio. DSS is used in industry due to its high mechanical strength and corrosion resistance, that are better than of ferritic or austenitic stainless steels. During the welding process an electromagnetic interaction of low intensity was induced by applying axial external electromagnetic fields of 0; 3 and 12 mT. Microstructural characterization and the assessment of localized corrosion resistance in terms of pitting corrosion were conducted. Resistance to nucleation and growth of cracks was also evaluated in the low-cycle regime of corrosion fatigue test to observe the short crack behaviour. The electromagnetic interaction of low intensity (3 mT) was found to improve the localized corrosion resistance but the 12 mT one showed no improvement in this aspect, in comparison to 0 mT. The resistances to crack initiation and fracture toughness were also improved with the application of the 3 mT external electromagnetic fields due to the modification of the microstructural evolution during thermal cycle involved in the welding process.

Keywords: *corrosion fatigue, duplex steel, stress intensity factor, fracture resistance.*

Дуплексна нержавна сталь 2205 (ДНС) – це сплав з 22% Cr і 5% Ni. Сталеві мікроструктури – матриця з вмістом *d*-фериту із ОЦК структурою із вкрапленнями гранецентрованої кубічної ґратки з g-аустенітом у співвідношенні 50:50. ДНС використовують у промисловості завдяки високій механічній міцності та корозійній стійкості, кращій, ніж у феритних або аустенітних нержавних сталях. Під час зварювання індукували електромагнетну взаємодію низької інтенсивності, застосовуючи осьові зовнішні електромагнетні поля 0; 3 і 12 mT. Виконано мікроструктурний аналіз та оцінку локалізованої корозійної стійкості в умовах піттингової корозії. Стійкість до зародження та росту тріщин також оцінювали в малоцикловому режимі випробувань на корозійну втому для спостереження за поведінкою короткої тріщини. Встановлено, що електромагнетна взаємодія низької інтенсивності (3 mT) поліпшує локалізовану корозійну стійкість, але за 12 mT покращення не спостерігали порівняно із 0 mT. Стійкість до зародження тріщин і в'язкість руйнування також посилювалися під час застосування зовнішніх електромагнетних полів завдовжки 3 mT через модифікацію мікроструктурної еволюції за теплового циклу зварювання.

Ключові слова: *корозійна втома, дуплексна сталь, коефіцієнт інтенсивності напружень, стійкість до руйнування.*

Introduction. Attractive mechanical and electrochemical properties have significant influence on the ferrite-austenite (δ–γ) phase balance of approximately 50:50 and are used in demanding industries such as chemical, petrochemical, nuclear and power generation. However, exposure of DSS's to the arc fusion welding thermal cycle deteriorates these properties as a result of profound changes in microstructure and balance of phases; i.e. increasing and coarsening δ-phase [1–3]. The weld metal solidifies into coarse columnar structures virtually in a completely ferritic matrix and γ-phase grows at

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Corresponding author: O. BILYY, e-mail: biloresti@gmail.com the ferrite grain boundaries either allotriomorphic and Widmanstatten shaped or acicular intragranular [1, 4].

It is shown that while there are attempts to refine the weld metal grain structure of austenitic and ferritic stainless steels there is no research into grain refinement of DDS's δ matrix during welding to promote an increase of sites for nucleation and growth of γ-phase. Instead, research efforts have focused on post-weld heat treatment [1, 5] or adding elemental γ-phase stabilizers [1, 6]. This study seeks to evaluate the use of electromagnetic stirring during welding in terms of δ phase grain refinement and its effect on the δ/γ ratio and the mechanical properties.

The behaviour of cracks in the components and structures in engineering constructed with duplex stainless steel is strongly influenced by the mode and type of load, and the microstructural characteristics including chemical composition of the alloy, volumetric fraction of the phases, distribution, of grain size and heat treatment [7, 8]. Although some researchers had proposed to minimize this problem with post-weld thermal treatments, we proposed to use the low intensity electromagnetic action during welding with inert gas by electric arc welding to minimize the precipitation of unwanted phases, and also the redistribution and the change of the phase ratio δ/γ, which greatly improved the resistance to localized corrosion since it suppressed the precipitation of the σ and χ phases, as well as the formation of chromium carbides and nitrides [9].

The present investigation evaluates the effect of the application of external magnetic field during the process of gas metal arc welding of the DSS 2205 in the microstructural evolution associated with the thermal cycle of welding and its impact on the increased resistance to localized corrosion and fatigue cracking.

Materials and methods. Plates of DSS 2205 (6.35×70×150 mm) with a single V groove preparation (Fig. 1*a*), were welded using the gas metal arc welding with an ER-2209 electrode of 1.2 mm in diameter and as shielding gas a mixture of 98% Ar + + 2% O_2 (17 L/min) was used. Fig. 1*b* shows the experimental setup for welding with the application of an external magnetic field. The axial magnetic fields applied during welding were 0, 3 and 12 mT.

The welding torch was displaced at 3.6 mm/s with a stick of 10 mm. Current (236 to 248 A) and voltage (27.5 V) were adjusted in order to maintain an approximate heat input of 1.4 kJ/mm considering an efficiency of 75% for the gas metal arc welding process.

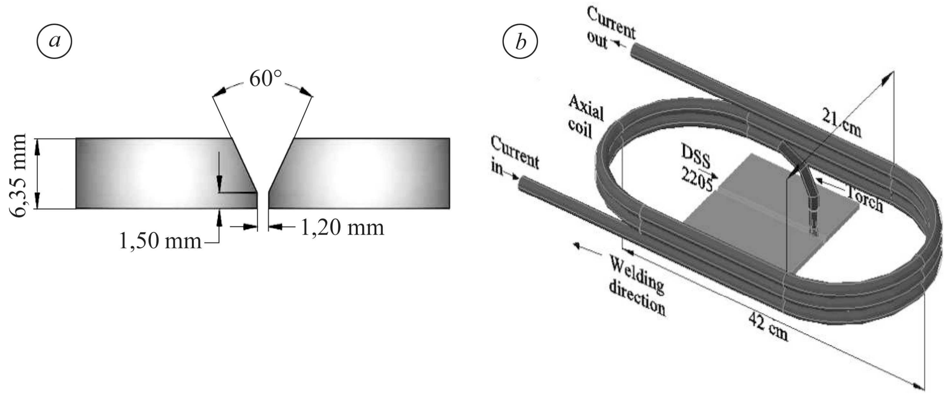

Fig. 1. Single V groove joint preparation (*a*) and experimental welding setup (*b*).

For the specimens preparation, transversal cuts were made in the direction of the weld bead and machined in a prism with a width of 5 mm, a height of 5 mm and a length of 100 mm, containing a weld bead in the centre, as shown in Fig. 2. Subsequently, they were cut with SiC paper of different granulometries up to 1200 and polished with diamond paste until a completely smooth surface was obtained. To reveal phases and grain boundaries, an electrochemical attack was performed in the 30% HNO_3 solution.

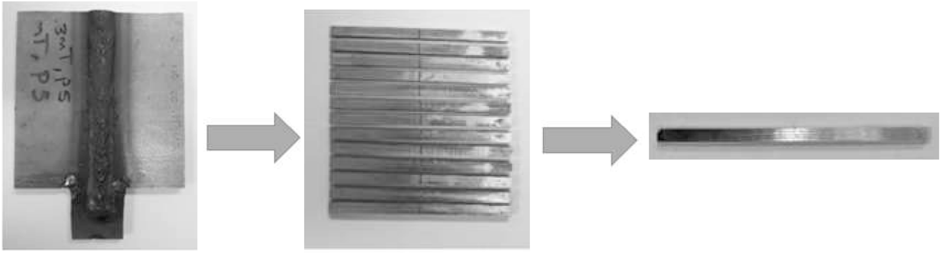

Fig. 2. Cross-section cuts to the weld bead.

Rectangular shape of the specimen with the geometric orientation shown in the right part of Fig. 2 was used for corrosion fatigue test with specimens dimensions of 5×5×100 mm. A sinusoidal waveform of load with a frequency of 0.90 Hz was used. The initial maximum stress of 0.99 σ_{ys} (yield strength) and a load ratio (R) of 0.5 was applied in the fatigue test. The loading was applied parallel to the short transverse (S) direction.

Fatigue tests were conducted in natural seawater at open circuit potential at ambient temperature. After determining the fatigue life (N_f), some interrupted fatigue tests at certain loading cycles were also performed. The cross-section and fracture surface were examined microscopically as demonstrated in Fig. 3.

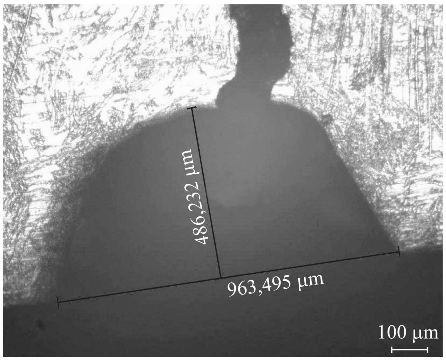

Fig. 3. A microscopy fracture surface view.

Results and discussion. The basis for determining the resistance of corrosion materials were the dependences of fatigue crack growth on the number of load cycles for different materials and working environments. These results are shown in Fig. 4.

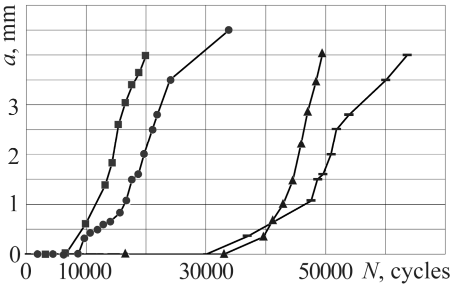

Fig. 4. Dependences of fatigue crack growth on the number of load cycles for different materials and working environments:
● – 0 mT – air;
■ – 0 mT – seawater;
lines – 3 mT – air;
▲ – 3 mT – seawater.

Using the crack growth data (Fig. 4) the statistical analysis of the Paris dependences was carried out for each of the cases. In Fig. 5 we can see that 0 and 3 mT have a similar behaviour with 3 mT being much better, on the other hand, welding with a 12 mT magnetic field presents an unfavourable behaviour even in the worse condition than conventional welding. In seawater 0 and 3 mT welds have a very similar behaviour until the stress is reduced to 90% of the sedation limit where the effect of the electrolyte is more evident and the electrochemical characteristics previously shown by 3 mT welds make a difference in favour of the same being more resistant to the initiation of cracks.

For the determination of the crack behaviour characteristics in the studies of structural elements, the experimental basis and the analytical relationship, described by the Paris dependence [10], were used.

$$\frac{da}{dN} = C(\Delta K)^n ,$$

where C and n – constants of the system "material–environment"; ΔK – stress intensity factor.

In addition, based on the presented results for the Paris curves, the parameters for the studied system "material–environment" were determined.

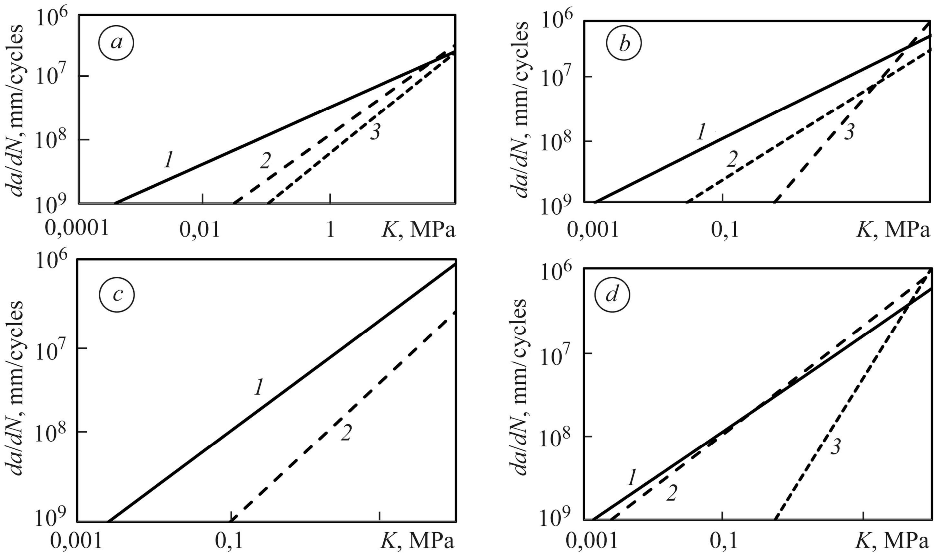

Fig. 5. Paris dependence for different systems "material–environment". *a* – in air (*1* – 0 mT – air; *2* – 12 mT – air; *3* – 3 mT – air); *b* – for 0 mT (*1* – air; *2* – 99 – seawater; *3* – 90 – seawater); *c* – for 3 mT (*1* – air; *2* – 99 – seawater); *d* – seawater (*1* – 0 mT – 99; *2* – 3 mT – 99; *3* – 0 mT – 90).

Parameters for the studied system "material–environment"

"Material–environment" system	C	n
0 mT – air	1.22×10^{-8}	0.716
12 mT – air	3.35×10^{-8}	0.448
3 mT – air	6.14×10^{-9}	0.808
0 mT – seawater	1.28×10^{-8}	0.346
3 mT – seawater	3.43×10^{-8}	0.622

The results of these studies are shown in the Table. These results will make it possible to enter the obtained results into existing databases for estimating the corrosion resistance of real objects made of the studied materials.

CONCLUSIONS

In fatigue tests it is concluded that the cracks nucleate on the surface of the weld metal, both in the joints welded in a conventional manner and in the welding assisted by the 0; 3 and 12 mT electromagnetic field. However, cracks take more time to start on welded joints under the influence of the 3 mT magnetic field than on welded joints without a magnetic field. Based on experimental research the criteria value of parameters of the system “material–environment” for the duplex stainless steel 2205 is determined. Applying analytical relations for SIF characteristics these results will make it possible to enter the obtained results into existing databases for estimating the corrosion resistance of real objects made of the studied materials.

1. *Varol I., Lippold J. C., and Baeslack W. A.* Welding of duplex stainless steels // Key Eng. Mat. – 1992. – **69–70**. – P. 217–252.
2. *Gunn R. N.* Duplex stainless steels: Microstructure, properties and applications. – Woodhead Publ. LTD, 1997.
3. *Kordatos J. D., Fourlaris G., and Papadimitriou G.* The effect of cooling rate on the mechanical and corrosion properties of SAF 2205 (UNS 31803) duplex stainless steel welds // Scripta Materialia. – 2001. – **44**. – P. 401–408.
4. *Effect* of weld metal chemistry and heat input on the structure and properties of duplex stainless steel welds / V. Muthupandi, P. Balasrinivasan, S. K. Seshadri, and S. Sundaresan // Mat. Sci. and Eng. – 2003. – **358**. – P. 9–16.
5. *Phase* transformation and mechanical behavior in annealed 2205 duplex stainless steel welds / R. Badji, M. Bouabdallah, B. Bacroix, and C. Kahloun // Mat. Characterization. – 2008. – **59**. – P. 447–453.
6. *Effect* of shielding gases on mechanical and metallurgical properties of duplex stainless-steel / P. Sathiya, S. Aravindan, R. Soundararajan, Haq A. Noorul // J. Mat. Sci. – 2009. – **44**. – P. 114–121.
7. *Вплив* карбідів титану на формування мікроструктури та підвищення механічних характеристик металу зварних швів / І. К. Походня, В. В. Головко, С. М. Степанюк, Д. Ю. Єрмоленко // Фіз.-хім. механіка матеріалів. – 2018. – **54**, № 5. – С. 76–81.

   (*Influence* of titanium carbides on the formation of microstructure and improvement of the mechanical characteristics of weld metals / I. K. Pokhodnya, V. V. Holovko, S. M. Stepanyuk, D. Yu. Yermolenko // Materials Science. – 2019. – **54**, № 5. – P. 690–696. https://DOI.org/10.1007/s11003-019-00234-x)
8. *Miller K. J.* The behaviour of short fatigue cracks and their initiation. Part I. A review of two recent books // Fatig. & Fract. of Eng. Mat. & Struct. – 1987. – **10**. –P. 75–91.
9. *Improvement* of localised corrosion resistance of AISI 2205 duplex stainless steel joints made by gas metal arc welding under electromagnetic interaction of low intensity / M. A. García-Rentería, V. H. López-Morelos, R. García-Hernández, L. Dzib Pérez, E. M. García-Ochoa, and J. González-Sánchez // Appl. Surf. Sci. – 2014. – **321**. – P. 252–260.
10. *Paris P. and Erdogan F.* A critical analysis of crack propagation laws // Trans. ASME: J. Basic Eng. – 1963. – **15**, № 4. – P. 528–534.

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